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On the cover: The railroad share of the grain and oilseed transportation market has declined in recent years. In “Rail Market Share of Grain and Oilseed Transportation,” Marvin Prater and co-authors identify the factors responsible for the decrease in rail market share of grain and oilseed transportation since 2001.

A Message from the JTRF Co-General Editors

Seven papers appear in this issue of JTRF. They are:

- Spatial Transferability: Analysis of the Regional Automobile-Specific Household-Level Carbon Dioxide (CO_2) Emissions Models
- A Framework for Determining Highway Truck-Freight Benefits and Economic Impacts
- Future Substitutes for Diesel Fuel in U.S. Truck and Railroad Freight Transportation
- U.S. and European Freight Railways: The Differences That Matter
- Modeling User Equilibrium in Microscopic Transportation Simulation
- Introduction of Heavy Axle Loads by the North American Rail Industry
- Rail Market Share of Grain and Oilseed Transportation

Siuhi et al. write on spatial transferability of household-level automobile-specific carbon dioxide emissions models and evaluate four methods that can be used to do so. These methods are: the Naïve Transfer method which uses the parameters of models estimated for one region to predict carbon dioxide emissions in another region; the Joint Context Estimation method combines datasets from the application and estimation regions to estimate parameters for an application region; the Bayesian Updating method "estimates parameters for the application region based on the combined parameter estimates from the estimation and application region;" and the Combined Transfer Estimator method which generalizes the Bayesian Updating method by accounting for transfer bias. Based on these methods, the authors estimate exponential regional models of carbon dioxide emissions, whose explanatory variables are population density, household size, vehicles per household, and total income. Then they evaluate these models based on their coefficients of determination and a transfer index measuring how well the parameters estimated for one region predict carbon dioxide emissions in other regions. Among their findings are population density reduces carbon dioxide emissions by reducing travel, and that larger household size, higher household incomes, and the number of vehicles per household increase carbon dioxide emissions from travel. Further, they find that models estimated for the Midwest, South, and West regions predict carbon dioxide emissions in the Northeast better than those developed for the Northeast. On the contrary, they find that models developed for the Northeast, South, and West do not perform well in predicting carbon dioxide levels in the Midwest. Another result is the Combined Transfer Estimator method produces superior prediction, followed by the Bayesian Updating, Joint Context Estimation and the Naïve Transfer method in that order.

Wang, Sage, Goodchild, Jessup, Casavant, and Knutson fill a gap in the freight transportation literature that results from the absence of a "nationally-accepted framework for analyzing the full range of freight-related impacts stemming from transportation infrastructure projects." Their goal is to provide a methodology that accounts for truck-specific benefits of projects within a general equilibrium framework. In developing their methodology, the authors drew from discussions they had with members of the Washington State Freight Plan Technical Teams. The authors were asked to identify important measurable community impacts of freight projects and review current methods the Washington State Department of Transportation (WSDOT) uses in prioritizing projects. The Technical Teams' prioritized benefits included improved travel times, travel time reliability, reduced truck operating cost, improved safety, truck network connectivity improvement, network resiliency, improved air quality, and long-term jobs. The proposed methodology included some, but not all, of these benefits. Particularly, it included travel time savings estimated from changes in truck vehicle hours traveled, operating cost savings, environmental impacts, and regional economic impacts in terms of job creation. To test their methodology, the authors applied it to a road widening project on a major interstate in the state of Washington. Further, they developed four scenarios to test the short- and long-term impacts of infrastructure improvements at the county and state levels. Their results show that freight investments improve transportation performance and confer direct benefits on other parties and generate economic impacts in terms of job creation. The authors also found that type of regional industrial base is important in determining what types of benefits will be realized.

In the third paper, Phillip Baumel writes on future substitutes for diesel fuel in U.S. trucking and railroad freight transportation. He notes the advantages and disadvantages of gasoline and diesel engines and discusses alternatives for diesel fuel. These alternatives include biodiesel from inedible fats and oils, renewable diesel from hydro-treated vegetable oils or animal fats, algae biofuel, natural gas, synthetic fuel, hydrogen, and electricity. He discusses the factors preventing each alternative from becoming dominant. For example, he notes that for natural gas, higher vehicle cost, reduced vehicle operating range, insufficient number of natural gas refueling stations, inadequate pumping capacities at some natural gas refueling stations, inadequate sizes of natural gas engines, fuel storage, and non-fuel storage costs (which are the costs of modifying an engine to burn natural gas) prevent its widespread use. In other parts of the paper, Baumel discusses improvements in fuel efficiency as partial substitutes for diesel fuel. He notes that between 1975 and 2011, railroad fuel efficiency increased by 128%, saving 4.7 billion gallons of diesel fuel in 2011, and gains in fuel efficiency will continue in the future as older rail cars and locomotives are replaced by newer more efficient ones. For trucks, he also notes gains in fuel efficiency that are not as high as in the railroads. Among Baumel's conclusions is that motor carriers' use of biodiesel and other mandated fuels is unlikely unless the prices of these fuels fall below those of petroleum-based fuels.

Furtado's article examines key factors that explain differences between U.S. and European freight railways with the aim of providing guidelines to improve European railroads and identifying lessons from European experiences that would be beneficial to U.S. railroads and policy makers. His methodology focuses on identifying modal share differences in terms of ton kilometers, competitive positions of non-surface modes, shipment distances, and commodity mix. He argues that his approach departs from others by accounting for intra-city truck movements. Furtado also analyzes structural factors, productivity and profitability, operations, institutional framework, and regulatory reforms that influence railroad activity. From his analyses he concludes that differences between U.S. and European railroads in terms of market shares can be explained by commodity mix, inland shipment distances, and competitiveness of non-surface modes. Additionally, his analysis shows that U.S. railroads have higher productivity than European railroads, which he found move less cargo, have higher costs, and are barely profitable. According to Furtado, differences in average train weight in U.S. and European railroads are due to infrastructure and equipment constraints. He suggests that European freight railways can be revived by reducing operating costs.

Cheng and Wang use the TRANSIMS to model user equilibrium in traffic assignment. They develop three heuristics to reach user equilibrium in the Waldrop sense and at the same time minimize computing burden and execution. The first, Routing Heuristic, produces routes for all travelers based on shortest paths; the second, Micro-simulation Heuristic, models travel actions and reroutes travel paths; and the third, Equilibrating Heuristic, "determines a network-wide dynamic equilibrium for all travelers … over time." By using TRANSIMS, the authors note that they combine static and dynamic traffic assignment techniques, improve simulation control, enhance convergence, and shorten computation time. They apply their method to the Texas Medical Center area of Houston, TX, which consists of 142 buildings, including hospitals, colleges, and research centers with 72,000 employees and 32,000 students. Among their results are that the performance of their simulation is comparable to the traffic model standards of the Houston MPO and show considerable improvements over others in terms of modeling efficiency. A sensitivity analysis they conducted using a fixed-time signal scenario shows that the scenario generates less traffic volume compared with time-actuated signals and results in less travel time.

Carl Martland writes on the introduction of heavy axle loads (HAL) by North American Railroads. He estimates the net benefits of increasing gross vehicle weight to 286,000 pounds by considering the impacts on operations and infrastructure. He notes that at the initial stage of the HAL implementation, Burlington Northern concluded that an increase of rail vehicle weight to 286,000 pounds was justifiable. Comparatively, the Canadian National railroad opted for a lower weight of 263,000 pounds because of its reluctance to invest heavily in strengthening its bridges; CSX concluded that the change was competitive with some of its projects; and Norfolk Southern railroads made the necessary investments to accommodate the change. According to Martland, the success of the initial move towards this change led many major railroads to accept railcars of this weight, and the change was quickest where traffic growth was greatest (e.g., coal transportation) and where the tracks and bridges could handle the stresses from such heavy railcars. In other areas where products such as grain move on light density lines (short lines and regional railroads), the ability to increase gross vehicle weight to 286,000 pounds was limited and required heavy investments. According to Martland the benefits from using vehicles with 286,000 pound axle weight depend upon the extent of implementation, car characteristics, and unit cost. These notwithstanding, important benefits include fewer freight cars and car miles, higher net-to-tare and lower gross-to-net weight, fewer train crews, and increased capacity. He found that after the switch to the larger car costs related to rail, turnouts, and bridges declined or rose less than expected due to improved inspection technologies, better maintenance practices, better rail metallurgies, and more effective grinding. This cost decline resulted in net benefits exceeding $600 million per year. Additionally, he found that as a result of the switch, railroads now operate shorter cars.

The last paper by Prater, Sparger, Bahizi, and O'Neil develops a state-level statistical model to determine the major factors contributing to the decline in rail market share of grain and oilseed transportation since 2001. They use a linear regression model whose dependent variable is rail market share of grain and oilseed-production per year and data for 21 states that produce grain and oilseed. Their independent variables include yearly production capacities of ethanol and biodiesel by state, barge and rail rates, diesel fuel price by state, distance to ports, and others. Prater et al. found that ethanol and biodiesel production, truck rates relative to rail rates, distance to port, the amounts of grains and oilseeds exported, the quantity of grains used in animal feed, size of grain shipment by rail, and commodity type affected rail market share. Some specific results are that every one million gallons of ethanol produced in a state reduced rail market share by 0.007%; the more soybeans transported by trucks reduced rail market share; and geographic concentration of animal feeding increased rail market share, as did commodity composition in a state (e.g., the area devoted to wheat, cottonseeds, and flaxseeds).

Michael W. Babcock
Co-General Editor

Kofi Obeng
Co-General Editor

Spatial Transferability: Analysis of the Regional Automobile-Specific Household-Level Carbon Dioxide (CO_2) Emissions Models

by Saidi Siuhi, Judith L. Mwakalonge, and Judy Perkins

This paper compared performance of methods for combining model information estimated in one region and applied to another region to improve estimation results. The application is for models developed to estimate household-level automobile-specific CO_2 emissions. The results indicated that automobile-specific CO_2 emissions models can be transferred from one geographical region to another. The estimates of CO_2 emissions can assist agencies such as policy makers, businesses, and transportation planners to track trends and identify opportunities to reduce CO_2 emissions and increase efficiency of transportation systems to lessen their impact on global warming, climate change, and air quality standards.

INTRODUCTION

The primary determinants of household-level carbon dioxide (CO_2) emissions produced from vehicle sources are fuel carbon content, vehicle fuel efficiency, and vehicle miles traveled (USDOT 2009, Chiou et al. 2009). Vehicle tailpipe carbon dioxide emissions contribute about 95% of total carbon dioxide emissions produced from transportation sector-related sources. In an effort to reduce emissions, most transportation and planning agencies are required by state and local governments to forecast the amount of emissions and propose strategies and policies for reducing the carbon dioxide in their regions. One of the approaches used to accomplish this is the development of statistical models to estimate the amount of the CO_2 emissions and then use the models to forecast future emissions. The models incorporate factors that influence vehicle travel to provide the estimates of CO_2 emissions produced per modeling unit selected, e.g., per trip. In other words, the models determine the magnitudes and patterns of various variables that capture characteristics related to socioeconomic, demographic, land use, and transportation systems of a region on vehicle travel (Chiou et al. 2009, Brownstone and Golob 2009). Most states and local governments require estimation of CO_2 emissions and other greenhouse gases to track trends of CO_2 emissions in their regions. The main objective is to reduce the impact of CO_2 emissions on global warming, climate change, and air quality standards. The estimates help policy makers, businesses, and transportation planners to evaluate current policies and propose future alternatives to improve efficiency of transportation systems and reduce CO_2 emissions.

Most of the models for predicting CO_2 emissions are estimated using cross-sectional data. The applications of such models are twofold. Firstly, the models can be applied to forecast the amount of CO_2 emissions produced in the same region but at different time periods based on extrapolation of cross-sectional variations. This type of application is referred to as "temporal transferability" of the models. Secondly, the models estimated from one geographic region can be applied to estimate CO_2 emissions in a different geographic region. This type of application is referred as "spatial transferability" of the models.

The potential benefits of the spatial transferability of the models cited in the literature include reduction and/or elimination of large data collection and model development efforts in the application region (Karasmaa 2007). Application region refers to a region where data and/or parameters were applied from another region, whereas estimation region refers to a region where data were collected and/or parameters were estimated. In addition, the spatial transferability of the models is more important to the application regions, which have limited data for estimation, evaluation, and prediction of the impacts of CO_2 emissions on air quality, climate change, and global warming. This is potentially very useful for small regions or communities that would like to quickly/easily estimate CO_2 emissions from vehicle use but do not have adequate data for developing their own model. The transfer methods can incorporate model information from other regions to make up for the local data shortfall. Additionally, the growing interest for integrating climate change into the transportation planning process to reduce the impacts of greenhouse gas emissions on global warming, climate change, and air quality conformity also highlights the importance and potential of the spatial transferability of regional household-level CO_2 emissions models (FHWA 2008).

In the literature, current empirical studies have mainly focused on establishing a relationship between CO_2 emissions and different attributes of socioeconomic, demographic, and land use variables. However, very limited research studies have been done to evaluate spatial transferability and prediction performance of regional household-level automobile-specific CO_2 emissions models formulated using cross-sectional data. To address this limitation, the primary objectives of this paper are as follows:

1. To analyze the potential of spatial transferability of regional household-level automobile-specific CO_2 emissions models. In this paper, the regional household-level CO_2 emissions models are developed for four regions in the U.S., namely, Northeast, Midwest, South, and West. These four regions were selected because they are included in the National Household Travel Survey (NHTS) datasets and provide opportunity to analyze the effect of sample size on the spatial transferability of the models. In this analysis, a model developed for each region is transferred to predict automobile-specific household-level CO_2 emissions in the other regions. In addition, a national CO_2 emissions model is developed and transferred to predict CO_2 emissions of the four regions.
2. To evaluate different methods for transferring travel data or parameters of a model from one geographical region to another and their prediction performance for the models developed in objective one (1) above.

Although significant changes have occurred since the mid-1990s in terms of vehicle travel, as of today the automobile is still the dominant travel mode in the United States. Also, most cars still use gasoline. This suggests that CO_2 emissions generated from household vehicles is still a major problem that needs to be addressed to reduce CO_2 impact on global warming, climate change, and air quality.

LITERATURE REVIEW

A review of literature on the amount of CO_2 produced from vehicle emissions revealed that several previous studies have attempted to develop a relationship that exists between socio-economic, land use, and transport systems and CO_2 emissions (Grane 2000, Ewing and Cervero 2001, Handy et al. 2005, Newman and Kenworthy 1989, Stead 1999). The most recent studies have also continued to investigate the relationship between CO_2 emissions as a function of land use patterns and travel behavior (Bento et al. 2005, Geurs and Wee 2006). The majority of these empirical studies agree that densification of land use measured in terms of housing units per square mile reduces vehicle miles of travel, energy consumption, and emissions (Stone et al. 2007, TRB 2009). In other words, regions with high housing units per square mile produce less CO_2 emissions compared with similar regions with low housing units per square mile. Another study by Akisawa and Kaya (1998) investigated the optimal land use in urban areas that would minimize energy consumption in transportation. This study concluded that minimum energy consumption occurs when business areas are located around the center of a city, whereas residential areas are located in suburbs.

Furthermore, some of the past studies have used disaggregate travel data to establish the relationship between attributes of land use, household, and vehicle use (Chiou et al. 2009, Brownstone and Golob 2009, Bento et al. 2005, Boussauw and Wiltox 2009). Similarly, these studies indicated that land use density directly influences vehicle usage, which in turn influences fuel consumption and emissions. For example, a study by Boussauw and Witlox (2009) indicated that vehicle energy performance increases with land use density. In addition to land use density, studies also have shown that residents residing in rural areas produce more carbon dioxide emissions per trip than urban or suburban households (USDOT 2009). This is could be partly due to rural residents driving relatively longer trips to service locations with less fuel-efficient vehicles than urban residents. A most recent study by Mwakalonge et al. (2012) evaluated prediction performance of carbon dioxide emission models.

Notwithstanding significant research efforts on estimation and prediction of CO_2, still very limited studies have evaluated the significance and importance of spatial transferability of the models. Siuhi et al. (2012) empirically assessed the spatial transferability of CO_2 emissions models using the 2009 National Household Travel Survey (NHTS) dataset. This study focused on a single pair of cities in one state. This was a major limitation of the analysis because the two cities shared similar populations, urban form, and climate and are of modest size. In other words, the study focused the analysis on a case of two cities within the same state and in relatively close proximity. Using a single pair of cities is unlikely to provide general insight and justification for other dissimilar pairs of cities. Thus, analysis of more pairs of regions or cities would warrant a justification for transferability of travel data or parameters of a model estimated from one region and applied to another region to improve prediction performance.

SPATIAL TRANSFERABILITY METHODS

This paper evaluates four transfer methods which are commonly used to transfer model parameters and/or travel data from one geographical region to another. In the literature, several empirical studies have evaluated different methods used for spatial transferability of model parameters and their predictive performance (Karasmaa 2007, Atherton and Ben-Akiva 1976, Badoe and Miller 1995a and 1995b, Koppelman and Wilmot 1982, Mohammadian and Zhang 2007, Zhang and Mohammadian 2008). The transfer methods evaluated include Naïve Transfer, Joint Context Estimation, Bayesian Updating, and Combined Transfer Estimator. These past studies have applied these methods to spatially transfer trip-generation and mode choice models. On the other hand, a recent study by Siuhi et al. (2012) also attempted to apply these four transfer methods to spatially transfer CO_2 emissions model between a pair of cities within one state. As stated earlier, applying the transfer methods for only a single pair of cities within one state does not provide sufficient information on whether the methods can be applied to other disparate pairs of cities or regions to produce similar results. The following subsection briefly discusses the transfer methods evaluated in this research.

Naïve Transfer

The Naïve Transfer method involves a transfer of model parameters estimated from one region to predict CO_2 emissions of another region while completely ignoring local travel data. For instance, the model parameters calibrated using the Northeast region is used to predict CO_2 emissions of the Midwest region without making any modifications. Application of this method assumes that socioeconomic, demographic, land use, transport systems, and other relevant factors that affect CO_2 emissions in the estimation region and application region are the same, which may be unrealistic. This implies that model parameters estimated from the estimation region can be used in the application region without any further modification. In other words, parameters of the estimation region are used in the application region while completely ignoring the travel data from the application region. Mathematically, this transfer of parameters is done by applying restrictions on the specified model as shown in Equation 1. The subscript i refer to estimation region while the subscript j refers to application region.

(1) $\boldsymbol{\beta_i} = \boldsymbol{\beta_j} = \boldsymbol{\beta}$ and $\lambda_i = \lambda_j = \lambda$

Where:

$\boldsymbol{\beta_i}$ is the vector of parameters from the estimation region
$\boldsymbol{\beta_j}$ is the vector of parameters of the application region
λ_1 is the constant term from the estimation region
λ_2 is the constant term from the application region

The least squares estimator $\boldsymbol{\beta}$ of the unknown vector of parameters of the model parameters is estimated as follows:

(2) $\boldsymbol{\beta} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y}$

Where:

Y is the vector of response variable from the estimation region.
X is the matrix of explanatory variables from the application region
$\mathbf{X}^T$ is the transpose of a matrix X

In practice, however, this is unrealistic and the assumption put forth is too strong to justify its validity, hence, transferability of the model is done with inclusion of travel data collected from the application region.

Joint Context Estimation

This method combines the datasets from the estimation region and application region to estimate parameters of the application region. For example, combined data from the south region (referred to as estimation region) and west region (referred as application region) are combined to estimate the parameters of the west region. This method assumes acceptance of the homogeneity hypothesis of the parameters from the estimation region and application region. Therefore, the true model parameters governing CO_2 emissions and their error variance are the same across space or spatially. In other words, the method assumes neither the observed factors known to impact the CO_2 emissions specified in the model nor that the unobserved factors are different across the two regions. For a detailed discussion about this method from past studies see Ben-Akiva and Morikawa (1990), Bradley and Daly (1991), and Ben-Akiva and Bolduc (1987). In this paper, datasets from the estimation region and application region are combined to yield the parameters used to predict CO_2 emissions of the application region. This is done by imposing restrictions on the specified model as shown below.

(3) $\boldsymbol{\beta_i} = \boldsymbol{\beta_j} = \boldsymbol{\beta}$ and $\lambda_i = \lambda_j = \lambda$

Where:

$\boldsymbol{\beta_i}$ is the vector of parameters of the estimation region

$\boldsymbol{\beta}_j$ is the vector of parameters of application region
λ_1 is the constant term of the estimation region
λ_2 is the constant term of the application region

The least squares estimator $\boldsymbol{\beta}$ of the unknown vector of parameters of the model parameters is estimated as follows:

(4) $\boldsymbol{\beta} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{Y}$

Where:

$\mathbf{Y} = \begin{bmatrix} \mathbf{Y}_i \\ \mathbf{Y}_j \end{bmatrix}$ is the vector of response variables from the estimation and application regions, respectively.

$\mathbf{X} = \begin{bmatrix} \mathbf{X}_i \\ \mathbf{X}_j \end{bmatrix}$ is the matrix of explanatory variables from the estimation and application regions, respectively.

$\mathbf{X}^T$ is the transpose of a matrix $\mathbf{X}$

Bayesian Updating

This transferability method was introduced by Atherton and Ben-Akiva (1976). The Bayesian Updating method estimates parameters of the application region based on the combined parameter estimates from the estimation region and application region. Unlike the Joint Context Estimation method, which directly combines the datasets from the estimation and application regions, this method combines the parameters of the two regions to yield unbiased parameters of the application region. The method uses traditional Bayesian analysis, assuming the two regions share the same set of parameters that are unbiased estimators of the true parameters of the application region. This method is expressed mathematically as follows:

(5) $\hat{\boldsymbol{\beta}}_{BU} = \left(\boldsymbol{\Sigma}_i^{-1} + \boldsymbol{\Sigma}_j^{-1}\right)^{-1} \left(\boldsymbol{\Sigma}_i^{-1}\hat{\boldsymbol{\beta}}_i + \boldsymbol{\Sigma}_j^{-1}\hat{\boldsymbol{\beta}}_j\right)$

Where:

$\boldsymbol{\beta}_{BU}$ is the transferred parameters of the application region
$\boldsymbol{\beta}_i$ is the estimated parameters from the estimation region
$\boldsymbol{\beta}_j$ is the estimated parameters from the application region
$\boldsymbol{\Sigma}_i$ is the covariance matrix of the estimation region
$\boldsymbol{\Sigma}_j$ is the covariance matrix of the application region

The corresponding covariance matrix is estimated as follows:

(6) $\boldsymbol{\Sigma}_{BU} = \left(\boldsymbol{\Sigma}_i^{-1} + \boldsymbol{\Sigma}_j^{-1}\right)^{-1}$

Where:

Σi is the covariance matrix of the estimation region
Σj is the covariance matrix of the application region

Combined Transfer Estimator

This transfer method is a generalization of the Bayesian Updating method. Unlike Bayesian Updating, which ignores transfer bias, this method takes into consideration transfer bias effects on the transferred parameters (Karasmaa 2007, Koppleman and Wilmot 1982, Ben-Akiva and Bolduc 1987). Transfer bias is defined as the difference between the parameter of the estimation and application region ($\beta_1 - \beta_2$). The basic theory of this method is that the contribution of the parameters of the estimation region to the application region decreases as transfer bias increases. On the contrary, the contribution of the estimation region to the application region increases as the transfer bias decreases. This is expressed mathematically as shown below.

$$(7)\quad \hat{\boldsymbol{\beta}}_{CTE} = \left(\left(\boldsymbol{\Sigma}_i^{-1} + \Delta\Delta^T\right)^{-1} + \boldsymbol{\Sigma}_j^{-1}\right)^{-1} + \left(\left(\boldsymbol{\Sigma}_i^{-1} + \Delta\Delta^T\right)^{-1} \hat{\boldsymbol{\beta}}_i + \boldsymbol{\Sigma}_j^{-1} \hat{\boldsymbol{\beta}}_j\right)$$

Where:

$\mathbf{B}_{CTE}$ is the transferred parameters of the application region
$\boldsymbol{\beta}_i$ is the estimated parameters from the estimation region
$\boldsymbol{\beta}_j$ is the estimated parameters from the application region
$\boldsymbol{\Sigma}_i$ is the covariance matrix of the estimation region
$\boldsymbol{\Sigma}_j$ is the covariance matrix of the application region
$\Delta = (\beta_1 - \beta_2)$ is the transfer bias
Δ^T is the transpose of a matrix Δ

The corresponding covariance matrix is computed as follows:

$$(8)\quad \Sigma_{CTE} = \begin{pmatrix} \Sigma_i^2 & 0 \\ 0 & \Sigma_j^2 \end{pmatrix}$$

Where:

$\boldsymbol{\Sigma}_i$ is the covariance matrix of the estimation region
$\boldsymbol{\Sigma}_j$ is the covariance matrix of the application region

The model transferability methods discussed above differ from each other mainly on how they incorporate datasets from the estimation region and application region to produce parameters of the transferred model or application region. In summary, all transfer methods attempt to minimize the variance of parameters of the transferred model of the application region that has a relatively small sample. A small sample of the estimation region travel data causes an increase in variance of parameters of the model, which is also reflected in the transferred model as well (Karasmaa 2007). To determine sample size from the estimation region that produces the best parameters of the transferred parameters requires evaluating prediction performance for various combinations of datasets of the estimation and application regions. In this research, prediction performances were evaluated using two measures discussed in detail in the next section.

MODEL SPECIFICATION AND ESTIMATION

This paper specified two multivariate functional form models, namely, linear ordinary least squares and exponential. Unlike the linear model, the exponential form restricts prediction of nonnegative CO2 emissions values. The parameters of the models were estimated and the best model was selected for further analysis based on R-squared (R^2) goodness-of-fit measure. In this paper, R^2 (coefficient of determination) measures how well a model explains and predicts outcomes of the estimated CO_2

emissions. The exponential functional form produced the highest R^2 measure compared with the linear ordinary least squares model. The final formulation of the exponential model is as follows:

$$(9)\quad y_h = e^{\beta_0 + \sum_{j=1}^{N} \beta_j X_{hj} + \varepsilon_h} \qquad \forall_j = 1,2,3,..., N$$

Where:

h indexes household observations
j indexes the explanatory variables
y_h is the annual total CO_2 emissions in kilograms produced by household h
X_{hj} is the k^{th} explanatory variable of household vehicle j
β_j is the k^{th} coefficient of the k^{th} explanatory variable
ε_h is the random term for household h, and
β_0 is the constant term
N is the total number of explanatory variables

The parameters of the model specified in Equation 1 were estimated using the nonlinear least squares regression technique. In a nonlinear model, the unknown parameters of the models are estimated by maximizing the log likelihood function. This paper used the Stata program nonlinear command "nl" to estimate parameters of the model. The Stata implements a modified Gauss-Newton method in estimating parameters of the models. Selection of explanatory variables for inclusion in the model was primarily done based on correlation analysis and analysis of variance. Final variables specified were the ones that exhibited higher correlation with the estimated CO_2 emissions (i.e., response variable) but with lower degree of correlation to each other. This was done to prevent multicolinearity and over-specification of the model.

Measures for Assessing Prediction Performance of Transfer Methods

Transfer R-squared (R^2) and Transfer Index (TI) are two measures that are used in this paper to assess prediction performance of the transferred models. The measures indicate how well a transferred model predicts the estimated CO_2 emissions in the application region. These measures have been widely used in past studies to assess prediction performance of model transferability (Karasmaa 2007, Ben-Akiva and Morikawa 1990, Badoe and Steuart 1997). Ideally, the measures are used to assess the prediction performance of transferred parameters from the estimation region for predicting CO_2 emissions of the application region. Transfer R^2 value, denoted as R^2_{ij}, indicates the ability of the parameters of the estimation region in explaining the variations of CO_2 emissions of the application region. As indicated earlier, subscript i refers to the estimation region while the subscript j refers to the application region. Mathematically, Transferred R^2 is defined as follows:

$$(10)\quad R^2_{ij} = \frac{SSE_{ij}}{SST_{jj}}$$

Where:

SSE_{ij} is the explained or regression sum of squares obtained by predicting the calculated CO_2 emissions in the estimation region using parameters from the application region
SST_{jj} is the total sum of squares obtained by predicting CO2 emissions in the application region

Transfer Index (TI_{ij}) is a relative measure which measures how good the parameters from the estimation region predicts the corresponding observed CO_2 emissions in the application region relative to the parameters estimated using local region travel data. It is expressed mathematically as follows:

$$(11)\quad TI_{ij} = \frac{R^2{}_{ij}}{R^2{}_{jj}}$$

Where:

$R^2{}_{ij}$ is the R^2 value obtained by predicting the calculated CO_2 emissions in the estimation region using parameters from the application region

$R^2{}_{jj}$ is the R^2 obtained by predicting the observed CO_2 emissions of the estimation region based on parameters estimated using application region data

DATA SOURCE

Data for the study came from 2009 National Household Travel Survey (NHTS) conducted by the U.S. Department of Transportation (USDOT 2009). This is a nationally representative survey of travel behavior conducted from April 2008 through April 2009. The data gathered trip-related information such as mode of transportation, duration, distance, and purpose. It then connected this travel related information to demographic, geographic, and economic factors for analysis. During the survey period, each household was sent a travel diary and asked to report all travel by household members on a randomly assigned "travel day." Interviewers followed up with a phone call that collected detailed information about their travel from each household member. Travel days for daily-travel trip reporting were assigned for all seven days of the week, including holidays. Data were weighted to correctly reflect the day of week and month of travel to allow comparisons of weekdays or seasons. The total sample size was 150,147 households, which consists of 25,000 nationwide and 125,147 obtained from 20 add-on areas, mainly state departments of transportation (DOTs) and metropolitan planning organizations (MPOs). The data were further expanded to provide national estimates of trips and miles of travel by travel mode, trip purpose, and other household characteristics. The survey is documented in detail at http://nhts.ornl.gov/. A major limitation of the NHTS Travel Day Survey is that it did not take into account longer-term trips (e.g., longer than 24 hours). However, most of the longer trips were inter-regional and therefore viewed as is inappropriate for an intra-regional analysis, which is the focus of this paper.

Method for Determining CO2 Emissions

The amount of CO_2 emissions associated with fuel combustion are a function of the volume of fuel combusted, density of the fuel, carbon content of the fuel, and fraction of carbon that is oxidized to CO_2 (EPA 2008). The NHTS dataset does not contain estimates of CO_2 emissions but has variables that can be used for estimating the amount of CO_2 emissions produced by combustion of different types of fuels. This paper estimated CO_2 emissions taking into consideration emission rates per gallon, amount of gallons consumed, vehicle miles of travel, and vehicle fuel efficiency in three steps as follows:

Step 1: Determining Emission Rates Per Gallon of Fuel

The amount of CO_2 created from combusting one gallon of fuel depends on the amount of carbon in the fuel. After combustion, a majority of the carbon is emitted as CO_2 and very small amounts of hydrocarbons and carbon monoxide. Carbon content varies by fuel, and some variation within each type of fuel is normal. The Environmental Protection Agency (EPA) and other agencies use the following average carbon content values to estimate CO_2 emissions (EPA 2008):

CO_2 emissions from gasoline: 8.887 kilograms per gallon
CO_2 emissions from diesel: 10.180 kilograms per gallon
CO_2 emissions from natural gas: 6.900 kilograms per gallon

The assumption put forth with respect to electric vehicles in this paper is that on-road "tailpipe" CO_2 emissions produced are negligible. This assumption, however, is unrealistic when evaluating CO_2 emissions on the life cycle basis.

Step 2: Determining Annual CO_2 Emissions of Each Household Vehicle

The annual CO_2 emissions emitted by each household vehicle are a function of a type of fuel, fuel economy of a vehicle, and number of miles driven a year. Thus, the total amount of CO_2 emissions produced over a year of driving a certain type of vehicle is estimated as follows:

$$(12)\quad \text{Annual } CO_2 \text{ emissions (kg)} = \frac{CO_2 \text{ per gallon}}{\text{miles per gallon}} \times \text{miles driven}$$

Step 3: Determining Annual CO_2 Emissions Emitted by a Household

The amount of CO_2 emissions produced by a household varies based on number of vehicles the household has driven over a year. The total annual amount of CO_2 emissions is the sum of emissions for all household vehicles and estimated as follows:

$$(13)\quad \text{Total annual } CO_2 \text{ emissions } (kg) = \sum_{j=1}^{N} \text{Annual } CO_{2\,j}$$

Where N is the total number of household vehicles and j is the household vehicle.

Table 1 shows a summary of variable codes and their corresponding descriptive statistics for the national, Northeast region, Midwest region, South region, and West region datasets.

ANALYSIS AND DISCUSSION OF RESULTS

Tables 2 through 5 show the results of the four transfer methods for different estimation and application regions. As discussed earlier, the transfer methods are Naïve, Joint Context Estimation (JCE), Bayesian Updating (BU), and Combined Transfer Estimator (CTE). Similarly, the four regions included in this analysis are Northeast, Midwest, South, and West. The tables show the number of observations in each region, coefficient (*coef.*), and t-statistic (*t-stat.*), and transfer R^2. The *t-stat* is used to measure statistical significance of the variables at 5% level. On the other hand, transfer R^2 measures how well the transferred model from the estimation region explains variation of CO_2 emissions in the application region.

The sign of the coefficient of population density variable (popden) is negative for all models presented in Tables 2 through 5. The negative sign indicates, all being equal, a land use that has more population per square mile produces significantly more CO_2 emissions per year compared with a similar land use with less population per square mile. This is consistent with what one would expect for this variable. This could be partly associated with residential location decisions relative to employment and public service areas. Residents residing in land uses with higher population density are likely to be closer to employment services relative to those who live in lower density,

Table 1: Variable Codes and Descriptive Statistics

National			
Codes	*Descriptions*	*Mean*	*Standard Deviation*
CO2	Annual total household CO_2 emissions (kg)	8627	8382
popden	Population density per mi^2 (in 1,000) (tract-level)	2.97	4.27
hhsize	Number of household members	2.41	1.24
vehcnt	Number of household vehicles	2.18	1.108
income	Total household income (in 1,000)	57.60	31.27
Northeast Region			
CO2	Annual total household CO_2 emissions (kg)	7799	7129
popden	Population density per mi^2 (in 1,000) (track-level)	3.28	6.14
hhsize	Number of household members	2.43	1.23
vehcnt	Number of household vehicles	2.07	1.04
income	Total household income (in 1,000)	60.0	30.85
Midwest Region			
CO2	Annual total household CO_2 emissions (kg)	9004	9128
popden	Population density per mi^2 (in 1,000) (tract-level)	2.08	2.80
hhsize	Number of household members	2.43	1.27
vehcnt	Number of household vehicles	2.29	1.17
income	Total household income (in 1,000)	55.36	29.7
South Region			
CO2	Annual total household CO_2 emissions (kg)	8973	8793
popden	Population density per mi^2 (in 1,000) (tract-level)	2.11	2.84
hhsize	Number of household members	2.37	1.20
vehcnt	Number of household vehicles	2.18	1.07
income	Total household income (in 1,000)	56.04	31.40
West Region			
CO2	Annual total household CO_2 emissions (kg)	8046	7497
popden	Population density per mi^2 (in 1,000) (tract-level)	5.47	5.39
hhsize	Number of household members	2.50	1.33
vehcnt	Number of household vehicles	2.19	1.16
income	Total household income (in 1,000)	61.31	31.54

hence making comparatively shorter trips per year than their counterparts. Additionally, most people put considerable weight on travel costs in their location decisions and reside fairly closer to the employment locations (Badoe and Steuart 1997). This translates to shorter travel distance per year and less CO_2 emissions than in areas with lower employment density.

The sign of the coefficient of household size variable (hhsize) is positive for all models. This is an indication that a household with many members releases significantly more CO_2 emissions than a household with fewer members. These results make sense because families with many members are expected to participate in many activities per year relative to households with fewer members. This contributes to longer cumulative annual traveled distances and more CO_2 emissions. Similarly, the sign of the coefficient of number of household vehicles variable (vehcnt) is positive across all models. This indicates, on average, a household that owns many vehicles produces comparatively more CO_2 emissions than a household with fewer vehicles per year. The reason for this result is similar to the one given for the household size. The sign of the coefficient of household income variable (income) is positive for all models. This implies that a high-income household produces significantly more CO_2 emissions than a low-income household per year. This is logical because most affluent households reside in less dense areas, which are relatively far from services locations such as shopping centers and hence travel longer distances per year. These results also reflect fuel efficiency of vehicles high-income households own in comparison to low-income households. The expectation is that high-income households are likely to own bigger vehicles (i.e., pickup trucks and SUVs), which have relatively low fuel efficiency than smaller vehicles. This result, however, contradicts with the expectation that high-income households are also likely to own newer vehicles which are subject to stricter regulations and emit less CO_2 emissions per year.

Tables 2 through 5 also indicate statistical significance of the variables measured in terms of t-statistic (t-stat). The critical t-statistic at the 5% significance level is 1.96. Comparing t-statistic results shown in Tables 2-5, it is evident that all variables are statistically significant at the 5% level (i.e., estimated t-statistics are greater than the critical t-statistic). This is an indication that there is statistical evidence that the variables are different from zero at the 5% level. As can be seen from Tables 2 through 5, transfer R^2 values range from 0.4598 to 0.6844. The values explain how well the models transferred from the estimation region explain variations of predicted CO_2 emissions in the application region.

Table 2: Naïve Transfer Results

Estimation Region	Application Region	Northeast		Midwest		South		West	
	No. obs.	17,203		13,721		72,298		27,544	
	Variable	*Coef.*	*t-stat*	*Coef.*	*t-stat*	*Coef.*	*t-stat*	*Coef.*	*t-stat*
National	const	8.2427	1207.73	8.2427	1207.73	8.2427	1207.73	8.2427	1207.73
	popden	-0.0324	-44.60	-0.0324	-44.60	-0.0324	-44.60	-0.0324	-44.60
	hhsize	0.1151	85.43	0.1151	85.43	0.1151	85.43	0.1151	85.43
	vehcnt	0.0049	65.25	0.0049	65.25	0.0049	65.25	0.0049	65.25
	income	0.1428	197.21	0.1428	197.21	0.1428	197.21	0.1428	197.21
	Transfer R^2	0.6695		0.6153		0.6276		0.6503	
Northeast	const	8.0779	468.51	8.0779	468.51	8.0779	468.51	8.0779	468.51
	popden	-0.0227	-15.75	-0.0227	-15.75	-0.0227	-15.75	-0.0227	-15.75
	hhsize	0.0984	28.04	0.0984	28.04	0.0984	28.04	0.0984	28.04
	vehcnt	0.0041	20.68	0.0041	20.68	0.0041	20.68	0.0041	20.68
	income	0.2027	70.04	0.2027	70.04	0.2027	70.04	0.2027	70.04
	Transfer R^2	0.6844		0.6203		0.5239		0.5618	
Midwest	const	8.2296	373.84	8.2296	373.84	8.2296	373.84	8.2296	373.84
	popden	-0.0411	-12.32	-0.0411	-12.32	-0.0411	-12.32	-0.0411	-12.32
	hhsize	0.0699	15.01	0.0699	15.01	0.0699	15.01	0.0699	15.01
	vehcnt	0.0047	19.02	0.0047	19.02	0.0047	19.02	0.0047	19.02
	income	0.2048	63.66	0.2048	63.66	0.2048	63.66	0.2048	63.66
	Transfer R^2	0.6745		0.6269		0.4598		0.5452	
South	const	8.2699	892.02	8.2699	892.02	8.2699	892.02	8.2699	892.02
	popden	-0.0448	-31.11	-0.0448	-31.11	-0.0448	-31.11	-0.0448	-31.11
	hhsize	0.1189	64.54	0.1189	64.54	0.1189	64.54	0.1189	64.54
	vehcnt	0.0053	52.68	0.0053	52.68	0.0053	52.68	0.0053	52.68
	income	0.1383	145.11	0.1383	145.11	0.1383	145.11	0.1383	145.11
	Transfer R^2	0.6596		0.6144		0.6269		0.6438	
West	const	8.1523	530.19	8.1523	530.19	8.1523	530.19	8.1523	530.19
	popden	-0.0145	-15.02	-0.0145	-15.02	-0.0145	-15.02	-0.0145	-15.02
	hhsize	0.1219	45.64	0.1219	45.64	0.1219	45.64	0.1219	45.64
	vehcnt	0.0046	29.48	0.0046	29.48	0.0046	29.48	0.0046	29.48
	income	0.1328	83.68	0.1328	83.68	0.1328	83.68	0.1328	83.68
	Transfer R^2	0.6718		0.6037		0.6171		0.6569	

Table 3: Joint Content Estimation Results

Estimation Region	Application Region	Northeast		Midwest		South		West	
	No. obs.	17,203		13,721		72,298		27,544	
	Variable	*Coef.*	*t-stat*	*Coef.*	*t-stat*	*Coef.*	*t-stat*	*Coef.*	*t-stat*
National	const	8.2427	1207.73	8.2427	1207.73	8.2427	1207.73	8.2427	1207.73
	popden	-0.0324	-44.60	-0.0324	-44.60	-0.0324	-44.60	-0.0324	-44.60
	hhsize	0.1151	85.43	0.1151	85.43	0.1151	85.43	0.1151	85.43
	vehcnt	0.0049	65.25	0.0049	65.25	0.0049	65.25	0.0049	65.25
	income	0.1428	197.21	0.1428	197.21	0.1428	197.21	0.1428	197.21
	Transfer R^2	0.6695		0.6153		0.6276		0.6503	
Northeast	const	8.0779	468.51	8.1491	590.83	8.2438	1001.54	8.1484	711.62
	popden	-0.0227	-15.75	-0.0279	-18.8	-0.0386	-34.22	-0.0182	-23.84
	hhsize	0.0984	28.04	0.0851	29.54	0.1182	72.12	0.1178	55.23
	vehcnt	0.0041	20.68	0.0042	26.92	0.0051	56.16	0.0046	37.35
	income	0.2027	70.04	0.2064	96.99	0.1421	165.13	0.1418	109.29
	Transfer R^2	0.6844		0.6246		0.6284		0.6556	
Midwest	const	8.1491	590.83	8.2296	373.84	8.2726	965.78	8.2305	661.67
	popden	-0.0279	-18.8	-0.0411	-12.32	-0.0447	-33.68	-0.0233	-24.13
	hhsize	0.0851	29.54	0.0699	15.01	0.1148	67.03	0.1094	45.81
	vehcnt	0.0042	26.92	0.0047	19.02	0.0053	56.23	0.0046	33.93
	income	0.2064	96.99	0.2048	63.66	0.1412	159.83	0.1434	104.31
	Transfer R^2	0.6822		0.6269		0.6288		0.6539	
South	const	8.2438	1001.54	8.2726	965.78	8.2699	892.02	8.2562	1054.55
	popden	-0.0386	-34.22	-0.0447	-33.68	-0.0448	-31.11	-0.0335	-40.01
	hhsize	0.1182	72.12	0.1148	67.03	0.1189	64.54	0.1184	77.41
	vehcnt	0.0051	56.16	0.0053	56.23	0.0053	52.68	0.005	58.66
	income	0.1421	165.13	0.1412	159.83	0.1383	145.11	0.138	168.64
	Transfer R^2	0.6666		0.6156		0.6269		0.6495	
West	const	8.1484	711.62	8.2305	661.67	8.2562	1054.55	8.1523	530.19
	popden	-0.0182	-23.84	-0.0233	-24.13	-0.0335	-40.01	-0.0145	-15.02
	hhsize	0.1178	55.23	0.1094	45.81	0.1184	77.41	0.1219	45.64
	vehcnt	0.0046	37.35	0.0046	33.93	0.005	58.66	0.0046	29.48
	income	0.1418	109.29	0.1434	104.31	0.138	168.64	0.1328	83.68
	Transfer R^2	0.6751		0.6131		0.6283		0.6569	

Table 4: Bayesian Updating Results

Estimation Region	Application region	Northeast		Midwest		South		West	
	No. obs.	17,203		13,721		72,298		27,544	
	Variable	*Coef.*	*t-stat*	*Coef.*	*t-stat*	*Coef.*	*t-stat*	*Coef.*	*t-stat*
National	const	8.225	1045.59	8.2465	851.15	8.2521	995.99	8.235	1540.79
	popden	-0.0308	-41.29	-0.0333	-66.05	-0.0356	-49.1	-0.0278	-18.17
	hhsize	0.1146	63.60	0.1126	69.97	0.1165	79.44	0.1158	64.12
	vehcnt	0.0048	45.97	0.0049	62.2	0.005	60.07	0.0048	49.77
	income	0.1466	192.13	0.1459	145.34	0.1413	181.85	0.1414	151.46
	Transfer R^2	0.6722		0.6164		0.6284		0.6522	
Northeast	const	8.0779	468.51	8.1332	392.09	8.2339	859.39	8.1463	439.02
	popden	-0.0227	-15.75	-0.0261	-16.29	-0.0362	-21.74	-0.0183	-27.2
	hhsize	0.0984	28.04	0.0869	23.6	0.1174	45.9	0.1156	38.66
	vehcnt	0.0041	20.68	0.0041	21.71	0.005	35.67	0.0045	25.49
	income	0.2027	70.04	0.2071	59.51	0.1454	132.11	0.1494	85.02
	Transfer R^2	0.6844		0.6240		0.6280		0.6539	
Midwest	const	8.1332	392.09	8.2296	373.84	8.2718	711.47	8.2232	323.52
	popden	-0.0261	-16.29	-0.0411	-12.32	-0.0448	-27.51	-0.0217	-244.63
	hhsize	0.0869	23.6	0.0699	15.01	0.1146	47.38	0.108	38.44
	vehcnt	0.0041	21.71	0.0047	19.02	0.0053	47.24	0.0045	29.87
	income	0.2071	59.51	0.2048	63.66	0.1433	102.33	0.1491	70.74
	Transfer R^2	0.6828		0.6269		0.6287		0.6525	
South	const	8.2339	859.39	8.2718	711.47	8.2699	892.02	8.252	1045.71
	popden	-0.0362	-21.74	-0.0448	-27.51	-0.0448	-31.11	-0.0298	-15.67
	hhsize	0.1174	45.90	0.1146	47.38	0.1189	64.54	0.1185	50.74
	vehcnt	0.005	35.67	0.0053	47.24	0.0053	52.68	0.0049	38.88
	income	0.1454	132.11	0.1433	102.33	0.1383	145.11	0.138	117.44
	Transfer R^2	0.6684		0.6161		0.6269		0.6504	
West	const	8.1463	439.02	8.2232	323.52	8.252	1045.71	8.1523	530.19
	popden	-0.0183	-27.20	-0.0217	-244.63	-0.0298	-15.67	-0.0145	-15.02
	hhsize	0.1156	38.66	0.1080	38.44	0.1185	50.74	0.1219	45.64
	vehcnt	0.0045	25.49	0.0045	29.87	0.0049	38.88	0.0046	29.48
	income	0.1494	85.02	0.1491	70.74	0.138	117.44	0.1328	83.68
	Transfer R^2	0.6768		0.6144		0.6279		0.6569	

Table 5: Combined Transfer Estimator Results

Estimation Region	Application Region	Northeast		Midwest		South		West	
	No. obs.	17,203		13,721		72,298		27,544	
	Variable	*Coef.*	*t-stat*	*Coef.*	*t-stat*	*Coef.*	*t-stat*	*Coef.*	*t-stat*
National	const	8.0781	474.83	8.2296	377.72	8.2698	907.97	8.15247	546.51
	popden	-0.0227	-15.95	-0.041	-12.51	-0.0448	-33.86	-0.0146	-14.67
	hhsize	0.0984	28.38	0.0700	15.21	0.11884	66.78	0.12187	46.33
	vehcnt	0.0041	20.93	0.0047	19.27	0.00534	54.19	0.00462	30.01
	income	0.2026	71.29	0.2047	64.43	0.13831	149.71	0.13285	85.30
	Transfer R^2	0.6840		0.6265		0.6289		0.6565	
Northeast	const	8.0779	468.51	8.229	378.35	8.2699	890.65	8.1523	507.48
	popden	-0.0227	-15.75	-0.0410	-13.78	-0.0448	-30.88	-0.0146	-16.09
	hhsize	0.0984	28.04	0.0701	15.72	0.1189	63.40	0.1219	44.49
	vehcnt	0.0041	20.68	0.0047	19.95	0.0053	51.73	0.0046	28.70
	income	0.2027	70.04	0.2048	62.60	0.1383	144.1	0.1329	81.80
	Transfer R^2	0.6844		0.6265		0.6289		0.6565	
Midwest	const	8.0782	449.55	8.2296	373.84	8.2699	885.86	8.1524	505.65
	popden	-0.0227	-15.4	-0.0411	-12.32	-0.0448	-31	-0.0146	-16.12
	hhsize	0.0983	27.73	0.0699	15.01	0.1188	63.99	0.1219	45.46
	vehcnt	0.0041	20.8	0.0047	19.02	0.0053	52.52	0.0046	29.58
	income	0.2027	67.22	0.2048	63.66	0.1383	143.29	0.1328	81.7
	Transfer R^2	0.6840		0.6269		0.6289		0.6565	
South	const	8.0781	478.28	8.2297	378.73	8.2699	892.02	8.1524	569.15
	popden	-0.0227	-15.65	-0.0411	-12.50	-0.0448	-31.11	-0.0146	-13.24
	hhsize	0.0984	28.40	0.0701	15.23	0.1189	64.54	0.1219	46.46
	vehcnt	0.0041	20.96	0.0047	19.32	0.0053	52.68	0.0046	30.28
	income	0.2026	72.07	0.2047	64.62	0.1383	145.11	0.1328	86.86
	Transfer R^2	0.6840		0.6265		0.6269		0.6565	
West	const	8.078	460.91	8.2296	369.59	8.2699	911.08	8.1523	530.19
	popden	-0.0226	-17.8	-0.041	-13.28	-0.0448	-29.75	-0.0145	-15.02
	hhsize	0.0984	28.97	0.07	15.47	0.1189	62.19	0.1219	45.64
	vehcnt	0.0041	21.14	0.0047	19.6	0.0053	50.84	0.0046	29.48
	income	0.2026	76.51	0.2048	65.31	0.1383	140.51	0.1328	83.68
	Transfer R^2	0.6840		0.6265		0.6289		0.6569	

Table 6 shows the results of Transfer Index (TI), which is used in this research as the measure for assessing prediction performance of the transferred models. From equation 13, TI greater than one means that the transferred model from another region explains variations of the predicted CO_2 emissions better than when compared with a local model. As can be seen from the table, some of the TI values (e.g., bolded) are greater than one which implies that the transferred model better predicts the predicted CO_2 emissions than the local model. For the Northeast region, all transfer methods indicate that the transferred models from the Midwest, South, and West regions produced relatively higher explanation power than the Northeast region. Similar observations are also seen for some of the transferred models in predicting CO_2 emissions in the South and West regions. On the contrary, all transferred models from the Northeast, South, and West to Midwest regions consistently performed poorly in explaining variations of the predicted CO_2 emissions than the Midwest region model. This suggests that factors that influence CO_2 emissions in the Midwest region are somewhat different compared with the Northeast, South, and West regions.

When comparing the four transfer methods, the CTE method produces superior prediction performance based on the transfer R^2 and TI measures as shown in Tables 2 through 6, followed by the other three transfer methods: BU, JCE, and Naïve, in that order. In other words, on the basis of transfer R^2 and TI, the results indicate that the CTE is the best transfer method, followed by BU, JCE, and Naïve. In essence, this pattern reflects how the transferred model incorporates travel data of the application region. It is expected that as transfer bias increases, more weight is assigned to the coefficients of the application region and less weight on the estimation region. These results are in agreement with past studies, which found similar patterns of prediction performance of these transfer methods (Badoe and Steuart 1997). Although the CTE and BU gave superior prediction results as measured in terms of transfer R^2 and TI as shown in Tables 2 through 6, in comparison with the JCE and Naïve transfer methods, they are computationally intractable. The intractability is primarily associated with additional steps required to compute a covariance matrix and/or transfer bias. The analyst, however, should evaluate and decide whether the incremental benefits gained are worth additional computational investment. Overall, the results of the measures of prediction performance demonstrate that the transferred models improved CO_2 emissions prediction performance.

SUMMARY AND CONCLUSION

This paper has empirically analyzed the spatial transferability of the regional automobile-specific household-level carbon dioxide (CO_2) emissions model. The regions considered in this analysis are Northeast, Midwest, South, and West. It also examined prediction performance of model transferability methods, including Naïve, Joint Context Estimation (JCE), Bayesian Updating (BU), and Combined Transfer Estimator (CTE). Prediction performance of the transferred models was assessed in terms of transfer R^2 and Transfer Index (TI). The data used came from the 2009 National Household Survey (NHTS) conducted by the U.S. Department of Transportation. In conclusion, the results indicated that the regional automobile-specific CO_2 emissions model can be transferred from one geographical region to another region and improve prediction performance. This is based on the following observations:

1. All transferred methods consistently indicated that the transferred models from the Midwest, South, and West regions to predict household-level CO_2 emissions in the Northeast region improved prediction performance compared with the Northeast region model. On the other hand, the results indicated that the Midwest region produced better prediction performance compared with the transferred models from the other regions to the Midwest region. This suggests that factors that influence CO_2 emissions in the Midwest region are somewhat different from the Northeast, South, and West regions.

Table 6: Transfer Index (TI) Results

Estimation Region	Northeast	Midwest	South	West
Naïve Transfer				
	Application Region			
Estimation Region	Northeast	Midwest	South	West
National	0.9782	0.9815	**1.0012**	0.9899
Northeast	1.0000	0.9063	0.7655	0.8209
Midwest	**1.0760**	1.0000	0.7334	0.8697
South	**1.0521**	0.9801	1.0000	**1.0270**
West	**1.0227**	0.9190	0.9395	1.0000
Joint Context Estimation				
National	0.9782	0.9815	**1.0012**	0.9899
Northeast	1.0000	0.9127	0.9182	0.9580
Midwest	**1.0882**	1.0000	**1.0031**	**1.0431**
South	**1.0634**	0.9819	1.0000	**1.0361**
West	**1.0276**	0.9333	0.9564	1.0000
Bayesian Updating				
National	0.9822	0.9833	**1.0023**	0.9929
Northeast	1.0000	0.9117	0.9176	0.9554
Midwest	**1.0892**	1.0000	**1.0028**	**1.0408**
South	**1.0662**	0.9827	1.0000	**1.0374**
West	**1.0303**	0.9354	0.9559	1.0000
Combined Transfer Estimator				
National	0.9994	0.9994	**1.0032**	0.9993
Northeast	1.0000	0.9155	0.9189	0.9592
Midwest	**1.0911**	1.0000	**1.0032**	**1.0471**
South	**1.0911**	0.9994	1.0000	**1.0471**
West	**1.0412**	0.9538	0.9574	1.0000

2. Comparison analysis of the transfer methods showed that the CTE produced superior prediction performance as measured in terms of transfer R^2 and TI, followed by other three transfer methods: BU, JCE, and Naïve, in that order. This is a reflection of the effect of incorporating local travel data in the analysis. This is because the CTE method assigns less weight to the parameters of the estimation region when the transfer bias — (e.g., difference between the parameters of the estimation and application regions) is large and vice versa.
3. Even though CTE and BU transfer methods gave superior results in comparison with JCE and Naïve, they are rather computationally intractable. This is primarily due to additional steps required to compute the covariance matrix and/or transfer bias. The modeler/analyst should determine whether the incremental benefits gained are worth additional computational investment.

These results can assist different agencies such as transportation planners to predict automobile-specific CO_2 emissions trends from household-level vehicle travel and identify ways for improving efficiency of transportation systems, and reduce its impact on global warming, climate change, and air quality. The results also can be useful to policy makers and businesses such as the automobile industry to evaluate current and future policies, such as vehicle fuel efficiency standards in order to reduce carbon footprints. The results of this paper are for the spatial transferability of large sub-regions and are unlikely to assist smaller communities. Spatial transferability is crucial to small Metropolitan Planning Organizations (MPOs) that have little travel data for estimation of CO_2 emissions, and future research efforts should address this limitation. In addition, similar analysis should be applied to region-pairs that have different travel behavior or regions where there is a higher proportion of non-automobile travel.

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Saidi Siuhi *is an assistant professor in the department of civil engineering at Abu Dhabi University. His research interests are mainly focused on developing solutions for improving traffic safety and operational efficiency of transportation systems. His primary focus includes traffic safety and operations, traffic flow modeling and simulation, transportation planning, travel demand analysis, carbon dioxide emissions in transportation. He received his Ph.D. in civil engineering from University of Nevada, Las Vegas.*

Judith Mwakalonge *is an assistant professor in the civil and mechanical engineering technology department at South Carolina State University. Her primary research interests include travel demand modeling, model transferability, and traffic operations. Mwakalonge's current work explores the use of Radio Frequency Identification (RFID) and Bluetooth technologies in transportation and climate change as it relate to transportation. She received her Ph.D. in civil engineering from Tennessee Technological University.*

Judy Perkins*, P.E, is a Texas A&M University System regents professor and a retired U.S. Army lieutenant colonel. Her research has focused on statewide intermodal transportation planning, transportation logistics, hurricane evacuation analysis, military logistics, engineering education, minority outreach, optimization of transportation infrastructure investments, and RFID technologies used by motor carriers and for underground utilities. She received her Ph.D. in civil engineering from Georgia Institute of Technology.*

A Framework for Determining Highway Truck-Freight Benefits and Economic Impacts

by Zun Wang, Jeremy Sage, Anne Goodchild, Eric Jessup, Kenneth Casavant, and Rachel L. Knutson

This paper proposes a method for calculating both the direct freight benefits and the larger economic impacts of transportation projects. The identified direct freight benefits included in the methodology are travel time savings, operating cost savings, and environmental impacts. These are estimated using regional travel demand models (TDM) and additional factors. Economic impacts are estimated using a regional Computable General Equilibrium (CGE) model. The total project impacts are estimated combining the outputs of the transportation model and an economic model. A Washington State highway widening project is used as a case study to demonstrate the method. The proposed method is transparent and can be used to identify freight specific benefits and generated impacts.

INTRODUCTION AND BACKGROUND

Though the Washington State Department of Transportation (WSDOT) has a long standing Mobility Project Prioritization Process (MPPP) (WSDOT 2000), which is a Benefit-Cost Analysis (BCA) framework used for mobility program assessment, it does not separately evaluate or account for the truck freight benefits of proposed highway infrastructure projects. It is therefore unable to evaluate and consider the economic impacts of highway projects that accrue to freight-dependent industries (those heavily reliant on goods movement) or non-freight-dependent firms (service sector) that are perhaps indirectly impacted by the productivity of the freight system. The established evaluation criteria of any transportation project largely influences the project selection and direction, thus for freight to become an integrated component of a managing agency's transportation program, it must be recognized and acknowledged through the project evaluation criteria (NCHRP 2007). Before implementing any freight project evaluation criteria, an agency must first be able to identify the measures that matter to freight and freight-related systems. At this time there is no known nationally accepted framework for analyzing the full range of freight-related impacts stemming from transportation infrastructure projects. Complex interactions with separate, but not isolated, effects among economic, environmental, and social components with sometimes conflicting priorities make freight impacts more difficult to measure than those of other highway users (Belella 2005).

To successfully compete in a new funding world with significantly reduced monies for transportation infrastructure, states must become even more pragmatic about the means by which they emphasize and prioritize investments. Identification of the necessity to include freight performance measures in local, state, and national transportation plans, and rise above anecdotal understandings of system performance, is becoming evident as more municipalities and state agencies move toward implementing freight-related plans (MnDOT 2008, Harrison et al. 2006). Therefore, WSDOT has undertaken the development of an improved methodology to assess highway truck-freight project benefits designed to be integrated into the department's existing prioritization processes. This paper lays out the development process of this effort and the resulting methodology. The contribution of this paper to the literature is to present a methodology that includes a truck-specific determination of the economic value of a project in addition to the economic impacts captured by a regional computable general equilibrium (CGE) framework. The proposed method is transparent, and can be used to identify freight-specific benefits and generated impacts.

The remainder of this paper is organized as follows: the second section provides a brief review of the state of practice in the evaluation of transportation infrastructure investments; the third section details the process by which the benefits to be included in the analysis were selected and the methodology subsequently developed; the next section applies the methodologies to a case study and provides its result; the last section offers conclusions of the proposed methodology as well as the limitations of the study and directions for future work on fully incorporating freight into state DOT investment decisions.

STATE OF THE PRACTICE

The most common approach to freight benefit cost analysis is a microeconomic consideration in which the analyst calculates the benefits as direct cost savings and travel time reductions (Weisbrod 2008). This is the approach characterized by the majority of benefit cost analyses (USDOT 2003, Lakshmanan 2011). In 2010, the American Association of State Highway and Transportation Officials (AASHTO 2010) released an updated resource for the benefit-cost analysis of highway projects. Known as *The Redbook*, the manual recognizes user benefit analyses in transportation planning as a fundamentally economic process, as opposed to simply that of an engineering issue. The manual identifies the need to use traffic performance data, including traffic volume, speed, travel time, and other data related to the segments under project consideration. These data are needed for both the current status of the segment as well as the expected data under any project alternative. Further, the manual breaks down the development of user cost factors based on values of time for various vehicle classes (i.e., auto, transit bus, and truck), occupancy rates of those vehicles, as well as their operating costs (fuel, oil, maintenance, tires, insurance, license, and registration), and accident rate cost parameters. These cost factors are then related to the obtained traffic performance data in order to determine user costs. Despite the enormity of considerations available in toolkits like *The Redbook*, they generally lack full consideration of regional economic impacts extending beyond the direct benefits of an improvement.

Economic Impacts

The need for a regional economic framework originates from the function freight transportation serves in the economy. Freight movement enables trade networks between industries and their market locations. Improvement to the routes reduces travel cost and thus production costs of goods, as well as reducing uncertainties and risk that come with unreliable delivery. Quick and reliable transportation allows for industry logistics reorganization that involves companies purchasing more transportation services and adjusting the number, size, and location of factories and warehouse to reduce logistics costs (FHWA 2008). Increased transportation efficiency and reduced logistics costs combine to increase industrial productivity and produce positive effects felt via job creation and economic activities (Weisbrod 2008, FHWA 2001a, FHWA 2001b, FHWA 2001c, Allen et al. 1994).

Regional economic and macroeconomic models have been developed to implement various functional interactions, like production and cost functions, to estimate relationships between infrastructure investment and productivity and long-term economic activity (NCHRP 1998). At the macro level, infrastructure investment is viewed as a direct injection to the economy that can be inserted as an additional factor of production alongside private capital and labor (FHWA 2004). Nadiri and Mamuneas (1996, 1998) measured the contribution of capital investment in highways to private productivity, finding that indeed it does contribute to growth and productivity at the industry and even national levels. Highway capital investment saw its largest impacts during the 1950s and 1960s at a point when capital was in short supply and the interstate system was under development.

Though the impact has since diminished, it remains positive. Generally speaking, broad agreement exists to suggest that transportation infrastructure investments positively contribute to the overall economy; however, the magnitude of that contribution remains debatable (FHWA 2004). In a 1990 work, Munnell (1990) found that public sector investment does produce a statistically significant impact on private sector output. Additionally, she found that a state's investment in public capital has a significant impact on the state's private employment growth (Munnell 1990). These potential impacts readily provide an impetus for more freight-inclusive benefit evaluation methods and to a greater degree, a regional economic framework that captures impacts to labor, markets, business and trade development, as well as increases in Gross Domestic Product (GDP) or Gross Regional Product (GRP), and other organizational changes, such as those related to facility consolidation, logistical adjustments, and location effects (USDOT 2003, Lakshmanan 2011, Peters et al. 2008, Lakshmanan and Anderson 2002).

In this light, federal and regional transportation agencies and several state departments of transportation have sought economic frameworks to capture the economic impacts in addition to the transportation performance benefits.

FHWA led the research on quantifying the full range of freight benefits associated with highway investments. The logistics reorganization benefits were captured as the consumer surplus of the induced freight users. The relationship between freight demand elasticity and transportation costs/performance were established based on the data collected from 55 corridors between 1992 and 2003. This method is not applied in the proposed framework for several reasons. Firstly, the freight demand elasticity does not reflect the current Washington State freight elasticity. Secondly, this elasticity represents general freight traffic and is not able to reflect the characteristics of different commodities in responding to the transportation improvements. Thirdly, the consumer surplus of induced demand does not reflect how the direct transportation-related benefits are transferred to other parties and generate economic impacts (FHWA 2001a, FHWA 2001b, FHWA 2001c).

The Port of Portland readily identified that not all transportation bottlenecks and delays are equal when it comes to its economic impacts on the region and its traded industries (Economic Development Research Group 2008). They have employed a three-step process to identify the types of projects that are economically significant. The steps include site-specific evaluations considering connectivity to key industrial sectors, vehicle usage characteristics like origin and destination, then finally, the magnitude of produced effects as they relate to travel time and predictability of travel time, size of same-day delivery markets, cost competitiveness of shipping rates, and access restrictions on trucks.

Kansas DOT (KDOT) and North Carolina DOT (NCDOT) developed highway project prioritization tools to assess the highway projects' economic impacts using the TREDIS economic modeling platform. The economic impact measures are direct and indirect employment, gross state product, personal income, and productivity (KDOT 2010, NCDOT 2011). Michigan DOT (MDOT) (2011) also developed methods to explore the economic effects of transportation investments on personal income, employment, business sales, and gross state product using the REMI (Regional Economic Model's, Inc.) economic model platform. Similarly, Indiana DOT evaluated the statewide long-range transportation plan by predicting the employees attracted from other states based on the improved market accessibility due to highway projects (Kaliski et al. 2010). This job creation was used as input to a REMI-based model to estimate the full economic impacts, including real personal income, gross state product, and output. Montana DOT (MDT) sought similar evaluative abilities in the development of its Highway Economic Analysis Tool (HEAT) based also on the REMI model. HEAT allows MDT to take travel performance metrics like travel time savings and ultimately relate them to commodity flows and subsequent benefit cost analyses (Cambridge Systematics 2005). Though many consider regional economic models like REMI and TREDIS to be state-of-the-art, given their proprietary (commercial) nature and the lack of complete transparency regarding their inner workings, some state agencies are hesitant to implement the models. Weisbrod (2008) provides a succinct discussion of the precursors to and evolution of these and other regional economic models to allow for an understanding of the necessary components of a valuable model framework. Early models covered the gamut of Input-Output (I-O) based impact models that relate highway spending to travel cost savings and the flow of business and household income. Further advances to the basic I-O models include an incorporation of the ability to include market access and location demand.

This brief literature review indicates that although the full benefits from transportation investments have been considered to be important, there is a need for a freight-specific framework that considers both the direct transportation-related benefits, and regional economic impacts using transparent economic models. This paper proposes a transparent, freight-specific methodology that relates the performance of the freight network to the regional economy through a regional CGE model framework. The next section lays out the steps used to identify project evaluation criteria, estimate those values, and calculate project benefits.

DEVELOPMENT OF A METHODOLOGY FOR BENEFIT EVALUATION

The set of benefits implemented in the methodology were developed from discussions with the Washington State Freight Plan Technical Teams, who were asked to identify the important impacts to the freight community of a truck freight infrastructure project and review the current project prioritization method employed by WSDOT. From these, many were removed due to a lack of data to support the calculation, or redundancy with WSDOTs current project prioritization process (the MPPP tool).

Learning from the System's Stakeholders

Freight benefits were identified through discussion and partnership with three state freight plan technical teams. These teams comprised experts involved in the movement of freight throughout Washington's intermodal system, and identified by the Washington State Department of Transportation's Freight Systems Division (2012a). The three teams were Urban Goods Movement, asked to focus on jobs, the economy, goods delivery, and clear air for all; Global Gateway, asked to focus on national and state import/export activities; and Rural Economy, asked to focus on farm-to-market and manufacturing goods movement. The discussion within the three technical teams was seeded by a presentation of evolving federal criteria. The teams were tasked with the identification of measurable benefits and potential data sources that are important to shippers, freight carriers, air quality stakeholders, labor, and federal, state, regional, and local governments, including ports. After consideration, the technical teams' list of prioritized benefits included:

- Improved travel times
- Improved travel time reliability
- Reduced truck operating cost
- Safety improvement
- Freight network connectivity improvement
- Network resiliency improvement (defined as the ability to recovery from a disruption)
- Improved air quality: truck emissions
- Economic output defined as long-term jobs (non-construction-related) and regional outputs

Reviewing Current Highway Mobility Project Prioritization Methodology (MPPP)

WSDOT has a long-standing MPPP tool supporting the highway mobility project prioritization process (WSDOT 2000). The benefits considered in the MPPP tool consist of travel time savings, operating savings, and safety improvements. Both the current performance of the roadway segment, as well as the expected performance under the project alternative, are needed to evaluate the project benefits. Travel time is calculated based on the average speed estimated using WSDOT speed-flow curves, which present the relationship between segment volume-capacity (V/C) ratio and operating speed. The segment V/C ratio is calculated based on the comparison between roadway capacity and the 24-hour traffic distribution predefined by WSDOT. The operating cost savings in the MPPP tool are estimated for the park-and-ride lot projects only, which is calculated as the cost savings of switching from driving alone to carpooling or taking transit. Operating cost savings for other modes and project purposes are not included in the MPPP tool. The safety savings are evaluated based on the number and monetary value of property damages, injuries, and fatalities. Collision reductions vary depending on the project types.

The MPPP benefit-cost tool provides a means of evaluating project efficiency and it makes up 65% of the project prioritization rubric (Other project evaluation criteria include: community support [14%], environment [8%], modal integration [7%] and land use [6%]). However, the tool does not separately evaluate, consider, or account for the truck freight benefits of proposed capital highway projects, nor evaluate the economic impacts of highway projects benefiting freight-dependent industries (heavily reliant on goods movement) or non-freight-dependent firms (service sector).

Proposed Methodology

Travel time, operating cost, the environment, and economic impacts will be estimated in the current method. Several measures identified by the technical teams are excluded. Safety is not included as it is estimated by the MPPP tool. Network connectivity can be captured through impacts on travel time. Travel time reliability is also excluded due to insufficient regional data sources as to reliability estimates, forecasts, and values. Although the FHWA and the America Transportation Research Institute (ATRI) have been collecting GPS data on system performance since 2002, these data are not sufficiently detailed to estimate reliability at the desired level of spatial detail, nor are we able to forecast reliability or value reliability with this data. In our approach, truck travel time is estimated from a regional travel demand model (TDM), which is deterministic and cannot reflect the actual travel time variability. The network resiliency is not included in the current framework due to lack of reliable data and methodologies to monetize resiliency. Both travel time reliability and network resiliency will be incorporated in future phases of this research.

The benefits analyzed in the proposed framework include:

- Improved truck travel times
- Reduced truck operating costs
- Environmental impacts linked to truck emissions
- Regional economic impact related to outputs such as long-term job creation and regional output

Direct Freight Benefit Models. Even though travel time savings have been included in the MPPP tool, in that method, travel time and speed are estimated using the speed-flow relationship of general traffic (both automobile and truck trips), which cannot reflect truck speed accurately. In addition, the current approach does not reflect the network effects when additional traffic is attracted to the improved segments from other roads. The proposed framework estimates truck travel time improvement using the change in truck vehicle hours traveled (VHT) estimated by the regional TDMs. VHT is computed by multiplying the link volume and link travel time. Network improvements are expected to reduce total system VHT when induced demand is not considered. TDMs employ a set of mathematical equations to replicate "real world" travel behavior and forecast future travel performance based on the household, land use, and transportation network data. In Washington State, most Metropolitan Planning Organizations (MPOs) have developed their regional TDMs to replicate current and forecast future travel patterns and travel conditions. For any project located in the areas that are not covered by the TDMs, we assume there is no travel time reduction outside of travel distance reduction, namely, trucks travel at free flow speed pre- and post-investment.

To convert the travel time savings to dollars, a value of truck travel time is used. Most transportation planning organizations will have a standard value. The value estimated by WSDOT is based on regional driver wage and fringe benefits. The operating cost reduction is monetized using the operating cost per time unit estimated by WSDOT, including fuel consumption, fuel taxes, truck maintenance and repair, engine oil change, truck lease or purchase payment, truck insurance premium, tire cost, and licensing and overweight-oversize permits. Details of the inputs and assumptions of value of travel time and operating cost estimation can be found in WSDOT (2009).

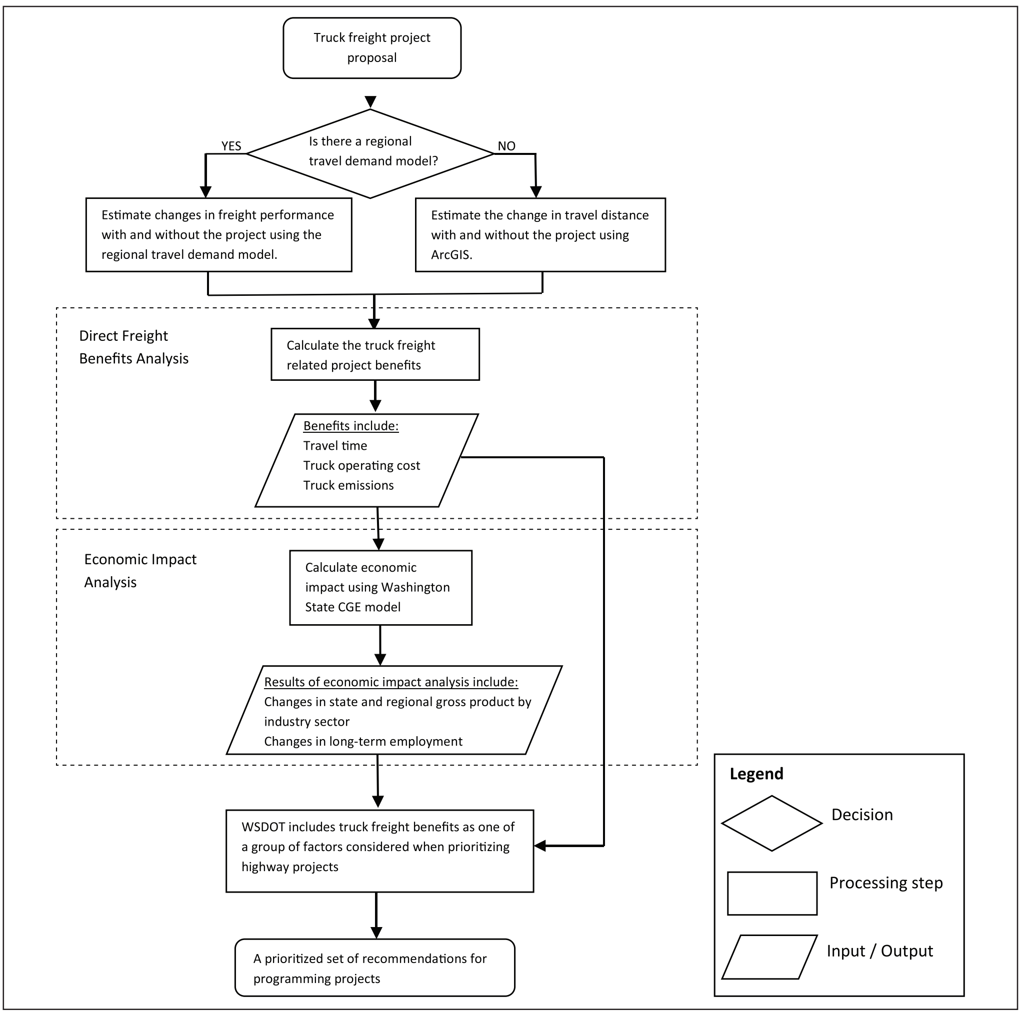
The value of any change in emissions from the project is evaluated as tons of desired air pollutants based on the operating speed, truck vehicle miles traveled (VMT), and emission rates (grams/mile). The operating speed and truck VMT are estimated from the TDMs (or speed-flow relationship when a TDM is not available). The regional emission rates vary depending on the truck operating speed estimates, road categories, and regional fleet information. They are estimated using the MOBILE6.2 developed and tested by U.S. Environmental Protection Agency (EPA) (2003). Five pollutants are analyzed in the framework including Carbon Monoxide, Carbon Dioxide, Nitrogen Oxide, Volatile Organic Compounds, and Particulate Matter 2.5. The monetary value per ton of each pollutant is consistent with the value employed in the Puget Sound Regional Council (PSRC) transportation benefit cost analysis, which was estimated based on reviews of existing research and represents a middle of the range of the available estimates (PSRC 2009). A major limitation of this method is the average travel speed cannot fully reflect the emission improvement due to less congestion and stop-and-go driving. The proposed method can only identify an improvement from either fewer VMT due to shorter trips or a change in travel speed. The mathematical version of the direct freight benefit model can be found in WSDOT (2013).

Economic Impact Models. Stemming from the transportation-related benefits to system users, there are economic impacts as businesses, consumers, and others respond to the transportation performance improvement and logistics cost reduction associated with infrastructure investments and improvements. These businesses may expand and grow as a result, possibly increasing employment, earnings, and total state revenue, which then may result in further statewide investment and increased personal consumption. These responses are captured in this methodology via an Economic Impact Analysis (EIA) using a Washington State Regional CGE model (Stodick et al. 2012). The travel time and operating cost benefits are utilized as inputs to the CGE model, with outputs composed of long-term employment and state/regional output by sector (industry).

The Washington State CGE model, developed by professors David Holland, Leroy Stodick, and Stephan Devadoss, is an adaptation of the Lofgren Model (Lofgren, Harris, and Robinson 2002) and has been used extensively for evaluating statewide economic impacts from a host of policy changes (Ghosh et al. undated, Holland and Devadoss 2006, Coupal and Holland undated). The model is a generic representation of the state's economy, although one developed to closely represent how its economy functions while adhering to traditional neoclassical economic theory. The underlying premise of CGE models is the Walrasian equilibrium, which states if all markets in a given economy are in equilibrium, then any specific or individual market will also be in equilibrium and therefore a market clearing price and quantity exists for any individual sector of the economy, as well as the whole regional economy (Wing 2004). The conceptual flow of activities is relatively simple and straightforward with all firms in an economy producing their own unique goods from factor inputs (labor and capital) which are provided by households. These goods, services, and commodities are then either utilized as inputs for other firms or consumed by households at the respective market clearing price. The model is solved utilizing the Generalized Algebraic Modeling System (GAMS) software and the PATH solver. In the proposed method, the direct transportation benefits (travel time savings and truck operating cost savings) are utilized as inputs to the CGE model to calculate regional economic impact stemming from the transportation costs reduction.

In summary, the project impacts on freight captured by the proposed methodology include direct transportation-related benefits as well as long-term economic impact. The transportation-related benefits are estimated based on either the outputs of the TDMs or the change in travel distance. The reduction of transportation costs is used as input to estimate the economic impacts on long-term job creation and regional output using the Washington State CGE model. The estimated project impact is one of the set of factors considered when prioritizing transportation projects. In addition, in order to support the transportation projects that improve efficient freight movement and promote regional economies, WSDOT classified roadways into five categories (T1 – T5) using the truck gross tonnage data, among which T1 and T2 roads represent the strategic economic corridors in Washington State and comprise 37% of all state route miles (WSDOT 2012b). The location of a highway project on a T1 or T2 corridor is one of many factors that are considered when prioritizing funding for projects. A schematic of the proposed truck freight highway economic impact analysis framework is shown in Figure 1.

Figure 1: Schematic of the Proposed Highway Truck-Freight Benefits and Economic Impacts Analysis Framework



CASE STUDY

A widening project on a major interstate in Washington was selected as the case study to evaluate the capability of the proposed framework in determining the full project impacts. This highway segment is a critical connector for the region and served approximately 5,000 to 7,000 trucks daily in 2011. It is also a strategic freight corridor carrying international and domestic trade. The freight demand using this route is projected to increase by 30% over the next 10 years, which will lead to considerable congestion and other negative impacts if this route cannot accommodate the growing demand. In light of this, WSDOT identified a widening project that supplemented the current four-lane highway with two additional lanes (one lane each direction). The segment length is approximately 10 miles.

The projected 2035 regional TDM outputs of build and no-build scenarios were provided by WSDOT using the relevant regional TDM, from which we calculated the changes in system total truck VHT and truck VMT to estimate the travel time savings, truck operating cost savings and environmental impact associated with the highway widening project. The estimated transportation related benefits were used as inputs to calculate the economic impacts using the Washington State CGE model. Details of the regional TDM, economic impact analysis, and calculated results are presented below.

Regional Travel Demand Model

The TDM relevant to the test project was employed to evaluate the pre- and post-investment traffic performance, including the freight specific performance. The model is a traditional four-step transportation planning model consisting of trip generation, trip distribution, mode choice, and trip assignment. It is used for estimating the daily travel patterns within the model area. The passenger and commercial traffic demand are estimated independently in the TDM (SRTC 2006). In contrast to the passenger travel demand estimated based on a household survey, the commercial travel demand is predefined by land use type, and truck trips are generated at different rates according to the land use type. For example, the commercial trip generation rate of CBD retail area is 5.95 while an industrial area is 1.33 (SRTC 2006). Future land use plans were provided by local DOTs. The commercial traffic is modeled in morning peak, middle day, evening peak and night time periods, respectively. The trip assignment is completed using an equilibrium assignment approach, by which travelers cannot reduce travel cost by shifting to other travel paths. Thus, once the transportation network is changed, the model is able to identify diverted traffic to the improved segments by reassigning the traffic. The model outputs include the segment traffic volume (passenger and truck traffic are estimated separately), average travel speed, and travel time. Segment-level truck VHT is calculated by multiplying the average travel time and the truck volume along the segment, and system total truck VHT is computed by adding together the segment-level VHT estimates.

Direct Freight Benefits Analysis Results

According to the TDM outputs, the system total daily truck VHT would decrease by 295 hours in a 2035 build scenario compared with the no-build scenario (approximately 1% of the total daily truck VHT), which would lead to reduction in travel time costs and truck operating costs. The travel time and truck operating cost savings were monetized using the truck costs per hour published by WSDOT (2009). The value of travel time and operating costs per hour are $27 and $48 respectively. Consistent with WSDOT practice, we assumed the annual benefits increased at a constant rate, equal to the total benefits in 2035 divided by number of project analysis years. The net present value was calculated by adding together the annual benefits over the 20-year analysis period with the discount rate of 4%, the same discount rate currently used by WSDOT. According to Table 1, more than $9,189,000 in travel time savings and $15,428,000 in operating cost savings would accrue to the freight system from 2016 to 2035. Though the system truck performance was improved, the emission costs would increase by $73,000 since the increased truck speed may lead to greater emissions when speed is higher than a certain threshold. The total transportation related benefits during the analysis period were calculated by adding together the travel time savings, operating cost savings, and emission impacts, and were equal to $24,544,000 as shown in Table 1.

Table 1: Summary of Transportation Related Benefit of Widening Project Over 20-Year Analysis Period (2016-2035), Thousands of 2010 Dollars

Benefit Category	
Truck travel time savings	$ 9,189
Truck operating cost savings	$15,428
Emission impacts	-$73
Total	$24,544

Economic Impact Analysis

Data. Reductions in transportation costs influence the production costs of freight dependent and other related businesses and industries. Responding to production cost changes, industries may alter their inter-sector relationships with the truck transportation sector and each other. These changes further contribute to the effects stemming from infrastructure investment on regional employment and output. Such economic impacts are captured by the Washington State CGE model. Data for the CGE model was generated from the most recent IMPLAN (2010) data (MIG 2010). Social Accounting Matrices (SAMs) detailing the economic exchanges occurring in the region are generated within IMPLAN, and exported to GAMS for CGE modeling. The CGE model then utilizes a set of equations and elasticities to reproduce the economy's inter-sector relationship in response to the produced counterfactual statements. Prior to introduction of the counterfactual, the models' parameters are calibrated such that it regenerates the original SAM. Example parameters used in calibration include various demand, substitution, and transformation elasticities. IMPLAN's basic structure contains 440 industries, of which we aggregate into 20 sectors in rough accordance with their 2-digit NAICS code.

Implementation: Conversion of TDM Outputs to Economic Impact Inputs. Four regional CGE models are constructed to evaluate the case study project. The four models are composed of two geographical scales, each with a short-run (SR) and long-run (LR) scenario. The SR variants assume capital is fixed across sectors and the region's total capital endowment is similarly fixed. Alternatively, a LR variant is established in which capital is mobile across sectors and the region-wide endowment is allowed to vary. The SR and LR variants effectively partition the results in a manner that displays the near term (e.g. first several years) economy response to the infrastructure, while the LR displays those impacts that could be expected once the economy has fully had an opportunity to adjust to the change. Unlike capital, both SR and LR models assume labor is mobile across sector and region. The labor closure considerations stem from discussions in Holland (2009), in which he suggests that lack of migration control at regional levels leave state borders and, to a greater extent county borders, more open to labor movement than national borders.

Though designed to represent the economy of Washington State, the Holland et al. (2006) model's geographic scale is dependent upon the scale generated in IMPLAN. Thus, to gain an understanding of the impact of changing model parameters of the SAM, as well as local purchasing coefficients, we model at both the state and county level. It is highly likely that the local industrial interactions modeled at the state level are different from those of a single county. For example, it is reasonable to expect that for some major industry input purchases, the county imports at a higher rate than the state if the state has a high supply of those commodities relative to the specific county. Given Washington's economy at the state level is highly correlated with that of the larger population centers found in Puget Sound, the state's purchasing pattern is very different from that of counties in other parts of the state. These changes may have significant impacts on the value and distribution of generated impacts of an infrastructure project.

Arguably, a transportation infrastructure project that reduces freight travel time and operating costs can be represented as an improvement in technology that permits the truck transportation industry to become more productive (increased efficiency) for a given level of capital and labor. These efficiencies are generally realized through reduced driver time on the road, resulting in reduced labor costs to the motor carrier and, increased trip miles per unit of time per vehicle, resulting in more productive individual vehicles; thus, potentially requiring fewer trucks to accomplish the workload and reduced vehicle repair and operating costs (FHWA 2002). As such, we develop a counterfactual to initiate the CGE models using the shift parameter (ad_A) for the truck transport industry's production function. This shift parameter, when adjusted, causes a shift to the industry's Leontieff-Constant Elasticity of Substitution (CES) production function (1). The production function is Leontieff-CES in such a manner that the intermediate inputs are in fixed proportions (Leontieff) while the factors of production possess CES technology.

(1) $QA_A = \frac{ad_A}{1-tb_A - \sum_C ica_{C,A}} * (\sum_{FF} del_{FF,A} QF_{FF,A}^{-rho_A})^{\frac{-1}{rho_A}}$, where

The shift parameter (2) is expressed as:

(2) $ad_A = \frac{(\frac{SAM_{TOTAL,A}}{PAO_A}) * (1 - tb_A - \sum_C ica_{C,A})}{(\sum_{FF} del_{FF,A} * QFO_{FF,A}{}^{-rho_A})^{\frac{-1}{rho_A}}}$, *where*

QA_A	=	Activity level (endogenous variable; where truck transport in the present model is the activity of concern)
tb_A	=	Indirect business tax rate of industry A (parameter calculated from initial data)
$ica_{C,A}$	=	Quantity of C (commodity) as intermediate input per unit of activity A (parameter calculated from initial data)
$del_{FF,A}$	=	Share parameter
$QF_{FF,A}$	=	Quantity of FF (factors of production) demanded by activity A (endogenous variable)
PAO_A	=	Initial activity price of A (user established)
rho_A	=	Exponent for production function
$SAM_{TOTAL,A}$	=	Social accounting matrix exported from IMPLAN
$QFO_{FF,A}$	=	Initial quantity of FF demanded by activity A (calculated from initial data)

For the present case, we are interested in the increased productivity within the region of consideration, as determined by the TDM, of the truck transport sector resultant of an infrastructure investment. An increase in the value of ad_A produces an increased QA_A for a set level of the factors of production. Thus the region's transportation industry has become more productive, producing a rightward shift in the supply curve. The CGE model does permit for the exchange of imports and exports for both domestic and foreign trade with the region under consideration. Composition of the export and import quantities with either of these regions is dependent upon relative prices.

The value assigned for the shift parameter is dependent upon the percent change in operating costs of the trucking industry. The percent change is a ratio based on benefits generated in the outputs of the TDM of the selected regional coverage as compared with the cost of the intermediate inputs (generated in IMPLAN) of the truck transport industry. Intermediate input costs include those purchases of goods and services used for production of trucking services, not including factors that may contribute to value added.

$$(3)\quad \textit{Percent Change in Costs of Production} = \frac{\textit{TDM Benefit Output}}{\textit{Intermediate Expenditures}}$$

The TDM outputs produce 3.24% and 0.26% increases in productivity to the trucking industries of the County and the State of Washington, respectively (Table 2). These values are input to the CGE model to inform the counterfactual statement to the production function shift parameter.

Table 2: Productivity Change to the Transport by Truck Sector

Travel Demand Model Benefit Output	$ 4,533,563[a]
County Intermediate Expenditures (transport by truck)	$ 139,875,763
Statewide Intermediate Expenditures (transport by truck)	$1,760,368,000
Change in Truck Transport Productivity–County	3.24%
Change in Truck Transport Productivity–State	0.26%

[a] All dollars are in 2010 dollars. Benefits include single analysis year (year 2035) of reduced operating and travel time savings. Emissions not included.

Impact Results. Though there are multiple ways to display the results of economic impact models, the most common, straightforward, and relevant are in relation to changes in employment and regional output activity of the various industries that rely on freight or are otherwise impacted by its movement. Given the calculated TDM output changes (direct impacts) resulting from the case study (Table 2), Tables 3 and 4 display the regional economies' response to increased truck productivity at the county and state levels, respectively.

Short-run considerations are included here to suggest the initial reactions that may be expected following completion of the infrastructure improvement, under the defined SR closure rules. Under these conditions (*ceteris paribus)*, the prices paid for truck services are suggested to decrease by 1.94%. This price decrease corresponds to the increase in activity output of the sector in Table 3 (refer to complete CGE documentation for the relevant equations to generate price changes [Stodick et al. 2012]). At the state level, price change is an expectedly much smaller 0.18% drop. Regional economy-wide employment increases in both the county and state models by nearly the same value; 25 and 22 jobs, respectively. Additionally, output sales in the two regional economies also increase by rather similar values of $9.8 million and $10.5 million, respectively.

Long-run scenarios allow for the suggestion of the achievable degree of economic impacts once the various sectors are fully able to respond. Closure rules in the LR permit a relaxing of constraints upon the movement of capital within the economy. With this increased flexibility, the county and state-wide models begin to show more divergence in their results. Here, the county model shows a growth of 78 jobs, while the state comes in at 47. Similarly, the county model suggests output sales increases of $28.7 million, and the state $22.2 million. Looking specifically at the initial impact generating activity, reduction in truck transport prices, the county and state models suggest price reductions of 1.67% and 0.14%, respectively.

Interestingly, the results reveal that in all the CGE models (SR and LR), the truck transport industry has negative changes in employment numbers. At first glance, this may appear counterintuitive. However, these results can be thought about in relation to a cost of congestion study done previously in Washington State (Taylor 2011). Taylor's survey and subsequent input-output modeling suggests that freight-dependent companies may respond to increased congestion (reduced productivity) by

Table 3: Industry Sector Specific Results at County Level

Sector	Initial Employment Level	Change in Employment Numbers		Change in Activity Quantity (%)	
		SR	LR	SR	LR
Agriculture and Forestry	3,993	4.6	14.5	0.021	0.361
Mining	255	0.1	0.2	0.005	0.078
Utilities	624	0.1	0.5	0.005	0.070
Construction	15,060	3.3	2.8	0.015	0.018
Manufacturing	14,046	26.8	45.8	0.133	0.325
Wholesale Trade	10,292	3.1	5.6	0.019	0.053
Retail Trade	30,532	8.0	9.6	0.022	0.031
Transportation and Warehousing	4,331	-2.4	-2.6	-0.038	-0.060
Transport by Truck	2,594	-45.0	-38.0	1.934	1.729
Information Services	3,362	0.4	0.8	0.004	0.022
Financial and Insurance	18,142	0.7	1.6	0.002	0.007
Real Estate	10,769	1.9	3.1	0.001	0.026
Professional and Technical	14,881	2.7	5.0	0.011	0.033
Management	2,687	2.1	4.1	0.069	0.154
Administration	11,940	5.2	6.5	0.034	0.054
Waste Management	357	0.2	0.2	0.025	0.068
Social Services	44,525	-0.6	2.5	-0.001	0.005
Arts and Entertainment	5,232	1.6	2.1	0.019	0.038
Food Services	17,216	3.6	5.8	0.014	0.032
Other (Including Government)	53,470	9.1	7.8	0.014	0.014

adding trucks (increasing employment) and producing a societal benefit, while also decreasing the purchases of services and non-freight dependent goods as more is paid towards trucking services. An opposite reaction is simulated here. In the present case, the TDMs suggest congestion relief stemming from the case study producing a positive effect, in that it simulates consumers increasing purchases of services and non-freight-dependent goods (increased activity in Tables 3 and 4), as well as a negative effect that simulates the trucking industry's response of reducing employment. In other words, we witness consumer benefits in the form of increased purchasing activity, and a societal cost in terms of potential employment reduction on the part of trucking services as congestion is eased.

The economic analysis results show that \$4.5 million direct transportation benefits (shown in the first row of Table 2) may generate additional \$28 million county-level output, which may have significant impacts on project prioritization, and should not be neglected from the project cost efficiency assessment. A change in output, sales, is reflective of the difference between the product of the base producer price and regional output quantity as compared with that after initiating the counterfactual. It is also important to note, in a policy context, that the results here are presented for the single region of consideration; however, given that the balance of regional imports and exports is price relative, there are additional impacts to external regions as a result of economic activity transfer. For future project prioritization, the direct transportation benefits will be added to already established passenger benefits, and compared with the project cost over the analysis period (20

Table 4: Industry Sector Specific Results at State Level

Sector	Initial Employment Level	Change in Employment Numbers		Change in Activity Quantity (%)	
		SR	LR	SR	LR
Agriculture and Forestry	1.17E+05	4.8	13.7	0.002	0.012
Mining	3,281	0.2	0.4	0.002	0.012
Utilities	5,376	0.1	0.3	0.000	0.006
Construction	2.07E+06	3.4	2.5	0.001	0.001
Manufacturing	2.67E+05	20.6	27.0	0.005	0.010
Wholesale Trade	1.29E+05	6.6	6.8	0.001	0.002
Retail Trade	3.77E+05	6.6	6.8	0.001	0.002
Transportation and Warehousing	72,712	-3.4	-3.2	-0.003	-0.004
Transport by Truck	32,647	-39.8	-32.8	0.185	0.157
Information Services	1.09E+05	-0.6	-0.9	0.000	-0.001
Financial and Insurance	1.87E+05	2.4	2.5	0.001	0.001
Real Estate	1.76E+05	1.9	2.4	0.000	0.001
Professional and Technical	2.83E+05	1.2	2.3	0.000	0.001
Management	32,319	1.1	1.7	0.003	0.005
Administration	1.64E+05	4.0	3.4	0.002	0.002
Waste Management	15,062	0.1	0.1	0.000	0.000
Social Services	4.47E+05	4.6	6.8	0.001	0.002
Arts and Entertainment	85,615	1.3	1.3	0.001	0.001
Food Services	2.39E+05	3.3	3.8	0.001	0.002
Other (Including Government)	8.35E+05	8.5	6.2	0.001	0.001

years in general) to identify the project net present benefits and benefit-cost ratio. Meanwhile, the economic impacts will be considered as one of a group of factors when prioritizing projects.

CONCLUSION AND DISCUSSION

In this paper we propose a transparent truck freight highway benefit and economic impact analysis framework, which estimates both freight transportation-related benefits and regional economic impacts associated with freight investments. The transportation benefits consist of travel time savings, truck operating costs savings, and emission impacts calculated based on regional TDM outputs (or ArcGIS spatial analysis results). The travel time and operating cost savings serve as inputs to estimate the economic impacts on regional employment and output using Regional CGE models. A highway widening project was selected as a case study. Four scenarios were created to evaluate both short-run and long-run impacts at the County and Washington State level. The results indicate that freight investments improve transportation performance and lead to direct transportation-related benefits. These direct transportation benefits are then transferred to other parties and generate economic impacts via job creation and regional economic activity improvement. The results also reveal that the industrial base of a geographical region can significantly impact model results, particularly as the length of the run is extended and the economy fully responds. This finding suggests that modeled analyses aimed at policy-relevant improvements should consider the appropriate geographical scale of consideration, thereby considering the industrial makeup and truck usage needs of the regional economy. For future project prioritization, the total project benefits will be added to already established passenger benefits, and compared with the project cost over the analysis period to calculate the project net present benefits and benefit-cost ratio. In addition, the economic impacts will be considered as one of a group of factors when prioritizing projects.

Despite the proposed methodology's ability to better capture the project benefits to direct and indirect freight users, and enhance the state's infrastructure project prioritization, future improvements can be made from the following aspects. First, some critical performance measures identified by the technical groups are excluded from the framework, including travel time reliability and network resiliency, due to the lack of quality regional data, and will be included in the next phase of development. Second, more efforts are needed to infuse both dynamic transportation models with equally dynamic economic models such that feedback between the two is more fluid.

The ability to reliably provide defensible performance measures and enable projection of future responses to infrastructure investments is a vital need for transportation agencies as funding becomes increasingly competitive. This study takes a valuable step forward in the development a methodologically sound framework to infuse freight benefits and regional economic impacts into existing agency level prioritization processes. The proposed framework can be applied in other states with local TDMs, economic models, and other factors.

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***Zun Wang** is pursuing a Ph.D. in transportation engineering in the Department of Civil and Environmental Engineering at the University of Washington. Her research interests lie in freight transportation, with a particular enthusiasm for freight project impacts assessment and freight performance measures. Her current research focuses on quantifying the full range of freight benefits associated with transportation investments. She is also working on freight performance measures using truck GPS data.*

***Jeremy Sage** is a research associate and assistant director of the Freight Policy Transportation Institute in the School of Economic Sciences at Washington State University. His research agenda includes assessment of regional economic impacts stemming from improved multi-modal commodity movement, effects of weather related catastrophes on transportation infrastructure and goods movement, and reliability of freight system networks.*

***Anne Goodchild** is an associated professor in the Department of Civil and Environmental Engineering at the University of Washington. She has a strong interest in the relationship between freight transportation activity, the environment, and the economy. This has led her to engage in many projects that are working to integrate business practice or shipper and carrier behavior, into freight transportation models, and seek environmental improvements that are economically efficient. Anne is chair of the Seattle Freight Advisory Board, and the paper review coordinator for the Freight Transportation Planning and Logistics, and Intermodal Committees of the Transportation Research Board.*

***Eric Jessup** is currently an honorary professor at the Albert-Ludwigs-Universität in Freiburg, Germany. He previously spent 10 years at Washington State University in the School of Economic Sciences as an associated professor and co-director of the Freight Policy Transportation Institute. His research has been in the field of transportation economics, but most recently in the area of renewable energy policies, both in the U.S. and Europe.*

***Ken Casavant** is a professor in the School of Economic Sciences and, after spending 45 years at Washington State University, has become a nationally renowned transportation economist. He has received numerous teaching, research and service awards throughout his tenure at Washington State University. Ken also serves as the faculty athletic representative to the president for Washington State University.*

***Rachel L. Knutson** is an economist with the Freight Systems Division at the Washington State Department of Transportation. Her primary interests are freight-related economics, transportation finance, and transportation performance measurement. Rachel received a B.S. in economics from the University of Puget Sound and an M.S. in economics from Oregon State University, where she was a William & Joyce Furman Fellow. Previously, she was an analyst for the Strategic Assessment Office at the Washington State Department of Transportation and worked for HDR, Inc., an engineering consulting firm.*

Future Substitutes for Diesel Fuel in U.S. Truck and Railroad Freight Transportation

by C. Phillip Baumel

This paper explains why diesel fuel is the preferred fuel in freight transportation. It identifies possible substitute fuels for motor carriers and railroads that are currently available and under development. It identifies which of these substitutes are likely to be used in the near and medium term years and the circumstances under which they will be used. The paper discusses which fuel efficiency measures have been successfully adopted by railroads and motor carriers. Finally, it suggests opportunities for transportation researchers to evaluate investment options to improve fuel efficiencies in freight transportation.

INTRODUCTION

In 1878, Rudolph Diesel, a student in Munich, Germany, learned that the new internal combustion gas engine, developed by Nikolaus Otto, converted only a small percent of the fuel energy into mechanical energy (Kong 2012). He also learned that a higher compression ratio in a combustion cylinder should produce greater fuel efficiency and more power. The theory was that higher air compression would create enough heat to ignite the fuel in the cylinder. The resulting high temperature explosion would burn more of the energy in the fuel; this would create greater energy efficiency and more power than Otto's spark-ignited engine. Five years later, Rudolph Diesel developed a compressed ignition—diesel—engine that worked. In 2010, medium- and heavy-duty trucks consumed 91% (33.3 billion gallons) of all the diesel fuel consumed on U.S. highways (U.S. Department of Energy 2012). Class I railroads consumed 3.5 billion gallons (AAR 2011).

The fundamental difference between diesel- and gasoline-powered internal combustion engines is the method of igniting the fuel in the combustion chambers (Kong 2012). The mixture of air and fuel injected into the cylinders of gasoline engines is ignited by a spark from the spark plug in each cylinder. Diesel engines have no spark plugs. Rather, the fuel is ignited by the very high air temperature in the high compression ratio diesel combustion chamber. The compression ratio is the volume of the cylinder and combustion chamber at the bottom of the piston stroke divided by the volume at the peak of the piston stroke (Kong 2012). The compression ratio in gasoline engines ranges from 8 to 12. The compression ratio of diesel engines ranges from 14 to 25. The lower compression ratio of gasoline engines restricts them to converting about 35% of the energy in the fuel to move a vehicle. The higher compression ratio of diesel engines enables them to convert up to 55% of the energy in the fuel to move a vehicle or ship. However, if a mixture of fuel and air is injected into the cylinder of a diesel engine, the high compression ratio could induce an undesired pre-ignition, causing the engine to knock. Thus, in Diesel's new engine, only air is induced into the cylinder and the liquid fuel is injected into the combustion chamber near the peak of the compression stroke.

Other advantages of diesel power over gasoline include:

1. Diesel fuel contains more energy than gasoline. One gallon of diesel fuel contains about 128,700 British Thermal Unit (Btu) while one gallon of gasoline contains 115,400 Btu (Table 2). One Btu is the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit.

2. Diesel fuel emits only small amounts of carbon monoxide and hydrocarbons that are attributed to global warming. However, diesel fuel emits large amounts of nitric compounds and soot that lead to acid rain, smog and health problems.
3. Diesel fuel has better lubricating properties than gasoline, which helps make diesel engines last longer. However, reducing the sulfur content in diesel fuel decreases its lubricating property.
4. Until recently, diesel fuel prices were lower than those for gasoline. Currently, diesel fuel prices exceed gasoline prices, in part, because of increased costs of removing sulfur, soot, and other pollutants.

With all of the advantages of diesel engines and fuel, why are we searching for alternative fuels?

1. Diesel fuel is made from crude petroleum. At the end of 2010, the United States had proven technically recoverable reserves of about 25.2 billion barrels of petroleum, up from 22.2 billion barrels in 2009 (Energy Information Administration [EIA] August 2, 2012). This increase was the result of crude oil discoveries associated with the recent major increases in natural gas reserves, mainly in Texas and North Dakota. Total domestic crude petroleum extraction in 2010 was 2.0 billion barrels (EIA August 2, 2012). At this rate of extraction, the U.S. has about a 13-year supply of proven domestic crude petroleum reserves. Of course, supplies in proven reserves change with discoveries, prices, and annual production. Proven recoverable reserves do not include non-conventional supplies like shale and sand oil and some off-shore deposits. The EIA (April 15, 2013) estimated that the total U.S. proved and unproved petroleum reserves in 2011 were 219 billion barrels.
2. The U.S. imported 40% of its 2012 petroleum usage (EIA April 15, 2013). A substantial amount of those imports came from Middle East and African countries that are hostile to the U.S.
3. The huge outflow of dollars to pay for petroleum imports increases our balance of payment deficits, and the cost of all imports, including oil.
4. Combustion of diesel fuel produces large amounts of carbon dioxide.
5. In 45 years, at current rates of extraction, conventional world petroleum prices will rise to a level that will prohibit its use for many of its current purposes (Brown and Brown 2012).

ALTERNATIVES TO DIESEL FUEL

Biodiesel

The major commercially available biofuel substitute for diesel fuel in the United States is biodiesel. A large amount of biodiesel is made from inedible fats and oils, waste restaurant oils, and byproducts like inedible corn oil. Biodiesel is also made from virgin vegetable oils, including soybean and canola oil. However, soybean and canola oil prices are higher than those of used and inedible fats and oils. Therefore, virgin oils are typically used in biodiesel plants that are not designed to use waste and inedible fats and oils, or if there are insufficient supplies of lower cost feedstocks.

The December 2007 Energy Independence and Security Act mandated that biomass diesel be blended into diesel fuel. Beginning in 2010, the Environmental Protection Agency (EPA) mandated that 800 million gallons of biomass diesel be blended into diesel fuels. This mandate could be satisfied by biodiesel and/or biomass diesel. Thus far, biodiesel has been the dominate fuel to satisfy the EPA mandate. This mandate increased to one billion gallons in 2011 and to 1.28 billion gallons in 2013 (Renewable Energy Group, Inc. [REG] 2012). This mandate insures that there will be a market for biodiesel even if biodiesel costs more than petroleum-based diesel. Data from REG, the producer of the largest number of gallons of biodiesel in 2012, illustrate this point. In 2012, this company sold 188 million gallons of diesel fuel in the United States (Table 1). The feedstocks for 84% of that production were inedible animal fat, used cooking oil, and inedible corn oil extracted from distillers' grains, a byproduct of ethanol production. The use of these lower-cost fats and oils helped make this company one of the low-cost biodiesel producers in the industry. Only 16% of its production came from higher-cost soybean oil.

Table 1 indicates that the average 2012 wholesale price of these 188 million gallons of biodiesel produced by this low-cost biodiesel producer was $5.31 per gallon. The average 2012 U.S. retail price of petroleum diesel was $3.97 per gallon (EIA February 5, 2013). This indicates that the average 2012 wholesale price of biodiesel paid to this low-cost biodiesel producer was approximately $1.34 per gallon above the average U.S. retail price of petroleum diesel. Table 2 suggests that, with a diesel price of $4.00 per gallon, the Btu value of 100% biodiesel is $3.64. There are four major reasons why this low-cost producer of biodiesel, with 9% fewer Btu than diesel, was able to sell its 2012 output at a price that was, on average, $1.34 above the average 2012 retail price of petroleum-based diesel. These reasons are:

1. The federal government mandated that one billion gallons of biodiesel be blended into diesel fuel in 2012.
2. To track the sales of renewable fuel production, the EPA created the renewable identification number (RIN) system. All EPA registered producers of renewable fuels may create an RIN for each gallon of renewable fuel produced (REG 2012). RINs have value to "obligated parties" to satisfy their renewable volume obligation under the Renewable Fuel Standard legislation. Most biodiesel is sold with its RIN attached. RINs may also be sold as a separate commodity. The 2012 values of RINs ranged from $2.39 per gallon in January to a low of $0.63 per gallon of the average Jacobsen B100 Upper Midwest spot price of a gallon of biodiesel (REG 2012).
3. The blender's tax credit provided a $1.00 excise tax credit per gallon of 100% biodiesel to the first person who blended biodiesel with petroleum-based diesel fuel (REG 2012). The tax credit could then be credited against the blender's excise tax liability, or the blender could obtain cash refunds from the U.S. Treasury for the value of the credits. This tax credit expired on December 31, 2011, and was renewed on January 1, 2013.
4. Many states and cities offer various types of mandates and financial incentives to encourage the use of biodiesel over petroleum-based diesel (National Biodiesel Board 2012).

Table 1: REG Biodiesel Sales and Cost of Goods Sold, 2012

Biodiesel sales	$1,006,471,000
Gallons sold	188,000,000
Sales per gallon	$5.35
Less assumed byproduct sales per gallon	$0.04
Net biodiesel sales per gallon	$5.31
Cost of goods sold	$956,448,000
Cost of goods sold per gallon	$5.09

Source: REG 2012

Table 2: Btu Content and Diesel Equivalent Gallons of Alternative Fuels

Fuels	Unit of Measure	Btu Content	Diesel Gallon Equivalent
Diesel	Gallon	128,7000***	1
Gasoline	Gallon	115,400***	1.12
Biodiesel	Gallon	117,093***	1.1
Compressed Natural Gas	100 Cubic feet	96,000***	1.34
Liquified Natural Gas	Gallon	75,000**	1.72
Ethanol	Gallon	75,670***	1.7
Hydrogen	100 Cubic feet	31,900**	4.03
Synthetic Diesel	Gallon	128,639*	1

Source:
*KiOR (2013)
**Wikipida (May, 2013)
***U.S. Department of Energy (2011-2013)

The market value of the RINs, in combination with the blender's tax credit, the Federally mandated blending of biodiesel, and state and city incentives, enabled biodiesel producers to sell biodiesel to obligated parties in a market in which the competitive product, petroleum-based diesel, is sold at a substantially lower price.

Biodiesel sold for transportation purposes is blended with petroleum-based diesel. A common blend, B10, is 10% biodiesel and 90% petroleum diesel. Blends can range from B1 to B99. There are several reasons for blending these two fuels:

1. The federal government mandates blending of biodiesel with petroleum based diesel.
2. The higher cost of biodiesel is an incentive to spread its high cost over a large number of gallons of a lower cost petroleum diesel fuel.
3. The blended biodiesel helps improve the lubricity of low sulfur petroleum-based diesel. Lubricity is the capacity to reduce friction.
4. Blending reduces the "cloud point" of biodiesel. The cloud point is the temperature below which the appearance of a fuel becomes cloudy. Cloudiness indicates that the fuel is likely to gel (REG 2012). This could lead to plugged fuel filters and other handling and performance problems. Biodiesel begins to gel at 30 to 60. The cloud point for diesel fuel is below 20^{o} F. Blending reduces the cloud point for the blended biodiesel, but increases the cloud point of the blended petroleum diesel.
5. Diesel fuel contains 128,700 Btu. Biodiesel contains 117,093 Btu. Blending results in a weighted average of the two.

There are three other issues with biodiesel. First, biodiesel contains oxygen, while diesel contains none. Oxygen makes the fuel unstable and tends to make it crystallize over time as well as in cold temperatures. The crystals tend to clog engine fuel delivery systems. Therefore, a good biodiesel management program is needed to prevent these problems (Ring 2011).

Second, there are limited supplies of low-cost feedstocks to produce biodiesel. Reidy (2012) suggests that finding feedstocks to produce the mandated blending, 1.28 billion gallons of biodiesel in 2013, will be tricky. According to Reidy (2012), the supply of inedible corn oil will top out at 300 million gallons of biodiesel production. The meat packing industry, the source of most animal fats, will supply enough animal fats to produce about 400 million gallons of biodiesel. The remaining 580 million gallons will need to come from used cooking oils and virgin soybean and/or canola oil. Reidy (2012) indicates that the EPA and USDA believe the additional soybean oil will come from reduced U.S. soybean exports; she also indicates that world demand for virgin vegetable oil is increasing. Thus, if Reidy (2012) is right, biodiesel producers will be forced to compete with international vegetable oil buyers for virgin vegetable oils. This suggests that biodiesel producers could be forced to pay higher prices for virgin vegetable oils and for inedible feedstocks to meet the 2013 EPA mandate of 1.28 billion gallons of biodiesel. Potential shortages of biodiesel feedstocks could increase the costs and/or slow the growth of biodiesel production above its current 3% of diesel consumed on U.S. highways.

Third, a fundamental principle of economics is that a firm will not produce a product if the price it receives for that product is equal to or less than the variable cost of producing that product. The logic of this principle is that a firm will continue to produce a product only if the price it receives covers its variable costs per unit of output and, at least, some of its fixed costs. Assuming that the REG (2012) variable cost of production was the $5.09 per gallon cost of goods sold (Table 2), it is likely that biodiesel producers would shut down some of their high-cost plants after the EPA mandated blending of 1.28 billion of gallons is reached. This is because wholesale buyers would no longer be forced to buy biodiesel when its price is substantially above the wholesale price of petroleum diesel. Unless the EPA increases the biodiesel mandate above the one billion or 1.28 billion gallons, biodiesel firms are likely to first close those plants that must use higher cost vegetable oils as their only feedstocks. Then, if biodiesel prices continue to fall to the variable cost per unit of plants that use lower-cost feedstocks, firms would then begin to close some of these plants as well.

How will trucking firms respond to biodiesel fuels in the future? As long as the EPA continues to mandate a minimal use of biodiesel fuel in transportation fuels, trucking firms have little choice but to buy biodiesel blended fuels. However, not all refueling stops sell biodiesel blended fuels. So, at least, truckers can avoid using some biodiesel blended fuels by their selection of where they refuel. Once the mandated quantities are sold, truckers can seek biodiesel that is priced below the cost of petroleum or avoid the use of biodiesel in states that do not mandate that all diesel fuel must be blended with biodiesel. Moreover, truckers will especially attempt to avoid purchasing biodiesel blended fuels in northern states during cold winter months to avoid fuel that becomes cloudy and clogs their fuel distribution systems.

How will railroad companies respond to biodiesel fuels in the future? Numerous biodiesel performance tests have been made on medium-speed diesel engines in North American railroad locomotives. These tests, including various blends of biodiesel and petroleum-based diesel, raised concerns about the following issues (Majewski et al. 2011):

1. Compatibility between biodiesel fuel and medium-speed diesel locomotive engines. These issues include material compatibility, fuel system compatibility including fuel leakage, and engine oil dilution. These issues were more serious on heavy-duty, line-haul locomotives than on lower power switch engine locomotives.
2. Higher NOx emission from biodiesel powered locomotives, particularly in heavy duty, line haul service.
3. Lower Btu content of biodiesel generally causing reduced locomotive power.
4. Handling, storage and engine performance problems associated with gel forming in low temperatures and oxidation of biodiesel.
5. Higher cost of biodiesel.
6. Potential problems with manufacturer's warranties on diesel engines and fuel injection systems, particularly with higher amounts of biodiesel blended with petroleum-based diesel fuel.

The general conclusion from the biodiesel tests on railroad locomotives is that railroads are unlikely to use biodiesel beyond the federal, state, and city usage mandates. After the mandated quantities are sold, railroads, like truckers, will likely try to purchase lower-cost petroleum in states that do not mandate that all diesel fuel must be blended with biodiesel or seek biodiesel that is priced below the cost of petroleum diesel.

Renewable Diesel

Renewable diesel usually refers to hydro-treated vegetable oils or animal fats (Majewski et al. 2011). The feedstocks for biodiesel are treated with hydrogen to remove their oxygen. This process produces a diesel fuel with no stability or low temperature operability problems that have been associated with biodiesel. The properties of renewable diesel are similar to gas-to-liquid (GTL) synthetic diesel fuels. The cetane number for renewable diesel, a measure of the fuel's ability to self ignite, is very high; the higher the better for diesel fuel. Renewable diesel has no sulfur, oxygen, or nitrogen. Its clouding point is well below freezing and its heating value is similar to diesel. Also, its storage stability is good (Majewski et al. 2011).

There are no published cost analyses of renewable diesel production costs, but they are believed to be higher than the cost of producing biodiesel, which is currently higher than the wholesale price of petroleum-based diesel. There are no commercial renewable diesel production plants in the United States. There are, however, two production plants in Finland (Majewski et al. 2011).

Algae Biofuel

Algae biofuel is a popular potential alternative to diesel fuel. President Obama suggested "a plant-like substance, algae" as a way of cutting dependence on oil by 17% (Gehrke 2012). Several companies, and some research institutions, predict that they will be capable of producing algae fuel on a commercial scale at the same price as petroleum in the near future (Brown and Brown 2012).

The algae that are proposed as a partial solution to our energy problem are not the algae plants commonly found in ponds of water across the country. Rather, it is a group of single-cell micro-organisms that produce large amounts of lipids. Lipids can be transformed into hydrocarbons that are essentially indistinguishable from gasoline or diesel fuels (Brown and Brown 2012). There are about 50,000 species of microalgae (Wen 2012). One of the major problems facing researchers in the development of algae fuels is finding those species of microalgae that produce the most lipids. At the present time, the average lipid content of algae is 5%–10% of their liquid content (Wen 2012). In theory, it is possible to genetically modify microalgae to contain in excess of 50% of lipids (Wen 2012). Other major problems include designing the most productive methods of growing the algae. Two methods of production currently getting the most research attention are open ponds and enclosed plastic "photobioreactors" (Brown and Brown 2012). Open ponds cost $100,000 per acre and the photobioreactors cost $1 million per acre. Another major problem is the harvesting and extraction of the lipids on a daily basis. A Department of Energy study suggests that it costs over $10 to produce a gallon of algae diesel from open ponds and about $20 per gallon from photobioreactors (Davis et al. 2011). The study suggests that the cost of algae diesel could fall to about $4 per gallon with major improvements in algae lipid content and production, greatly reduced harvesting and extraction costs, and the sale of the spent biomass at $500 per ton (Davis et al. 2011). Some researchers suggest that they are three to five years from large-scale production (Herman 2010). Others indicate that there have been no major breakthroughs and that commercialization of algae diesel is decades away (Wen 2012).

Algae fuels are sometimes referred to as third generation biofuels. Other potential sources of lipids for diesel fuel are palm oil, jatropha, a hardy group of wild tropical plants, and salicornia, a salt-tolerant plant that grows in marshes and beaches. Both jatropha and salicornia face several decades of development if they prove to be good sources of lipids (Brown and Brown 2012). There is substantial environmental resistance to the use of palm oil for fuels because of the destruction of rainforests to produce palm oil (Brown and Brown 2012). Trucking and railroad firms will not need to decide if they should purchase algae fuels until it becomes available commercially, likely some decades away.

Natural Gas

Natural gas (NG) consists of about 90% methane. It originated from the remains of historical plants and animals and was formed by the great pressure exerted over centuries by the thousands of feet of rocks, sand, and debris covering the plant and animal remains. Small droplets of the odorless gas accumulated into NG deposits and petroleum and coal deposits. Recently, large quantities of NG have been found in shale formations.

In 2010, the United States had proven NG reserves of 317 trillion cubic feet (tcf). The 2012 production of NG was 23.2 tcf (EIA May 2013). At that level of production, the 317 tcf would only last 13 years. The good news is that the U.S. has huge quantities of unproven NG reserves locked deep in shale formations. The EIA (June 2012) estimated that the total technically recoverable NG reserves in the United States were 2,214 tcf. At the 2012 level of production, 2214 tcf would be more than a 95-year supply. Other observers suggest that the EIA estimate of total technically recoverable reserves is too low (National Geographic News 2012).

A large portion of the huge unproven reserves of NG has been made available to U.S. markets by hydraulic fracturing, commonly called fracking. Fracking pumps more than one million gallons of water, chemicals, and sand under high pressure into each well. These wells vary in depth, but can be as deep as 10,000 feet. After reaching the desired depth, the drilling extends horizontally across the shale formation (EIA September 19, 2011). The high pressure of injected water, chemicals, and sand fractures the shale formations and allows the NG and other hydrocarbons that exist there to escape the shale and flow up the well. The sand keeps the fractures open, allowing the gases to flow into the well over time.

NG has been used extensively to heat homes and buildings, in industrial production and for generating electricity. Because of its gaseous nature, only about 3% of NG has been used in transportation, much of it to propel NG through pipelines. The huge quantity of NG now being produced from shale formations has resulted in sharp declines in NG prices. In March 2008, the NG futures price was above $13 per million Btu (MMBtu). By late November 2011, the price had declined to just over $2 MMBtu, a decline of 85% (Irwin 2012). During the same period, the NYMEX crude oil futures price declined from $140 per barrel to $98 per barrel, a decline of 30% (Irwin 2012). These sharply declining NG prices have made it a potential fuel for freight transportation.

Table 3 shows the average national retail prices of diesel, CNG, and biodiesel prices on a diesel equivalent basis for seven time periods from October 2011 to April 2013. These were retail pump prices and included state and federal taxes. CNG prices averaged $1.61 per diesel gallon equivalent below diesel prices. B100 biodiesel prices averaged 77 cents per gallon higher than diesel prices. Table 2 suggests that the BTU value of a gallon of B100 biodiesel is about 9% below the Btu value of a gallon of petroleum-based diesel.

Table 3: Natural Gas, Diesel, and Gasoline Prices in Diesel Gallon Equivalent, Selected Months, 2011-2013

Month	Year	CNG	Biodiesel*	Diesel
April	2013	$2.34	$4.72	$3.99
January	2013	2.34	4.88	3.96
October	2012	2.36	4.82	4.13
July	2012	2.28	4.64	3.75
April	2012	2.32	4.78	4.12
January	2012	2.38	4.61	3.86
October	2011	2.33	4.59	3.81

*B100

Source: U.S. Department of Energy, (various issues, 2011-2013)

NG has several major advantages as an alternative to diesel fuel. These include:

1. As shown in Table 3, its low price is its major advantage.
2. A large domestic supply is made available mostly by fracking
3. Its use as an alternative to diesel fuel would help reduce U.S. petroleum imports. This would help reduce the deficit in the U.S. balance of payments, and increase the value of the U.S. dollar. It would also help decrease the cost of imports and domestic and imported petroleum.
4. NG is safer to use than petroleum diesel. It is inflammable in liquid form. In gaseous form, NG is flammable only in the range of a 5%–15% mixture of NG with air. It is lighter than air and, if spilled, quickly rises and dissipates into the air. NG fuel tanks are sturdier than diesel fuel tanks. In an emergency, release valves in NG tanks open above ambient temperatures and below ignition temperatures to allow the gas to harmlessly rise into the atmosphere (about.com 2013).

As with all alternatives to petroleum diesel, NG has some obstacles. These include:

1. NG is a gas, not a liquid. It requires major costly changes in engine and fuel distribution systems.
2. Its low energy density and gaseous form requires that it be converted into alternative forms to be used as a fuel for freight transportation. Two common conversions are "compressed NG" (CNG) and "liquefied NG" (LNG). CNG is NG under pressure of 3,000- to 3,600-pounds per square inch. LNG is NG that has been cooled to -260°F. At that temperature, it changes from a gas to a liquid that is 1/600th of its original volume. CNG is less expensive to produce and store than LNG, because it does not require expensive cooling and cryogenic tanks.
3. There are only a limited number of public NG fueling stations. Moreover, most of these early NG fueling stations have low capacity — one-to-two gallons per minute — refueling pumps, requiring long wait times to fill the NG tanks of trucks.
4. There is substantial environmental resistance to fracking. The argument is that the waters and chemicals used in fracking contaminate local water supplies.
5. NG is less energy dense than diesel. The reduced energy density means that a vehicle powered with CNG must either be used for short distances before being refueled, or carry large amounts of CNG. LNG-powered vehicles can travel longer distances before refueling, but still shorter distances than with diesel-powered vehicles.
6. Special refueling infrastructure must be provided to refuel vehicles that travel beyond the vehicle CNG or LNG carrying capacity. CNG powered trucks are typically limited to 200 one-way mile trips.

7. It is not clear that natural gas emissions, particularly nitric oxide emissions, are always less than those of diesel fuel (Majewski et al. 2011).

The recent availability of large supplies of NG, combined with its dramatic decline in price, make NG a potential substitute for diesel fuel.

EIA (June 2012) estimates that only 1,000 (0.3%) of the 360,000 heavy-duty vehicles sold in the U.S. in 2010 were NG fueled. In 2012, approximately 1% of the heavy-duty trucks sold in the U.S. were NG fueled (Carrick 2012). What is preventing NG from becoming a dominate fuel for the heavy duty, long-distance trucking industry? The major reasons are:

1. Higher NG vehicle costs
2. Reduced NG vehicle operating range
3. Insufficient number of refueling stations
4. Inadequate fuel pumping capacities at some existing NG refueling stations
5. Inadequate size NG engines to pull full loads over hills and mountains at acceptable speeds

The major additional costs of heavy-duty NG-fueled trucks over diesel-fueled trucks are fuel-storage and non-fuel-storage costs. The non-fuel-storage costs are the basically the costs of modifying the diesel engine to burn CNG or LNG. To make the engine operate entirely on NG, the piston is replaced to reduce the compression ratio and a spark plug is installed to ignite the fuel (Kong 2012). This modification makes the NG engine perform like a gasoline engine (Kong 2012). For new engines designed to operate on both NG and diesel, NG can be introduced into the intake port or directly into the cylinder. Another option is to use a new fuel injector designed to inject both NG and diesel into the cylinder (Kong 2012). EIA (June 2012) reports the cost of modifying the diesel engine of a semi-tractor-trailer truck to use NG is $30,000. One firm, operating several NG-fueled semi-tractor-trailer trucks, reported non-fuel storage costs of less than $20,000 per truck.

The fuel-storage cost is to replace the diesel tanks with tanks to hold either CNG or LNG. CNG storage tanks are designed to withstand internal pressure of up to 3,600 pounds per square inch. The tanks can be mounted on the sides of the frame and/or on the back of the cab. EIA (June 2012) estimates the cost of CNG storage tanks at $350 per gallon of storage.

The amount of storage needed depends on the miles per gallon, the length of the haul, and the distance between NG refueling stations. The firm that operates several CNG semi-tractor trucks reported that its trucks each have four high pressure tanks, one on each side of the frame and two on the back of the cab. Each tank costs $10,000 plus installation. Thus, the cost of the four CNG tanks was over $40,000. The total additional cost of converting these tractors to CNG was $60,000 each. EIA (June 2012) reports the incremental cost of NG class 8 (semi) trucks at $80,000.

The trucking firm reported the CNG tractors achieved 5.53 mpde (miles per diesel equivalent). A diesel equivalent gallon is the amount of alternative fuel required to equal the energy content of one gallon of diesel fuel. Table 1 illustrates the diesel gallons equivalent of several alternatives to diesel fuel. The round-trip distance for its NG trucks was a maximum of 400 miles. Therefore, these trucks need enough fuel storage for the 400-mile round trip.

LNG is NG cooled to -260^{o}F (Center for Liquefied Natural Gas 2012). At that temperature, the gas turns to a liquid that is 1/600th of its original volume. It is stored at this very cold temperature but not under high pressure. LNG must be stored in cryogenic tanks to maintain the very low temperature. Therefore, LNG tanks are more expensive than CNG tanks. LNG tanks cost about $475 per gallon of capacity (EIA June 2012). The advantage of LNG over CNG as a transportation fuel is that it is more energy dense. It requires fewer gallons of tank storage for a given distance, or it can power a truck for longer distances on the same tank storage. Some companies are developing new materials that will likely allow more CNG or LNG to be stored in smaller containers (Carrick 2012). These developments offer the promise of longer lengths of haul per tank of NG and possibly lower cost per gallon of NG storage.

A third problem hindering increased usage of NG by trucking firms is the lack of NG fueling stations. In May 2012, there were only 1,047 CNG fueling stations and 53 LNG fueling stations in the United States (EIA June 2012). Only 47% of the CNG stations and 43% of the LNG stations were accessible for public purchase of NG fuels. This means that many CNG trucks are limited to 400 round-trip miles.

The fourth problem is that the NG refill pumps at many of the existing fueling stations have very low pumping capacities (one-to-two gallons per minute) (Carrick 2012). These low pumping capacities require long refueling stops, adding to the cost of NG as a fuel. The longest refueling times are for trucks waiting in line to be refueled. These refueling problems are in the process of being solved. First, new fueling stations are coming on stream each month, most with refueling capacities of up to 10 gallons per minute. Some observers are predicting that within three years, there will be an additional 500 fueling stations, each with pumping capacities of 10 gallons per minute (Carrick 2012). Moreover, existing fueling stations are upgrading their refueling capacity.

The fifth obstacle to increased purchases of NG-powered trucks is that, until recently, the maximum size NG engine available for heavy-duty trucks was nine liters with 320-hp and 1,000 foot-pounds of torque. Liter refers to the volume of the cylinder from the top of the piston stroke to the bottom. Thus, a nine-liter NG engine has six cylinders. Therefore, each cylinder has a volume of 1.5 liters. One liter equals 1.0567 U.S. quarts. The relatively low Btu content of NG enables the nine-liter engine to generate adequate power for only local and regional service pulling 80,000 pound loads over level terrain (Carrick 2012).

Twelve-liter, six-cylinder engines (each cylinder having two liters of volume) with 400-hp and 1,450-foot pounds of torque are required for local and regional trucking service at acceptable speeds (Carrick 2012). The first 12-liter NG engine (Cummins Westpoint ISX12G) with an automatic transmission became available in early 2013 (Carrick 2013). This engine, with sufficient power to pull a full 80,000-pound load, enables NG-fueled trucks to become more prevalent in local and regional truck movements. Moreover, a 15-liter NG engine with 450-hp and 1,650-foot pounds of torque is under development for highway use. This engine will pull an 80,000-pound load at acceptable speeds over all types of U.S. terrain. With the introduction of the 15-liter engine in four to five years, and continued improvements in NG refueling infrastructure, trucking firms will likely be using NG as a fuel in coast-to-coast truck freight movements (Carrick 2012).

The question facing trucking companies is “What is the return on investment from NG fueled trucks?” One study reports that when diesel fuel is $1.50 per gallon higher than CNG, and the trucks are driven at least 70,000 miles per year with a spark-ignited CNG engine, the return on investment from CNG will be about 20% per year. Romba (2012) suggests that NG can be a viable alternative to diesel for relatively short line haul distances.

Carrick (2012) suggests that a good rule of thumb to evaluate the economic feasibility of investing in NG trucks is that, with 80,000 miles per year, and the CNG price at 50% of the diesel fuel price, the initial investment in an NG truck will be recovered in 18 months. The data in Table 3 indicate that CNG prices were 40% below diesel prices. However, these were retail pump prices. A trucking firm, with its own NG facilities and/or contracts with refueling companies, is likely to face CNG prices near a 50% discount to diesel prices. After the recovery of the initial investment, NG-fueled trucks will save $25,000 in fuel cost per truck per year. Carrick (2012) also suggests that by 2020, 5% to 10% of all heavy duty trucks sold in the U.S. will be NG trucks.

Under the assumption of no change in government programs and business as usual, EIA (June 2012) projects that NG heavy-duty truck sales will be about 26,000 per year by 2035 and the total number of heavy-duty NG trucks in the fleet would be 275,000 units.

Under more optimistic assumptions, including:

1. The availability of NG fueling stations
2. NG priced on a cost basis rather than on competing fuel prices
3. Differential NG prices for fleet and non-fleet operators
4. Taxes remain at current levels

EIA (June 2012) projects that heavy duty NG truck sales will increase dramatically to 275,000 per year by 2035. Under the more optimistic assumptions, EIA (June 2012) projects that the number of heavy duty NG trucks in the U.S. fleet would total 2,750,000 units or 21.8% of the fleet.

Railroads have been experimenting with NG products as a fuel for locomotives for over 75 years (AAR 2007). The first experiment took place in Missouri in 1936. The Joplin-Pittsburg Railroad placed a propane-fueled, 450-hp spark-ignited locomotive in service. This locomotive was later put in local service by the Kansas City Public Service Company. Several experiments were conducted from 1959-1980. One experiment, with a gas turbine locomotive, was abandoned because of low fuel efficiency; other experiments were conducted with locomotives using propane and CNG.

In 1992, the Burlington Northern Railway converted two diesel-electric SD-40 locomotives to run on a duel LNG-diesel mode. A 25,000-gallon fuel tender (LNG tank car) placed between the two locomotives, contained fuel for both locomotives. The two locomotives were then placed in unit train coal service. They were converted back to diesel fuel and general service in 1995.

In 1993, MK Rail Corporation introduced an LNG-fueled switch engine. Burlington Northern and Union Pacific each purchased two of these new switch engines. All four switch engines are still in service in California. The LPG is hauled into California by truck from Arizona. The conversion from diesel to dual diesel-LNG fuels reduced the horsepower of the switch engines from 2,000 to 1,250. The fuel consumption of the converted diesel-LNG engines to do the same work increased by 33%.

The railroad industry reached the following conclusions from these early experiments:

1. NG is not likely to provide the needed power for heavy duty, long-distance unit train service with the locomotive technology available at that time.
2. NG would require major investments in refueling facilities across the entire railroad system. NG prices at that time would not generate the savings needed to finance these refueling investments.
3. There were no NOx benefits and all other pollutant emissions were much higher than from the clean-burning diesel electric locomotives.
4. There may be a niche market for NG in switch locomotives. Switch locomotives usually remain in one location, thereby eliminating the refueling problem that NG would impose on line-haul locomotives traveling throughout the entire United States.

These early experiments were conducted when diesel and NG prices were close to being equal. Since then, NG prices have fallen dramatically relative to diesel fuel. These much lower NG prices have motivated all Class I railroads to begin reevaluating the possibility of using NG to power both long-haul, heavy-duty locomotives and switch locomotives (Fronczak 2013). Several railroads are currently working with locomotive manufacturers to develop efficient, clean-burning, and powerful NG locomotives (Bloomberg 2013). NG engines will need to be at least as clean burning as today's diesel engines to meet EPA emission standards. These reevaluations and actual experiments will attempt to determine if NG technologies can provide the power and clean burning performance of diesel-electric technologies at a lower cost. If the NG technologies can meet or exceed the diesel-performance at lower costs, the railroad industry will likely invest in NG locomotives and fuel tenders, and refueling, maintenance, and repair facilities. Other than biodiesel, NG is the only near-term alternative to diesel fuel for trucks. Thus, it is the most likely candidate to be a major substitute for diesel fuel for some decades until other alternatives are developed in laboratories and then take the long journey to commercialization.

Synthetic Diesel Fuel

Diesel fuel can be produced synthetically from NG, coal, and biomass. Biomass includes crop residues, grasses, and wood products. The United States has huge quantities of biomass and coal. The U.S. has the largest reserves of coal (27%) in the world (Brown and Brown 2012). The coal industry points out that the U.S. has a 250-year supply of coal at current rates of consumption (Brown and Brown 2012).

The best known synthetic fuel technology is the Fisher Tropsch (FT) process (Brown and Brown 2012). The FT process was developed in Germany during World War II when Germany was denied access to world petroleum supplies. South Africa also employed FT technology to produce fuel during its apartheid period. FT fuels are synthetic hydrocarbons produced by the action of metal catalysts at elevated pressures.

Another technology being developed to produce diesel fuel from biomass is fast pyrolysis. Fast pyrolysis deconstructs the biomass at very high temperatures to produce a mixture of organic compounds called bio-oil (Brown and Brown 2012). Hydro processing is then used to convert the bio-oil into renewable diesel.

There are several advantages of synthetic diesel fuels:

1. Synthetic diesel fuels require no modifications to existing engines.
2. These fuels can be mixed with and actually improve the quality of petroleum diesel.
3. They are liquids and can be distributed within the existing diesel distribution system.
4. Their sulfur content is near zero.
5. The supply of feedstocks (NG, biomass, coal) for synthetic fuel production is large.
6. Synthetic fuels have very high cetane levels.

Their disadvantages include (Majewski et al. 2011):

1. Except for synthetic diesel made from biomass, they have little or no greenhouse benefit relative to petroleum.
2. They have poor lubricity and cold flow properties.
3. Synthetic diesel made from coal has high carbon content, unless capture and sequestration technologies are incorporated in the production process.
4. They are likely to cost more than petroleum.

Chevron is using NG as a feedstock to produce a "gas-to-liquid" (GTL) synthetic diesel fuel in a new plant being built in Escravos, Nigeria. When completed in 2013, the new plant will convert 325 million cubic feet of natural gas into 33,000 barrels (1,386,000 gallons) of low-sulfur, synthetic diesel fuel each day (Chevron 2012).

In April 2013, KiOR, a Texas company, completed construction of a synthetic fuel plant in Columbus, Mississippi, that uses fast pyrolysis to produce cellulosic gasoline and diesel fuels from biomass (KiOR 2013). This plant has an annual production capacity of 13 million gallons per year. Its preferred feedstock is southern yellow pine wood chips. KiOR indicates that it will begin construction of a second plant in Natchez, Mississippi, in late 2013 (KiOR 2013). This second plant, also using yellow pine wood chips, will have an annual production capacity of 40 million gallons per year.

KiOR's revenues will come from the sale of gasoline and diesel fuels and from the sale of RINs to customers who are not obligated parties under the Renewable Fuel Standards. The diesel production from this plant will count toward the EPA-mandated 1.28 billion gallons of biofuels.

KiOR estimates that its cost of production of cellulosic gasoline and diesel will be about $1.80 per gallon plus financing and facility depreciation costs (KiOR 2013). This estimate is based on assumed input quantities and prices and excludes financing and depreciation costs. KiOR's actual cost of production awaits production cost data from the operations of its two plants.

The demand for KiOR's products, beyond the EPA, state, and city mandates, will depend on their selling prices. If its diesel price exceeds the price of petroleum diesel, truckers and railroads are unlikely to purchase quantities above the mandated amounts. The price of its non-mandated synthetic diesel will need to be about the same as or less than the price of petroleum diesel, because KiOR states that its fuels will be 1.7 GEE (gallons ethanol equivalent) (KiOR 2013). Assuming 75,670 Btu per gallon of ethanol, 1.7 GEE converts to 128,639 Btu per gallon for the KiOR diesel.

Petroleum-based diesel contains about 128,700 Btu per gallon, approximately the same as the 128,639 Btu in the KiOR synthetic diesel (Table 2).

When synthetic diesel becomes available commercially, it will likely become part of the EPA-mandated biomass fuels that truckers and railroads will be required to purchase up to the mandated quantities. Once the mandated quantities are sold, truckers and railroads will unlikely be willing to pay more for KiOR and other synthetic diesel than for petroleum diesel. On the other hand, even if the price of KiOR diesel is less than the price of petroleum diesel, KiOR will continue producing synthetic diesel as long as the price they receive exceeds their actual variable cost of production.

Given the huge supplies of NG, coal, and biomass in the United States, it appears that substantial research funds should be allocated to the Fisher Tropsch, fast pyrolysis, and other synthetic fuel production processes; this research should focus on reducing production costs and making synthetic diesel fuels more environmentally friendly.

Hydrogen

Fuel cells are self-contained devices that convert hydrogen directly into electricity. The electricity then powers an electric motor to move the vehicle. Some experimental fuel cells have been installed in small autos, trucks, and one railroad locomotive. Thus far, fuel cells have been unable to produce adequate power for these vehicles and costs have been high. The conclusion from these tests is that commercial use of fuel cells for freight transportation is decades away (Chevron 2012). Some observers believe that fuel cells will one day replace diesel engines (Majewski et al. 2011)

A second hydrogen option is the hydrogen internal combustion engine. The hydrogen combustion engine is closer to commercial deployment than the fuel cell and it can be manufactured at prices costing 15% more than petroleum engines (Majewski et al. 2011). It can run on pure hydrogen or on a combination of hydrogen and CNG.

Hydrogen, a tasteless, odorless, and colorless gas, is not found freely in nature. It must first be extracted from other substances such as coal and biomass. Fundamental problems with fuel cells and hydrogen internal combustion engines include (Brown and Brown 2012):

1. The extreme difficulty and cost of extracting and storing gaseous and liquid hydrogen
2. The low energy density of hydrogen
3. High levels of emissions from extracting hydrogen from fossil fuels

It is likely that fuel cells and hydrogen internal combustion engines are decades away from commercialization.

ELECTRICITY

Almost all U.S. railroad freight locomotives use a diesel-electric drive system. The output from the diesel combustion engine is used to generate electricity. This electricity drives the electric motor on each of the six drive axles on most heavy-duty, long-distance locomotives, to provide the high torque required to move the train (AAR 2007). This idea has been in existence for over a century. In the early 1900s, General Electric Company sold a gas-electric version of this idea to railroad companies (General Electric Company 1911).

The major benefit of the diesel-electric system is that it eliminates the need for mechanical transmissions. The issue being discussed in this section is not about the use of electricity to power trains. Railroads already do that. The issue is whether the electricity should be generated on-board the locomotive by a diesel engine, or generated elsewhere and transmitted to locomotives in movement from one location to another.

In this paper, railroad electrification refers to generating the electric elsewhere and transmitting it to locomotives. There are numerous electrified transportation systems around the world. One example is the Trans-Siberian railway that extends 9,880 km from Moscow to Nakhodka, Russia. Many U.S. railroad passenger systems are electrified.

Electricity is supplied to railroad locomotives by an overhead wire (catenary) system. The technology for this system is well established and mature. Therefore, major innovations are unlikely. The advantages of electrified rail systems include (Majewski et al. 2011):

1. Zero emissions from the locomotives
2. Reduced noise
3. High power-to-weight ratios in passenger trains allowing rapid acceleration and high speeds
4. Alternative fuels (fossil, nuclear, renewable) can be used to generate the electricity
5. The use of regenerative brakes, which put the electric motors in reverse to convert the kinetic energy of a vehicle already in motion, into electricity. Reversing the electric motors acts as a brake on the vehicle and, at the same time, the kinetic energy of the moving vehicle powers the reversed electric motors to generate electricity that is fed into batteries to be used as power at a later time (howstuffworks 2013 and Kinetic Energy 2013).

The disadvantages include:

1. There is an exceedingly high cost of infrastructure and locomotives.
2. The high infrastructure cost would be prohibitive on low-traffic main and branch rail lines. Therefore, an electrified rail system would require capital investments in the entire electrical transmission infrastructure, new electric locomotives and a completely new electrical maintenance and support system. In addition, a complete duplicate diesel-electric infrastructure system, including diesel-electric locomotives and a maintenance and support system would be required to service the traffic to and from the lower traffic main and branch rail lines.
3. There are potentially high emissions from electrical generation.
4. Some tunnels may not be large enough to accommodate the centenary system.
5. A single infrastructure failure on the electrified system would close down the entire electrified system served by that infrastructure.
6. The maturity of the technology means that major innovations are unlikely.

Given the huge cost of electric infrastructure, the need for dual electric and diesel systems and the lack of new technology, an electrified rail freight system is not likely to be economic under most short- and medium-term fuel price scenarios.

In the 1920s, the railroad system in the Northeast United States, called the Northeast Corridor, was converted from coal-fired steam engines to an electrified system. This electrified system was an improvement for both passenger and freight traffic over the steam engine system. During the 1950s and 60s, the remaining U.S. rail freight system was converted from the steam engine system to the diesel-electric system. By the 1970s, it became abundantly clear that the diesel-electric system was superior to the electrified system for freight traffic. In the 1980s, the Northeast Corridor rail freight system was converted from electricity to diesel-electric. The Northeast Corridor passenger rail system remains electrified and 80% of that system is owned and operated by the government-owned Amtrak passenger service. In fact, the fast starts and high speeds of light weight passenger trains are well served by electrified rail systems. Today's highly efficient, powerful, clean burning diesel-electric system, however, is operationally and profitably preferred for heavy-duty freight traffic over an electrified system. Nevertheless, the question continues to be asked "Should the entire current rail system be electrified to reduce petroleum consumption and imports in the United States?"

The answer to the above question is that electrification of the U.S. rail freight system will not occur unless and until diesel and diesel substitute prices rise to a level that will economically justify the huge expenditures needed to build and operate a new electrified system. Today, no one knows what those prices will need to be to economically justify the conversion of railroads to electrification. Another alternative is that the government, in an effort to reduce petroleum imports, politically mandates the electrification of the railroad system. If that happens, the government will need to determine where it will obtain the huge amounts of capital to finance the electrification and operation of the rail system.

FUEL EFFICIENCY

Freight transportation fuel efficiency is often defined as the number of miles one ton of product is moved per gallon of fuel. It is expressed as revenue ton-miles per gallon. Therefore, higher ton-miles of revenue freight per gallon indicate higher fuel efficiency. There has been more discussion of finding substitute fuels for petroleum-based fuels than in identifying the role of fuel efficiency as a substitute for petroleum. This section will discuss the role of fuel efficiency as a partial substitute for diesel fuel in the railroad and trucking industries.

In 1975, Class 1 railroads used 3.7 billion gallons of diesel fuel to produce 754 billion revenue ton-miles of freight. In other words, in 1975, Class 1 railroads achieved 206 revenue ton-miles of freight per gallon of diesel fuel (AAR 2011). In 2011, the Class 1 railroads again used 3.7 billion gallons of diesel fuel to produce 1,729 billion revenue ton-miles of freight. This represents 469 revenue ton-miles per gallon of fuel, an increase of 128% over 1975. Thus, in 2010, the Class 1 railroads moved 128% more ton-miles of freight with the same amount of fuel that they used in 1975. This is a major improvement in fuel efficiency. In effect, the gains in railroad fuel efficiency saved 4.7 billion gallons of diesel fuel in 2011 compared wotj the 1975 revenue ton miles per gallon. These gains in fuel efficiency were achieved in several ways, including the following (National Petroleum Council 2012):

1. The tons of revenue freight per car were increased by reducing the tare weight of the empty cars. In addition, improved wheel and truck design reduced rail car resistance.
2. Improved engine technology and shifting from direct current to alternating electric current technology reduced the amount of power needed to move a given amount of freight.
3. Positioning locomotives throughout the train reduced the power requirements to start moving the train, as well as to change speeds.
4. Infrastructure improvements reduced the number of slow speed operations, idle time, and the number of speed changes. An illustration of this infrastructure improvement was the rebuilding of the Kate Shelley Bridge, located on the heavily traveled Union Pacific Railroad mainline from Omaha to Chicago. This bridge is located three miles west of Boone, Iowa. This double track bridge, built in 1901, was designed for the small trains in use at that time. By the year 2000, typical unit coal trains on this mainline consisted of 115 cars, each with gross loaded weights of 143 tons and pulled by three highly efficient, fast locomotives. The condition of the bridge had deteriorated to the extent that train speeds were limited to a maximum of 25 mph and only one train could cross the bridge at a time. Trains would often be backed up for miles waiting for their turn to snake across the bridge. With their diesel engines idling as they waited for their turn, trains would cross the bridge at slow speeds and then use more fuel to resume their assigned travel speeds. The Union Pacific Railroad spent more than $50 million to build a new double track bridge that was opened in 2009. Now, two trains travel across this bridge simultaneously at speeds up to 70 mph with no slowdowns or waiting stops, thus saving substantial amounts of fuel compared with the old bridge.
5. Track technology, maintenance and control systems have been improved.
6. New GenSet switch locomotives have two or three 627 or 700 hp diesel engines rather than one 2,000+ hp diesel engine (AAR 2007). The purpose of GenSet locomotives is to match the engine power with the needed power to perform an assigned function. One engine is used for light functions and the other(s) remain off. Two or three engines are used to move

heavier loads. So far, GenSet locomotives have been used mostly in switching duties and have saved up to 37% of the fuel used by single engine switch engines.
7. Lubrication of railheads and wheel flanges reduces train friction, and automatic sanding reduces locomotive wheel slippage when starting train movement.
8. Electronic controls operate trains more efficiently, and engine shutdown policies and start-stop systems have been implemented.
9. Empty backhauls have been reduced and more efficient routing has been achieved.
10. Aerodynamics have been improved.
11. Crew training, including reward programs for top fuel efficiency, have been implemented.

Each of these developments contributed to the railroad's 128% increase in revenue ton-miles per gallon of fuel since 1975. Railroad fuel efficiency is expected to continue to increase as older rail cars and locomotives are replaced by new ones that have all of the current fuel efficient features in place. In addition, railroads will implement new efficiency developments as they become available.

Trucks have also achieved substantial gains in fuel efficiency. Many of these gains were obtained from the following developments:

1. Hybrid electric vehicles have generated a 14% improvement in fuel efficiency. Most of the gains in fuel efficiency from hybrid electric trucks occur in high density stop and start service (Walkowicz et al. 2012).
2. Diesel engine technology has been significantly improved to increase the fuel efficiency and to meet exhaust emissions mandates. The advancements in the combustion technology include high fuel injection pressure to create better fuel-air mixture, multiple fuel injection pulses in one engine cycle to facilitate combustion control, variable geometry turbo for better air control, and exhaust gas recirculation to help control combustion phasing (Kong 2012).
3. Vehicle aerodynamics (including cab mounted deflector shields, trailer skirts, and wheel covers) have been improved.
4. Electronic control features, including road speed governors have been added.
5. Tire rolling resistance has been reduced.
6. Longer, wider, and higher trailers are being used.
7. Operational improvements, including reducing the number of empty and partially loaded miles, and driver training, have been implemented.

Each gallon of fuel saved through fuel efficiencies eliminates a gallon of petroleum imports. Moreover, a gallon of unused fuel emits zero pollutants. On a gallon-to-gallon basis, fuel efficiencies contribute more to clean air than replacing petroleum with lower pollutant emitting fuels.

CONCLUSIONS

1. The U.S. does not have a shortage of freight transportation fuels. It is developing a shortage of low cost, liquid fuels for trucks and railroads that meet environmental standards.
2. The U.S. has an abundance of NG that can be used as CNG or LNG fuels. Currently, LNG and CNG prices are substantially below those of petroleum based diesel. In addition, CNG, LNG, and natural gas can be converted into liquid synthetic diesel fuels. These fuels could power some freight transportation until fuel cells and environmentally friendly synthetic biomass and coal-to-liquid diesel fuels are developed and commercialized at prices that are competitive with petroleum based diesel.
3. In the short- or medium-term years ahead, the most likely commercially available substitutes for petroleum-based diesel fuel for freight transportation will be biodiesel, NG, electricity for railroads, and fuel efficiencies.

4. Motor carriers and railroads are unlikely to use more biodiesel and other mandated fuels than government blending mandates require, unless their prices decline below those of petroleum-based diesel,
5. Motor carriers will most likely increase their consumption of NG. Larger and more powerful NG engines, improved and lower cost per gallon NG storage tanks, and a substantial increase in the number of NG fueling stations and refueling capacity will be the major forces motivating trucking firms to purchase increasing numbers of NG-fueled trucks. Within the next five years, the major focus will be in using the new 12-liter NG engine in local and regional freight movements. The introduction of the 15-liter NG engine in the next four to five years, will expand the use of NG into national coast-to-coast truck movements.
6. The dramatic decreases in NG prices has motivated all Class I railroads to reevaluate their strategy of maintaining a completely diesel-electric system. Three railroads are now testing LNG locomotives. These reevaluations and actual experiments will determine if NG technologies can provide the power and clean burning performance of diesel-electric technologies at lower costs. If the NG technologies can meet or exceed the diesel-electric power and clean burning performance at lower costs, the railroad industry will likely invest in NG locomotives and fuel tenders, along with refueling and maintenance and repair facilities.
7. Railroads will not convert their freight operations to an electrified rail system unless diesel and diesel substitute fuel prices rise to a level that justify the huge capital investments needed for electrification. At the present time, no one knows how high diesel and diesel substitute fuel prices would need to rise to make the conversion to electricity economically feasible.
8. Fuel efficiency technologies have resulted in major improvements in fuel efficiencies of railroad and truck freight operations. New and existing technologies have a high probability of continuing to make large improvements in freight fuel efficiencies. In addition to developing alternative fuels, emphasis should continue to be placed on improving fuel efficiency in freight transportation. Each gallon of fuel saved through increased fuel efficiency emits zero pollutants and helps make the U. S. economy more competitive in domestic and world trade.
9. If and as they are developed and commercialized, renewable biofuels, hydrogen-based fuel cells and internal combustion engines, and environmentally friendly synthetic biomass and coal-to-liquid diesel fuels will substitute for some petroleum diesel if mandated by the EPA or if competitively priced with diesel.

There are numerous opportunities for research on alternative fuels for freight transportation. Some that are suggested by this analysis include:

1. Investment and operating costs of alternative NG truck engine sizes and fuel storage tanks and diesel powered trucks now and in the future. This is particularly needed for the new 12- and 15-liter NG engines.
2. Costs of producing alternative types of synthetic fuels now and in the future,
3. Diesel and diesel substitute fuel prices levels that will make an electrified railroad system economically feasible,
4. Return on investments in developing and commercializing alternative synthetic fuels,
5. Return on investments in developing alternative fuel efficiency options,
6. Return on investment to shift alternative parts of the U.S. railroad system to NG and/or other alternative fuels,
7. The impact of potential U.S. energy independence on the prices and quantities of diesel fuel and alternative diesel substitute fuels for use in freight transportation,

8. The potential demand (prices and quantities) for synthetic diesel fuels and hydrogen to be used in U.S. freight transportation, and
9. Available data on comparable retail prices of alternative fuels at refueling stations are extremely limited. There is a need to generate retail price data on diesel, NG, and other substitute fuels for freight transportation.

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C. Phillip Baumel *is a distinguished professor emeritus at Iowa State University. He received the Transportation Research Forum's Distinguished Transportation Researcher Award in 1993, the Transportation Research Forum's Outstanding Research Paper Awards in 1982, 1989, and 1999, and the Transportation Research Forum's Agricultural and Rural Transportation Awards in 1989, 1991, and 1995. He is a fellow in the American Agricultural Economics Association. Baumel pioneered the use of network models for analyzing issues in agricultural product transportation by rail, truck, and barge. He retired in 2003 and currently lives in Iowa (summer) and Arizona (winter).*

U.S. and European Freight Railways: The Differences That Matter

by Francisco Manuel Bastos Andrade Furtado

This paper examines the differences between the United States (U.S.) and European (EU27) freight railways. The inherent or structural factors influencing the railways modal share will be evaluated. It was found that nearly all of the disparity in modal share can be explained by structural or inherent differences, like the competitiveness of non-surface modes, shipment distances (both influenced by geography), and commodity mix (namely, coal). More striking are the differences in productivity, to move the same number of tons seven times, more trains are required in Europe compared with the U.S.. Operational revenues per ton-mile are around two times higher in Europe, while the operational expenses in the U.S. are four times lower than in Europe. It is argued that setting a goal for modal share similar to the U.S. is not realistic for the EU27. A key concern for European freight railways should be the reduction of operational costs, by increasing the trains' sizes.

Distinct policy answers were given to the railroads' crisis in the post WWII years. Soon after 1980 when reforms were introduced in the U.S. there was a revival of the sector. The same has not happened in Europe, where questions regarding infrastructure financing or the coordination of network investments and operational needs remain.

INTRODUCTION

Over the last 30 years, the U.S. rail freight industry has witnessed an increase in its modal share, productivity, and profitability (Association of American Railroads 2012, Shi, Lim, and Chi 2011). In Europe (EU27), the industry has been unable to achieve the same results, even after the introduction of legislative and regulatory reforms that started in 1991 and culminated in 2007 with the implementation of full open access for freight rail operators (European Commission 2010, European Commission 2009b).

There are significant differences between the United Stated (U.S.) and European freight railways and these differences can be classified into three broad groups. First, there are structural or inherent natural disparities (Table 1), that can limitedly (or not at all) be changed by any level of decision making. Second, train characteristics (Table 4) and operations vary widely between the two areas (Table 5). Third, both in Europe and the U.S., railways faced a deep crisis in the post World War II years, but the policy answers and how the market evolved followed distinct paths (Table 6).

It was found that the disparity in modal share can be mostly explained by structural or inherent differences like the competitiveness of non-surface modes, shipment distances (both influenced by geography), and commodity mix (namely, coal and other bulk materials). More striking than the differences in modal share are the discrepancies in productivity and train sizes with U.S. railways greatly surpassing the European ones. Soon after 1980, when major regulatory reforms were introduced in the U.S., there was a revival of the sector. The same has not happened in Europe, where questions regarding infrastructure financing or the coordination of network investments and operational needs remain. But other factors, besides legislative reform, influenced both the U.S. revival and the anaemic European results.

All of the above—structural, operational, and policy factors—impact the performance of the freight rail industry. When comparing the railroads' stance in the U.S. and Europe, all these factors should be taken into account. This paper attempts to provide a comparative analysis that covers the key factors conditioning the freight railroads on both sides of the Atlantic and contrast them. The goal is to be able to contribute to answering the following question: what are the differences that really matter? More precisely, given the underperformance of European railways when compared with the U.S., are there any guidelines that can be obtained to foster the industry in Europe from a comparative analysis with the U.S.? On the other hand, are there any lessons from the European experience that can be useful for U.S. railroads and policy makers? In addition, can valuable insights be obtained for other regions in the world where rail freight plays an important role in the economy or is intended to do so?

In the European Union (EU), the Commission's 4th Railway package proposal that reinforces the separation between infrastructure and operations is under discussion and awaiting approval by the European parliament (European Commission 2013). In the U.S., there are requests to reform existent legislation and change the current switch agreements (Surface Transportation Board 2012). In Brazil, a major expansion of the rail network is planned, as well as a change in the railroads' governance model (Governo Federal Brasil 2012). These are some examples of current policy proceedings that might benefit from the insights provided by this paper. Moreover, in these policy discussions, features of other regions' railroad models are often mentioned, but they are generally handpicked and taken out of context. One example is the discussion in the European Commission (2013) regarding infrastructure governance. In that document, the North American model of parallel competition is mentioned and is immediately followed by a defense of EU endeavors to reinforce the separation of infrastructure managers (that run the network) and rail undertakings (that run the train services). The fact that this separation is the opposite of one of the cornerstone elements of the current North American model, vertically integrated railroads, is not mentioned.

This paper is divided into four parts. First, a literature review of other studies in this area of research is presented. Second, the modal share in the two regions will be compared. A measure of the effect of the structural differences in the gap between shares will be provided. It follows a similar methodology to Vassallo and Fagan (2007), which is briefly described in the literature review. Third, productivity indicators (including financial results) will be presented. The disproportion between these numbers will be discussed, including the influence of structural differences, plus the impact of the train characteristics and operations. Fourth, the diverse policy and market answers will be examined. Conclusions will then be delivered, highlighting the differences that matter and providing some guidelines for European freight railways improvement.

For the analysis, the insights provided by several interviews with academics and industry representatives, plus visits to rail terminals and yards, were valuable. Both these visits and interviews were done in the U.S. and the EU (Furtado 2012).

LITERATURE REVIEW

This research area has been addressed by several academic and non-academic studies. Vassallo and Fagan (2007) focused their research on the modal share difference measured in ton-km (tkm) between the U.S. and European freight railways. Their aim was to quantify how much of the existing difference can be attributed to structural factors and how much to policy differences, thus determining if it was plausible for the EU to increase rail´s modal share by adjusting its policies.

The year 2000 was chosen for this analysis. The authors identified four inherent differences: the transportation volume (total tkm over all modes), competitive position of non-surface modes (coastwise/sea, inland waterways, and pipeline), shipment distances, and commodity mix. For each of these differences, the structural conditions of Europe are sequentially applied to the U.S., while maintaining the relative difference between the U.S. road and rail modes – e.g., to assess the impact of the transportation volume, the U.S. percentage share of each mode is kept, but the total tkm applied is the European value. The 38% U.S. rail modal share was applied to a 3,068 billion tkm total movement, which is the European total; the U.S. total was 6,495 billion tkm. So, if the total transportation volume in the U.S. would be the same as in Europe, the U.S. railroads would have moved 1,166 billion tkm (not the 2,468 billion actually moved). For measuring the impact of the competitiveness of the non-surface modes, the non-surface modes share in Europe was applied while keeping the U.S. road/rail relation. So, in Europe, the non-surface modes have a 48.24% share (in the U.S. it's 35.4%), which means that road+rail modes have a 51.76% share. The U.S. road/rail relation is 26.6/38.00=0.7. So in the U.S., the rail share would be 51.76/1.7=30.45%. Considering the previous 1,166 billion tkm total, the U.S. would move 934 billion tkm. Thus, the higher competitiveness of the non-surface modes in Europe explain 232 billion tkm (1,166 - 934 billion) of the U.S.-EU rail freight volume gap. A similar logic is then applied to evaluate the shipment distance and commodity mix differences. All the numbers presented above were taken from the article.

The authors found that about 83% of the modal share difference was probably due to natural differences. It is argued that the remaining difference (17%) is presumably due to public policy differences like priority of passenger services, lack of productivity-enhancement infrastructure, and lack of incentives of the rail operators (lack of competition between rail companies). It is stated that "One policy difference which is unlikely to impact the residual is the European Union's requirement to separate infrastructure from operations and require open access." In fact, it is suggested that unbundling infrastructure from operations as a way to introduce competition might be one of the ways of increasing the European railroads' market share, having a somewhat similar affect to what deregulation did in the U.S.

Rodrigue and Notteboom (2010) present a qualitative analysis of the different configurations of the European and North American transport and logistics networks. They point to several relevant contrasts, e.g., the higher number of ports in Europe when compared with North America, the shorter distances between the ports and respective hinterlands in Europe, the nonexistence in Europe of anything like the land bridge between the east and west coasts in North America, the more concentrated nature of traffic flows along certain corridors, and thus the possibility of bigger scale economies in North America. Regulatory, policy, and governance differences are also discussed. Europe's multitude of nations with their respective histories and cultures means that coordinated action is much more difficult to attain than in North America. Important infrastructure projects are designed in a more national than continental logic. The market is much more fragmented and less homogeneous than in the U.S. and there is a higher need of customization for each specific national market, thus there is less room to take advantage of scale economies in distribution centers and networks.

Pouryousef, Lautala, and White (2013) provide a review of capacity definitions used in both Europe and the U.S., followed by a description of differences in the respective rail systems regarding infrastructure and operations. They then present several methodologies to evaluate capacity, including case studies both in the U.S. and Europe. In Europe, the preponderance of passenger services and corresponding requirement of on-time performance for train services requires a level of reliability that is typically secured through structured/planned/scheduled operations. In the U.S., operations commonly follow a more flexible dispatching pattern. This difference leads to different metrics, concepts, and methodologies to evaluate capacity. The European rail networks typically take advantage of several commercial simulation software available in Europe, which have been developed based on the timetable compression concept, while the U.S. railroads usually apply the non-timetable-based simulation, in addition to the general analytical tools and modeling approaches. The authors argue that as the U.S. continues developing its passenger traffic on shared corridors, the future operational patterns of shared corridors in the U.S. will likely have a closer resemblance to the European shared-use lines. The accuracy of capacity analysis methods becomes more important, and tools applied in Europe may become more applicable to the U.S. conditions as well.

Drew (1999) reviews the history of rail legislative and regulatory reforms in North America and different parts of Europe. The study underlines that the ideal form of regulation depends on a number of other inter-related choices, like the type of ownership of the assets, vertical separation or integration, open access. or limited access. Furthermore, these choices should take into account the particularities of the market for rail services, e.g., whether freight or passenger services dominate the railway. In the conclusion, the author warns that open access might not always maximize efficiency since it can reduce the fragile profitability margin of railway operators acting in certain markets.

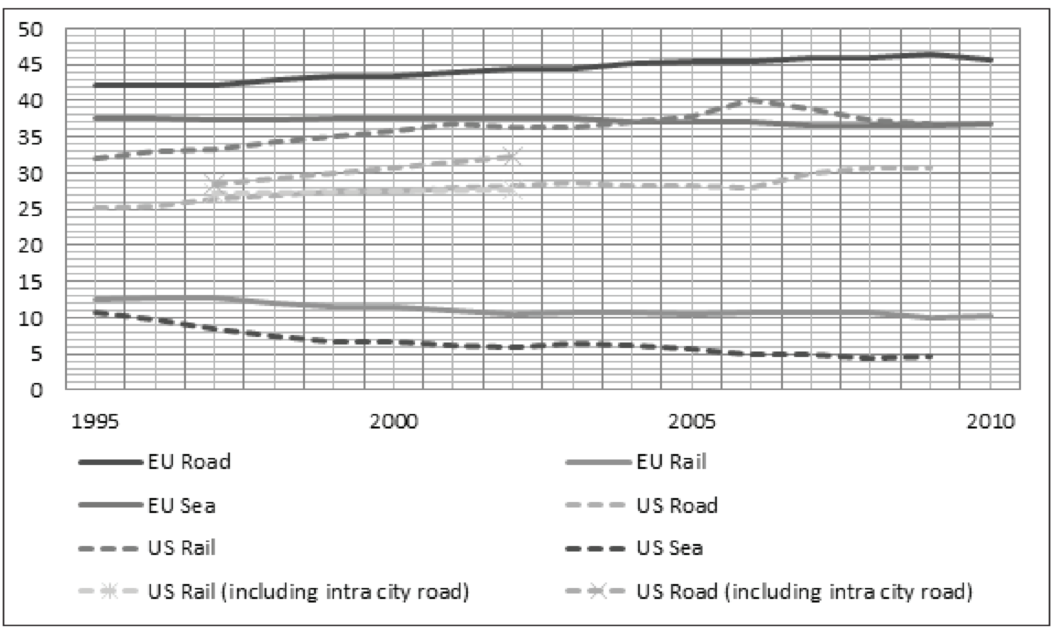
Posner (2008) bases his essay on the experience he had as a manager and investor in freight railways both in the U.S. and Europe. This work mentions several physical and geographical differences between Europe and North America that condition the freight railroads' activity, but the article emphasizes the institutional differences. Posner argues that parallel competition between vertically integrated railroads in the U.S. was a result of deregulation, whereas on-rail perfect competition in Europe was artificially induced by restraining regulations. Moreover, while EU policymakers' efforts were focused on promoting intra-rail competition, important service and capacity requirements were not considered.

Concerning the available literature, the present paper brings three key contributions. First, it updates the discussion on this area, whether it is on the modal share trends or regulation and its impacts on the railroads' performance. Second, it presents a comprehensive analysis that encompasses several factors that influence the freight railroads' activity which are inter-related, such as structural factors, productivity and profitability, operational logic, institutional framework and history of the legislative reforms. Third, productivity and profitability differences are mentioned in other studies, but not with the emphasis presented here.

MODAL SHARE AND STRUCTURAL DIFFERENCES

In 2009, the rail share of the modal split, based on tkm, was 36.8% in the U.S. (the mode with the highest share) and 9.9% in EU27 (below road and sea). This gap has existed for several decades (Figure 1) and it is mentioned in several European publications, including policy setting European Commission documents (European Commission 2001).

Figure 1: EU27 and U.S. Freight Transport Modal Split (% based on tkm)



Source: Eurostat, U.S. Department of Transportation (DOT) Bureau of Transportation Statistics (BTS), DOT-BTS 2004.

There are structural factors that limit the share of rail in Europe when compared with the U.S. Europe has around half the land mass of the U.S., but more than three times the U.S. coast line. This limits the shipments' distances for surface modes in Europe, where there is no equivalent to the inland coast-to-coast trips in the U.S. While in the U.S., 48% of the shipments (in ton-miles) of surface modes (road and rail) are above 1,200 km, in EU27, only 15% are above 1,000 km (Eurostat, DOT-BTS 2010, Tavasszy and Meijeren 2011).

Furthermore, geography is a major factor in creating higher competitiveness of the sea mode (coastal shipping) in Europe (36.7% of the modal share in 2009) compared with the U.S. (4.6% of the modal share in 2009); adding to geography, the sea mode is constrained in the U.S. by the Jones Act of 1920[1] (Rodrigue and Notteboom 2010). As for other non-surface modes – inland waterways (river and lakes) and pipelines – they have higher shares in the U.S. than in Europe. While in the U.S. inland waterways and pipelines move, respectively, 6.5% and 21.1% of the total ton-miles; in Europe they have a 3.6% and 3.1% share. The difference in the pipelines' modal share is significant, which is probably due to geography and because the U.S. produces more petroleum products than Europe. Still, the combined share of non-surface modes (sea, inland waterways, pipelines) is higher in Europe (43.7%) than in the U.S. (32.2%) (Eurostat, DOT-BTS).

Another key factor is the type of goods moved. Rail is especially suited for heavy low-value commodities over long distances. In the U.S., coal accounts for about 29% of the ton-miles of surface modes and around 44% of the ton-miles moved by rail, while in Europe, it is less than 3% of the surface modes and around 13% for rail (DOT-BTS 2010, Eurostat).

Table 1: Structural Differences

	Europe (EU27)	*U.S.*	*Comments*
Geography	Area = 4,414 thousand km^2 Coastline = 65,993 km	Area = 9,629 thousand km^2 Coastline = 19,924 km	Higher competiveness of sea mode in Europe. Higher inland shipment distances in the U.S.
Commodity Mix	More manufactured goods	More raw materials	Higher share of bulk, high weight and low value commodities more suitable for rail in the U.S.

Source: Eurostat, DOT-BTS, CIA World Factbook

To measure the impact of these factors in the gap between the rail modal share in the U.S. and Europe, the methodology applied will be similar to Vassallo and Fagan (2007), briefly described in the literature review. But there are three important differences. First, it will be taken into account the fact that the statistics in the U.S. exclude intra-city truck movements (Dennis 2005), underestimating this mode share. The latest estimates found for those numbers are in DOT-BTS (2004) and they can be seen in Figure 1. According to this, the U.S. rail share in 2002 would be 27.8%, below road's 32.1% share. Second, the data for this analysis refer to the last year with comparable estimates (2009), not to 2000. Third, Europe is represented by the EU27 (which includes Central and Eastern Europe), not the EU15 (which only includes Western Europe).

The estimation involved five steps (see Table 2). The data sources for the calculations were the Eurostat and DOT-BTS databases, plus Tavasszy and Meijeren (2011).

Table 2: Structural Factors Influence on Europe and U.S. Rail Share Differential[2]

	Vassallo and Fagan - 2000		*Furtado – 2009*	
	Value (million tkm)	% of gap	Value (million tkm)	% of gap
Total gap	925,794	100%	903,385	100%
Structural factors share of the gap				
Non-Surface/ Sea mode - Step 3	231,748	25.0%	237,847	26.3%
Shipment distances - Step 4	413,104	44.6%	413,206	45.7%
Commodity mix/ Coal - Step 5	123,680	13.4%	237,831	26.3%
Not explained by structural factors	157,262	17.0%	14,502	1.6%
Contribution of structural factors	768,532	83.0%	888,884	98.4%

Source: Eurostat, DOT-BTS, Vassallo and Fagan (2007), Tavasszy and Meijeren (2011)

The first step was to take into account intra city trucks. To do this, the ton-miles of the road/truck mode in the U.S. were increased so that this mode would obtain the same share as rail. According to DOT-BTS, in 2009, rail moved 1,582,093 million ton-miles and trucks moved 1,321,396 million ton-miles. It was assumed for the subsequent steps that the truck mode actually moved the same 1,582,093 million ton-miles as rail. By doing this, U.S. rail obtains a 35% modal share (below the original 36.8%) equal to truck. Other modes also see their shares slightly decreased. This is a conservative approach, since in the later estimates available road share was actually above rail (DOT-BTS 2004).

In the second step, the U.S. rail share (35%) is applied to Europe´s total tkm movements (3,646,788 million tkm), to take into account that the total tkm in Europe for all modes is around half of the U.S. (the U.S. total movements correspond to 7,343,465 million tkm). So, if in EU27 the rail share would be the same as in the U.S., there would be 1.264 trillion tkm moved by rail (0 .34672086×3,646,788=1,264,417). According to Eurostat, 0.36 trillion tkm were actually moved by rail in Europe in 2009. This means that there is a 0.903 trillion tkm difference (1,264,417-361,032=903,385) between what European rails actually moved and what they would move had they a modal share equivalent to the U.S.

How much of this 0.903 trillion tkm gap can be attributed to structural differences? This is evaluated in the next three steps.

In the third step, the sea and other non-surface modes European share (43.7%) is applied to the U.S. (30.66% share for non-surface modes), while keeping the same road/rail ratio (1 for the U.S.). In this way the higher competitiveness of non-surface modes in Europe (namely sea, since there is a lower share of pipelines and inland waterways in Europe) is taken into account. In this situation the Road+Rail share in the U.S. would be equal to 56.3% (100-43.7). The U.S. road/rail relation would be kept (road/rail share=1). So the U.S. rail share would drop to 28% (56.3%×0.5=28.15%). In Europe, a 28% share would represent 1.026 trillion tkm (0.2815×3,646,788=1,026,571). When the higher share of non-surface modes in Europe is taken into account, the gap between European and U.S. rail share is reduced. The gap would be 0.66 trillion tkm (1,026,571-361,032=665,539) not 0.903 trillion tkm (as calculated in the second step). So of the modal share gap, around 0.238 trillion tkm (903,385-665,539=237,847, or simply 1,264,417-1,026,571=237,847) can be explained by the different competitive advantages of non-surface modes in Europe.

The fourth step takes into account the differences in shipment distance. The European distribution of surface modes tkm according to shipment distance class is applied to the U.S. rail share (versus road) by distance class. European shipment distance characteristics are applied to the U.S. rail vs road competiveness. For instance, in Europe 15% of the surface modes tkm (the total tkm for surface modes is 2,053,142=0.563×3,646,788) are for shipments above 1000 km (this corresponds to around 0.317 trillion tkm = 2,053,142×0.1546). In the U.S., rail has about 70% of the surface mode share for shipments above 1000 km. So, for the distance class above 1000 km, rail would move 0.22 trillion tkm (317.366×0.7=222,156). The same calculations are performed for the other distance classes (0-50; 50-150; 150-500 and 500-1000 km) and then summed. In this scenario, rail would have moved 0.613 trillion tkm. So, 0.413 trillion tkm of the gap (1,026,571-613,365=413,206) can be explained by the longer shipment distances in the U.S.

The fifth and last step is to take into account the differences in commodity mix, namely coal. The U.S. proportion of coal in the tkm of surface modes (almost 30%) is applied to the European modal split between rail and road by commodities (it is 80% for coal and 8% for others). Had Europe moved the same share of coal as the U.S., 0.599 trillion tkm would have been moved by rail. This would represent a 66% increase compared with current numbers. That increase of 0.238 trillion tkm (598,863-361,032=237,831) corresponds to the difference accounted for by coal in the modal share gap.

The results show that Europe´s and the U.S.' rail share differential can be mostly explained by the structural differences, nearly all for 2009 and around 80% for 2000. This divergence is related to the increase in the fraction of coal in the commodity mix in the U.S. (from 23% in 2000 to 29% in 2009). Moreover, there was a reduction of the starting gap caused by two factors. First, in 2009, there was a correction of the U.S. value to take into account intra city trucks (Vassallo and Fagan 2007, for the year 2000 had a 38% share for rail, versus a 35% share applied in this study). Second, the EU27 in 2009 had a higher rail share (9.9%) than the EU15 in 2000 (7.8%). The EU27 includes the Central-Eastern European countries that on average have higher rail shares than Western Europe. See Figure 4.

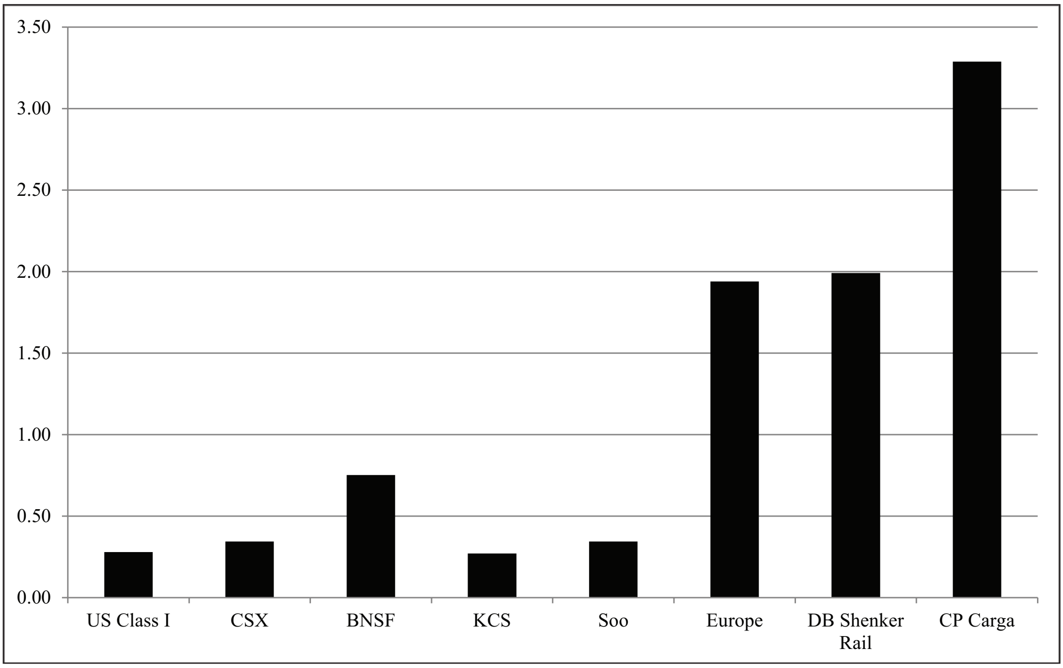
The structural factor that has the highest impact is the difference in inland shipment distances, which explains around 46% (almost half) of the differential. The higher competiveness of non-surface modes in Europe and the differences in the importance of coal explain (for 2009) a similar amount of the gap, about 26% each. This analysis was based on the comparison of tkm. If the measure to compare would be in tons moved, the results would be different. For 2010, rail moved 1,515,332 thousand tons in Europe and 1,850,996 thousand tons in the U.S., which means 18% less in Europe (Eurostat, DOT-BTS). A much smaller starting gap than if measured in tkm (86% less in Europe). The difference in distances not only allows the rail industry in the U.S. to capture a higher share of the market, it also means that each ton moved by rail goes a much longer distance, multiplying the U.S. tkm *vis à vis* the EU27.

When comparing the U.S.' and Europe's railways performance measured by modal share, the difference is marginal (if the structural constraints existing in Europe versus the U.S. are accounted for). Therefore, it is not reasonable to expect the EU27 railways to ever achieve a similar modal share to the U.S., even less to set this as a policy target. So, is this the difference that matters?

PRODUCTIVITY

To move the same number of tons, around seven times more trains are necessary in Europe. For a thousand tons the U.S. Class I railroads require 0.28 trains; in Europe it is 1.94 (Figure 2). Even taking into account the higher costs of the larger U.S. trains, this is a very significant distinction that implies that European railways have much higher costs per ton and tkm, which is the case. As shown in Figure 3, the operational revenues per ton-mile are higher in Europe, almost two times more than in the U.S. (DB Shenker, being the largest European freight railway, will be used in the comparison, and data for CP Carga the main Portuguese freight railway are also presented). But the operational expenses are almost four times higher than the ones in the U.S. In fact, European railways are barely profitable or not profitable at all (European Commission 2009b).

Figure 2: Number of Trains Per Tons Moved (thousand) in 2010

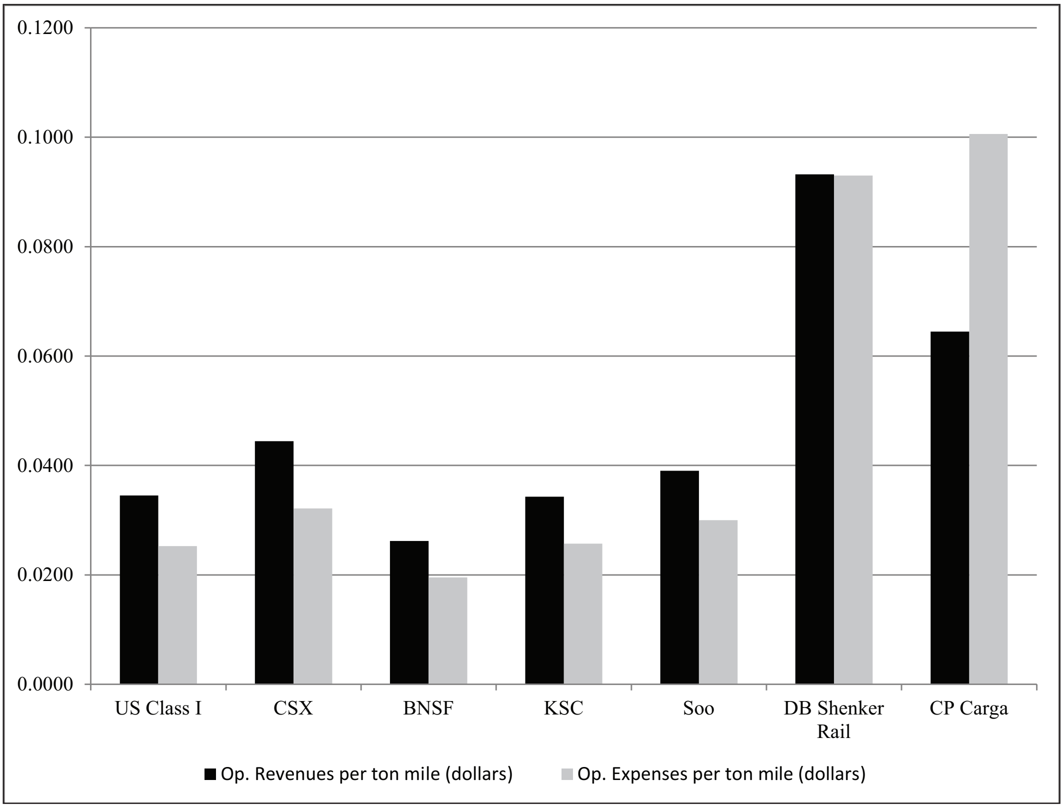


Source Eurostat; Association of American Railroads (AAR); Surface Transportation Board (2010); DB, CP Carga annual reports.

Having more trains (even if smaller) for less cargo moved implies higher fixed and variable costs. It implies more labor, line capacity use, and a smaller net/gross tons ratio per train for the same amount of goods moved. This explains to a large extent why U.S. railways are profitable and have been financially stable for the last 10 years, while in Europe their financial situation is, at best, precarious.

Besides the train's weight/length, the much longer shipment distances also contribute to a higher productivity in the U.S., especially if the outputs are measured in ton-miles. In Europe, the length of haul is mainly restrained by structural factors already mentioned. There are fewer long distance inland shipments than in the U.S. There are also interoperability barriers in the EU27 that are nonexistent in the U.S., such as different gauges, signalling systems, and electric systems (in the U.S. there is almost no electrification, while in the EU27, half the lines are electrified).

Figure 3: Operational Revenues and Expenses for U.S. and European Freight Railways in 2010



Source: Association of American Railroads (AAR); Surface Transportation Board (2010); DB, CP Carga annual reports.

Table 3: Freight Railways Statistics for 2010

	Average[3]					*trains per*	
	Length of haul (miles)	net tons (per train) A	tons (thousands) B	ton-miles (million)	trains (B/C)	tons (thousands)	ton-miles (million)
U.S. Class I	913.6	3585	1,850,996	1,691,000	516,338	0.28	0.31
CSX	549.2	2902	417,303	229,172	143,789	0.34	0.63
BNSF	1114.3	1330	580,206	646,549	436,295	0.75	0.67
KSC	390.7	3692	75,833	29,629	20,540	0.27	0.69
Soo	426.7	2902	77,703	33,157	26,771	0.34	0.81
Europe	159.9	516	1,515,332	242,335	2,938,746	1.94	12.13
DB Shenker Rail	158.3	502	415,500	64,737	826,921	1.99	12.58
CP Carga	138.6	304	9,224	1,278	30,331	3.29	23.73

Source: Eurostat; Association of American Railroads (AAR); Surface Transportation Board (2010); DB, CP Carga annual reports.

As for the trains' weight, the structural factors also have some influence. Heavier trains on average are expected in the U.S. versus EU27 since the commodities shipped by rail in the U.S. are heavier, and include more bulk and fewer manufactured goods than in Europe. Still, this is not the main explanation for the huge discrepancy in the average tons per train (86% less in Europe). In fact, if the comparison is made only between heavy bulk trains, most of the difference concerning tons per train remains. The disparity in the train's average weight is much more a result of the infrastructure and equipment constraints in Europe than any structural factor (see Table 4).

Table 4: Train Characteristics

	Length *(feet/m)*		Containers (40' – 2 TEUs) per Intermodal train[5]	Net tons per bulk train (typical)
	Typical	Maximum[4]		
U.S. Class I	6500/2000	10000/3000	150-300	9000-12000
Europe	1640/500	2460/750	25-50	1200-2000

Source: several industry reports

Nonetheless, to reach a financially stable situation, European railways do not need to have trains with the exact same characteristics as in the U.S. They do need to get bigger, but not to the same level. The fuel prices in Europe are around double that of the U.S., which increases the railways costs, but also allows them to have higher charges (the effect of higher fuel costs is felt more by trucks than rail [Owens, Seedah, and Harrison 2013]). Road charges are applied much more extensively in Europe than in the U.S. (increasing the costs of the road mode, which also allows higher charges by rail), e.g., in the U.S., only about 6% of the interstate highway system has tolls (Weiss 2008). In Italy and France, almost all the motorways (Autostrade and Autoroutes) have tolls and in Germany, there is a "truck-toll" (LKW-Maut) for all trucks that drive on the motorways (Autobahnen).

Besides the train size, other features also constrain European freight railways' productivity (see Table 5). The existence of passenger trains, which constitute 79% of the train-kms in the European rail network, have priority over freight trains (Eurostat 2007). Access to the network and dispatching flexibility is more constrained in Europe. Additionally, in the U.S., investments in the past 40 years were focused on increasing freight trains' productivity (Martland 2012) by: increase in train length (with associated changes in terminals and increase in sidings); increase in the net weight per rail car; and increase in track resistance and double stacking of containers (with the associated increase in clearances). In Europe, investment was concentrated on passenger services, namely, high speed rail. Since 1990, there was a 545% increase in the length of high speed lines (some of which cannot be used by freight), while the total rail network had a 10% decrease (Eurostat, European Commission 2012).

Even more striking than the difference in modal share are the differences in productivity. More importantly, there are strong structural restraints on increasing the railways modal share in Europe. They also affect productivity, but to a lesser extent. One of the key restrictions in productivity, the train size, is more limited by a lack of investment due to other priorities than any unchangeable natural obstacle.

A key concern of all agents involved in fostering freight railways in Europe should be to decrease the costs per unit moved (ton and tkm). To achieve this, one of the solutions is to increase the net tons per train and reduce the number of trains. Other strategies include restructuring the services offered (namely by dropping unprofitable services/routes), changes in charges to the customers, and a concentration of efforts and investments on the network segments that will provide higher returns.

Table 5: Train Operations

	Europe (EU27)	*U.S.*	*Comments*
Scheduling	Most services follow a strict schedule	There are some scheduled services, namely for intermodal trains (generally these schedules are not strict having 1-3 hours lags). In many cases the dispatchers define the arrival and departure times to maximize the load per train	In Europe the railway operators do not control scheduling it is an Infrastructure manager decision. Freight train's schedules are subject to the passenger train's schedules. For more on these differences see Pouryousef, Lautala and White (2013)
Passenger services	Extensive passenger services, 79% of the train-km are by passenger trains	Few passenger services mostly concentrated along the Northeast corridor, some commuter services	In Europe passenger trains have priority. Lines are more congested. Most investment goes to improve passenger services

Source: Eurostat, Furtado 2012, Pouryousef, Lautala and White (2013)

Even if sizable gains in the train's capacity were to occur in Europe, it is not clear to what extent this could indeed ensure financial stability of the railways. A reduction in the number of trains would imply a reduction in frequency of service and an increase in the lot sizes to be shipped. Can this be accommodated by the market and industry? Such a move would probably narrow the client base of European railways to heavy industries and ports, but that is exactly the client base that sustains freight railways. The question then is, to what extent, given the market conditions, the investments required to enhance productivity can be covered by the productivity gains, namely, the reduction in operational costs?

POLICY AND MARKET STRUCTURE

Some policy differences have already been mentioned: the Jones Act that restricts cabotage in the U.S., the priority given to passenger rail in Europe, plus higher fuel costs and more extensive road tolls. But what about the distinct market structure and regulation? How does it affect the railroads' performance and productivity?

Both in Europe and the U.S., railways faced a deep crisis in the post World War II years, but the policy answers and how the market evolved followed distinct paths. In the U.S. the railways had been privately owned but heavily regulated. The "Northeast rail crisis" in the 1970s (when several major U.S. railways went bankrupt) was the starting point for sweeping reforms. The Rail Passenger Service Act of 1970 that created Amtrak relieved freight railroads from the losses associated with providing intercity passenger services, around $200 million per year, or $850 million in today's dollars, according to Association of American Railroads (2012). The Regional Rail Reorganization Act of 1973 consolidated all the bankrupt railroads into Conrail (Consolidated Rail Corporation). The Railroad Revitalization and Regulatory Reform Act of 1976 allowed for extensive federal funding to ensure both Conrail´s financial survival and capital investments. It also significantly reduced federal regulation of railroads, starting the deregulation process. In 1980, the Staggers Rail Act, the most mentioned legislative reform, was passed. It allowed railways to decide which routes to use, which services to offer and what prices to charge. Two other events occurred, including a process of mergers. There were more than 70 Class I railroads in the early 1970s; now and for the last 10 years there were only seven (DOT-BTS). Second, there was an increase in the quantity of track owned by non-Class I railroads (regional, local, and switch and terminal). They owned 10% of the tracks in 1980 and 32% in 2008 (Martland 2012). These companies took over many low density traffic lines abandoned by the Class I railroads and concentrated in "maneuver intensive" sites (large industrial sidings, ports, some terminals).

These reforms, together with the productivity enhancement investments already mentioned, resulted in a revival of the U.S. railways (see Figure 1) (Wright 2011, Kriem 2011). A key driver for this was a dramatic reduction in costs that led to a great increase in productivity (Wilson 1997, Vellturo et al. 1992).

In order to revitalize the industry in Europe, the EU response, starting in 1991 (Council of the European Communities 1991), was to move towards a single and open market. An open market means the end of state-owned monopolies, and the separation of infrastructure and operations, either through full separation or the creation of holdings where different divisions of the same group are responsible for either operations or infrastructure. This allowed different railway operators to compete for rail services on the same network. A single market means that no country could block companies of other countries (at least from the EU) to provide services on their network, and also that technical and operational barriers between different countries' networks should progressively be removed.

Table 6: Policy and Market

	Europe (EU27)	*U.S.*	*Comments*
Political	27 sovereign member states	One sovereign state	It is slower and more complex to implement common policies across the EU27.
Market Structure	Open access. Separation of infrastructure and operations. Regulator supervises non-discriminatory access to the infrastructure	Vertical integration. Railways provide transportation and own the infrastructure	In the U.S. each railway has control over its network. In Europe no operator controls the network.
Competition	"Coincident" over the same lines/routes rail competition.	Parallel competition with other railways. Competition with trucks and sometimes barges.	In the U.S. almost all regions/clients can be served by two railways, nonetheless they can better protect their market.
Types of railroads	Infrastructure Managers, Freight Operators, Passenger Operators, Freight and Passenger Operators, Holdings	Class I, Regional, Local, Switch and Terminals (difference is business volume and length of network owned)	In the U.S. railways are classified by their size. In Europe by their function.

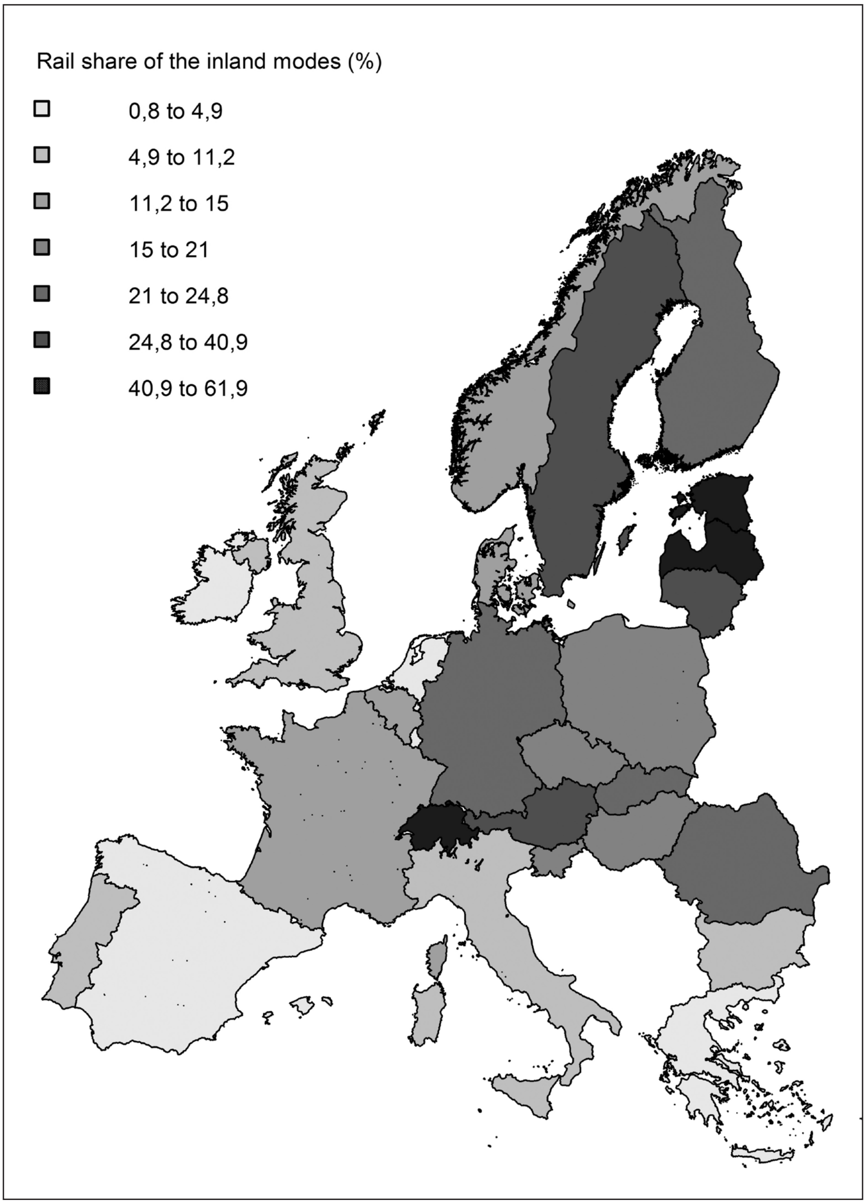
Source: Author

The first railway package in 2001, the second package in 2004, and the third in 2007 all introduced legislation in order to further pursue the original goal of a single and open market. For freight services, the second railway package introduced full open access in 2007. This was applied in all EU countries except Ireland, but the removal of barriers to interoperability is still an ongoing process (Zunder, Islam, and Marinov 2010). The European Commission 4th Railway package draft proposal of December 2012 aimed at the complete separation between infrastructure and operations, no longer allowing for a holding model (e.g., Deutsche Bahn). This was dropped in the final proposal due to intense lobbying by Germany (Berkeley 2013).

The results of these reforms are far from what was achieved in the U.S. It is recognized in European Commission (2010) that, at best, there was a stabilization of rail modal share and that de facto monopolies still exist in most EU countries. As was previously mentioned, the financial results of most rail undertakings are precarious.

Posner (2007) argues that "in North America there is competition as a result of deregulation, whereas in Europe, you are trying to force competition through regulation.(...)It is an institutional fundamental of the European environment, and I think it is the single biggest problem.(...)In Europe, in my opinion, the focus has been more on having competition even before considering service or capacity, so the priorities have been reversed and I think that explains much of the results."

Figure 4: Rail Share of Inland Modes, 2010 (% based on tkm)



Source: Eurostat

The assumptions made in Europe regarding the positive effects of introducing intra-rail competition on the same network/lines and implementing a market structure that completely separates operations and infrastructure are disputable (Cantos 2001, Growitsch and Wetzel 2009, Ivaldi and Mccullough 2008, Friebel, Ivaldi and Vibes 2010, Asmild et al. 2009, Merkert, Smith and Nash 2010, Bitzan 2003). As stated in Association of American Railroads (2011a), "open access would make it more difficult to operate a railroad efficiently and profitably due to government interference and a lack of coordination between infrastructure investment decisions and operational goals."

It is also challenging under an "open access" model to capture private investment for infrastructure management. The UK experience with Railtrack had to be reverted because access charges could not finance a privately owned company (Jupe 2009). In Estonia, the vertically integrated railways were privatized in 2001, but in 2007 they were renationalized because regulation made private management unfeasible (Posner 2007). The only significant privately owned rail infrastructure in Europe is the Eurotunnel.

Still, the ongoing reforms seem to be delivering some positive results (Friebel, Ivaldi, and Vibes 2010, Growitsch and Wetzel 2009), including vertical separation (Cantos, Manuel Pasto, and Serrano 2010, Asmild et al. 2009). But many of the studies do not take into account external factors that greatly influence freight railways' productivity, e.g., in the United Kingdom, coal production decreased and imports increased, so the tkm of coal moved by rail greatly increased (Posner 2008). External factors like these vary widely across Europe, as do the ways the reforms were implemented (IBM Business Consulting Services 2006). The networks and railways themselves are very distinct, including their modal share (Figure 4). Finding causal relationships between each component of the reform and its effects on productivity (either positive or negative) across Europe is problematic.

The situation in Eastern Europe and Scandinavia is examined by Ludvigsen and Osland (2009). In Norway, the reforms were an opportunity for wider changes in the existing system, namely, in the services provided. The main railway operator (the incumbent) focused on the most profitable services (combined/intermodal), while new entrants (including incumbents from other countries) picked up some of the abandoned markets (carload). This situation has some similarities with what happened in the U.S. between Class I railroads and Short Lines. In Norway, there was some recovery of rail modal share and the financial situation of the railways improved, although it is not yet stable.

In Eastern Europe, new entrants competed directly with the incumbents for the same services (namely, the more profitable unit/block trains) and gained a sizable market share (40% in Romania and, above 20% in Poland, according to European Commission 2009a), but rail modal share continued to decrease.

The article by Santos, Furtado, and Marques (2010) about the effects of regulatory changes in Portugal, illustrates the complexity of actually implementing reforms beyond legislative compliance. The negative (in the case of the infrastructure manager), or anaemic (in the case of the operator), evolution of productivity during the period studied, in a country where the reforms "seemed to be appropriate and ambitious, at least when compared with those that occurred in other EU countries, like in France, where the regulator is not separate from the government, or in Germany, where there is vertical integration," should lead to the question: Are there other factors more relevant to productivity increase than regulatory changes per se? The Portuguese freight operator average net ton per train is 60% of the European average (see Figure 2). This greatly explains the high expenses per ton-mile (see Figure 3). Without significantly decreasing this number there is little hope of obtaining increments in productivity and a financially stable situation. The regulation adopted should help solve this problem, or at least it should not be an obstacle. But it cannot, by itself, solve the problem.

The same can be argued for the increase of rail´s modal share. There is evidence of structural inelasticity of modal substitution in freight transport. Rich, Kveiborg, and Hansen (2011) examined the Scandinavian case (where rail has a higher share than the EU27 average). For many commodities and Origin – Destination pairs, modal substitution from truck to rail does not occur even if rail prices decrease and service level increases. The main reason is the sparsity of the rail network when compared with the road network. A reduction of this inelasticity and correspondent increase in demand is only possible if there are improvements (or extensions) of the rail infrastructure/network.

In the U.S., the legislative reforms gave railways a free hand so that they could adapt their services and network to the market. But these reforms were not confined to deregulation (Staggers Act). They were part of a wider set of changes: some services were abandoned; some routes were consolidated; charges were lowered or increased depending on existing competition and cost coverage; investments were focused on productivity enhancements like longer and heavier trains or double stacking, especially on high density lines where demand justifies it. At the same time there were mergers between the bigger companies, which likely allowed gains from economies of scale and gave the railroads networks that are closer to the size of their markets (Martland 2012, Furtado 2012). Still, it is hard to quantify the exact impact of mergers and if those impacts were all positive (Vellturo et al. 1992). Specialized non-Class I railroads took over several lower density lines abandoned by the Class I and "maneuver intensive" sites such as ports or other large industrial sidings. Coal production increased in the Poweder River Basin (whereas, before it was mostly concentrated in the Appalachian Region), increasing the distance of coal shipments from production to consumption centers and the corresponding length of haul for rail (Association of American Railroads 2011b). Technological breakthroughs in other fields, like advances in communications and information technologies, allowed increases in labor productivity (Martland 2012).

All the above are examples of developments, some more related to regulation changes than others, that played a role in transforming the industry. From a situation of crisis, which the "Northeast rail crisis" of the early 1970s is the most acute example, the railroads recovered and have stable financial results.[6] The critical contribution of regulation reform to the sector revival was that it increased the control railways have over their own networks and services provided.

In Europe, the regulation introduced did the opposite, control over the rail systems was divided. In each European country there are different nuances on how this was implemented (European Commission 2009b), but the trend to split control over the system between different entities is common. Like in the U.S., changes were necessary in order to revive the sector. The previous model of state-owned monopolies closely linked to the government needed to be reformed. The shock provoked by the introduction of competitive pressure and the dismantling (or reorganization) of the previous monopolies seems to have produced some positive results, but they are far from uniform across the EU27. Contrary to the U.S., a clear revival of the sector did not occur after the reforms were set in motion. It should be noted that full open access for freight was implemented only in 2007 and soon after there was a world crisis that caused a sharp fall in freight movements.

CONCLUSIONS AND FURTHER RESEARCH

U.S. railways have around 35% of the modal share measured in tkm. In Europe the number is close to 10%. Structural differences can explain nearly all that gap, about 98% according to the methodology employed. Competiveness of non-surface modes accounts for around 26% of that difference, underlying the importance of the sea mode in Europe. Shipment distances for surface modes is responsible for almost half the gap (46%); the much longer shipment distances in the U.S. play a crucial role. The difference in the commodity mix corresponds to 26% of the gap. This gives a measure of the impact of the much higher proportion of coal moved in the U.S. by surface modes. Given these inherent differences, the modal share gap between the U.S. and Europe is very small. So, it is not reasonable to expect that railways in the EU27 should have a similar modal share to the U.S., even less to set this as a policy target.

To move the same number of tons, seven times more trains are necessary in Europe. The average net tons per train in Europe is 86% less than in the U.S. In addition, this disparity is much less constrained by structural factors. This is an important reason why the U.S. railways have a stable financial situation, while the same is not true in Europe. Costs per ton-mile in Europe are four times higher than in the U.S., while revenues are only two times higher. The revival of U.S. railways was greatly due to an increase in productivity, for which a reduction in costs was crucial.

A key component for a revival of European freight railways has to be a reduction of operational costs, of which an increase in the net tons per train, by increasing their length/weight, is an important component. An important question for future research is to what extent, given the existing market and its medium-term evolution, the investments required to enhance productivity can be covered by the productivity gains, i.e., the reduction in operational costs. This question can be further detailed: given an investment plan and set of actions geared to enhance productivity, could the freight railways be financially sustainable? Or what would be the share of public funding needed? To what extent could the freight operator cover the infrastructure investment costs required for its own sustainability? To answer this, a more in-depth analysis of a case study is required. Portugal, where the average net tons per train is 60% below even the European average, is a case where productivity enhancements are even more necessary than in other EU27 member states.

Changes in legislation and regulation impact productivity, only to the extent that they can actually induce pressure that results in technical, operational, or service changes that increase the outputs/inputs ratios, including the financial ones. The European "open access" model faces some questions for which there are no conclusive answers yet. To what extent can an alignment in operational needs and infrastructure investment be achieved? How will the returns of such investments be shared by the different agents? How can there be private financing of infrastructure, when there is no control over the charges and services there provided? The changes introduced in the U.S. from 1970 to 1980 seem to have delivered more than the European reform process started in 1991, and that culminated in 2007 with full open access for freight services. But other factors, besides these reforms, influenced both the U.S. revival and the anaemic European results.

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Endnotes

1. Requires that all goods transported by water between U.S. ports be carried in U.S. flag ships, constructed in the United States, owned by U.S. citizens, and crewed by U.S. citizens or U.S. permanent residents.

2. The number of significant figures used in the table was the same as Vassalos and Fagan (2007) in order to present a consistent comparison. These numbers do provide an order of magnitude of the effects studied, but it should be taken into account that they are strongly dependent on the assumptions made and on the accuracy of the data employed (some of which are also obtained through estimation).

3. These numbers are averages and common statistical indicators for freight railroads' performance. Length of haul is the ratio between total ton-miles and total tons moved (ton-miles/tons). Net tons is the ratio between total ton-miles and total train-tons (ton-miles/train-miles). The number of trains presented in the table was obtained by dividing the total tons (B in the table) by the net tons (A in the table). So the number of trains presented is a reasonable estimation, but not the actual number of trains.

4. Contrary to Europe, in the U.S., there is no maximum train length imposed by regulation. Still, trains are generally no more than three km long. In Europe, some bulk trains in Eastern and Scandinavian countries are longer than 750 meters, but even there they are the exception.

5. Besides the difference in length, with intermodal trains in the U.S. ranging mostly from around 1.2 to 2.4 km (in Europe they are from 0.5 to 0.75 km), in the U.S. along many routes, double stacking was made possible by upgrades to the infrastructure and rolling stock.

6. Although railways can finance maintenance, renewals and some new projects, major new investments require some degree of public funding. In Cambridge Systematics (2007) and Association of American Railroads (2007), it is estimated that around 30% of the capital investment necessary to increase the network capacity will have to come from some sort of government financing. It is argued that this is necessary in the long term (having 2035 as a horizon) to relieve congestion in the main rail corridors, due to an increase in demand. Another issue would be to have public policy explicitly designed to move freight from trucks to rail. This was not the case in the U.S. Such policies may even require railroads to focus less on productivity. Indeed much of the short-haul and general merchandise traffic was abandoned by the railways, which concentrated resources in more productive long-haul bulk and container traffic.

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Francisco Manuel Bastos Andrade Furtado *is a civil engineer with experience in planning and management of major civil construction projects; master's in complex transportation and infrastructure systems from IST, on the MIT Portugal program; PhD student in transportation systems at the MIT Portugal Program. Research is focused on freight railways, namely, network improvement for enhanced productivity.*

Modeling User Equilibrium in Microscopic Transportation Simulation

by Liang-Chieh (Victor) Cheng and Heng Wang

User equilibrium refers to the network-wide state where individual travelers cannot gain improvement by unilaterally changing their behaviors. The Wardropian Equilibrium has been the focus of a transportation equilibrium study. This paper modifies the dynamic traffic assignment method through utilizing the TRANSIMS system to reach the dynamic user equilibrium state in a microscopic model. The focus of research is developing three heuristics in a Routing-Microsimulation-Equilibrating order for reaching system-wide equilibrium while simultaneously minimizing the computing burden and execution. The heuristics are implemented to a TRANSIMS model to simulate a subarea of Houston, TX.

INTRODUCTION

In transportation models, road users reach a Wardropian equilibrium when a user cannot benefit by making a unilateral move (Haurie and Marcotte 1985; Jeihani, Sherali, and Hobeika 2006). In reality, road users frequently change routes and alter driving speeds in response to network conditions to optimize travel plans. Currently, transportation control entities have utilized communication technologies, e.g., message signs, internet mapping, and GPS, to help the general public assess instant traffic states. This information sharing enhances road users' decision making based on nearly real-time knowledge related to on-road conditions. When all road users are making attempts to improve travel experience but fail to obtain substantial gains, the system reaches a point closely resembling the theoretical equilibrium state.

Matching supply and demand is a key challenge in the economic system (Haurie and Marcotte 1985). In a complex system, equilibrium between supply and demand requires effective use of supply resources against market requirements. The effectiveness of the transportation network is conditioned by features of the supply and demand sides. An equilibrium state of a transportation system indicates the balance of supply and demand (Maillé and Stier-Moses 2009).

Reaching equilibrium in transportation analysis is a key objective for the modelers to assess policies' impacts (Bernstein and Smith 1994). Assessments and policies based on the equilibrium state can more accurately represent the real transportation network (Patriksson 2004). Analyses based on non-equilibrium states, where road users can still achieve substantial travel improvement, may underestimate the efficacy of control arrangements, or overestimate unusual congestion, gridlocks, and uneven traffic patterns. The model is thus less likely to diagnose the actual problems embedded in the network. Accordingly, analyses based on non-equilibrium models will not result in the optimal policies (Flyvbjerg, Skamris Holm, and Buhl 2006).

Consider the segment of U.S. 59 crossing Houston, TX. Policy makers intend to evaluate the benefit of widening the segment of U.S. 59 due to congestion problems. Without reaching the equilibrium criteria, planners may overestimate traffic volume assigned on the widened highway 59. Some of those estimated traffic volumes may be traveling on its frontage roads, and the widening of highway 59 would not necessarily reduce the congestion. This error occurs because the model does not reach assignment equilibrium criteria, thus preventing the policy maker from identifying the real factors that cause the congestion. As a consequence, policymakers will make judgments and evaluate projects based on the unreliable data source.

Transportation equilibrium has been extensively studied by macroscopic models. Recently, microscopic models begin to be employed to assess equilibrium. The advantage of the microscopic model is the level of detail and maneuverability of the study method (Lawson 2006). However, the complexity of the modeled vehicular interaction in a transportation network causes challenges for the model to stabilize. As such, a stream of research has begun to develop heuristics to help microscopic models converge (Jeihani, Sherali, and Hobeika 2006).

This paper develops and applies heuristics to approximate the exact Wardropian equilibrium. A heuristic is a modeling strategy that produces a quick and satisfactory solution as the perfect equilibrium entails exhaustive and lengthy computation efforts (Sherali, Hobeika, and Kangwalklai 2003). The heuristics and the simulation model are based on the Transportation Analysis and SIMulation System (TRANSIMS). The TRANSIMS-enabled model combines static traffic assignment (STA) and dynamic traffic assignment (DTA) techniques to simulate individual travelers' movements on studied networks (Stone et al. 2000). This composite method improves simulation control, enhances convergence, and shortens computation time as compared with approaches such as the gap-based methods (Kim and Rilett 2003).

The present research illustrates to researchers and planners how the dynamic simulation model leads to network-wide convergence and approach the Wardropian equilibrium under scenarios. This paper intends to contribute to the microscopic transportation simulation literature with the following aspects: 1) An in-depth review of the TRANSIMS literature to identify its similarities and distinctions versus prevalent microscopic approaches; 2) A composite, STA-DTA system of heuristics to approach a dynamic Wardropian equilibrium state at the microscopic level; 3) Applications of the heuristics to a TRANSIMS-enabled simulation framework; 4) Implementing the microscopic simulation to a subarea in Houston, TX; 5) Incorporating transportation modelers' best practices to validate the simulation model.

The remainder of this paper is arranged as follows: This paper first reviews literature on equilibrating process for transportation models. Next, a set of heuristics is presented under the framework of the TRANSIMS system. The heuristics will be executed on a TRANSIMS simulation using a real transportation network. Actual traffic data are used to validate the model, and sensitivity analyses are performed to examine the impacts of traffic control measures on the simulation model. The paper concludes with a summary and directions for future research.

LITERATURE REVIEW

Methods for Modeling Wardropian Transportation Equilibrium

A perfect Wardropian equilibrium exists where no road users can make any improvement by unilateral actions. Early equilibrium research focused on static equilibria that did not account for temporal variations of a traffic system (Haurie and Marcotte 1985). The analytical model primarily identifies the shortest travel plans for road users. A body of recent research has examined Wardropian equilibria over different durations of a day and captured on-road travelers' interaction (Maillé and Stier-Moses 2009; Ordóñez and Stier-Moses 2010).

A stream of mathematical research uses equation systems to represent actual traffic conditions to model the Wardropian equilibrium (Bernstein and Smith 1994; Patriksson 2004). Modelers amend parameters to reflect different scenarios. Complex road features, namely, speed limits, number of lanes, and signal phasing are examined simultaneously. For a dynamic equilibrium, time-related variables are inserted to account for changes over a predetermined time period.

Heuristics research is designed to approximate the perfect Wardropian state (Lo and Wong 2002). Equilibrium in an actual system is the result of interplays of the supply and demand forces. At the microscopic level, the set of heuristics needs to address road users' cost-minimizing intents that identify most efficient routes in a network and capture the resulting vehicular actions (Ordóñez and Stier-Moses 2010). This logic resembles the progression in which road users comprehend the operational features of the road system through repeated learning cycles.

Practically, modelers cannot reach a perfect equilibrium in which all users gain no improvement after each change. As such, managing the computation time becomes a key challenge. Jeihani, Sherali, and Hobeika (2006) develop a system of heuristics that repeatedly simulate portions of travelers until models converge. They also specify the rationale to terminate the iterative process at the near-equilibrium state within a manageable time frame (Jeihani et al. 2006).

Simulation applies mathematical and heuristic approaches to study road systems. Simulations capture the complexities of a system and intend to minimize the discrepancies from reality. As an example, road users' interactions and responses to various control strategies, a primary cause of on-road delays, are difficult to be examined through mathematical equations. A simulation model may develop realistic stopping criteria for a state when the system lacks incentives for further travel benefits and travelers will not make changes – a stage of the Wardropian equilibrium.

Macroscopic Traffic Assignment for Equilibrium Modeling

Macroscopic models set equilibrium as the goal for traffic assignment (Lawson 2006). Equilibrium represents the expected system performance. Modelers assume road users have full knowledge of the system. Therefore, macroscopic approaches gain insights into the system's supply aspects and are more effective in examining policies of control and capacity strategies, such as numbers of lanes and speed limits (Rilett, Kim, and Raney 2000).

Macroscopic models move vehicles by applying aggregate equations and provide gross approximations of the study system (Ben-Akiva et al. 2007). Researchers have utilized the four-step urban transportation planning (UTP) method to model and forecast transportation systems (Ben-Akiva et al. 2007; Buliung and Kanaroglou 2007). Details in the study system are missing due to high level of aggregation (Jeihani, Sherali, and Hobeika 2006). The modeling process does not consider on-road vehicular moves and cannot demonstrate travelers' behaviors (Rickert and Nagel 2001). The UTP method, for example, statistically assigns the volumes on all the links without considering time aspects of travel by the study population (Koohbanani 2004).

Dynamic Traffic Assignment for Equilibrium Modeling at More Detailed Levels

The Dynamic Traffic Assignment (DTA) models address the macroscopic models' limitations on modeling details and complement static traffic assignment (STA) approaches by including time-related variables (Ben-Akiva et al. 2007). DTA research incorporates conditions associated with time variations in traffic flows. Time variations result from changing levels of travel demand, finite speed of vehicular movement, and changes in network capacity (Jeihani, Sherali, and Hobeika 2006). Traffic flows of DTA models are hence time-dependent (Nagel et al. 2008).

Simulations are feasible tools to incorporate DTA methods (Hobeika and Paradkar 2004; Lawson 2006). These tools simulate traffic demand's stochastic responses against supply across a controlled time frame (Rilett, Kim, and Raney 2000). A microscopic simulation provides the most detailed information: individual travelers' travel plans and activities, interactive on-road behaviors, and traveler responses to various road conditions. Each synthetic traveler conducts a series of activities in different locations on a second-by-second basis (Nagel et al. 2008).

While microscopic simulation is able to capture on-road vehicular behaviors and interactions, it does not attempt to accomplish equilibrium (Hobeika and Paradkar 2004). Rather, it usually arrives at a state where supply-demand interactions manifest fluctuation. Microscopic models need to assess how a simulated population identifies solutions under given system constraints, and how these constraints are reinforced by travel needs and the traffic environment.

Finally, mesoscopic simulation models were also developed to implement DTA. They incorporate the features of macroscopic and microscopic models. Mesoscopic models simulate individual travelers' on-road behaviors, similar to microscopic models. However, macroscopic mathematical equations and average speeds on street links are utilized in mesoscopic models (Jeihani, Sherali, and Hobeika 2006). The mesoscopic model with DTA performs the time-varying traffic assignment and simulates travelers' planning processes and their interactions.

Gap-Based Modeling Methods

Gap-based methods are widely used in STA models and can be applied to macroscopic, mesoscopic, and microscopic studies. A gap-based simulation compares experienced travel times to shortest-path travel times (Paschai, Yu, and Mirzaei 2010). A modeler keeps modifying travelers' paths before models converge. An advantage of the gap-based measures is the direct application of the equilibrium principle (Boyce, Ralevic-Dekic, and Bar-Gera 2004).

Gap-based methods may cause long computation times in DTA models (Paschai, Yu, and Mirzaei 2009). This disadvantage is more significant for large metropolitan areas. Accordingly, for large metropolitan planning organizations (MPOs), the gap-based methods may not be the best trade-off solution as MPOs consider the necessary model convergence and computation time.

TRANSIMS Model Used to Develop Research Framework

TRANSIMS is developed by the Federal Highway Administration of the US Department of Transportation. TRANSIMS consists of microscopic mathematical models and incorporates specific rules to help control vehicular movements and network characteristics. The modeling system of TRANSIMS applies the cellular automata method, a matrix-based mathematical calculation to model traveler moves (Rilett 2001; Simon and Nagel 2008).

The cellular automata mechanisms generate sequential matrices that reflect second-by-second vehicular movements in the entire network. Geographical Information Systems (GISs) are used to facilitate the creation of traffic matrices and coordinates of vehicles and travelers. While this approach cannot perfectly reflect the continuity of on-road behaviors in the real world, the small time frames allow researchers to model the system to the most possible details. TRANSIMS can perform DTA study to simulate dynamic equilibria (Rickert and Nagel 2001).

Heuristics are presented in the TRANSIMS literature to achieve simulation convergence (Jeihani, Sherali, and Hobeika 2006; Koohbanani 2004). However, research probing the heuristics for a network-wide Wardropian equilibrium is limited. Accordingly, three heuristics are developed below. The set of heuristics in the modeling procedures includes three consecutive loops: 1) the Routing Heuristic; 2) the Microsimulation Heuristic; and 3) the Equilibrating Heuristic.

The use of stopping criteria is a key technique used in TRANSIMS simulations to reach convergence (Paschai, Yu, and Mirzaei 2009). The convergence may take place under two conditions: the actual Wardropian equilibrium has been reached, or the algorithm cannot make any more effective progress even though the Wardrop conditions are not satisfied. The stopping criteria is to trade off the model's practicality against the optimal state (Boyce, Ralevic-Dekic, and Bar-Gera 2004; Jeihani, Sherali, and Hobeika 2006).

HEURISTICS FOR DTA AND NETWORK-WIDE USER EQUILIBRIUM

A set of heuristics is developed below to approach a dynamic Wordropian equilibrium. First, the Routing Heuristic produces routes for all travelers. The outcome is a static state where all travelers develop shortest paths. Next, the Microsimulation Heuristic models traveler actions and reroutes travel paths. This heuristic takes into account all road-users' on-road behaviors and seeks a stabilized condition between traffic supply and demand. Finally, the Equilibrating Heuristic determines a network-wide, dynamic equilibrium for all travelers in the network over time. The heuristics developed below combine STA and DTA methods accordingly.

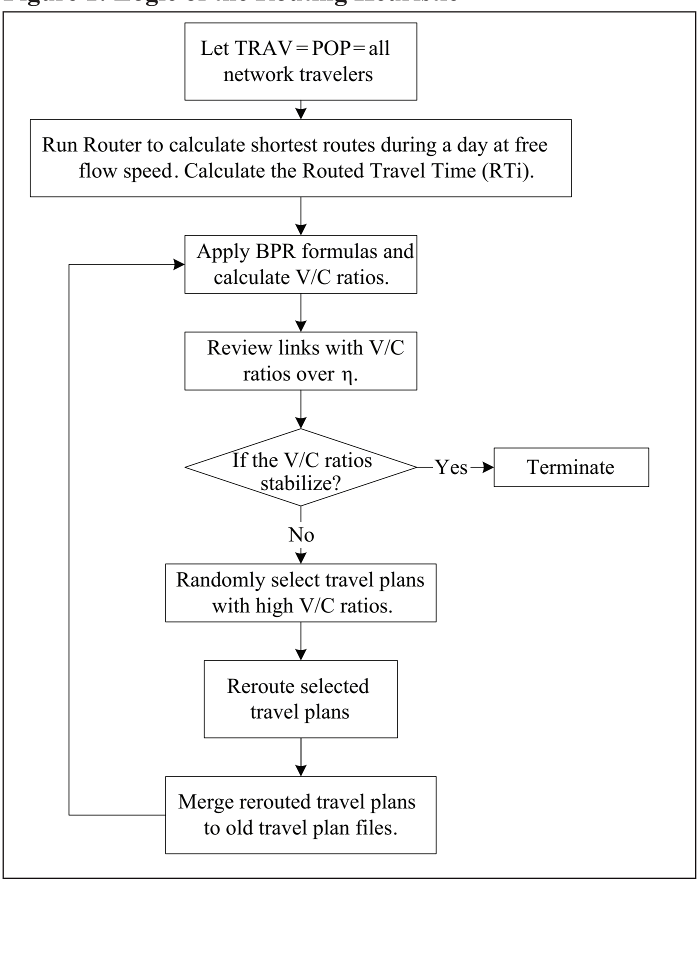
An underlying assumption of the heuristics is that road users intend to minimize the costs associated with their travels. The action of shifting travelers on high-cost paths to lower ones in the heuristics is at the core of equilibrium literature (Ordóñez and Stier-Moses 2010). However, the cost-minimizing behaviors are conditioned by the road-users' on-road interaction.

Routing and Microsimulation Heuristics intend to minimize the simulation running time. Contrastingly, the Equilibrating Heuristic models the equilibrium of traffic supply and demand for the entire study area. The combination of the foregoing heuristics aims to efficiently simulate the network so the model can converge to a state that reflects the Wardropian Equilibrium.

Routing Heuristic

The Routing Heuristic determines each road user's shortest travel length. It loads their origin-destination trips to the transportation network. The travel speeds are at free flow, and the resulting routes do not consider on-road interactions. This heuristic modifies the Incremental Individual Loader (IIL) in Jeihani, Sherali, and Hobeika (2006) and Koohbanani (2004), which computes road users' paths one at a time and in turn updates volumes and travel times of related road links. The iterative loop below identifies shortest travel plans for travelers. Figure 1 illustrates the logic of the heuristic. Details are discussed below.

Figure 1: Logic of the Routing Heuristic



1. Let $TRAV_{Router}$ = POP be the set of all network travelers.
2. Run Router to calculate shortest-paths travel plans during a day at free flow speed. Calculate the Routed Travel Time (RT_i), the shortest-path travel time for traveler *i*.
3. Apply Bureau of Public Roads (BPR) equations and calculate V/C ratios. (See endnotes).
4. Review links with V/C ratios over a predetermined value, η.
5. Randomly select travel plans by p_{Router}% containing links with high V/C ratios. The subset of selected travelers is $TRAV'_{Router.}$ $TRAV'_{Router}$ is expected to be smaller than $TRAV_{Router}$, since not all travel plans in $TRAV_{Router}$ contains links with high V/C ratios.
6. Reroute selected travel plans in $TRAV'_{Router}$.
7. Merge rerouted travel plans to old travel plan files. Let $TRAV_{Router}$ = the new set of all network travelers. The new $TRAV_{Router}$ is expected to include updated travel plans with better travel performance, i.e., lower V/C ratios.
8. Repeat 3 through 7.

The iterative design of this heuristic accounts for the time-consuming rerouting process. The heuristic selects p_{Router}% of travel plans with high V/C ratios for the next routing assignment. While there is no strict rules to determine the value of p_{Router}%, the modeler can determine the baseline value through two approaches: 1) Using values documented in the TRANSIMS literature; or 2) Consulting MPOs that provide data and conduct similar simulations.

To have a finite number of Routing Heuristic iterations, one stopping criterion is added: if the number of links with high V/C ratios does not strictly decrease, the heuristic loop is stopped. At this point, the synthesized network creates static, optimal travel plans for each traveler. It shall be noted that at this stage, the on-road interactions of travelers are unknown, and the network performance is yet to be fully analyzed. The DTA method will be incorporated into the following Microsimulation Heuristic.

Microsimulation Heuristic

The Microsimulation Heuristic reflects the DTA process and captures the actions between travelers and the features of traveling behaviors in the study area. In doing so, this heuristic addresses the relatively unrealistic states of no on-road interactions developed by the Routing Heuristic (Hobeika and Paradkar 2004; Jeihani, Sherali, and Hobeika 2006; Nagel et al. 2008). The Microsimulation Heuristic's logic is illustrated in Figure 2. The details are as follows:

1. Let $TRAV_{Microsimulation}$ = POP be the set of all network travelers.

2. Run MicroSimulator for $TRAV_{Microsimulation}$. Calculate Experienced Travel Time (ET_i), the resulting travel time including on-road delays for traveler *i* at driving speed,

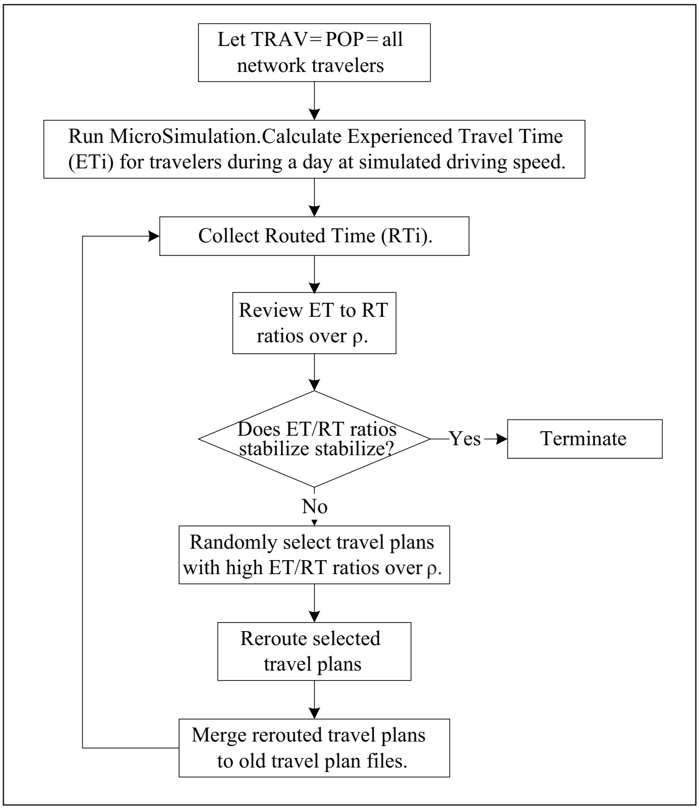
3. Collect data on Routed Travel Time (RT_i) for traveler *i* in $TRAV_{Microsimulation}$ calculated from the Routing Heuristic.

4. Review travel plans with ET_i to RT_i ratios. Examine when the ET/RT ratio is higher than a predetermined ρ for traveler *i* in $TRAV_{Microsimulation}$.

5. Randomly select $p_{Microsimulation}$% of travel plans with high ET/RT ratios more than ρ. The set of selected travelers is $TRAV'_{Microsimulation}$. $TRAV'_{Microsimulation}$ is expected to be smaller than $TRAV_{Microsimulation}$, since not all travel plans in $TRAV_{Microsimulation}$ contains links with high ET/RT ratios.

6. Reroute selected travel plans in $TRAV'_{Microsimulation}$.

Figure 2: Logic of the Microsimulation Heuristic



7. Merge and sort rerouted travel plans with old travel plan files. Let $TRAV_{Microsimulation}$ = the new set of all network travelers. The new $TRAV_{Microsimulation}$ is expected to include updated travel plans with better travel performance, i.e., lower ET/RT ratios.

8. Run MicroSimulator for $TRAV_{Microsimulation}$.

9. Repeat 3 through 8.

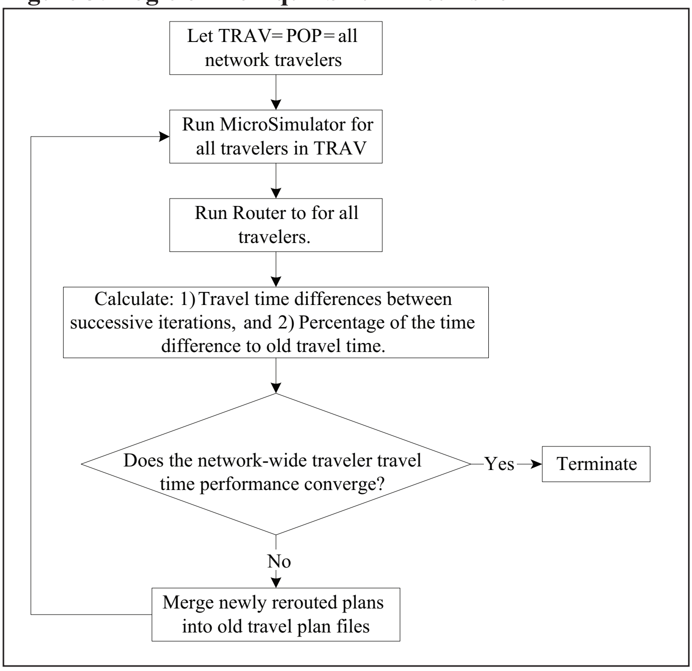
This heuristic attempts to improve the rerouting efficiencies. It intends to help the routing process converge faster by selecting $p_{Microsimulation}$% of travel plans with high ET/RT ratios. The modeler can determine $p_{Microsimulation}$% by using values documented in TRANSIMS literature or consulting MPOs conducting similar simulations. To have a finite number of Microsimulation iterations, one stopping criterion is created: If the number of plans with high ET/RT ratios does not strictly decrease or arrive at a predetermined level, the heuristic loop is stopped.

By far, the two foregoing heuristics modify and complete the DTA process comparable to Jeihani, Sherali, and Hobeika (2006). The objective of the two heuristics is a stable state of the entire model under controlled efficiencies. In the following section, an additional and final heuristic is developed to simulate the user equilibrium state for the entire studied network.

Equilibrating Heuristic

The Equilibrating Heuristic seeks a dynamic equilibrium for the entire study transportation system. The heuristic and the entire simulation logic are terminated when network travelers cannot make significant travel time improvements by a pre-determined percentage. Figure 3 illustrates the logic of the Equilibrating Heuristic. The details are discussed below:

Figure 3: Logic of the Equilibrium Heuristic



1. Let $TRAV_E$ = POP be the set of all network travelers.

2. Run Microsimulation for all travel plans in $TRAV_E$.

3. Utilize ET (the Experienced Travel Time) as inputs for Router and then route all travel plans in $TRAV_E$.

4. Compare the new travel plans in Step 3 against old travel plans in $TRAV_E$ from the last iteration. Calculate p_{iE}%, the ratio of $Travler_i$'s travel time difference in new and old files to old plan's travel time.

5. Let ε be a predetermined percentage of POP. In addition, let π be a predetermined percentage that represents travel time improvement. If modeling outcomes have more than ε of travelers of POP whose travel time improvement (p_{iE}%) is larger than π, it represents a non-equilibrium state. Namely, travelers still have room to make travel time improvement. Continue with Step 6 below. However, if modeling outcomes have fewer than ε of travelers of POP whose travel time improvement (p_{iE}%) is larger than π, terminate the equilibrating loop.

6. Merge newly rerouted plans obtained from Step 3 into old travel plan files and obtain $TRAV'_E$. Number of travelers in $TRAV'_E$ and $TRAV_E$ will be identical.

7. Let $TRAV_E = TRAV'_E$.

8. Rerun 2 through 7.

In this heuristic, the supply and demand of the entire transportation network are modeled through multiple iterations. All travel plans are rerouted, and all vehicle motions and interactions are simulated at the most detailed, road user level. This iterative mechanism mimics network-wide travelers' learning behaviors, and the modelers will seek that the vast majority of the travelers can approach near-optimal travel times through iterative runs (Nagel et al. 2008). Each iteration seeks improvements of all road users from the last iterative runs, and the modelers will compare traveling performances of successive iterations. A stopping criterion is developed to have a finite number of the Equilibrating iterations: If the values of p_E% in successive iterations do not strictly decrease, the loop is stopped.

TRANSIMS' Relations to Gap-Based Microscopic Simulation Methods

Table 1 summarizes the relations between TRANSIMS and microscopic gap-based approaches. Both methods can apply STA and DTA approaches. Further, similar to the gap-based methods, TRANSIMS allows modelers to compare experienced travel time against shortest-path time.

Table 1: TRANSIMS vs. Microscopic Gap-Based Methods Comparison

<table>
<tr><th></th><th>STA</th><th>Decision Rules for Sequential Iteration Improvement</th><th>DTA Convergence</th><th>Simulation Duration</th></tr>
<tr><td>Gap-Based Methods</td><td>Yes</td><td rowspan="2">Comparing experienced travel times to shortest-path travel times for all routes.</td><td>Requiring more iterations to stabilize modeling outcomes</td><td>Long computation time for large metropolitan areas</td></tr>
<tr><td>TRANSIMS</td><td>Yes</td><td>Allowing adjustments for control parameters to reach convergence criteria faster</td><td>Short computation time with predetermined convergence accuracies</td></tr>
</table>

A distinction differentiates TRANSIMS from the gap-based methods. The TRANSIMS system allows the modeler to control parameters to quickly reach convergence criteria. An example is to identify a predetermined percentage of problematic paths that displays abnormally high experienced travel times. With the inclusion of stopping criteria, TRANSIMS may be quicker to reach model convergence. For DTA tasks in the large metropolitan areas, TRANSIMS hence has appeal for planners seeking feasible solutions under modeling time constraints.

SIMULATION METHOD

Preparation for Simulation

A subarea in Houston, the Texas Medical Center (TMC), is the study area to perform the heuristics developed previously. TMC has the world's largest complex for patient care, medical research, and educational institutes for illness and injury treatment and prevention. It consists of approximately 142 buildings, including hospitals, colleges, and research centers. There are 72,000 employees, 32,000 students, and thousands of patients traveling to TMC every day. A significant of number of households and other people travel to work through the TMC area.

GIS data on network shapefiles and trip tables are collected from the Houston TRANSTAR and Houston-Galveston Area Council (H-GAC). The modelers synthesize the transportation network into TRANSIMS format. ArcGIS and TRANSIMS are utilized to process data to establish the skeletal network files. Skeletal network files only display the center lines of all streets; hence, more specific data below are required to specify the supply side of the simulation.

TRANSIMS requires numbers of lanes and speed limits for road links to specify the characteristics regarding the network capacities. Further, data on traffic signal phasing at intersections, one-way/two-way regulation, and U-turns, are necessary for the study area. In the absence of data items (e.g., control signal and stop sign data), TRANSIMS built-in functions are used to generate synthetic control systems.

The next task is trip table conversion. Traffic Analysis Zone (TAZ)-based, O-D trip tables represent the TMC transportation demand. O-D zone trips are hence demand inputs to the simulation. TRANSIMS trip table conversion functions are used to calculate trip counts.

Key characteristics of the TMC transportation network and traffic demand are as follows:

- Number of Input Node Records = 1,223
- Number of Input Link Records = 1,553
- Number of Input Zone Records = 37
- The total number of daily trips = 358,210

Simulation Procedures and TRANSIMS Programs Utilized in Executing Heuristics

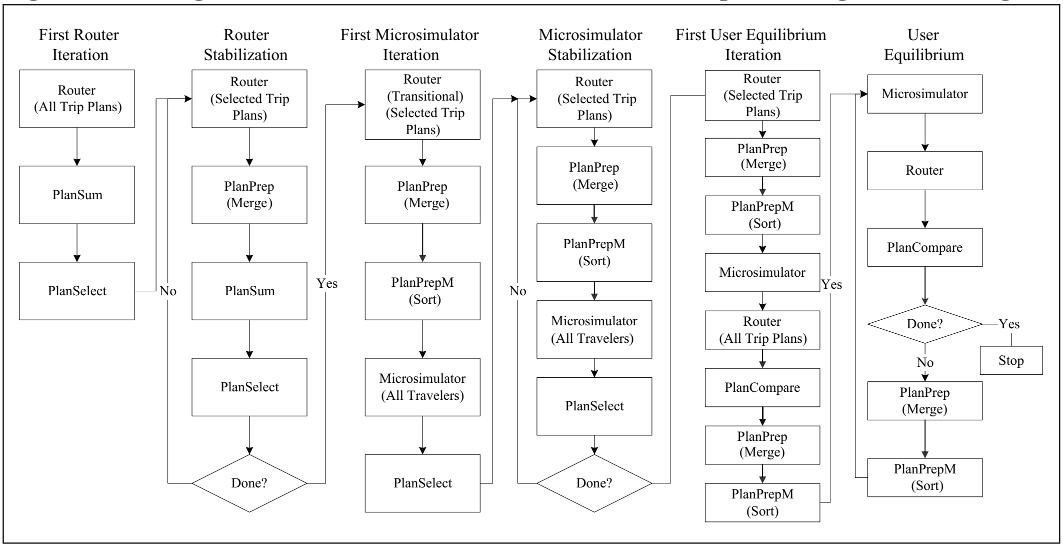
The simulation model specifies a 24-hour clock for a complete run. Each iteration starts at 0:00 and completes at 24:00. The computing environment is a high performing computer with Core 2 Duo, 2.66 GHZ CPUs. Table 2 lists the TRANSIMS programs and their associations with respective heuristics. The table briefly explains their main functions in the simulation iterations.

Table 2: TRANSIMS Programs Utilized in the TMC Simulation Study

TRANSIMS Program	Functions	Heuristic
Router	To develop the travel plans for all travelers	Router, Microsimulation, and Equilibrium
PlanSum	To generate Router performance summary	Router
PlanSelect	To select travel plans for rerouting	Router & Microsimulation
PlanPrep	To merge new travel plans from new Router into travel plan files for all travelers	Router, Microsimulation, and Equilibrium
PlanPrepM	To sort all trips according to the time of day	Microsimulation and Equilibrium
Microsimulator	To model all traveler actions in the network	Microsimulation and Equilibrium
PlanCompare	To examine whether the network traffic pattern arrived at an equilibrium state according to outputs from prior process.	Equilibrium

Figure 4 shows the simulation processes for the study. The first heuristic, Routing Heuristic, is executed after the completion of the trip table conversion process. This step loads and distributes the travelers to the network according to a trip table and diurnal distribution, which describes the recurring 24-hour traffic patterns in Houston, TX. The Routing Heuristic loop is repeatedly executed until the traffic volume and network capacities converge (Roden 2007).

Figure 4: Routing Heuristic, Microsimulation Heuristic, and Equilibrating Heuristic Logics



The next step is the Microsimulation Heuristic process. The MicroSimulator program of TRANSIMS is utilized to model individual travelers' activities and on-road vehicle interactions (Stone et al. 2000; Roden 2007). Each Microsimulation process identifies travel plans with performance worse than predetermined values and reroutes them.

The model proceeds with the Equilibrating process. In the various iterations, all travelers' travel plans are routed and all vehicles' interactions are simulated with multiple repetitions (Roden 2007). Similar to prior two loops, the modelers repeat the Equilibrating loop until the model displays convergence on link performance parameters and all travelers arrive at the optimal travel state. The entire TRANSIMS simulation process is complete when no travel time could significantly improve in consecutive runs.

Execution of the Routing Heuristic Loop

The Router program produces shortest paths at free flow speed. A system of built-in BPR equations (see endnotes) computes and updates the link travel times (or delays) and calculates link V/C ratios in the transportation network (AECOM Consult 2007). Practically, selecting the most problematic travel plans for rerouting is a more efficient way to reach convergence (Stone et al. 2000). A set of TRANSIMS programs allows modelers to identify non-optimal network links. The travel plans are selected for rerouting according to the following criteria:

1. Links of travel plans which have high V/C ratios
2. Discrete modeling time periods during morning peak hours of the day (6:00-9:00 AM)

The selected travel plans are then loaded to the next Router iteration for rerouting. For the 25 iterations performed, V/C ratios of the selected links oscillate in early iterations but appear to stabilize after iteration 15 until the end. The number of links with V/C ratios ≥ two (η) decreases from 795 to 600 from iteration 1 to iteration 24. Thus, the heuristics lead to a more stable status.

However, a closer observation identifies a number of links with unexpected high V/C ratios. For instance, V/C ratio is 3.03 for Link 1493 between 7:00 AM and 7:15 AM of the 24th iteration. These links are likely to generate long delays. One of the reasons for the high V/C is the feature of traveling at free-flow speed assumed by Router (AECOM Consult 2007). Router runs do not consider on-road behaviors and the resulting actual travel speeds. This causes more trips to be loaded on the same links and result in high V/C values.

Execution of the Microsimulation Heuristic Loop

The Microsimulation Heuristic generates road users' travel routes, which account for on-road interactions, and finds realistic travel plans, as opposed to routes produced previously with free flows (Jeihani, Sherali, and Hobeika 2006). Microsimulation runs include on-road interaction to be a key additional dimension for rerouting travel plans. Modelers utilize the outcomes by the MicroSimulator program to identify links with low performance and develop new travel plans in subsequent iterations. Travel plans are selected for rerouting according to the following criteria:

1. Experienced Travel Time to Routed Travel Time (ET/RT) ratios
2. Percentage of travel time difference between two consecutive runs

The iterative loop chooses a small number of problematic travel plans for rerouting (Roden 2007). Afterwards, MicroSimulator will simulate all vehicles after the modified travel plan files are merged into old travel plans.

The TMC Project executes 11 runs for the Microsimulation Heuristic process. Table 3 presents the progress over Microsimulation Heuristic iterations. The table reports the numbers and percentages of travelers whose ET/RT ratios are larger than a predetermined ρ (1.2) in each iteration. Numbers of links with high V/C ratios (≥ two) remain at one throughout the iterative processes. In addition, percentages of traveler with high travel time ratios show a convergence across iterative runs. While the numbers of travelers with high ET/RT ratios does not decrease strictly, the numbers display a decreasing trend, as attempted by the Microsimulation Heuristic.

Table 3: Progress in Travel Time Performance in Microsimulation Runs

Iteration	No. of Travelers with Travel Time Rate > 1.2	Percentage of Travelers with Travel Time Rate > 1.2
1	55449	15.50%
2	36528	10.20%
3	26701	7.50%
4	22487	6.30%
5	13774	3.80%
6	9804	2.70%
7	16795	4.70%
8	14024	3.90%
9	5813	1.60%
10	4402	1.20%
11	3391	0.90%

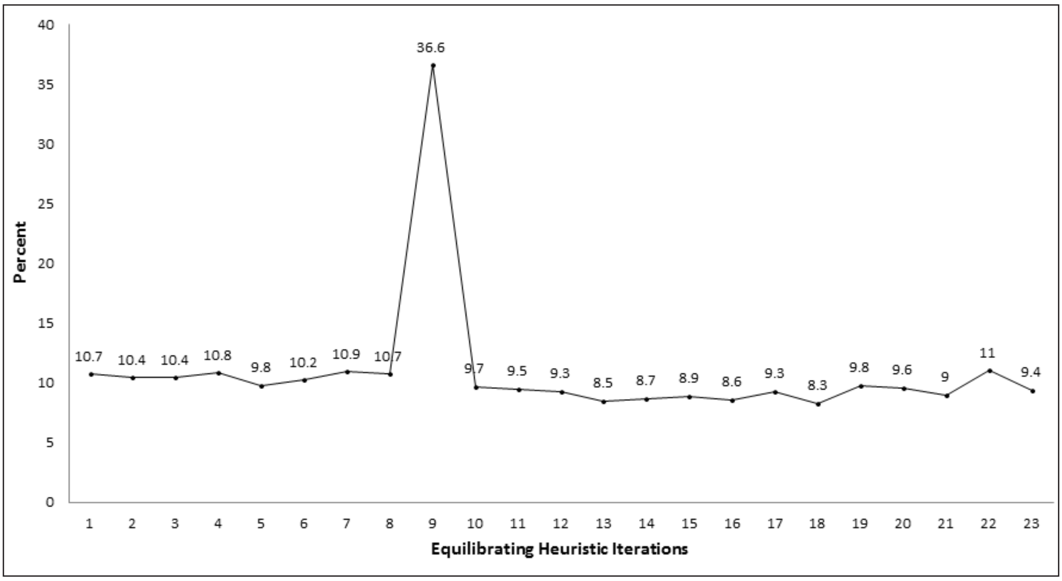
At iteration 11, travelers with ET/RT ratios higher than ρ become lower than 1%. The percentages of travelers with high ET/RT ratios decrease from 15.5% to 0.9%. Because of the low percentage, the Microsimulation runs are terminated and the simulation proceeds to the next loop.

Execution of the Equilibrating Heuristic Loop

This loop is aimed at identifying a dynamic equilibrium state to complete the simulation. The simulation process will stop when no travel times can improve by a predetermined percentage. Travel plans are selected when the displayed Travel Time changes are larger than 2% (p_{iE}%) in consecutive Equilibrium iterations. The simulation is stopped when fewer than 10% (ε) travelers have time changes, or no travelers have larger than 2% travel time changes.

In executing the loop, V/C ratios remain constantly low. The number of links with V/C ratios larger than two reduces from one to zero gradually. In terms of travel times, Equilibrating iterations have most of the links improved. In Figure 5, percentages of trips with changes larger or less than 2% in absolute values remain below 10% after the 9th iteration, except iteration 22.

Figure 5: Percentages of Trips Experiencing High Travel Time Change



According to the stopping criterion, the progress suggests a state similar to the Wardropian Equilibrium (Nagel et al. 2008). The iterative runs are stopped since the loop displayed convergence in terms of travel time improvement through consecutive iterations. Completion of the Equilibrating runs concludes the simulation run for the study network.

In summary, 25 Routing iterations are completed in 26 minutes, 11 Microsimulation iterations in one hour and two minutes, and 22 Equilibrating iterations in approximately four hours and two minutes. Compared with the CPU time (30 hours) consumed by Jeihani, Sherali, and Hobeika (2006), the combination of the computing platform and simulation framework of the present research demonstrates considerable improvement regarding modeling efficiency.

Validating Baseline Simulation Results for TMC Transportation Networks

This task examines the validity of the baseline simulation outcomes. Convergence in simulation iterations indicates a proper setup of the modeling procedures, whereas the validity test determines to what degree the simulation approaches or deviates from realistic traffic conditions.

Two primary parameters are utilized to validate the TMC simulation model:

1. Total daily volumes of major roads of all directions
2. Total peak hour volumes of major roads of all directions

Data on actual traffic volume are collected to be the basis of validation. The researchers calculate H-GAC's (Houston-Galveston Area Council's) daily volumes for major roads in the TMC. Traffic counts for "links" (or road segments in the model) of major roads are then retrieved from the simulation outputs. The data values of links are combined to be the simulated major road's total traffic volume. Lastly, H-GAC traffic volumes are compared against simulation outcomes.

According to the H-GAC's decision rule for traffic simulation runs, an interval of plus and minus 15% difference between a major road's actual traffic volumes and simulated outcomes are deemed as an acceptable range. An 8% interval is considered excellent for modeling performance. The difference intervals may be widened to be as much as plus and minus 30% for less traveled streets. Differences between actual and simulated outcomes beyond these ranges suggest potential errors in original data or simulation procedures.

The simulated TMC traffic volumes of major roads are compared with H-GAC's daily traffic volume. The differences are within the plus/minus 15% interval, suggesting that the simulation performance is comparable to the local MPO's traffic model standard.

Sensitivity Analysis

A sensitivity test is performed to evaluate the variations of simulation under different scenarios (Patriksson 2004). The extant model consists of time-actuated signals at major and local road intersections. Time-actuated signals are similar to fix-time (also known as pre-timed) signals in that they are constrained by time limits. However, unlike fix-time signals, actuated signals can change phases before they reach their time limits if the demand is low. They can even skip a phase if there is no demand for that phase (e.g., left turns). For this reason, actuated signals are especially useful in low-demand settings, such as in rural areas or at night.

As a comparison, the scenario of fixed-time signalization is created. The new model replaces the time-actuated signals with fixed-time signals. After the changes, the modelers execute identical TRANSIMS procedures and examine changes in the simulation outputs.

Interestingly, the fixed-time signal scenario generates fewer volumes comparing to the time-actuated signal system. The fixed-time system also results in less travel time. Stopping criterion is met faster by fixed-time signals than actuated signals: The number of travelers with significant change in travel time decreases to 7.5% in 14 iterations. In sum, the three heuristics are successfully executed in the new scenario and the simulations reach convergence.

DISCUSSION AND FUTURE RESEARCH

Discussion

The equilibrium state needs to serve as the baseline for policy-oriented analyses. For variants of simulation scenarios, a modeler can adopt the method reported in the paper and maneuver simulation parameters to capture tentative occurrences as well as long-term development in the study network. For instance, the changes in signalization designs may affect the system's travel performance. The modelers can also alter performance parameters to fine-tune model designs.

Interviews are conducted to verify the importance of equilibrium modeling. For H-GAC, reaching equilibrium has nontrivial benefits. The system-wide equilibrium can reduce model assignment uncertainty for major roadway projects, such as freeway widening and new major arterial streets. Further, vehicle miles traveled (VMT) and total vehicle times (VHT) are crucial parameters to evaluate regional performances of major roadway projects. Reaching system-wide equilibrium is necessary for keeping the regional VMT and VHT stable in the model.

For instance, H-GAC recently ran a macroscopic travel demand model with forecast data in the year 2035. The system-wide equilibrium nearly reaches convergence criteria in the 40th assignment iteration. The VMT in the 11th iteration is 156,163 miles lower than that in the 10th iteration. However, the VMT in the 40th iteration is only 8,556 miles lower than that in the 39th iteration. Hence, model stability improves when system-wide equilibrium criteria is satisfied after more simulation iterations. This underscores that system-wide equilibrium criteria help provide reliable project evaluation sources to policy makers.

Hence, deficiencies in policies based on unstable models cannot be overstated. They may cause suboptimal development efforts, and public investments will not be adequately allocated. It will eventually lead to a vicious cycle of inaccurately allocated resources and low performance.

Limitations and Future Research

The assumption of the simulation framework is that road users will identify cost-minimizing travel plans by learning from on-road experiences. A solution to validate the assumption is to use real data showing the actual route choice process over time. Future research may simulate day-to-day dynamic equilibrium over a week. This approach requires richer data sets and more sophisticated analyses. Using TRANSIMS, modelers need to collect new data on trip tables diurnal distributions on both weekdays and weekends. Continual simulation over multiple weekdays and weekends is necessary with new data.

In this paper, the convergence measures are based on the improvement of the solution. The equilibrium of the simulation is actually a heuristic. At the termination, the model does not specify how closely the end state satisfies the Wardropian conditions. It is difficult to tell whether the algorithm terminates because the actual Wardropian equilibrium has been reached, or because the algorithm simply cannot make any more effective progress even though the Wardropian conditions are not satisfied.

Actual data on travel patterns will be necessary to assess the gap between the equilibrium outputs and road users' behaviors. According to H-GAC, there are no existing data or survey plans for the route choice in the TMC area. Traffic counts are the only available, real data to validate the algorithm applied in the paper. Future research can consider developing a method to collect data on actual travel paths in a study area on a constant basis. A longitudinal database of the dynamic travel pattern is necessary. For longitudinal traffic data, sample observations are collected from a larger population over a given time period. This database can help validate the DTA outcomes as well as refine the parameters (e.g. p_{Router}% and $p_{Microsimulation}$%) for the sensitivity analyses.

The comparison between the TRANSIMS models and other methods is not performed in this study. Planning agencies in the Houston area do not have plans to evaluate the benefits of running different simulation models. Future research can perform cross-evaluation among traffic planning methods and examine the characteristics of respective equilibrium states. Specifically, a methodology comparing various microscopic simulation systems will allow policy makers and planners to analyze the resources entailed to execute different models (e.g., TRANSIMS vs. gap-based methods). Respective benefits, such as convergence speeds, and costs, such as man-hours, can be quantified to assess the impacts of implementing various approaches.

CONCLUSION

This paper makes the following accomplishments: First, the research reviews microscopic simulation literature and positions TRANSIMS methods relative to prevalent methods. Second, this paper develops a set of heuristics and stopping criteria to route travelers and model traveler movements and on-road interactions. The TRANSIMS system is used to implement the heuristics and perform microscopic simulation. Finally, the simulation approximates a system-wide Wardropian equilibrium at the most disaggregate traveler level.

Three heuristics are developed to simulate a transportation system and reach an equilibrium state. The Routing Heuristic produces routes for individual travelers and reroutes travelers to seek optimal routes. In turn, the Microsimulation Heuristic generates traveler behaviors to obtain realistic on-road interactions. Ultimately, the Equilibrating Heuristic finds the network-wide state where individual travelers cannot gain improvement by unilaterally changing travel plans.

The heuristics are executed in TRANSIMS simulation loops. Stopping criteria are developed according to a number of link performance measures. The heuristics, TRANSIMS model, and stopping criteria work jointly to determine the equilibrium for the study network. The sensitivity test also leads to convergence in the presence of distinct transportation characteristics. Lastly, potential directions are discussed to extend microscopic simulation research for assessing transportation improvement plans of action or policy. These plans are designed to achieve transportation goals such as travel time reduction, emission reduction, and safety improvement. The value of the present research to examine the effectiveness of these plans are also discussed.

Endnotes

A set of built-in BPR equations computes and updates the link travel times (or delays) and calculate link performance in the transportation network (AECOM Consult 2007). The BPR function default values for α, β, and γ in the present research are 0.15, 4.0, and 0.75, respectively. The BPR equation for computing the link travel time is as follows:

$t = t_0 * (1 + (\alpha * (Volume/Capacity)^{\beta}))$,
where
t = Average travel time in seconds
t_0 = Baseline (free flow) travel time in seconds
$\alpha = 0.15$
$\beta = 4.00$

Volume = Traffic volume on the link in a given time period
Capacity = Adjusted Capacity of a link in a given time period

Capacity of the link in a given time period is calculated by the following equation:
Capacity = γ*Hourly Capacity * (Time Increment/3600)
Where
$\gamma = 0.75$
Time Increment = Time Period (in seconds)

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***Liang-Chieh (Victor) Cheng** is an associate professor in the College of Technology at the University of Houston. He received his Ph.D. in business logistics and supply chain management (SCM) from the University of Maryland in 2005. His current focus of research is transportation simulation, strategic supply chain management, and inter-organizational information technology (IT). Cheng has conducted a stream of research projects, utilizing the TRANSIMS simulation technology. This research stream originated with a US DOT-funded project for the transportation network surrounding the Texas Medical Center (TMC). His research has resulted in publications at* Decision Sciences, Journal of Business Logistics, Industrial Management & Data Systems, International Journal of Production Economics*, among many others.*

***Heng Wang** is a senior transportation analyst at the Houston-Galveston Area Council (H-GAC), Houston, Texas. He has applied his expertise in micro- and meso-simulation to support the transportation modeling projects related to the H-GAC service region for the past five years. Wang was a transportation engineer and assistant project manager of Best Control Technology in China and developed a number of highway control systems for the provincial government of Guandong in China. He holds a master of science in Civil Engineering from Virginia Tech, Virginia, in 2005.*

Introduction of Heavy Axle Loads by the North American Rail Industry

by Carl D. Martland

The Association of American Railroads (AAR) initiated the Heavy Axle Load (HAL) Research Program in 1988 in order to "provide guidance to the North American railroad industry about whether to increase axle loads and to determine the most economic payload consistent with safety" (Kalay and Martland 2001). The research demonstrated the technical feasibility and economic desirability of increasing axle loads and the ability of technology to mitigate the adverse effects of heavier loads. In 1991, the industry decided to accept cars with 286,000 lb. gross vehicle weight (286k GVW) in interchange service. Since then, more than 90% of all bulk equipment acquired has been rated for 286k GVW. By 2010, nearly 100% of coal traffic and 30% of general freight moved in 286k loads.

Technological improvements resulting from the HAL research program have been critical in enabling the industry to reduce costs of 286k operations. Stronger materials, better designs, and improved maintenance techniques reduced life cycle costs for rail and other track components. Bridge costs did not increase as much as expected, because of technological developments and better understanding of their ability to withstand HAL loads.

Net benefits of HAL operations to railroads, suppliers, and their customers were approximately $6 billion between 1994 and 2010. Annual net benefits exceeded $600 million in 2010. Benefits included reductions in equipment expense, more efficient operations, and increases in line capacity. Given the technological advances in railroad engineering over the past 20 years, further increases in GVW or loading density should now be considered.

OVERVIEW OF THE HAL RESEARCH PROGRAM

This paper has two major objectives. First, it estimates the net benefits achieved by increasing the maximum GVW to 286k, taking into account impacts on operations and infrastructure. Second, it reviews the literature related to HAL implementation and the technological developments that helped mitigate infrastructure costs resulting from HAL loads.

Strengthening track to allow larger, heavier cars has long been a major factor helping railroads improve their productivity (Hay 1982; Chapman and Martland 1997 and 1998). If cars can carry more freight, then fewer cars, trains, crews, and gallons of fuel are needed to carry any given amount of freight. Decisions to increase load limits must balance these benefits against potentially higher infrastructure costs.

During the 1970s, the widespread introduction of the 100-ton car (GVW of 263,000 pounds) caused havoc with the track structure for many railroads. Rail that was adequate for 70-ton cars (GVW of 200,000 pounds) was unable to withstand the higher forces associated with 100-ton operations. Instead of replacing rail because of wear or battered joints, railroad replaced rail because of fatigue and risks of broken rails. Zarembski (1981) concluded that fatigue would limit rail life on tangent (i.e., straight) track, reducing rail life from 580 million gross tons (MGT) under mixed freight to 416 MGT under 70-ton unit trains and to 267 MGT under 100-ton unit trains. Until the rail life problem could be resolved, it was impossible to consider any further increase in GVW.

During the 1980s, railroads and the supply industry addressed fatigue by developing harder rails and better maintenance techniques, including grinding the rail in order to maintain the proper shape of the rail head so as to control the forces at the wheel/rail interface. In June 1987, the Transportation Research Board's Committee on Railway Maintenance sponsored a conference on "Rail: Replacement Strategies and Maintenance Management" at the University of Illinois that featured presentations by AAR and DOT researchers, steel manufacturers from Japan and Europe, other suppliers of maintenance services, rail engineering officials, and consultants. Roger Steel, the chief metallurgist for AAR's Research and Test Department, chaired a remarkable session in which he allowed steel manufacturers from Japan and the UK to describe what they were doing, then challenged them to develop better steel more attuned to the needs of the heavy haul railroads. It was clear that the rail industry was pushing suppliers to improve their metallurgies in order for rail to withstand the forces of HAL operations.

In the mid-1980s, Burlington Northern Railroad (BN) was the leader in the introduction of better rail and better maintenance, because its coal routes were the highest density lines in North America. BN knew that its rail in high density mainline track would last up 1,400 MGT and that premium rail in high-degree curves would last 300-500 MGT:

> *Advancements in rail technology (head hardened and fully heat treated rail, clean steel practices), lubrication, road bed improvement (undercutting and shoulder cleaning) and rail grinding have all contributed to this increase in rail life. However, it has been the practice of rail grinding that has allowed the full potential of these improvements and advancements to produce the rail longevity characteristics we now enjoy. (Glavin 1989, p. 239)*

BN knew that heavier axle loads would increase the efficiency of moving rapidly growing volumes of coal out of the Powder River Basin in Wyoming. They therefore initiated an internal study (Newman, Zarembski, and Resor 1990) of the feasibility of increasing GVW limits from 263,000 to 315,000 pounds (initially known as the 125-ton car). BN and other railroads were aware that heavier axle loads had already been introduced in Australia (Marich 1986), but it was unclear whether such loads would be technically and economically feasible under North American operating conditions. With fresh memories of the troubles from introducing 100-ton cars, senior railroad executives deferred further increases in GVW without thorough assessment of the technical and economic feasibility of heavier loads. The HAL Research Program focused on coal, by far the highest-volume commodity handled by railroads.

The HAL research began in 1988 and continued through 2000 in five phases. Much of the research was conducted at the 2.4-mile High Tonnage Loop of the Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center in Pueblo Colorado. Operation commenced in the mid-1980s with a train of cars loaded to 263,000 pounds GVW (axle loads of 33 tons). In HAL Phase I, the same cars were loaded to 315,000-pounds (axle loads of 39 tons), allowing a direct comparison of stresses and deterioration for 33- and 39-ton axle loads. These tests confirmed that it was technically feasible to increase axle loads. Economic feasibility was examined under the supervision of industry officials with backgrounds in engineering, operations, planning, and economics. The economic analysis built upon the FAST/HAL research, research conducted by individual railroads and government agencies, and the experience of other heavy haul railroads. At the end of Phase I, the HAL Economic Advisory Committee concluded that an increase to either 286,000 lb. or 315,000 lb. GVW for 4-axle equipment would reduce overall costs for operations over good infrastructure. Increasing to 286,000 GVW (36-ton axle loads) was most cost effective, primarily because costs related to rail fatigue, turnout deterioration, bridge life, routine maintenance, and freight car wheels would rise more than linearly with axle loads (Hargrove 1991).

In 1991, the major railroads began to introduce 286k GVW loads in interchange service via bilateral agreements. The pace of implementation was limited by concerns about bridges and the ability of premium components and better maintenance to limit cost increases, two issues that became the focus of HAL Phase II. New tests at FAST and sophisticated engineering analyses addressed life cycle costs of rail, turnouts, field welds, bridges, and other areas most sensitive to increases in axle loads. Phase II concluded that a) bridge costs would be manageable, b) net benefits would be somewhat greater than predicted in Phase I, because of technological advances, and c) the best option would still be to increase GVW limits to 286,000 pounds (Hargrove et al. 1995). In 1995, the industry adopted a design specification (known as S-259) for 286k cars that would be accepted in interchange service.

HAL Phases III and IV examined the extent to which better equipment could ameliorate the stresses associated with 39-ton axle load operations. The trucks of a rail car hold the wheel sets in place and determine how lateral and vertical forces are transmitted through the car body and the wheels into the track structure. By adding cross-bracing and other technical improvements, so-called "improved suspension" trucks can reduce curving resistance, thereby extending both wheel and rail life. Phase III repeated many Phase II tests using upgraded equipment running over the same infrastructure as in Phase II. Since improved suspension trucks were also expected to reduce the need for lubrication, Phase IV tested operations with the upgraded equipment over dry track. Although the industry did not choose to implement the types of improved suspension trucks tested in Phases III and IV, the railroads did adopt better trucks, which were installed in the FAST equipment for Phase V.

Following the completion of Phase V, the HAL research program continued as one of the AAR's Strategic Research Initiatives (Kalay, LoPresti, and Davis 2012). As a result of this continuing research, the industry adopted new recommendations and specifications for track components, structures, equipment, inspection, and maintenance. In 2003, the industry adopted a new design standard (M-976) for trucks for 286k cars, and in 2004 the industry adopted a new design standard (S-286) for 286k cars used in interchange service.

The economic analyses conducted for Phases I to V of the HAL research encompassed the following steps:

- Determine the characteristics of freight cars, locomotives, and trains used to transport coal, assuming GVW of 263k, 286k, and 315k.
- Define the characteristics of hypothetical routes representing typical conditions for high density coal lines in the east and in the west.
- Estimate engineering costs per 1,000 net ton-miles for operating coal trains over each route.[1]
- Estimate operating benefits for each route using AAR models.[2]
- Estimate net benefits/1,000 NTM for each route.

The major sources of information concerning the economics of heavy axle loads are the HAL economic analyses completed at the end of Phase I (Hargrove 1991), Phase II (Hargrove et al. 1995; Hargrove et al. 1996), Phase III (Guins, Robert, and Martland 1998), Phase IV (Martland, Guins, and Hargrove 1999), Phase V (Kalay and Martland 2001), TTCI's thorough review of research results and benefits from Phases I, II, and III (Kalay and LoPresti 2000), and a subsequent TTCI summary of HAL research (Stone and Conlon 2004).

The HAL economic analyses identified potential operating benefits that would commence as soon as GVW were increased. With more tons per load, fewer cars and less fuel would be needed to transport a given amount of freight, and more net tons could be handled without increasing the number of train-miles or crews. What was unknown were the rate and extent of HAL implementation, the actual impacts on track costs, and the ability of equipment to withstand heavier loading. Now that HAL loads have been operating for more than 20 years, it is possible to document the nature and extent of implementation, to estimate the benefits of HAL operations, and to determine whether or not the life cycle costs of infrastructure increased following the implementation of 286k operations.

IMPLEMENTING 286K GVW OPERATIONS

Initial Steps Toward Implementation (1991 to 1999)

Some railroads began to allow 286k GVW cars in interchange service only after extensive studies, others were ready to make changes based upon the AAR's research and the high quality of their infrastructure, and some proceeded cautiously until they were sure that their infrastructure (especially bridges) could handle the loads. Concurrently with Phase I of the HAL program, Burlington Northern conducted a thorough, independent study of the potential costs and benefits of HAL operations (Newman, Zarembski, and Resor 1990). The study, which was conducted by Zeta-Tech, used an approach similar to what was used in the AAR's HAL Economic Analysis for Phases I and II. As an internal railroad study, it used route-specific data and costs and addressed implementation issues. Based upon their review of the Australian experience, they anticipated that increases in bridge maintenance and the need to strengthen or replace bridges would be the major factors causing maintenance costs to rise with axle load. Although their models and assumptions were not always the same as the AAR's, they also concluded that an increase in GVW to 286k was justifiable.

CN also worked with Zeta-Tech to evaluate potential costs and benefits of HAL operations, using the same methodology that had been used with BN. As of the end of 1992, CN retained a maximum GVW of 263,000 pounds for essentially all four-axle cars, based primarily upon their reluctance to invest heavily in strengthening a large number of bridges to handle a relatively small incremental volume of traffic (Worth 1993).

CSX Transportation formed an inter-disciplinary team to assess HAL economics (Shughart 1991). While strategic planners were interested in the potential cost savings, many transportation officers were wary of heavier loads, based upon their experience in the 1970s. The CSX study addressed potential economies that the AAR study did not consider, e.g., fewer waybills to process, more capacity for staging yards for coal traffic, lower costs for loading and unloading, ability to ease strict restrictions on load limits, and fewer derailments as a result of fewer trains. Instead of modeling steady state costs, as was done in the AAR study, CSX projected cash flows, including tax consequences, for a long-term investment horizon. They concluded that the investments required to enable heavier axle loads could be competitive with other CSX projects. By 1991, CSX had begun loading of existing equipment to 270,000 lbs., but had not yet decided whether to purchase new equipment that would allow heavier loads.

Before 1990, NS had already made the necessary investments to bring essentially the entire railroad up to a quality adequate for handling 286k loads (McClellan 1991). Since they had operated 286k cars for many years in unit coal trains that originated and terminated on line, they did not need a detailed study to move ahead. By 1991, NS had already started to order 286k steel/aluminum cars with 120-ton payloads for their coal traffic.

Prior to the HAL research program, UP had made major investments in track and structures to provide the capacity necessary to move large volumes of coal from the Powder River Basin in Wyoming (Wimmer 2003; Van Trump 2009). UP originally moved coal in 263k equipment weighing 30 tons, but switched to 286k aluminum cars (tare weight of 22 tons) once they were introduced in 1990. To handle the heavy tonnage at lower expense, UP increased routine inspections and maintenance and improved their track components for their high density coal routes.

By 1999, each Class I railroad allowed at least limited operation of 286k cars. Some accepted any 286 cars, but others accepted HAL loads only for specific routes. Embargoes, where imposed, were based upon bridges and light rail. The benefits of HAL operations were insufficient to justify replacing or upgrading existing equipment. Instead, the railroads purchased new 286k cars as needed to replace 100-ton cars that were retired or to provide additional capacity to handle growing traffic volumes.

Extent of HAL Implementation in 2012

The original impetus for HAL came from the railroads that were hauling large volumes of coal, and coal has indeed been the commodity benefiting most from HAL operations. Table 1 shows carloading data for the Class I railroads for bulk commodities with the highest average tons per load. Variations among railroads reflect differences in local conditions, e.g., the age and capacity of equipment, the ability of access lines and customers to handle heavier cars, and differences in density of commodities. Note that the average shown at the bottom of the table is a weighted average of the tons/load for the individual railroads; this is not equal to the average tons/load for the industry, as cars that move over more than one Class I railroad are counted more than once. The final row in this table estimates the extent of implementation. If all traffic were fully loaded to a gross vehicle weight of 286k, the average tons per load would be approximately 112.5 tons in steel cars and 121.5 tons in aluminum cars (see Table 3). If half of the cars were steel, then the average tons per load would be about 117 tons. Essentially all coal traffic, which averaged just under 117 tons/car in late 2012, appears to be moving as 286k loads. HAL is not as fully implemented for the other commodities shown in this table, as the average tons/load is less than 112.5 tons for each commodity for each of the Class Is. For iron ore and crushed stone, there are wide differences in the average tons per load, which is likely caused by the use of old cars for some services. For the other commodities, the average tons/load are less variable across the Class Is. The extent of implementation can be estimated by comparing the average tons per load to what would be achieved if all traffic moved as 286k loads. For an older fleet of steel cars, the average load would be about 103 tons per car at 25% implementation (100 tons/car x 0.75 + 112.5 tons/car x 0.25 = 103.125 tons/car) and about 106 tons per car at 50% implementation (100 tons/car x 0.5 + 112.5 tons/car x 0.5 = 106.25 tons/car). For a new fleet of aluminum cars, the average load would be 116 tons at 50% implementation (110 tons/car x 0.5 + 121.5 tons/car x 0.5 = 115.75 tons/car). For a fleet with an equal mix of steel and aluminum cars, the average load would be about 111 tons at 50% implementation (i.e., an average of 106 for steel cars and 116 for aluminum cars). Coal is known to move in both steel and aluminum cars, and the high average tons/car for coal indicates a very high rate of implementation of 286k loads. Table 1 shows a range of estimates for the other commodities, because the mix of steel and aluminum cars is unknown; the low number assumes a mix of steel and aluminum cars and the high number assumes all steel.

The full benefits of the 286k GVW limit cannot be achieved unless there is a match between the cubic capacity of the car and the density of the commodity; it is quite possible that a car rated for 286k GVW can be fully loaded without reaching the 286k limit. The extent of implementation therefore may be underestimated for some of the commodities listed in Table 1.

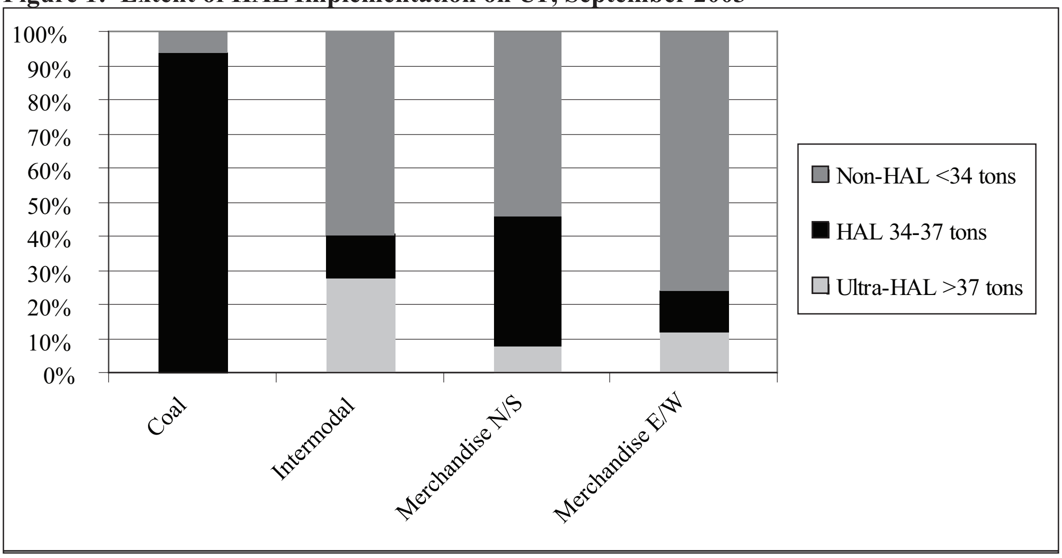
Another approach to estimating the extent of implementation is to use data from wheel impact load detectors (WILD data). For example, Figure 1 shows the distribution of axle loads for loaded traffic on representative UP routes in 2003. Traffic was separated into three categories based upon axle loads: non-HAL (6-34 tons), HAL (34-37 tons), and Ultra HAL (>37 tons). The chart shows that all but 6% of coal was HAL traffic – and none was Ultra HAL. The figure also shows that HAL loads and overloads were a quarter to nearly half of all axle loads on two primary merchandise corridors.

Table 1: Extent of HAL Implementation in 2012 (Commodities with an average of more than 104 tons/load on at least two Class I railroads)

	Corn	Wheat	Iron Ore	Coal	Crushed Stone	Sand & Gravel	Hydraulic Cement
BNSF	106.1	107.3	105.6	119.2	106.7	101.5	106.5
CSX	105.0	104.6	106.2	113.9	101.3	99.0	108.5
GTW	100.8	103.8	78.3	117.5	84.9	103.0	111.5
KCS	103.0	102.4		120.2	110.1	110.2	104.0
NS	104.4	102.4	94.7	111.9	103.8	101.7	107.0
SOO	100.1	100.8		118.7		106.2	107.7
UP	106.9	104.4	97.4	118.3	104.6	104.3	107.2
Average	104.8	105.1	86.1	116.7	102.4	102.9	107.3
% Implemented	0-40%	0-40%	0-50%	90-100%	0-20%	0-25%	20-60%

Source of Data: *STB Quarterly Report of Freight Commodity Statistics*, Third Quarter 2012.

Figure 1: Extent of HAL Implementation on UP, September 2003



Source of Data: Wimmer, 2003.

Figure 1 also shows that 29% of axle loads on this route were over 37 tons for intermodal traffic. It is well-known that loaded containers that are double-stacked on articulated intermodal cars may cause some of the axle loads to exceed 36-tons. This potential problem is exacerbated by the fact that many international containers may be overloaded (Ogard 2012). However, excessive axle loads on articulated intermodal equipment were evident well before Phase I of HAL, and the average loads for intermodal traffic have been little if at all affected by the adoption of the 286k GVW limit. Therefore, the rest of this paper addresses the costs and benefits of HAL operations for coal and general freight, without consideration of intermodal traffic.

Factors Influencing the Rate of Implementation

Railroads initially implemented HAL by increasing the maximum load for existing bulk equipment (open top hoppers, covered hoppers, and gondolas). The ability to do so depended upon the cubic capacity of the cars and the average density of the commodities, and it was not always possible to load cars to 286k. Over time, cars designed for 286k GVW were added to the fleet, either to replace older cars or to expand the capacity of the fleet. By 2000, essentially all new bulk equipment was designed for 286k loads.

Since the predicted benefits of HAL operations were insufficient to justify early retirement of 263k cars, the rate of implementation was quickest where the traffic growth was greatest. The role of traffic growth was most evident for coal. In the west, HAL loadings and average tons/load increased rapidly as coal production ramped up in the Powder River Basin; coal tonnage nearly doubled from 1982 to 1986 and increased another 50% by 2008 (Table 2). The fleet had to be expanded to handle all of this new traffic, and once the GVW limit was increased, all the new acquisitions were designed for 286k. Despite the drop in 2009, coal traffic was still more than 250% of the 1982 levels. By 2009, in the west, nearly all coal traffic moved in 286k loads. In the east, there was a completely different story. Between 1982 and 2008, there was essentially no increase in the tons of coal handled by eastern railroads. In 2009, coal tonnage dropped well below 1982 levels, because of the recession. The average tons/load therefore increased more slowly in the east than in the west.

Table 2: Coal Tonnage and Average Tons/Load, Selected Years

	Year	U.S.	East	West
Tons (Millions)	1982	523	337	187
	1986	705	344	361
	2008	879	340	539
	2009	787	292	495
Tons/load	1982	91.6	88.9	97.1
	1996	104.5	101.1	108.0
	2008	113.9	108.8	117.4
	2009	115.0	110.4	117.9

Source of Data: AAR, *Analysis of Class I Railroads*, various editions.

The rate of HAL implementation is also limited by infrastructure characteristics. HAL loads can only be handled over routes where the track structure and bridges are capable of handling the stresses imposed by 286k operations. For coal traffic, this is a relatively minor problem, because coal generally moves in very large quantities from mines to power plants or ports; there will be sufficient operating benefits to justify considerable investments in infrastructure. For other commodities, notably grain, the ability to handle 286k loads may be constrained by track quality on light density lines or load limits on bridges; shippers located on lines limited to 263k operations may be at a disadvantage compared with other shippers, because their transport costs will be slightly higher (Bitzan and Tolliver 2003). Although most grain shipments are expected to eventually move in 286k loads (Prater and Sparger 2012), major investments may be needed for this to happen. Resor et al. (2000) estimated that investments costing nearly $7 billion would be required to enable 286k loads to move over all of the nearly 50,000 route-miles operated by short line and regional railroads. As of 2011, according to a survey conducted by the American Short Line and Regional Railroad Association (ASLRRA), the proportion of route-miles open to 286k loads was 55% for short lines and 63% for regional railroads (ASLRRA 2012). Bridges are the most critical problem for small railroads, because of the potential for catastrophic failure and the high costs of strengthening or replacement. ASLRRA estimated that approximately two-thirds of bridges on small railroads were able to handle 286k loads in 2011. If traffic volumes are high enough – more than 200 carloads per mile per year according to Bitzan and Tolliver (2003) - then small railroads will be able to finance investments necessary to upgrade their infrastructure.

BENEFITS FROM HAL OPERATIONS

Predicted Benefits, HAL Phases I and II

Benefits of 286k operations depend upon the extent of implementation, car characteristics, and unit costs. The most important benefits fall into the following areas:

Fewer freight cars and car-miles. HAL allows more freight to be moved in each car, thereby reducing the carloads and car-miles needed to move a given amount of freight. The HAL effects must be separated from the effects of the concurrent introduction of higher capacity aluminum cars. The benefits from these lighter cars were similar to the HAL benefits, because both changes allowed more freight to be carried per car. The differences between steel 263k and aluminum 263k need to be attributed to the change in materials, while the HAL benefits need to be based upon a comparison between 263k aluminum cars and 286 aluminum cars. Table 3 shows the characteristics of typical steel and aluminum cars. The net weight is the weight of the shipment; the tare weight is the weight of the empty freight car; the gross vehicle weight (GVW) is the combined weight of the car plus the shipment.

Table 3: Characteristics of Bulk Equipment

Equipment	Net Tons	Net-Tare	Gross-to-Net	Ratio to Base	Reduction in MGT
Steel 263	101.0	3.31	1.604	100.00%	
Steel 286	112.5	3.69	1.542	96.15%	-3.851%
Aluminum 263	110.0	5.12	1.391	100.00%	
Aluminum 286	121.5	5.65	1.354	97.37%	-2.635%

Source of data: Martland 2000.

Higher net-to-tare and lower gross-to-net weight. The ratio of net tons to the tare weight of the equipment generally increases with GVW. The ratio of gross-to-net weight is a related measure that gives the gross tons to be moved to move a single net ton of freight. For unit trains with 100% empty return, this ratio is calculated as:

Gross-to-net = (Net Weight + 2* Tare Weight)/(Net Weight)

If gross tonnage is reduced, there will be a corresponding reduction in train-miles, crew miles, locomotives, locomotive miles, and fuel consumption. Table 3 shows differences in the ratios of net-to-tare and gross-to-net for steel and aluminum cars along with the reduction in MGT achieved by moving from 263k to 286k loads.

Fewer train crews. There will be a small reduction in train crews as a result of better gross-to-net ratios; there will be a larger benefit if trains are length-limited as opposed to weight-limited.

Table 4 summarizes the results from Phase II for the 80 MGT western coal route and the 30 MGT eastern coal route. Both 286k and 315k operations were predicted to reduce total costs, with the greatest reductions for 286k operations. The largest expected increases in costs were for track maintenance and bridges. Although the percentage reduction in costs related to cars, locomotives, and train operations were predicted to be less than the percentage increases in infrastructure costs, the absolute savings were more than sufficient to cover the cost increases.

Table 4: Summary of Phase II Results

	West 263	West 286	West 315	East 263	East 286	East 315
Track						
- Maintenance	100%	111.3%	132.7%	100%	122.6%	147.5%
- Capital	100%	102.6%	108.6%	100%	106.5%	110.0%
Total Track	100%	105.0%	115.1%	100%	110.3%	118.8%
Bridges	100%	112.7%	156.9%	100%	114.0%	137.7%
Operations	100%	90.4%	93.8%	100%	91.1%	95.3%
Total	100%	92.6%	97.5%	100%	94%	99.6%

Source: Hargrove et al. 1996.

Capacity. Since fewer trains would be needed, HAL was expected to increase line capacity. Benefits associated with operating fewer trains were predicted to be more than enough to offset the added time needed for track maintenance on high density lines (Romps 1993; Robert and Martland 1997; Guins, Robert and Martland 1998; Robert, Martland and Guins 2003). Although line capacity was a minor issue for most railroads when Phase I was completed in 1990, it has since become a significant issue for the industry (Cambridge Systematics 2007).

Actual HAL Benefits: Reductions in Equipment Acquisitions

The widespread implementation of HAL traffic began in the mid-1990s, and the savings from buying cars with larger capacity began immediately. The first column in Table 5 shows the fleet size as of 1993 for three types of equipment used to haul bulk traffic; the second column shows the maximum fleet size for each of these types of equipment for the period 1994 to 2010. If the fleet size increased, as it did for covered hoppers and gondolas, then new cars must have been acquired, as shown in the third column. In addition, cars had to be acquired to replace cars that were retired because of age or condition. Assuming an average life of 40 years for freight cars, the average annual retirement rate would be 2.5%. Over the 17-year period from 1994 to 2010, 42.5% of the fleet would have been replaced. If the original fleet consisted entirely of 263k cars, then an equal number of 263k cars would have been needed to replace the retired cars. If that had been the case, then it would have been necessary to acquire 441,000 new bulk cars. However, if the older cars could be replaced with 286k cars with a 10% boost in average loading capacity, then only 414,000 cars would have been needed. Since the vast majority of all covered hoppers, gondolas, and hoppers acquired since 1993 were designed to handle 286k GVW, the rail industry (consisting of railroads, car supply companies, and customers) avoided purchasing 27,000 bulk freight cars, an average of about 1,600 per year. At an average cost of about $67,000 in 2010, the annual savings in capital expenditures exceeded $100 million per year (Table 6).

Table 5: Estimating the Number of Bulk Freight Cars Acquired From 1994 to 2010

Car Type	Fleet Size in 1993	Max after 1993	Min new after 1993	Annual Retirements	Total New Cars 263k GVW	Total New Cars 286k GVW
Covered Hopper	302,903	414,418	111,515	7,573	240,249	227,375
Gondola	148,541	220,238	71,697	3,714	134,827	128,514
Hopper	190,094	175,350	-14,744	4,752	66,046	57,967
Total	641,538	810,006	168,468	16,038	441,122	413,856

Source of Data: AAR, *Railroad Facts*, various editions.

Table 6: Savings in Equipment Acquisition for Bulk Transportation (Reduction in Purchases of Covered Hoppers, Hoppers, and Gondolas at $67,000/car)

	Total, 1994 to 2010	Average Annual 1994 to 2010	Total Savings 1994 to 2010	Average Annual Savings
Estimated New 286 Cars Acquired (1000s)	414	24.3		
Estimated New Cars Required, if GVW were still 263k (1000s)	441	25.9		
Reduction in cars purchased because of increase in HAL limit (1000s)	27	1.6	$1.8 Billion	$107 million

Actual HAL Operating Benefits for Coal Traffic

Estimating the operating benefits required additional assumptions concerning train length, locomotive consists, fuel consumption, and shipment characteristics (Table 7). The average number of cars on a train could be limited by either train length or train weight. Train length is limited by the length of sidings on single track lines, by the layout of yards and terminals, or by the nature of loading and unloading operations. Train weight is limited by locomotive characteristics and equipment technology; train weight limits can be overcome by using distributed power, i.e., by placing additional locomotive units within or at the end of a train. Railroads have, for many years, been increasing siding length, improving locomotive technology, and using distributed power to enable the use of longer, heavier trains (e.g., Van Trump 2009). The analysis in this paper therefore assumes that most trains are length-limited rather than weight-limited. The assumptions in Table 7 make it possible to estimate changes in service units resulting from the shift to HAL operations. By using larger cars, railroads had to move fewer loads, which resulted in fewer car-miles. Since there were fewer car-miles, there were fewer train-miles and locomotive-miles. Since the gross-to-net tonnage ratio was lower, there were fewer gross ton-miles, providing additional savings related to locomotives and fuel consumption.

Table 7: Equipment and Operating Assumptions Used to Estimate Operating Savings

Characteristics of Operations	Parameter	Comments
Average cars/train, 263k operations and length-limited 286k operations	120	Typical unit train
Average cars/train, 286k weight-limited operations	110	The gross weight of 110 286k cars equals the gross weight of 120 263k cars
Fraction of 286k trains that are length-limited	2/3	Conservative estimate
Average locomotives/train	2.7	Average locomotive miles per train-mile in 2008
Average locomotive miles per day	174	Locomotive miles divided by total locomotives in 2008
Average car-miles per carload	1216	Average loaded car-miles per carload in 2008 plus 100% empty return
GTM/gallon	484	Average for Class Is, 2010

Source of Data: AAR, *Railroad Facts*, various editions.

Unit costs were estimated using aggregate data provided by railroads to the STB. These costs are intended to support a reasonable estimate of the costs associated with operating unit trains. In any particular situation, costs could be significantly higher or lower than these industry averages. Moreover, there are other costs that are not considered at all; for example, yard costs are not considered because yards are a minor factor in bulk unit train operations.

Table 8: Unit Costs Used to Estimate Operating Savings from 286k Operations

Cost Category	Unit Cost	Comments
Crew cost	$9.93 per mile	Total wages for train crews divided by total train-miles for 2010
Locomotive purchase	$1.17 million	Average cost of new or rebuilt locomotives in 2008
Locomotive ownership	$135 thousand per year	Assuming cost of capital 11% and 30-year life
Locomotive maintenance	$1.00 per locomotive-mile	Locomotive labor, fringe benefits, and materials & supplies divided by total locomotive miles in 2008
Car maintenance	$0.036 per car-mile	Freight car labor, fringe benefits, and materials & supplies divided by total car-miles in 2008
Fixed cost per load	$160 per load	Estimated costs for local switching to place cars for loading and unloading plus general administrative expense
Fuel	$2.24 per gallon	Average for 2010

Source of Data: STB, *Analysis of Class I Railroads 2009*; AAR, *Railroad Facts 2011*.

Because the cars each carry more freight, there are fewer cars to load and unload and fewer car-miles. Table 9 estimates savings related to the increase in average tons per load for coal. As noted above, the average tons per load would be about 117 tons if coal moved entirely in 286k cars and if the fleet of coal cars were equally made up of steel and aluminum equipment. Since the average tons per load was 110 for all loads hauled from 1994 to 2010, the average extent of HAL implementation for coal was 59% because (110 actual tons/car – 100 base tons/car)/(117 max tons/car – 100 base tons/car) x 100%. = 59%).

At an estimated cost of $160 per load, the cumulative benefit of reducing the number of loads was $0.8 billion and the annual benefit in 2010 was $110 million for local switching, loading, unloading, and general administration (Table 9, row f). For each load that is eliminated, an entire trip is eliminated, saving car-miles, both loaded and empty, for an estimated cumulative benefit of $220 million, and an annual benefit of $30 million by 2010 (Table 9, row g). Since more freight is carried per train, fewer crews were needed, saving $340 million over the entire period, and $50 million per year by 2010 (Table 9, row h). The total savings related to reducing the number of carloads of coal is estimated to be $1.36 billion for 1994 to 2010 and $190 million per year by 2010. Since there were 7.06 million carloads of coal in 2010, the estimated operating benefits were approximately $27 per car.

Table 9: Operating Savings Resulting From Fewer Carloads ($160/load, $0.0360 per car-mile and $9.93/train-mile)

	Total or Average 1994 to 2010	Amount in 2010	Total Savings 1994 to 2010 (millions)	Savings in 2010 (millions)
a. Total Tons of Coal Shipped	13 billion	814 million		
b. Average Load with 263k GVW (50% steel and 50% aluminum cars)	105 tons/car	105 tons/car		
c. Loads Required with 263k GVW (= a/b)	123 million	7.75 million		
d. Actual Loads	118 million	7.06 million		
e. Actual Average Tons/load (a/d)	110	115		
f. Reduced loads and related savings @ $160 per load	5 million	0.69 million	$800	$110
g. Car-mile savings @ $0.036 per car-mile	6,100 million	840 million	$220	$30
h. Train-mile savings (crew costs for length-limited 120-car trains @ $9.93 per mile; 2/3 of trains are length-limited)	34 million	5 million	$340	$50
i. Total savings			$1,360	$190
j. Savings per carload of coal			$12	$27

Source of Data: Tables 7 and 8; tons and loads (rows a and d) are from AAR, *Railroad Facts, various editions.*

The next category of savings results from the fact that the ratio of GTM to NTM is lower with HAL equipment. If half of the 286k cars are steel and half are aluminum, then there would be a 3.2% reduction in MGT if all traffic moved in HAL equipment (see Table 3 above). The number of locomotives, locomotive-miles, gallons of fuel, train-miles and other service units needed to move a given quantity of coal can be estimated with the parameters given in Table 7 above. Table 10 shows the actual loads of coal handled by Class I railroads from 1994 to 2010 (Column 2) as well as the loads handled in 2010 (Column 5). If HAL had not been implemented, then more service units would have been required. The amount of the hypothetical increase (and therefore the estimated savings) depends upon the extent of HAL implementation. In 2010, when HAL was essentially fully implemented for coal traffic, 3.3% more service units would have been needed if GVW had not been increased (since 1/(1-.032) = 1.033). The avoided increase in service units and the estimated cost savings for 2010 are shown in Columns 6 and 7 of Table 10. The percentage savings for the entire period were lower (0.59 x 3.3% = 1.95%), because the average implementation is estimated to be 59% for the entire period (Table 10, Columns 3 and 4). The cost savings related to locomotives, locomotive-miles, train-miles, and fuel are calculated using the assumptions and unit costs from Tables 7 and 8 above. The crew savings in this table relate only to weight-limited trains (so there is no double counting of crew savings in Tables 9 and 10). Together, the cumulative savings resulting from the reductions in MGT and car-miles are estimated to be $1.365 billion, while the savings in 2010 are estimated to be $145 million or approximately $20.50 per car.

Table 10: Operating Benefits for Coal Traffic Resulting from the Reductions in MGT and Car-Miles

1. Service Units (SU)	2. Total SU 1994-2010 (millions)	3. Increase in SU 1994-2010 if GVW were still 263k	4. Total Savings 1994-2010 ($ million)	5. Actual SU in 2010	6. Increase in SU in 2010 if GVW were still 263k	7. Savings in 2010 ($ million)
a. Coal loads	123 million			7.06 million		
b. Car-miles (@ 1216 per load)	150 billion			9.42 billion		
c. Train-miles @ 120 cars per train (cost savings for weight-limited trains)	417 million	8 million	$80	26 million	0.9 million	$9
d. Locomotive Miles @ 2.7 locomotives per train	3,365 million	65.5 million	$65	212 million	7.0 million	$7
e. Locomotive-years @ 174 miles/day	53,000	1,030	$140	3,340	110	$15
f. Net Ton-miles @ 608 miles per ton	8 trillion			0.5 trillion	16.5 billion	
g. Gross ton-miles @ 1.5 gross tons per net ton	12 trillion			0.75 trillion	24.75 billion	
h. Fuel saved (@ 484 GTM/gallon)	25 billion	50 million	$1,080	1.55 billion	50 million	$114
i. Total			$1,365			$145
j. Savings per car			$11			$20.50

Source of Data: coal loads are from AAR, *Railroad Facts,* various editions; all other entries are calculated using efficiency factors and unit costs from Tables 7 and 8.

Actual Operating Benefits for Traffic Other than Coal

Substantial amounts of other bulk commodities move as 286k loads. The evidence from WILD data such as that obtained by UP (Figure 1 above) indicates that more than a quarter of general freight moved in HAL loads more than 10 years ago, and the percentage of HAL freight is certainly higher today. To estimate benefits for non-coal traffic, a conservative assumption was made that 30% of non-coal general freight moved in HAL loads in 2010. This assumption is consistent with the traffic data presented above in Table 1 and Figure 1.

The benefits associated with car acquisitions for these commodities were included in the savings estimated in Table 5 above. The operating benefits would likely be similar, on a per-car basis, to the $27 and $20.50 per car estimated for coal in 2010 in Tables 9 and 10 above. For these 4.5 million non-coal HAL loads, total operating benefits in 2010 are therefore estimated to be $209 million. If cumulative benefits were similar to those for coal, they would be estimated to be at least 7 times as great, i.e., on the order of $1.5 billion.

Table 11: Estimated HAL Implementation as of 2010

Category	2010 Loads	Estimated HAL Loads	Estimated HAL %	Estimated Operating Benefit per Car in 2010	Total Operating Benefit in 2010
Coal	7.06 million	7.06 million	100%	$47.50	$335 million
General Freight	14.6 million	4.4 million	30%	$47.50	$209 million
Total, without intermodal	21.7 million	11.46 million	53%	$47.50	$544 million
Total, with intermodal	29.2 million	11.6 million	40%	$47.50	$544 million

Source of Traffic Data: AAR, *Railroad Facts,* 2012.

The total benefits from HAL therefore were on the order of $6 billion from 1994 to 2010 and $600 to $700 billion per year by 2010:

- Equipment acquisition (Table 6): $1.8 billion ($107 million per year for all bulk equipment)
- Fewer loads of coal (Table 9): $1.4 billion ($190 million per year)
- Better net-to-gross for coal (Table 10): $1.4 billion ($145 million per year)
- Operating benefits, other traffic (Table 11): $1.5 billion ($209 million per year)
- Total: $6.1 billion ($651 million per year)

These benefits were spread among car owners, customers, suppliers, and railroads. Car owners benefited from being able to purchase capacity at a lower cost per ton. Railroads saved fuel because they moved less gross tonnage, and they operated fewer trains with fewer locomotives and fewer car-miles than they would have if the GVW had not been increased. Who has profited from HAL is a question that is beyond the scoped of this paper, because such a question must delve into hitherto unexplored pricing issues.

INCREASES IN INFRASTRUCTURE COSTS RESULTING FROM HAL OPERATIONS

Predicted Increases, HAL Phase II

The effects of HAL operations on infrastructure costs were estimated for hypothetical eastern and western coal routes using detailed engineering models for track components and bridges. The base cases had operating, route, and component characteristics typical for high density coal lines in each region. The western route had 80 million gross tons per year, including 45.12 million tons of coal and 34.88 tons of equipment. The eastern route had 30 million gross tons, including 17.28 million net tons of coal. In the 286k case, the net tonnage remained the same (45.12 million tons per year in the west and 17.28 million tons in the east), but the gross tonnage declined because of improved gross-to-net. Life cycle costs were predicted to rise for rail, ties, ballast & subgrade, turnouts, bridges, and routine maintenance. Estimated cost increases included both capital and operating expenditures, assuming full implementation of HAL. Track costs for both the base case and the 286k case assumed that the maintenance and replacement of rail, turnouts, ties, and ballast had reached a steady state. Increases in bridge costs were estimated by considering the effect of HAL on reducing the life of bridges and major bridge components.

Table 12 shows the base case costs and the predicted increases in costs once HAL operations were fully implemented. The base case costs in Phase II were approximately $46,000/mile for the 80-MGT route and $21,000 for the 30-MGT route. TTCI estimated that 10,500 miles of mainline track were more similar to the 80-MGT route, while 46,200 miles were more similar to the eastern route. Hence, base case track costs for the total of 56,700 miles of high density mainlines were estimated to be $1.5 billion/year, and the HAL effect under 286k loads was estimated to be $124 million per year. The added costs for bridges increased the HAL effect for both routes.

The predicted increases in track costs were estimated on a yearly basis by considering the projected cost increase of approximately $0.08 per 1,000 NTM together with the estimated extent of HAL implementation. Although HAL was essentially fully implemented for coal by 2010, only abut 40% of the total traffic moved in cars with 286k axle loads (see Table 11 above). Adjusting for the extent of implementation, the predicted annual increase in costs would have been approximately $50 to 60 million in recent years rather than the $135 million shown in the table. The adjusted prediction of cumulative cost increases for the entire period (from 1991 to 2011) would have been $0.7 billion, based upon the extent of HAL implementation.

The Phase II Economic Analysis included detailed estimates of costs for each major component of the track structure. Overall, the HAL effect was predicted to be much greater for maintenance expenditures than for capital expenditures. Spot surfacing, rail defects, and rail grinding were expected to be the maintenance expenses most affected by HAL, while shorter lives for rail and turnouts were expected to cause the greatest increases in capital costs. Costs related to ties and fasteners were not expected to increase significantly under 286k loads.

Table 12: HAL Phase II Base Case Costs and Cost Increases Resulting from 286k Operations

	Annual MGT Base Case	Track-Miles	Annual Cost per Mile	Annual Cost (Millions)	Annual MGT 286k Case	% Increase	Increase (Millions)
Track							
Western Route	80	10,500	$46,000	$480	76.4	5.0%	$24
Eastern Route	30	46,200	$21,000	$970	28.7	10.3%	$100
Total Track				$1,450		8.6%	$124
Bridges							
Western Route	80	N.A.	N.A.	$30	76.4	12.7%	$4
Eastern Route	30	N.A.	N.A.	$50	28.7	14.0%	$7
Total Bridges				$80		13.8%	$11
Total				$1,530		8.8%	$135

Source of Data: Hargrove et al. 1996. pp. 23-24.

Because of the risks associated with bridge fatigue, railroads were careful to determine whether bridges would need to be strengthened or replaced before introduction of HAL traffic (Newman et al. 1990; Sweeney et al. 1996). In Phase II, the HAL Economic Analysis estimated increases in bridge costs based upon analysis of the effects of heavier loads on typical bridges. For timber structures, it was assumed that railroads would either replace the caps or replace the entire structure at some point during the next 20 years (i.e., by 2012). For steel structures, a thorough engineering analysis was conducted to determine the effect of higher axle loads on stresses on and fatigue life of critical bridge components (Sharma 1995). The shorter fatigue life was converted into an equivalent increase in annual costs for bridge maintenance. Analyses were completed for a representative sample of bridges provided by the Class I railroads; the results were used to estimate bridge costs by choosing sets of bridges to represent what might be found on typical eastern or western coal routes.

Actual Effects of HAL on Infrastructure Costs

The actual effects of HAL on infrastructure costs were less than expected, primarily because costs related to rail, turnouts, and bridges either declined or rose much less than predicted. For rail, the single most costly track component, costs actually declined; better rail metallurgies and more effective grinding techniques allowed railroads to increase rail life and reduce lifecycle costs (e.g., Clark et al. 1999; Martland and Massot 1999). Following the widespread introduction of HAL traffic, rail life and life cycle costs were better, not worse. Turnouts were another area where initial FAST/HAL results indicated that increasing axle loads could cause major increases in cost. As was the case with rail, new technologies and better maintenance practices extended component lives and reduced life cycle costs despite the introduction of HAL traffic (Byers 2007). As expected, there were concerns with ballast and subgrade (Worth 1993).

Research conducted as part of subsequent phases of the HAL and tests conducted by individual railroads led to a better understanding of bridge strength, efficient means of strengthening bridges, and railroad-specific programs for upgrading and replacing weak structures (Unsworth 2003). The actual expenses related to bridges were not as severe as anticipated, in part because the pace of implementation was slow enough to allow railroads time to prepare for the increase in axle loads within the context of their normal engineering budgets.

Analysis of aggregate operating plus capital expenditures on track and structures (CAPEX) provides more evidence that HAL traffic did not lead to an increase in infrastructure costs.[3] When capital and operating expenditures are combined, the average cost per 1,000 revenue ton-miles (RTM) increased from $6.70 in 1990 to $9.41 in 2010. However, when expressed in constant 2010 dollars, the average expenditures per 1,000 RTM declined from $10.25 in 1990 to $9.41 in 2010. The decline is more pronounced if the railroad cost recovery index is used to convert expenditures to constant dollars, as unit costs for labor, fuel, and materials and supplies increased more rapidly than general inflation over this 20-year period.

Aggregate analysis, which cannot document cost changes related to specific shifts in traffic mix or axle loads, does support two important conclusions. First, infrastructure expenses per revenue ton-mile declined from 1990 to 2010, despite the rise in 286k traffic. Second, rising traffic volume had a much larger impact on infrastructure expense than the predicted 8.8% increase resulting from full HAL implementation (Table 12 above). As shown in Table 13, total CAPEX, in 2010 constant dollars, rose 50% from $10.59 billion to $15.92 billion from 1990 to 2010, a period in which revenue ton-miles rose 63% from 1,033 billion to 1,691 billion.[4]

Table 13: Index of Constant Dollar Expenditures per Revenue Ton-Mile, 1990 to 2010

Expenditures on Way and Structures by Class I Railroads	1990	1995	2000	2005	2010
Operating Expense	$4.28 billion	$5.45 billion	$5.03 billion	$6.50 billion	$8.07 billion
Capital Expense	$2.64 billion	$3.65 billion	$4.55 billion	$5.36 billion	$7.85 billion
Total CAPEX	$6.92 billion	$9.10 billion	$9.58 billion	$11.86 billion	$15.92 billion
Revenue Ton-Miles	1,033 billion	1,306 billion	1,466 billion	1,696 billion	1,691 billion
$/1000 RTM	$6.70	$6.97	$6.53	$6.99	$9.41
Federal Reserve Implicit Price Deflator for GDP (2005 = 100)	72.593	81.710	88.903	100.461	111.045
Total CAPEX (2010 $)	$10.59 billion	$12.37 billion	$11.97 billion	$13.11 billion	$15.92 billion
$/1000 RTM (2010 $)	$10.25	$9.47	$8.16	$7.73	$9.41
Railroad Cost Recovery Index (RCR, 1981 = 100)	139.9	160.4	187.1	238.9	294.9
$/1000 RTM (using RCR)	$14.12	$12.81	$10.29	$8.62	$9.41

Source of Data: AAR, *Railroad Facts*, 2011 edition.

SUMMARY AND CONCLUSIONS

Nearly 100% of coal traffic and approximately 40% of all freight now moves in 286k loads. If all bulk traffic had continued to move in 263k cars, many more cars would have been purchased, more trains would have been operated, and more fuel would have been consumed. Cumulative benefits were approximately $6 billion from 1994 to 2010, and annual benefits were $600 to $700 million in 2010.

The greater stresses caused by HAL traffic were predicted to increase expenditures for track and structures by $135 million per year at full implementation (Table 12 above). Adjusting for the actual level of implementation, the predicted increases would have been $50 to $60 million in 2010 and a total of $0.7 billion from 1994 to 2010. Had the predictions been accurate, the net benefits of HAL implementation would still have been more than $500 million in 2010 and more than $5 billion for the entire period. In fact, because of the technological research and development, investments by railroads in better components, improved inspection technologies, and better maintenance management, constant dollar infrastructure expenditures per 1000 RTM actually declined. The net benefits from the introduction of HAL and from the improvement of the track structure are now well in excess of $600 million per year.

Railroads, and their customers and suppliers, are already starting to introduce shorter cars that retain the 286k GVW limit, a strategy that was investigated as part of the HAL research (Robert 1997; Guins et al. 1998; Chapman 1998; Wille 1998; Chapman, Martland, and Guins, 2003). Shorter 286k cars provide most of the cost and capacity benefits of heavier cars without increasing stresses on the track structure; their impacts on bridges are similar to the impacts that would be imposed by 315k cars. In North America, there has been little interest in operating with axle loads in excess of 36-tons, although such loads have been operated by mining railroads in Australia since the 1980s (Marich 1986). More recently, FMG, a new iron ore railway in Australia, began to move iron ore 256 km from mine to port in the world's first cars designed for 44-ton (40 metric ton) axle loads (Shughart 2012). Higher axle loads can clearly be justified in certain circumstances, especially when track and equipment can be designed or upgraded for an operation that is controlled by the shipper, as was the case with FMG.

The industry should consider taking further steps to improve capacity, either by increasing axle loads or by continuing to invest in shorter 286k cars. Technological improvements have extended the life of track components, improved equipment, and enhanced inspection capabilities, while investments in bridges and track have strengthened the mainline infrastructure. Higher fuel costs and greater concerns with line capacity make it more important to pursue the most efficient means for transporting bulk commodities. Modest increases in GVW (e.g. an increase from 286k to 290k) would provide immediate operating benefits with minor impacts on track and structures. An increase in GVW to 315k, long considered the next logical step, may be justified now or in the not too distant future. Even heavier loads might be justifiable for special circumstances or restricted routes.

Whether or not higher loads or loading densities can be justified is a question that can be addressed using the results of FAST/HAL research and the models and evaluation techniques developed as part of that research. As documented in this paper, the benefits from implementing more efficient equipment can be very substantial. Even a small increase in axle loads or loading density, if the infrastructure is able to withstand that added stress, can result in very substantial savings for the railroads, their suppliers, and their customers.

It makes sense to conclude this review of the decades-long process of implementing HAL traffic with the first sentence of the first paper describing the economic interpretation of the Phase I HAL research:

> *The history of freight railroad technology shows a pattern of increasing vehicle size with increasing axle loads as developments in materials and engineering knowledge have made their use technically feasible and economically desirable* (Hargrove, 1991 p. 227).

Is there any reason to believe that 286k is the ultimate limit?

Endnotes

1. The TRACS model (Martland and Auzmendi 1989; Auzmendi 1994; Hargrove and Martland 1990 and 1991) was used to estimate deterioration rates and lifecycle costs related to rail, ties, ballast and routine maintenance. TRACS was calibrated based upon studies conducted in cooperation with individual railroads, including, most recently, studies of wear and fatigue on a high density coal route operated by Norfolk Southern (Clark, Bowman, and Martland 1999; Martland and Massot 1999). A model developed by MIT and TTCI was used to estimate turnout maintenance requirements and lifecycle costs (Smith, E.W. et al. 1993). Results from TRACS and the turnout model were incorporated into HALTRACK, a spreadsheet model that was used repeatedly in the economic analyses conducted as part of Phases II to V of the HAL research. A sophisticated structural analysis supported the estimates of the effects of HAL on bridges (Sharma 1993).

2. TTCI estimated the costs of operating a specific train consist over a particular route by using the Train Energy Model and the Rail Energy Cost Analysis Package, known collectively as TEM/RECAP (Stephens 1989). This model had previously been used to assess various options for increasing fuel efficiency by reducing train resistance (Smith, M.E. 1987).

3. It would be possible, but well beyond the scope of this paper, to investigate how much lower infrastructure costs would have been had GVW limits not been increased. The engineering models used in the HAL research could be used to compare 263k and 286k operations over routes with current engineering and traffic characteristics.

4. Costs rose less rapidly than revenue ton-miles because of economies of density. In Table 12, the cost per mile per annual MGT was predicted to be $575 in the west ($46,000 per mile/80MGT) vs. $700 in the east ($21,000 per mile/30MGT). A 267% increase in density therefore resulted in a predicted 18% decrease in costs per mile per MGT for these two routes. If the same relative proportions applied to CAPEX for rail infrastructure, a 63% increase in traffic would produce a 4.2% decrease in costs per mile per MGT (18% x 0.63/2.67 = 4.2%). In fact, between 1990 and 2010, constant dollar CAPEX for rail infrastructure declined 8.9% from $10.25 per 1000 RTM to $9.41 per 1000 RTM. A portion of the actual decline can be attributed to the 2.6% to 3.9% decrease in the ratio of gross-to-net vehicle weight for HAL traffic (see Table 3), which led to a similar reduction in MGT per RTM.

Acknowledgments

This paper builds upon the many research reports and professional papers that have been published over the past 25 years as a part of or as a result of research sponsored by or conducted for the Association of American Railroads. I greatly appreciate the opportunities I have had over this long period to work with so many knowledgeable researchers and railroad officials on matters related to track maintenance management, evaluation of new track technologies, and assessing the economic impact of heavy axle loads. Although I am aware of other unpublished studies that are relevant to the topics addressed by this paper, the analysis in this paper is based solely upon information from published papers and data made available to the public by the AAR or the STB. The analysis and opinions presented in this paper do not necessarily reflect the views of the AAR, the STB, TTCI, or any of the railroads or people that I have worked with on HAL studies over the past three decades. I alone bear full responsibility for the structure, findings, and conclusions of this paper.

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***Carl D. Martland** was a senior research associate and lecturer in the Department of Civil and Environmental Engineering at M.I.T. prior to retiring in 2007. During his 35 years at M.I.T., he supervised numerous studies related to railroad operations, engineering and economics, including studies concerning HAL economics that were critical components of the AAR's Heavy Axle Load Program. He also developed and taught subjects related to transportation systems, rail operations, and project evaluation. Since retiring from M.I.T., he has continued research and consulting related to rail productivity, freight systems planning, and public policy for transportation systems. He has testified before Congress and the Surface Transportation Board on issues related to rail capacity, service, and regulation.*

Martland has authored or co-authored more than 100 professional papers and reports, including two papers that received the TRF's Best Paper Award. In 2011, he published Toward More Sustainable Infrastructure: Project Evaluation for Planners and Engineers, *a textbook based upon a class on project evaluation that he designed and taught for undergraduate engineering and planning students. A past-president of TRF, Martland was the second recipient of the Herbert O. Whitten Award, which he received in 1991 for sustained professional contributions to TRF. In 1997, he received TRF's Distinguished Transportation Researcher Award "in recognition of pioneering the planning and costing techniques that are now commonly used by many U.S. railroads."*

Rail Market Share of Grain and Oilseed Transportation

by Marvin E. Prater, Adam Sparger, Pierre Bahizi, and Daniel O'Neil, Jr.

The share of the grain and oilseed harvest moved by rail has been declining since 1980, when the Federal Motor Carrier Act and the Staggers Rail Act were passed. Large structural changes associated with these acts affected the decline over the following two decades. Yet, even though the large structural changes had already taken place by 2000, the rail market share of grain and oilseed transportation has continued to decline. This paper develops a state-level statistical model for 21 of the top grain-producing states (which produce 86.6% of all grain and oilseeds) to investigate which major factors have been responsible for the decrease in the rail market share of grain and oilseed transportation since 2001. Twenty variables are tested in the model, and 10 are found to have a statistically significant impact on rail market share. Of these, three are most important in the decrease of rail market share: ethanol production, biodiesel production, and the concentration of animal feeding.

INTRODUCTION

The share of the grain and oilseed harvest moved by rail has been declining since 1980, when the Federal Motor Carrier Act and Staggers Rail Act were passed. These acts provided partial deregulation of the truck and railroad industries, which fundamentally changed transportation patterns. In 1980, railroads moved half the grain and oilseed harvest, trucks moved 30%, and barges moved the remainder (Marathon and Sparger 2012). By 2010, the rail share had declined to 29% while the truck share had risen to 58% (Marathon and Sparger 2012). The effects of deregulation contributed to much of the decline in the rail market share of grain, stemming from structural changes such as abandonment of track, consolidation within the rail and grain industries, the shifting of costs for railcars and sidings to the grain and oilseed industry, and ease of entry into trucking. Although the acquisition of Conrail by Norfolk Southern and CSX in June 1999 marked the end of most of the large structural changes attributable to deregulation, other factors continued to affect the decrease in the rail market share of grain and oilseed transportation from 33% in 2001 to 29% in 2010 (Marathon and Sparger 2012).

An affordable and reliable transportation network is necessary to maintain the strength and competitiveness of American agriculture and our rural communities. Rail service is a particularly important part of that network for U.S. agriculture, because it is often the most cost-effective shipping alternative available for low-value, bulky commodities in those rural areas that are distant from water transportation and markets. As rail market share continues to decline, policy makers may view this as a concern for agriculture and wish to understand what is driving changes in the marketplace.

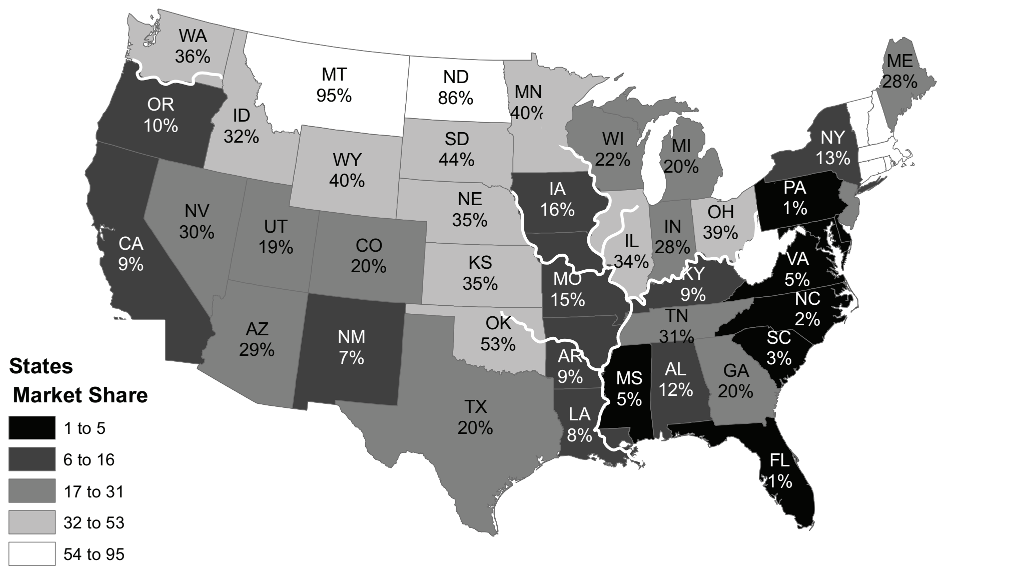
The objective of this paper is to identify the factors responsible for the continued decrease in the rail market share of grain and oilseed transportation since 2001. Specifically, by developing a state-level statistical model, this study evaluates and tests which factors have been primarily responsible for the recent decrease.

After a brief background on how recent changes in rail market share have differed at the state level, this paper reviews the literature to identify the potential factors impacting the rail market share of grain and oilseed transportation. Next, the methodology describes the statistical model and data used to test these factors, followed by a discussion of the findings. The paper concludes with a summary of the findings and their application to future studies.

RAIL MARKET SHARES

Agricultural shippers in Montana and North Dakota are particularly dependent on rail transportation because of their distance to inland waterways and the prohibitive cost of hauling grain long distances to markets by truck. Figure 1 shows that, on average, railroads transported 95% of Montana and 86% of North Dakota grains and oilseeds during the crop marketing years from 2007 to 2010 (STB; USDA f). In addition, railroads transported between 32% and 53% of the grain and oilseed production for eight states clustered around Montana and North Dakota. Many states with river access—those stretching from Iowa and Indiana to Louisiana, Mississippi, and Alabama—had comparatively lower rail market shares (between 5% and 31%). Illinois (34%), Ohio (39%), Minnesota (40%), Washington (38%), and Idaho (32%) were the exceptions.

Figure 1: Rail Market Share of Grain Transportation 2007-10[1,2]



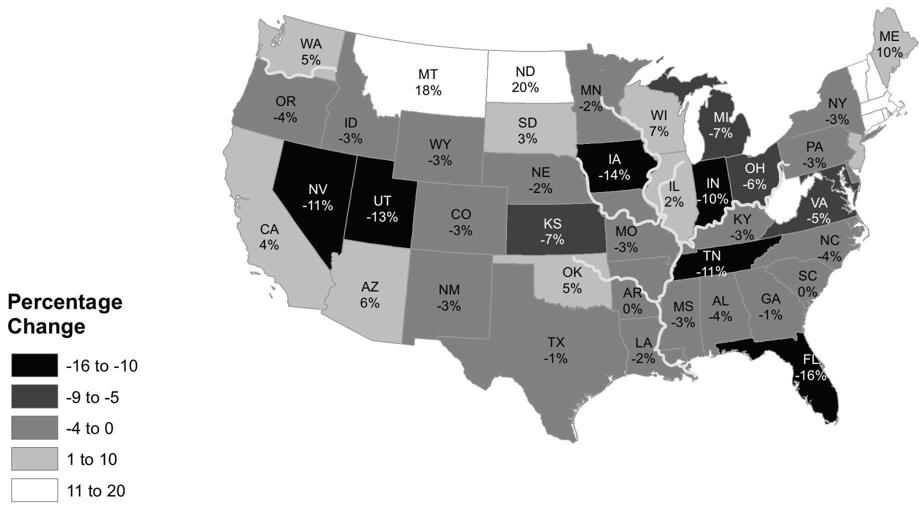
Notes: 1) Grains and oilseeds include Barley, Corn, Cottonseeds, Flaxseed. Oats, Peanuts, Rough Rice, Rye, Sorghum, Soybeans, and Wheat.
2) Annual crop production compared to rail movements during the subsequent marketing year for each grain and oilseed.

Sources: Surface Transportation Board, Confidential Waybill Samples
USDA National Agricultural Statistics Service, Crop Production Annual Report

The 2007–2010 average rail market shares of grain and oilseed transportation are generally lower than 2001–2004 (STB; USDA f). While the rail market share increased for 12 states, it decreased for 30 states (Figure 2). The states most dependent on rail service increased their rail market share the most: Montana (18%), North Dakota (20%), Oklahoma (5%), and South Dakota (3%).[1] Other important grain and oilseed producing states that had increases in rail market share were California (4%), Illinois (2%), Washington (5%), and Wisconsin (7%).

Major grain and oilseed producing states that had the largest decreases in the rail market share were Iowa (14%), Tennessee (11%), Indiana (10%), Michigan and Kansas (7% each), Ohio (6%), North Carolina (4%), and Idaho, Mississippi, and Colorado (3% each). Other states having large decreases in rail market share include Florida (16%), Utah (13%), and Nevada (11%).

Figure 2: Changes in Rail Market Share of Grain Transportation 2007-10 Average Compared to 2001-2004 Average[1,2]



Notes: 1) Grains and oilseeds include Barley, Corn, Cottonseeds, Flaxseed. Oats, Peanuts, Rough Rice, Rye, Sorghum, Soybeans, and Wheat.
2) Annual crop production compared to rail movements during the subsequent marketing year for each grain and oilseed.

Sources: STB Confidential Waybill Samples
USDA/NASS/Crop Production Annual Report

LITERATURE REVIEW

While rail market shares have often been calculated across states and regions, there have been few previous studies conducted regarding the determinants of rail market share. Babcock and German (1990) attempted to quantify the impact of policy changes at the federal level on the share of manufactured products shipped by rail as opposed to truck. The model they developed incorporated rail and truck prices for various goods lagged one year, the interest rate lagged one year, and a truck productivity index and yearly dummy variables were used to capture the effects of the relevant legislation, the Motor Carrier Act of 1980. Changes in rail market share were defined as the change in rail tonnage compared with the change in total industrial production. Any deviations between the growth of shippable products and the volumes transported via rail signaled a change in the rail market share. The study found that lifting certain regulations on the trucking industry decreased rail market share for the products examined. Additionally, the unrestricted use of certain larger truck types, if allowed, would further decrease rail share.

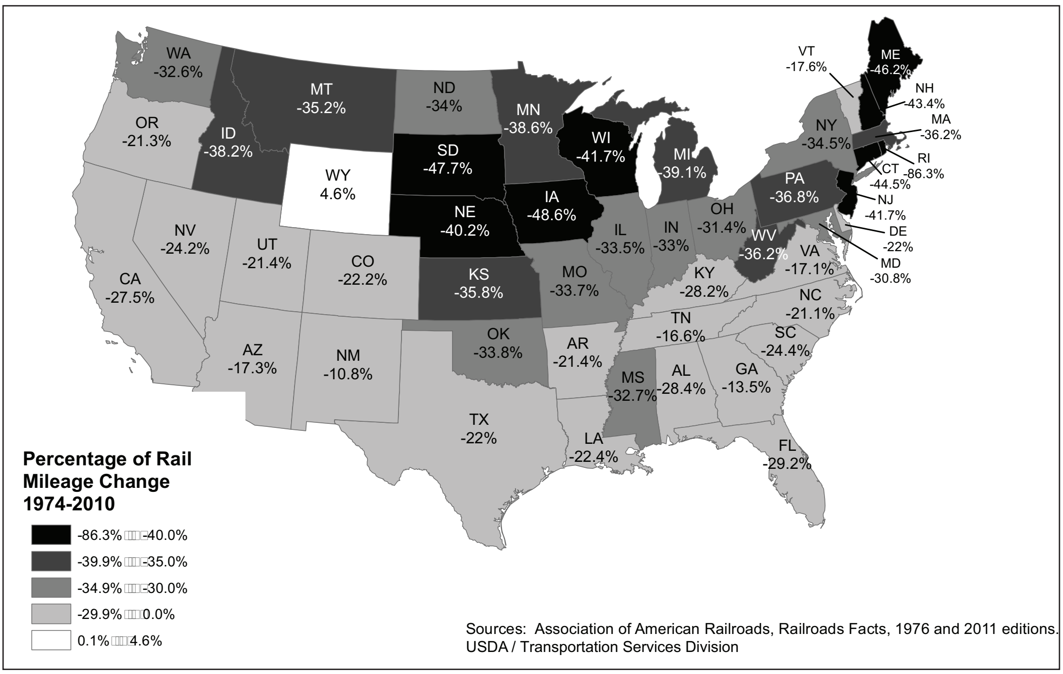
Wilson (1984) examined the factors affecting the market share of rail using time series data on wheat and barley transportation from North Dakota to Minneapolis and Duluth. The study found that as rail rates increased relative to truck rates, rail market share goes down. However, the study also found that as shipments of grain increased, so did the market share of the dominant transportation mode, which for most of the shipment routes was rail. For both wheat destinations, higher shipments resulted in higher rail market share, while only one barley destination was deemed rail intensive.

FACTORS INFLUENCING THE RAIL MARKET SHARE OF GRAIN AND OILSEED TRANSPORTATION

Following the 1980 Staggers Rail Act, railroads abandoned unprofitable lines and merged, eliminating duplicate lines and some reciprocal switching and terminal agreements that had provided shippers with more options to market their grain, oilseeds, and byproducts. Between 1974 and 2010, the national rail network shrank by 31% (AAR 1976 and 2011).

In some cases, grain and oilseed shippers that were left without rail service from line abandonment had to rely more heavily on truck or barge transportation due to fewer rail origination and termination locations. Several major grain-producing states have lost more than 40% of their rail network since 1974: Iowa (48.6%), South Dakota (47.7%), Wisconsin (41.7%) and Nebraska (40.2%) (AAR a 1976 and 2011) (Figure 3).

Figure 3: Percent Change in Railroad Route Miles by State, 1974–2010



Grain-producing states that lost more than 35% of their rail network include Michigan (39.1%), Minnesota (38.6%), Idaho (38.2%), Pennsylvania (36.8%), Kansas (35.8%), and Montana (35.2%). These states account for 48.9% of the U.S. grain and oilseed production.

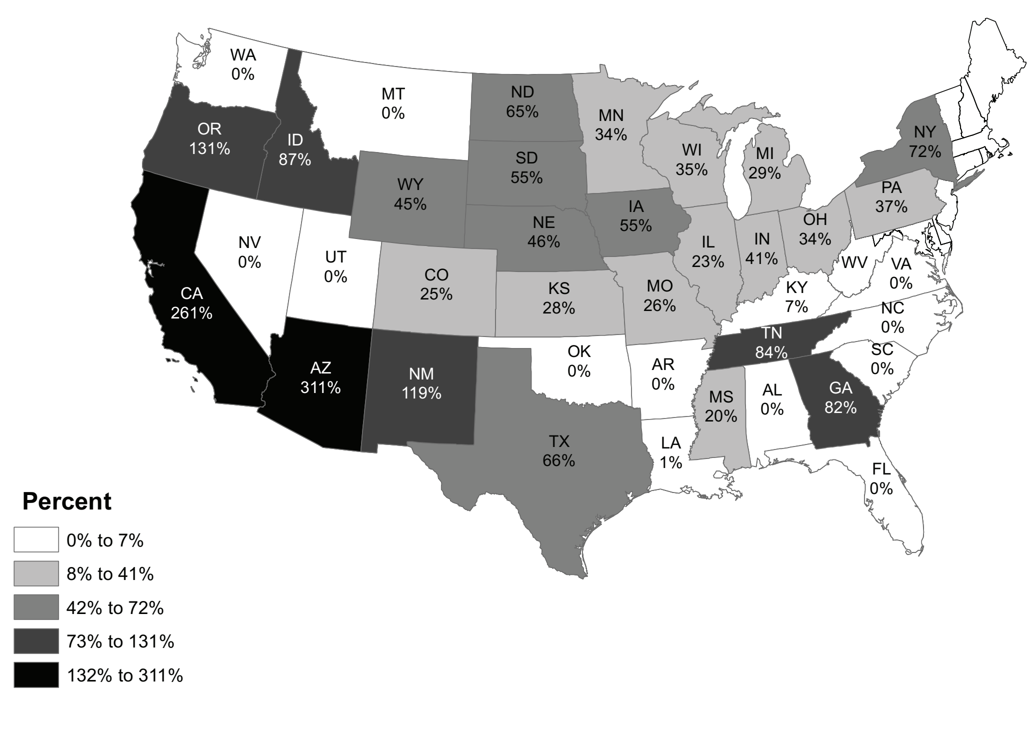
On the other hand, the rationalization of the rail network contributed to increased railroad efficiency for other grain and oilseed shippers (Wilson 1998). Concentrating traffic over a smaller network together with longer hauls, greater car capacity, increased shipment sizes, and other operational efficiencies have encouraged corresponding changes in the grain marketing system. This has included a reduction in the number of grain elevators, larger elevator storage capacities, and greater rail loading capacities. As of 2010, 13 of the top 27 grain-and-oilseed-producing states were shipping a majority of railroad-transported grain and oilseeds in shipment sizes 50 railcars or greater, up from eight states in 2001 (USDA f; STB). Thus, increased railroad efficiency is likely to have increased the rail market share of grain and oilseeds, both directly and indirectly, through greater efficiencies in consolidated grain loading facilities.

The use of corn to produce ethanol and distillers dried grains (DDGS) has increased from 1.6 billion gallons of ethanol in 2000 to 13.9 billion gallons in 2011, providing a renewable source of fuel, which decreases U.S. dependence upon foreign-sourced oil (Renewable Fuels Association 2012). In addition, the co-product, DDGS, is a valued feed source for animal production that provides an alternative to the traditional use of corn for feed.

The Official Nebraska Government website (2012) and World Agricultural Supply and Demand Estimates (USDA k 2012) report that during 2011, approximately 40% (5 billion bushels) of the U.S.-produced corn was used to produce 13.9 billion gallons of ethanol and about 42 million tons of DDGS. Iowa was the nation's top ethanol-producing state, with enough operating capacity to produce 3.58 billion gallons, 25% of the nation's ethanol production capacity (Official Nebraska Government website 2012). The other top five ethanol-producing states had enough operating capacity to produce another 5.34 billion gallons (37.6% of the nation's ethanol production capacity): Nebraska (1.96 billion gallons), Illinois (1.23 billion gallons), Minnesota (1.13 billion gallons), and South Dakota (1.02 billion gallons).

Figure 4 shows that Iowa and South Dakota used an estimated 55% and 56% of their corn production for the production of ethanol within those states.[2] Nebraska used 46%, Minnesota 34%, and Illinois 23% of their corn production for the production of ethanol within those states. North Dakota (65%) also used a major portion of its corn crop to produce ethanol. California, Arizona, Oregon, and New Mexico imported corn from other states to produce ethanol close to major population centers. Other states that likely imported grain to produce ethanol include Texas, Idaho, Tennessee, Georgia, and New York.

Figure 4: Estimated Percentage of Corn Crop Used for Ethanol Production, 2011



Sources: USDA/NASS/Crop Production Annual Report; http://www.neo.ne.gov/statshml/121.htm

The majority of ethanol plants are clustered in the Midwest, specifically around Iowa, Minnesota, South Dakota, and Nebraska. Most of the grain used for ethanol moves relatively short distances, less than 500 miles, between farm and ethanol plant (Minnesota Department of Transportation 2007). Trucks are most competitive with rail and barge for movements under 500 miles. One example of this is reported in the *Southwest Minnesota Regional Freight Study* (Minnesota Department of Transportation 2007). The study found that within the region, most plants producing ethanol are located near corn production centers. The report finds "…ethanol production facilities [in Southwest Minnesota] rely for much of their [corn] supply on regular truck shipments from area farms." Further, an estimated 25% of DDGS from ethanol production were destined for export. The report states that once ethanol is produced, it is often transported out of the region via rail. This is supported by another report, *The 2007/08 Iowa Grain and Biofuel Flow Study: A Survey Report* (Yu and Hart 2009). Findings include that the main form of transportation used by ethanol plants were trucks and the necessary crops are largely supplied by area production. In addition, Babcock, Holmgren, and Russell (2009) found that truck shipments accounted for 91% of total inbound corn and sorghum shipments to Kansas ethanol plants. Therefore, the increase in ethanol production is expected to decrease the rail market share of grain transportation.

Biodiesel and ethanol share a commonality through the use of grains and oilseeds to produce energy. Like ethanol, biodiesel production has increased significantly over the past decade, from two million gallons in 2000 to 1.07 billion gallons in 2011 (National Biodiesel Board 2012). For the marketing year 2011/12, bio-diesel production is expected to consume nearly 19% of the soybean oil produced (USDA k).

Animal production has continued to concentrate in specific geographic locations around the country – the Southwest, the Great Plains, the Corn Belt, parts of California and the Pacific Northwest, and areas of the mid-Atlantic. Not all these regions are co-located with adequate grain and feed production. In others that are co-located, the demand for animal feed may be greater than an individual area can supply. The top five animal-feeding states—Texas, North Carolina, Iowa, Nebraska, and Kansas—produced enough livestock and poultry between 2001 and 2010 to account for 35.6% of the grain-consuming animal units (GCAUs)[3] in the United States.

The increased geographic concentration of animal feeding operations depends on the interstate movement of grain, oilseeds, and feed. In general, these interstate hauls should increase the rail market share for those states supplying the feed grains and decrease the rail market share for those states receiving the grain.

Grain and oilseed shippers seek to maximize profits by minimizing the total cost of transportation. Railroads compete with barges and trucks, as well as with other railroads. The level and effectiveness of transportation competition can vary by locality and depend upon such factors as distance, price, availability, and shipment size. For example, Grimm and Winston (2000) find strong negative effects on rail rates when competition with barges, trucks, and/or other railroads is present.

In a study using rail and truck transportation data for Canada, Oum (1979) found that for commodities with a low value, railroads have a clear advantage in long-distance transportation. He also found that for these commodities, trucks are only competitive in short-distance movements. Yet in areas where barges are available, the rail share of grain and oilseed transportation ought to be lower given the increased competition from barges.

Holding other factors constant, shipping grains and oilseeds long distances by barge is usually the cheapest option and shipping by truck is the most expensive. Barges take advantage of their large capacity by spreading fixed transportation costs across more tonnage than either trucks or rail can, resulting in lower per-unit transportation costs. For example, one barge tow of 15 individual barges can hold almost 787,500 bushels of grain compared with 400,000 bushels in a 100-car unit train or 910 bushels in a large semi-truck.

A particular transportation mode's ability to serve different shipping routes plays a central role in shippers' consideration of which mode to use. Although they often offer a lower price than truck, rail and barge must serve the same origins and destinations in order to provide effective modal competition. Compared with the roadways available to trucks, rail and barge transportation are not universally available for land-based shipments. A 2002 GAO report discussing the options available for corn shipping found that because many corn growing regions are located in the vicinity of waterways, barge competition may result in less dependence on rail and reduce rail market share. This is in contrast to the widespread use of rail in the Northern Plains States, a major wheat growing region, where little intermodal competition can be found (MacDonald 1989). Babcock and Bunch (2002) survey grain shippers to understand the factors influencing transportation choice, particularly between truck and short line railroad. They found that the area served by a particular mode was a major influence on shippers of certain crops. The most common explanation among corn shippers for choosing truck was that "the best corn markets are not rail served." To a somewhat lesser degree, this reason was also cited by sorghum shippers.

Similarly, barges are only an option for shippers located within a reasonable distance to barge facilities by truck or for shippers with access to rail service that also serves a barge facility. For example, wheat loaded onto barges in Peoria, IL, comes by truck from nearby farms and by rail from as far away as Kansas and North Dakota. The farther away production occurs from any barge facility, the less competitive it becomes as a final mode of transportation. Bitzan et al. (2003) find that as the distance from the closest barge loading area increases 1%, the rate per ton-mile increases .055%.

Thus, the relative price/ton among barge, truck, and rail transportation helps determine which transportation mode is utilized. Relative prices also affect the geographic areas in which one mode is competitive to another, for example how far a shipper is willing to ship grain by truck or rail in order to access a barge facility. Holding other factors constant, as the price/ton of rail transportation decreases relative to truck or barge, the rail share of grain and oilseed transportation should increase.

Marathon and Sparger (2012) report that between 1978 and 2010, production of major grains increased more than 15%, primarily for domestic use. The amount of major grains transported domestically increased 217% between 1978 and 2010, as opposed to the 15% increase for export. The total tonnage hauled by rail and barge during this time period remained relatively constant compared with truck tonnage. Rail tonnage increased from 117 million tons (mt) in 1978 to 151 mt in 2010; the tonnage hauled by barge increased to a smaller extent, from 51 mt in 1978 to 65 mt in 2010. In contrast, the amount hauled by truck increased from 74 mt in 1978 to 297 mt in 2010, representing a 300% increase over 32 years.

Marathon and Sparger (2012) also report that trucks have gained significant market share of domestic grain and oilseed movements at the expense of barge and rail. Between 1978 and 2010, the domestic grain movements by truck increased from 60% to 77%, indicating that truck transportation is necessary for many domestic grain and oilseed movements. Grain shippers often have difficulty obtaining railcars for smaller shipments and rely on trucks or intermodal containers for these movements because of the flexibility they offer. Some domestic users of grain state that they prefer to receive shipments by truck because it is neither convenient nor economical to accept larger shipment sizes by rail. In contrast, the 6% truck share of export grain movements did not change from 1978 to 2010.

Grain and oilseed exports favor barge and rail over truck for longer hauls associated with export movements due to their cost savings. Rail rates per ton-mile decrease as the distance moved increases, because the fixed costs incurred by rail shipments (such as switching and loading cars) are independent of distance shipped (MacDonald 1989; USDA/USDOT 2010). As the number of miles increases, decreasing average fixed cost causes the cost per mile to decrease, resulting in more competitive rates for long-haul shipments. This is similar to the way barges are able to distribute fixed costs over large quantities of goods due to their large capacity. The increase in grain and oilseed exports is expected to increase the rail market share of grain and oilseeds.

Table 1: Average Percentage of Grains and Oilseeds Moved by Rail, MY 2001-2010[1]

Crop	Percentage
Barley	64%
Corn	26%
Oats	32%
Rough Rice	4%
Rye	17%
Sorghum	30%
Wheat	72%
Cottonseeds	23%
Peanuts	15%
Soybeans	25%

Sources: USDA Crop Production; STB Waybill Sample
[1]Weighted average of the 10-year period.

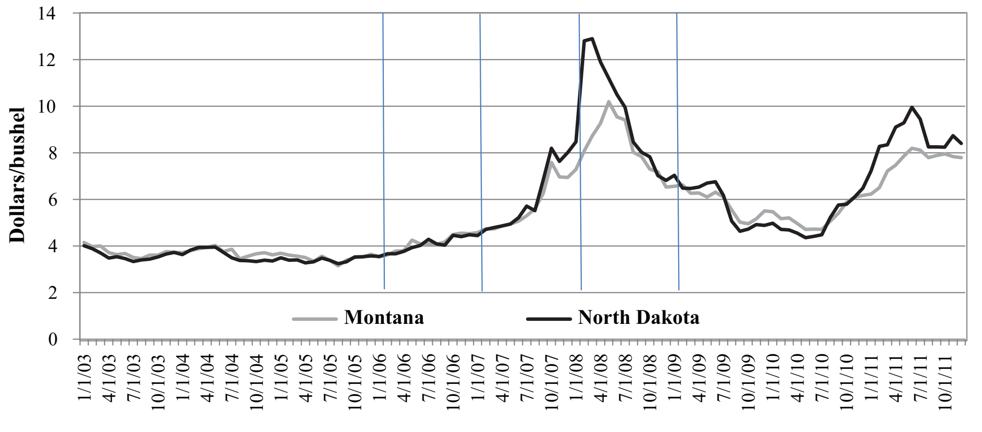
The composition of the crops grown within a state may affect the rail market share of grain transportation for the state (Table 1). The dependence on rail transportation ranges from 4% for rough rice to 72% for wheat (STB; USDA f). The particular crop composition within a state is correlated with geographic characteristics of the region in which the crops are grown and whether the crops are for domestic use or export. Crop composition within each state is included in this study in order to control for these effects on rail market share.

The varying extent to which rail is utilized by the producers of different agricultural products has been referenced by many studies up to this point. For example, Bitzan et al. (2003), Babcock and Bunch (2002), and the GAO report (2002), all state that a larger percentage of the wheat crop is shipped by rail than corn or soybeans, two other major crops. This may be due to the regions in which the production of these crops is centered; wheat largely in the Northern Plains and corn and soybeans nearer inland waterways.

For example, Arkansas—in which rough rice comprises about 50% of grain and oilseeds production—has a rail market share of grain production of only 6% to 17% (USDA f; STB). Due to its proximity along the Arkansas and Mississippi rivers, it is not highly rail dependent. In contrast, Montana, in which barley and wheat comprise about 97% of the annual grain and oilseed production, is highly dependent on rail, with its rail haul to production ratios ranging from 66% to 121% (exceeds 100% with the addition of grain taken from storage during times of high grain prices) (Vachal 2012). Furthermore, almost half of wheat production is exported while less than 20% of corn is exported (Marathon and Sparger 2012). Table 1 shows that the more heavily exported grain is also the most rail-dependent grain. For a state with a high export grain and oilseed composition, the rail market share should be higher.

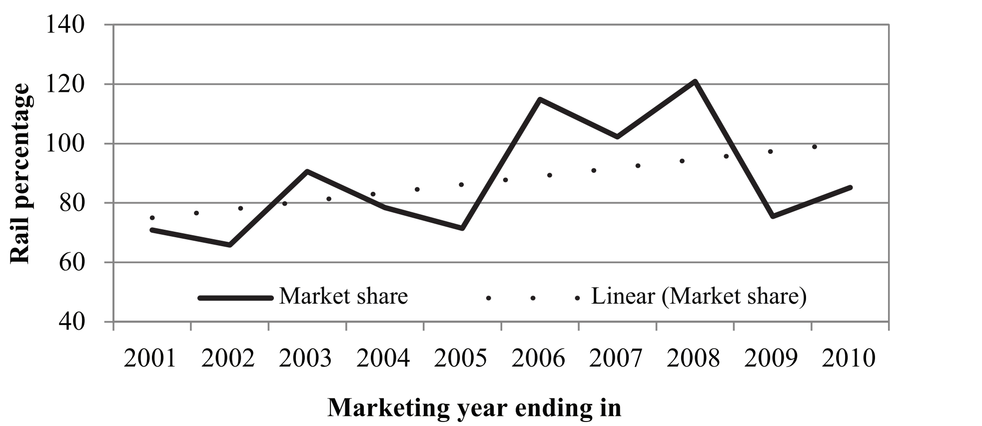
As the price of grain increases, producers wanting to take advantage of the high grain prices demand additional grain transportation in order to move new grain quickly and move old grain out of storage. Figure 5 shows the average monthly wheat prices from January 2003 through December 2011 (USDA c). During the last half of 2006, wheat prices rose above $4.00 per bushel, peaking dramatically during March 2008 in North Dakota and May 2008 in Montana. In marketing years 2006, 2007, and 2008, Montana and North Dakota producers removed grain from storage to capture the relatively high wheat prices. Since rail is the dominant mode of transporting grain in these two states, the rail market shares for those years were unusually high (Figures 6, 7) (USDA f; STB). As the prices for grains and oilseeds increase, additional transportation demand should increase the rail market share of grains and oilseeds, especially for more rail-dependent crops.

Figure 5: Farm Prices of All Wheat



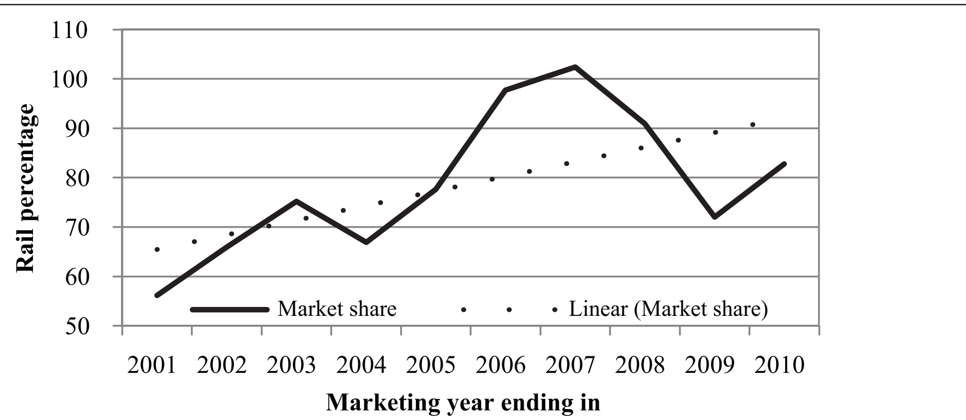
Source: USDA/NASS, Agricultural Prices

Figure 6: Montana Rail Market Share of Grain Transportation



Sources: Surface Transportation Board Waybill Samples; National Agricultural Statistics Service Annual

Figure 7: North Dakota Rail Market Share of Grain Transportation



Sources: Surface Transportation Board Waybill Samples; National Agricultural Statistics Service Annual

METHODOLOGY

Based on the factors discussed above, a linear regression model[4] was developed (Equation 1) to explain variations in the rail market share of grain and oilseed transportation. Of the top 27 grain and oilseed-producing states, which produce 96.7% of the U.S. grain and oilseeds, only 21 were included in the model for the marketing years 2001-2010 (Table 2) for a total of 210 observations. Together, these 21 states account for 86.6% of U.S. grain and oilseed production. California, Colorado, Georgia, Michigan, North Carolina, and Texas were excluded from the model because they do not have proximate access to grain facilities on the U.S. inland waterway system.

(1) MARKET SHARE = f (ETHANOL, BIODIESEL, BARGE/RAIL, TRUCK/RAIL, DISTANCE, RRMILES, EXPORTS, GCAU, CROP PRICES, ≥50CAR_SHIPMENTS, $\sum COMMODITY_i$)

Variables:

MARKET SHARE =	Rail market share (percent) of grain and oilseed production by state and marketing year
ETHANOL =	Conventional ethanol operating production capacity (million gallons/year) by state and calendar year
BIODIESEL =	Millions of gallons of production by state and calendar year
BARGE/RAIL =	Average barge rate ($/ton) divided by average rail rate for grains and oilseeds (cents/ton-mile) by originating state and marketing year
TRUCK/RAIL =	Average yearly on-highway diesel fuel price for a state's Petroleum Administration for Defense District divided by average rail rate for grains and oilseeds (cents/ton-mile) by originating state and marketing year
DISTANCE =	Average distance (miles) to ports on major inland waterways (Mississippi, Illinois, Ohio, Columbia/Snake rivers) or to export ocean ports by state
RRMILES =	Ratio of route miles of railroad track compared to route miles in 1974 by originating state and year
EXPORTS =	Each state's contribution to total national grain exports (million tons), adjusted for surpluses and deficits related to animal feed requirements.
GCAU =	Estimated grain consuming animal units (millions) for milk cows, beef cows, sheep, poultry broilers, turkeys, and hogs by state and year
CROP PRICES =	Index of crop prices weighted by the amount of each crop produced (bushels) in each state and marketing year, with the marketing year ending in 2001=100.
≥50-CAR_SHIPMENTS =	Proportion of grain and oilseed moved by rail in more than 50-railcar shipments to total tons of grain and oilseed shipments by state and marketing year.
$\sum COMMODITY_i$ =	Percent of total grain and oilseed production belonging to commodity *i* by state and marketing year. Commodities include soybeans, wheat, rice, cottonseeds, peanuts, flaxseeds, barley, oats, rye, and sorghum.

Table 2: 2000 to 2010 Grain and Oilseed Production by State (million bushels)

Rank	State	11-Year Total	Average	Percent of Total	Cumulative Percent
1	IA	28120.25	2556.39	14.2%	14.2%
2	IL	26140.30	2376.39	13.2%	27.3%
3	NE	17335.97	1576.00	8.7%	36.0%
4	MN	16368.88	1488.08	8.2%	44.3%
5	IN	12555.88	1141.44	6.3%	50.6%
6	KS	11784.47	1071.32	5.9%	56.5%
7	SD	8296.38	754.22	4.2%	60.7%
8	OH	7974.92	724.99	4.0%	64.7%
9	ND	7401.72	672.88	3.7%	68.5%
10	MO	7304.53	664.05	3.7%	72.1%
12	WI	5440.93	494.63	2.7%	74.9%
13	AR	5010.53	455.50	2.5%	77.4%
15	KY	2528.67	229.88	1.3%	78.7%
17	MS	2365.85	215.08	1.2%	79.9%
19	MT	2177.40	197.95	1.1%	81.0%
20	LA	2106.29	191.48	1.1%	82.0%
21	OK	2080.54	189.14	1.0%	83.1%
24	WA	1879.06	170.82	0.9%	84.0%
25	ID	1730.89	157.35	0.9%	84.9%
26	TN	1688.57	153.51	0.9%	85.7%
27	PA	1648.42	149.86	0.8%	86.6%

Source: USDA/NASS/Crop Production Annual Summary

DATA

MARKET SHARE is estimated by dividing the annual marketing year rail volume of grain and oilseeds by the grain and oilseed production for each state. Total grain and oilseed production by state for each year was obtained from annual USDA *Crop Production Annual Reports* (USDA f) and includes barley, corn, cottonseeds, flaxseed, oats, peanuts, rough rice, rye, sorghum, soybeans, and wheat. The tonnage of grain and oilseeds hauled by rail for each state by marketing year was obtained from the Surface Transportation Board's Confidential Carload Waybill Samples (STB).[5] These values were divided by the marketing year's production of each grain and oilseed to obtain the annual rail market share of grain and oilseed transportation.[6]

ETHANOL directly captures the amount of conventional ethanol produced in a state. Ethanol production by state was estimated from national totals apportioned by each state's production capacity. National ethanol production is available from the U.S. Energy Information Administration. State production capacity for ethanol is available through the Renewable Fuels Association (RFA) and the Official Nebraska Government website.

BIODIESEL is measured in millions of gallons. State-level data were obtained from the National Biodiesel Board.

Together, BARGE/RAIL, TRUCK/RAIL, and DISTANCE capture the effects of modal competition. BARGE/RAIL and TRUCK/RAIL capture how relative price changes between modes affect which mode is more competitive and likely to attract business from grain shippers. DISTANCE is the average distance to barge or port facilities within a state.

Rail rates were obtained from the Surface Transportation Board's Confidential Carload Waybill Samples (STB) while barge rates were obtained from the Transportation Services Division of USDA (USDA a). Rail rates were calculated as the rate per ton mile to account for differences in distance hauled, which have different cost structures. Barge rates were calculated as the rate per ton because mileage is already factored into the per-ton prices found at different points along the river. Barge rates for states not directly adjacent to waterways were based upon the prevailing barge rates at the nearest grain-handling facility located on the Mississippi, Ohio, Illinois, and Columbia/Snake rivers.

Rates for grain trucks were more difficult to obtain. On-highway diesel fuel prices were chosen as a proxy for grain truck rates because fuel costs make up a large part of overall truck rates. According to the American Transportation Research Institute, fuel and oil costs comprised 35% of total average truck costs in 2011, the single largest factor, followed by driver wages at 27% (ATRI 2011). On-highway diesel fuel prices are reported by the U.S. Energy Information Administration by Petroleum Administration for Defense District, which includes groupings of individual states. The general truck rate index provided by the American Trucking Association was also tried as a proxy and provided nearly similar statistical results in terms of coefficients and significance (ATA 2011). However, it was not used as on-highway diesel fuel prices provided a slightly better fit for the model.

Distances were calculated from the center of the Federal Information Processing Standard (FIPS code) (Commerce a 2012) of the county producing the grain and oilseeds to the center of the county having the grain-handling facility on the major navigable rivers (Mississippi, Ohio, Illinois, and Columbia/Snake) or grain export facility. The distances calculated are as air-miles,[7] not highway miles (Table 3). Counties not producing grain or oilseed crops were excluded from the average.

Table 3: Average Distance to Nearest Grain-handling Barge or Export Facility (miles)

Origin State	Distance
AR	27.62
IA	101.53
ID	212.08
IL	20.58
IN	61.26
KS	319.34
KY	50.33
LA	29.46
MN	77.11
MO	76.57
MS	52.09
MT	335.80
ND	332.30
NE	345.69
OH	112.90
OK	227.63
PA	196.27
SD	300.02
TN	80.84
WA	70.34
WI	79.65

Source: USDA spatial analysis of FIPS data from NIST, Department of Commerce

RRMILES were obtained from the Association of American Railroads, *Railroad Facts* (AAR). An index for each state was developed that compares total railroad route miles in a given year to the base year, 1974. Route miles in 1974 = 100. Route miles are for all freight railroads operating within a state, including Class I, II, and III. Trackage rights were excluded to eliminate double-counting.

EXPORTS directly captures the quantity of grains and oilseeds grown for export in a state. National exports are available from U.S. Census Bureau, Foreign Trade Statistics (Commerce b 2000-2010). Each state's contribution to total national exports is estimated by its share of the national production for each year, adjusted for surpluses and deficits related to animal feed requirements and ethanol production.

GCAU captures increases in the geographic concentration of animal feeding through the number of grain-consuming animal units (GCAU) within a state. GCAUs were obtained by multiplying the inventory for each type of animal within a state by the appropriate conversion factor to derive a standardized total of GCAUs within a state based on the feed requirements of the individual animal types (USDA b, d, e, g, h, i, and j).

CROP PRICES is an index of grain and oilseed crops that captures how the prices producers receive affect their demand for rail transportation. The index is based on a weighted average of the price per bushel of each crop produced within a state, weighted by its respective portion of total production within a particular year. A separate index was developed for each state, with the weighted average during marketing year 2001 used as the base year and set equal to 100. Prices for individual field crops are available from USDA NASS' annual *Agricultural Prices* (USDA c).

≥50CAR_SHIPMENTS captures how changes in the quantity of grain shipped by rail in larger shipments (those over 50 carloads) have affected railroad market share. It is measured as the proportion of a state's total tonnage of grains and oilseeds moving in more than 50 carloads by state and year. Tonnages by shipment size were obtained from the Surface Transportation Board's Confidential Carload Waybill Samples (STB).

The composition of individual grains and oilseeds produced within a state is captured by 10 COMMODITY variables: soybeans, wheat, rice, cottonseeds, peanuts, flaxseeds, barley, oats, rye, and sorghum. The percentages of grain and oilseed production by state for each marketing year were obtained from the USDA *Crop Production Annual Reports* (USDA f).

Corn was excluded from the model due to multicollinearity. Multicollinearity occurs when explanatory variables are highly correlated and can affect statistical significance. Many grains and oilseeds are correlated because they are often produced in the same areas. Corn is produced in every state in our model and is, thus, correlated to some degree with each of the grains and oilseeds, especially wheat and rice. By dropping the corn composition variable, we eliminated the primary source of multicollinearity. Other methods were attempted to correct for multicollinearity, such as including the composition of an individual crop relative to the amount of corn grown, including the absolute amount of each commodity grown, or dropping another commodity variable. However, these methods either did not successfully mitigate the multicollinearity between commodity variables or created multicollinearity among other explanatory variables.

RESULTS

The results shown in Table 4 indicate that 10 of the selected variables had an influence on rail's market share of grain and oilseed transportation during the past decade. These variables are statistically significant at the .05 level or higher.

Because the explanatory variables are in different units of measurement, Figure 8 shows the minimum, average, and maximum impacts across all states from changes in each variable between MY 2001 and MY 2010 on rail market share. The commodity variables and distance to barge facilities, which did not change over time, are discussed separately. Ethanol and biodiesel production and animal feeding (GCAU) decrease rail market share while truck competition, exports, and shipment size increase rail market share. The significant variables are discussed in the following sections.

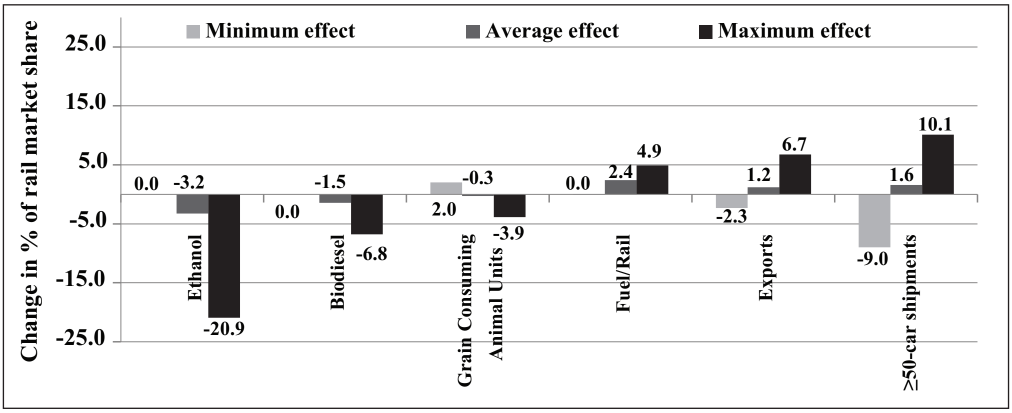
Table 4: Regression Results

Independent Variable	Parameter Estimate	Standard Error	t-value	p-value
Intercept	-25.570	16.803	-1.52	0.130
Ethanol	-0.007	0.003	-2.37	0.019
Biodiesel	-0.142	0.068	-2.09	0.038
Barge/rail	-0.223	0.688	-0.32	0.746
Truck/rail	11.799	5.452	2.16	0.032
Distance	0.062	0.017	3.74	0.000
RR miles	0.301	0.212	1.42	0.157
Exports	1.525	0.284	5.37	0.000
Grain Consuming Animal Units	-0.255	0.096	-2.65	0.009
Crop prices	0.021	0.013	1.58	0.116
≥50-car_shipments	16.174	5.846	2.77	0.006
Soybeans	0.188	0.169	1.11	0.268
Wheat	0.336	0.079	4.25	0.000
Rice	-0.156	0.119	-1.31	0.192
Cottonseeds	0.494	0.225	2.19	0.030
Peanuts	1.714	2.141	0.8	0.424
Flaxseed	9.844	3.356	2.93	0.004
Barley	-0.228	0.234	-0.98	0.330
Oats	0.779	1.069	0.73	0.467
Rye	-6.969	10.328	-0.67	0.501
Sorghum	-0.293	0.319	-0.92	0.359
Yule-Walker Estimates				
Number of Observations	210			
Error Degrees of Freedom	188			
Total R-Square	0.89			
Durbin-Watson	1.9607			

Ethanol

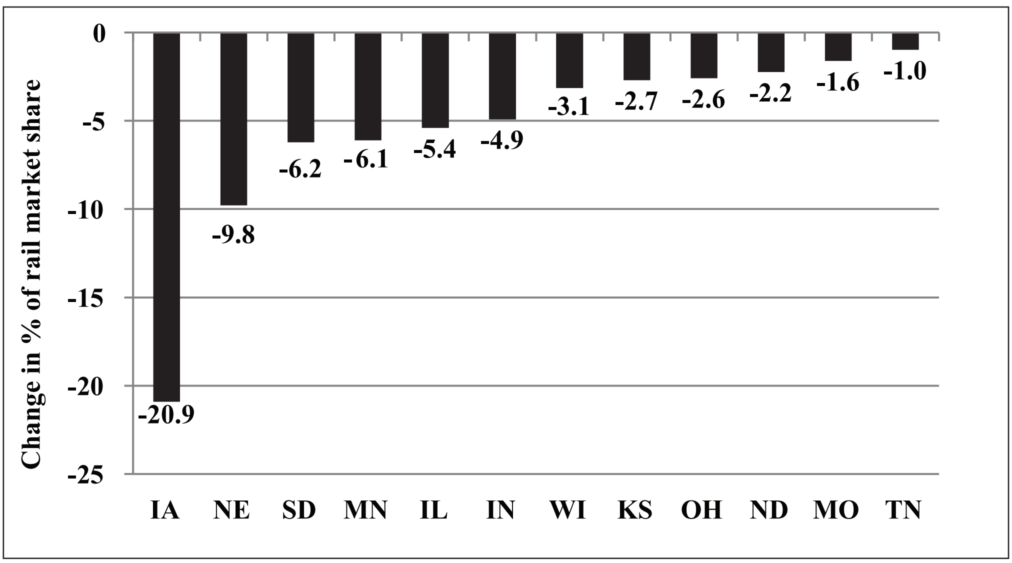
The model shows that for every million gallons of ethanol produced within a state during a year, the rail market share of grains and oilseeds decreases by 0.007% (Table 4). This is quite large considering that some states produce billions of gallons of ethanol. Iowa, the leading ethanol producing state, produced approximately 3.64 billion gallons of ethanol during 2010, compared with 4.26 million gallons in 2001 (Official Nebraska Government website 2012). Holding all other variables constant, this reduced the grains and oilseeds hauled by rail in Iowa by approximately 20.9% in 2010 compared with 2001 (Figure 9).

Figure 8: Effects of Changes in Significant Variables Between MY 2001 and MY 2010 on Rail Market Share



Source: USDA analysis of Surface Transportation Board Confidential Waybill Samples

Figure 9: Effects of Changes in Ethanol Production Between MY 2001 and MY 2010 on State's Rail Market Share

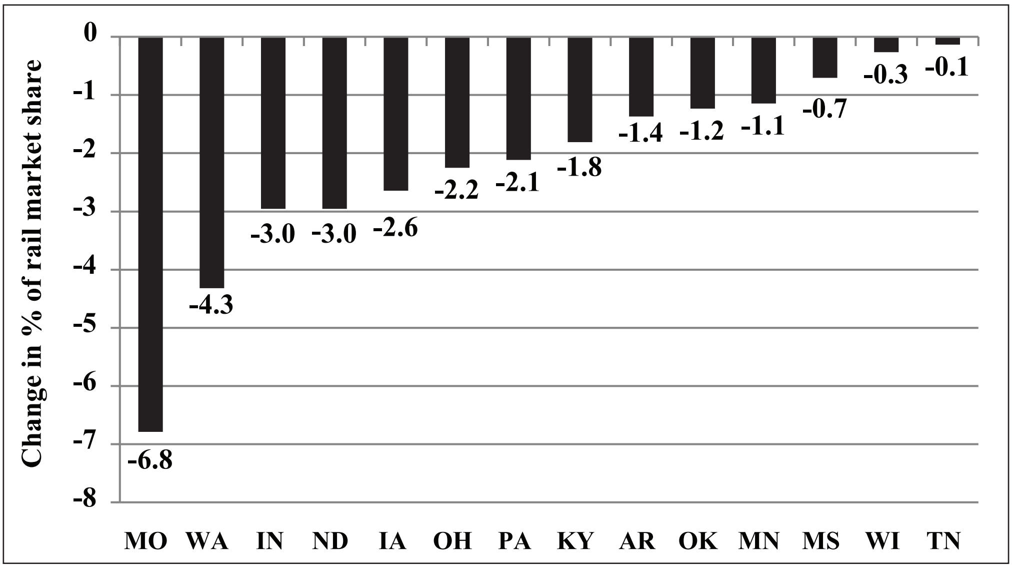


Source: USDA analysis of Surface Transportation Board Confidential Waybill Samples

Biodiesel

Unlike ethanol which was already widely produced in the United States in 2001, biodiesel production totaled only two million gallons in 2000, compared with almost one billion gallons in 2010. As more soybeans were transported by truck to biodiesel refineries, this decreased the rail market share of soybeans for states such as Missouri. Missouri's rail market share decreased 6.8 % as its biodiesel production increased by almost 48 million gallons, showing the diversion from rail to truck (Figure 10).

Figure 10: Effects of Changes in Biodiesel Production Between MY 2001 and MY2010 on a State's Rail Market Share



Source: USDA analysis of Surface Transportation Board Confidential Waybill Samples

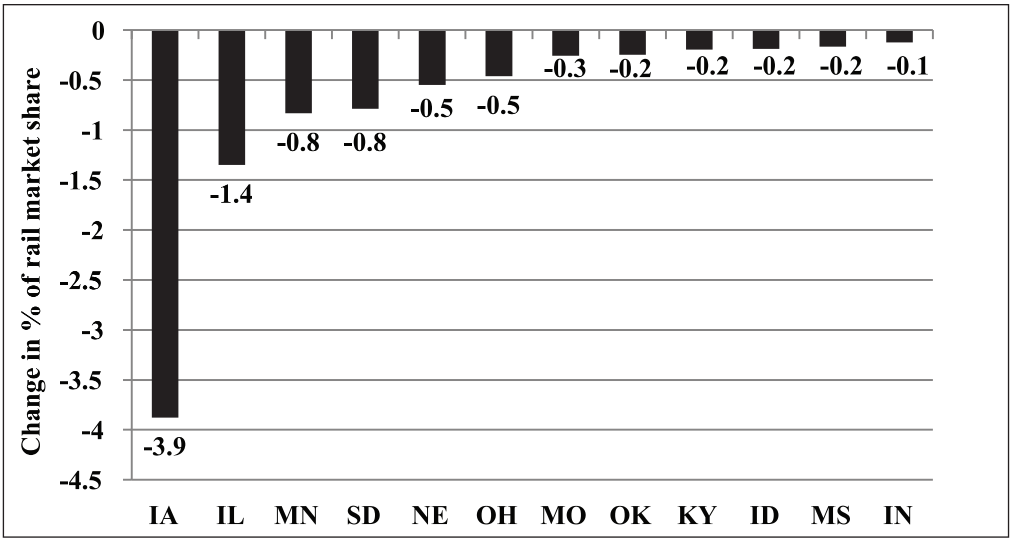
GCAU

The increased geographic concentration of animal feeding has resulted in many feed grain hauls being interstate. These interstate hauls increase the rail market share for those states supplying the feed grains and decrease the rail market share for those states receiving the grain. Everything else being equal, longer haul interstate movements tend to favor rail while shorter-haul movements within a state tend to favor truck. However, even at the sometimes longer distances hauled, the service characteristics of truck transportation may be better suited to moving grain and oilseeds to animal feeding regions than rail, according to grain shippers. This is because it is easier for grain customers to receive shipments by truck than by rail due to the lower handling costs.

Furthermore, the increased use of DDGS and soymeal in feed rations has resulted in less grain and oilseeds being transported to animal feeding regions. Instead, they are transported by truck to ethanol facilities and soybean crushing plants. For instance, during 1994, 58% of U.S. corn was used for feed purposes and only 6% for ethanol. In 2011, only 37% of U.S. corn was used for feed purposes while 39% was used for ethanol (USDA b). Therefore, the rail market share of grains and oilseeds has decreased in states with high concentrations of GCAUs because DDGS and soybean meal have been substituted for grains and oilseeds.

For example, the number of grain consuming animal units in Iowa increased by 15.2 million between MY 2001 and MY 2010, which decreased its rail market share by 3.9% during this time period (Figure 11).

Figure 11: Effects of Changes in Grain Consuming Animal Unit Concentration Between MY 2001 and MY2010 on a State's Rail Market Share



Source: USDA analysis of Surface Transportation Board Confidential Waybill Samples

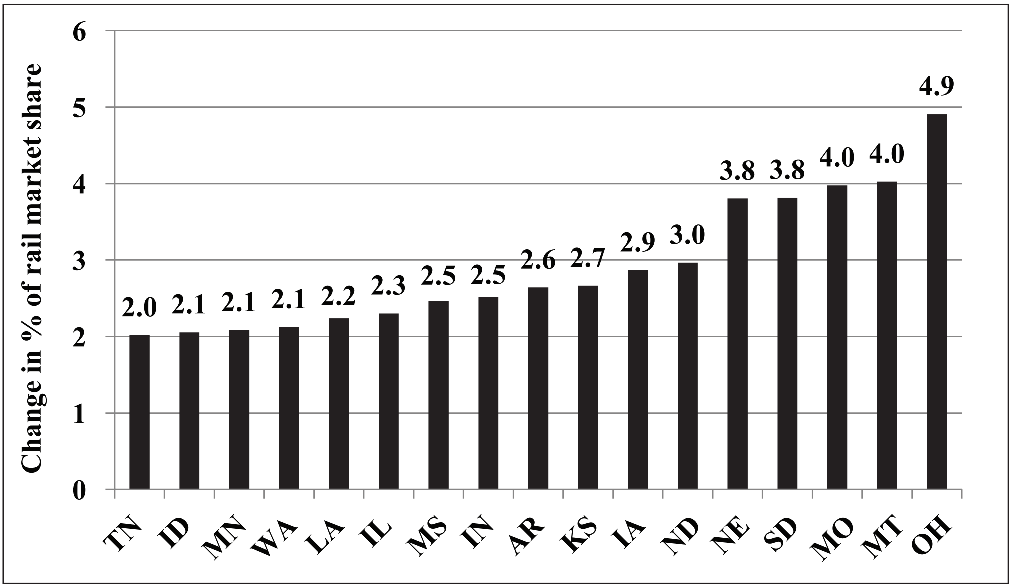
Truck Competition

Between 2001 and 2010, on-highway diesel fuel prices increased almost 2.5 times faster than rail rates. Despite trends showing truck's increasing market share of grain and oilseed transportation at the expense of rail and barge, the model indicates that recent higher fuel prices shifted some traffic from truck to rail. Rail market share increases by almost 12% for every one dollar increase in diesel fuel relative to rail rates. This indicates that large increases in diesel fuel prices may have mitigated some of the long-run trend and increased rail's market share higher than it otherwise would have been. Grain rail rates in Ohio stayed constant between 3 and 4 cents per ton-mile between 2001 and 2010, while average diesel prices in the state rose from $1.40 to to $2.96, contributing 4.9% to rail market share.

Exports

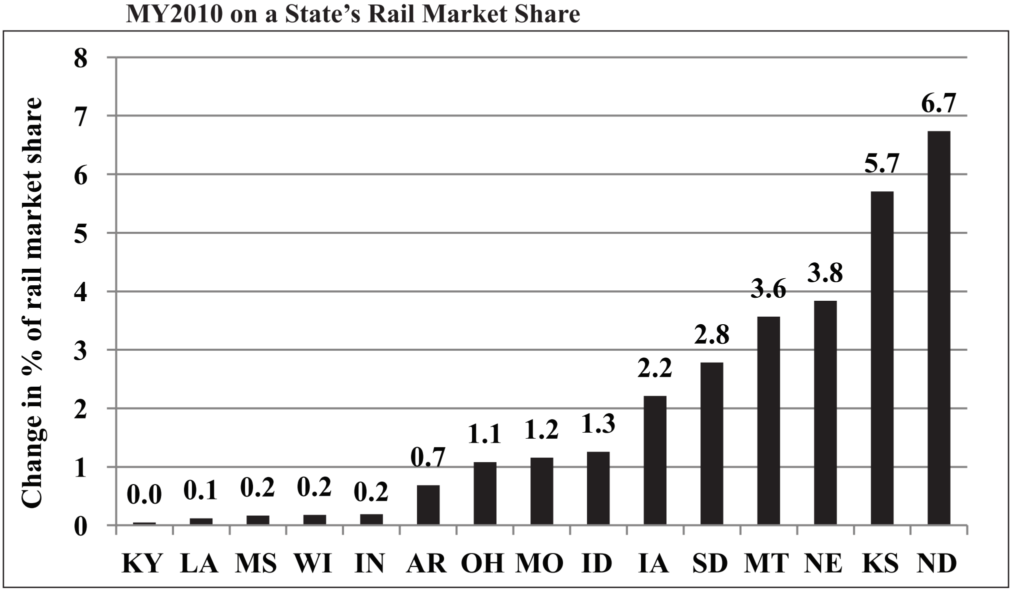
Exports are typically hauled over longer distances to market than grain and oilseeds sold in domestic markets. Because longer-haul movements usually favor rail over truck, increases in exports tend to increase rail's market share of grain transportation. Between 2001 and 2010, U.S. grain exports increased 12.4%, and the rail market share of exports increased from 39% to 50%, in stark contrast to the decrease from 30% to 22% of rail's market share of domestic grain and oilseed movements (Marathon and Sparger 2012). The model indicates that a state's rail market share of grain and oilseed transportation increases 1.53% for each million tons grain and oilseed exported. North Dakota increased the amount of grain and oilseeds it produced for export by 4.4 million tons between MY 2001 and MY 2010, increasing its rail market share by 6.7%.

Figure 12: Effects of Changes in the Truck (Diesel)/Rail Rate Ratio Between MY 2001 and MY2010 on a State's Rail Market Share



Source: USDA analysis of Surface Transportation Board Confidential Waybill Samples

Figure 13: Effects of Changes in Grain and Oilseed Exports Between MY 2001 and MY2010 on a State's Rail Market Share

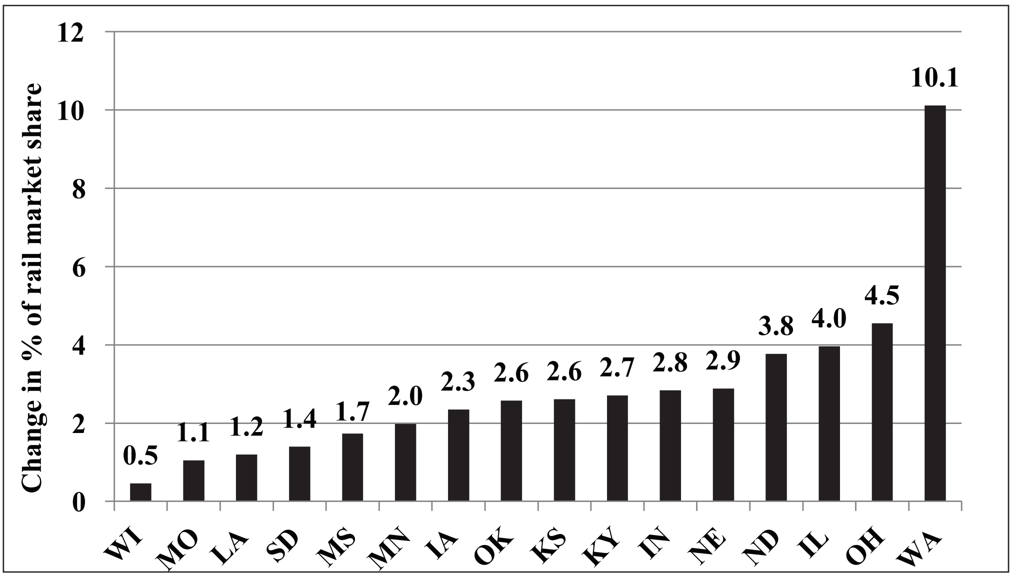


Source: USDA analysis of Surface Transportation Board Confidential Waybill Samples

Shipment Size

Railroad market share increases by 16% for a one-unit increase in the ratio of grain and oilseed traffic moved by rail in 50-car or greater shipments to all grain and oilseed traffic moved by rail (Table 4). Areas with consolidated grain loading facilities and rail access may take advantage of larger, more efficient shuttle trains, often shipping 100 or more cars at lower per-car rates. Furthermore, trucks can offer more flexibility and availability for smaller shipment sizes and may be more competitive to rail shipments under 50 cars. Washington's proportion of grain and oilseeds shipped in 50-car or greater shipments increased from 1% in 2001 to 64% in 2010, resulting in a 10.1% rail market share increase (Figure 14).

Figure 14: Effects of Changes in Shipment Size Between MY 2001 and MY2010 on a State's Rail Market Share



Source: USDA analysis of Surface Transportation Board Confidential Waybill Samples

Distance

Distances to barge grain-loading facilities did not change during the time period of study, as they are based upon the location of rivers and waterways within a state. These geographical features are, for practical purposes, permanent. Thus, this variable should not be thought of as contributing to the change in rail market share between 2001 and 2010. However, it does show how the location of rivers and waterways affects rail market share among states at any given time. As the distance to grain-loading facilities on the inland waterway system or at export ports increases by one mile, the rail market share increases by 0.06% (Table 4). When all other variables are held constant, the rail market share of Montana's grain and oilseed transportation is 19 percentage points higher than that of Illinois. This shows how a landlocked state such as Montana, with an average distance of 336 miles to barge or port facilities, can rely more heavily on rail for transporting grain and oilseeds than a state with access to water such as Illinois, with an average distance of only 21 miles to nearby barge facilities.

Commodity Variables

The composition of crops in a state affects the rail market share of grains and oilseeds transported, because different crops favor different modes of transportation due to the geographic characteristics of the production regions and the particular uses of the crop—such as exports, ethanol, or feed. Special care must be taken when analyzing crop composition variables, because they are included as relative percentages rather than absolute areas. For different states, relative percentages could represent very different total areas. Nevertheless, the model indicates that increasing the area devoted to wheat, cottonseeds, and flaxseeds is associated with an increase in rail market share while there is no corresponding change associated with the other commodities.

CONCLUSION

Structural changes in the trucking and railroad industries since 1980 have resulted in rail losing market share of grain and oilseed transportation to trucks. However, this trend has continued in recent years with the overall rail market share continuing to decline, although varying state to state, with rail market share decreasing in 30 states and increasing in 12. The major factors responsible for lower rail market shares within states are increased ethanol and biodiesel production and the increased concentration of animal feeding. The major factors contributing to higher rail market shares for some states are increased fuel costs contributing to higher truck rates, increased exports, and increased rail shipment sizes representing efficiency gains. Average distances to barge loading facilities did not change during the past decade, but differences between states show that strong barge competition does negatively impact rail market share. Crop production choices are also related to rail market share, with increased flaxseed, cottonseed, and wheat production related to rail market share increases. Future studies related to this research could examine how the increasing usage of grains and oilseeds to produce biofuels has affected the rail market share of ethanol, biodiesel, DDGS, and other co-products, establishing what relation this has had with the decreasing rail market share of grains and oilseeds.

Endnotes

1. For instance, the market share of North Dakota increased from 66% in 2001–2004 to 86% in 2007–2010, a gain of 20%.

2. Grain consumption for ethanol use is estimated by dividing the operating ethanol production capacity of each state (Official Nebraska Government website 2012) by 2.78 gallons of ethanol production per bushel of corn or sorghum. Then the estimated grain consumption for ethanol use for each state is divided by each state's corn production for 2011 (USDA f) to obtain the estimated percentage of corn used for ethanol production. Actual 2011ethanol production of 13.9 billion gallons was 98% of the 14.217 billion gallon U.S. operating ethanol production capacity as of December 2011.

3. A grain consuming animal unit (GCAU) is a standard unit used to compare actual numbers of livestock and poultry. The standard unit is based on the dry-weight quantity of feed consumed by an average milk cow in the base year. Different rates are used to convert each type of livestock and poultry into the standard unit.

4. A pooled estimator is the most basic estimator for panel data. By pooling the data, it treats observations for each state as being serially uncorrelated, with homoscedastic errors across states and time. This rests on the assumption that state-specific errors are uncorrelated with

the observed explanatory variables. An F test rejected that state-specific (fixed) effects were insignificant at the .01 significance level. However, ETHANOL was the only statistically significant variable when state-specific effects were included, with an almost identical parameter estimate to what is shown in Table 4. Thus, a pooled estimator was chosen to model these specific factors. To account for the presence of autocorrelation within the model, which can affect the estimates and significance of parameters, an autoregressive error model was estimated using the Yule-Walker method as described in Gallant, A. R. and J.J. Goebel (1976).

5. To match crop production to the transportation of each crop during the subsequent marketing year, the estimated expanded tons hauled by rail were based on each crop's marketing year. The marketing year for barley, flaxseed, oats, rye, and wheat is June 1 through May 31. The marketing year for corn, sorghum, and soybeans is September 1 through August 31. The marketing year for cottonseeds, peanuts, and rough rice is August 1 through July 31.

6. For instance, if the actual grain production occurred in 2004, the rail haul occurred during the marketing year ending in 2005.

7. An air-mile equals 1.15 land miles.

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Marvin Prater *is a transportation economist specializing in railroad transportation and rural infrastructure issues and is employed by the Transportation Services Division, Agricultural Marketing Service, U.S. Department of Agriculture. Marvin earned a B.S. degree in horticulture, a master's in business administration, and a Ph.D. in economics from Kansas State University. Marvin has been a member of the Transportation Research Forum since 1997, presented papers at the annual forum, and authored papers for the* Journal of the Transportation Research Forum *and the U.S. Department of Agriculture.*

Adam Sparger *is an economist with the Transportation Services Division, Agricultural Marketing Service, U.S. Department of Agriculture. He performs research and analysis on a broad range of agricultural transportation issues but his primary focus is on rail transportation. He received an M.S. in agricultural economics from Virginia Tech and a B.A. in economics from the College of William and Mary.*

Pierre Bahizi *is an economist with the Transportation Services Division at the U.S. Department of Agriculture. Prior to working for USDA, Pierre was an economist in the Division of Consumer Expenditure Surveys at the Bureau of Labor Statistics. He has also worked in the Travel and Tours Department at the Smithsonian Institution. Pierre graduated from the University of Texas at Arlington with a B.A. in economics.*

Daniel O'Neil, Jr. *graduated from the University of Oregon in June 2013 with a bachelor's degree in economics and German. He worked as an economics clerk with the U.S. Department of Agriculture's Transportation Services Division from June 2012 through April 2013, focusing on rail transportation.*

Book Review

Staley, Samuel R. and Moore, Adrian T. Mobility First: A New Vision for Transportation in a Globally Competitive Twenty-First Century. *Lanham, MD: Rowman & Littlefield Publishers, Inc., 2009. ISBN 978-0-7425-5879-3*

Mobility First

by Marcus Bowman

Sam Staley and Adrian Moore put forward a revolutionary perspective in their 2009 transportation vision, *Mobility First*. This book was not an instant best seller, neither is it a destined classic. However, it is a mind-expanding, idea-generating presentation of challenges and solutions to modern transportation problems. It may read just as well 30 years from now.

Transportation intellectuals who are comfortable with today's conventional wisdom are likely to throw this book against the wall in the first chapter. Come to this book prepared to hear a radical departure from the typical language and code the authors say has "bogged down" transportation discussions. For example, *Mobility First* includes a chapter entitled "Seven Steps to Expanding Current Road Capacity," and Sam Staley opens the book with a quote: "If cars get us to where we want to go faster, that's not a problem." The authors point out that "we have yet to begin a serious discussion" about reformulating our transportation system. The ideas and concepts in their book have largely been left out of many policy debates.

Mobility First may not be your cup of tea, but it can be the spoon for your cream and sugar—providing a fresh, different perspective to spur new thinking. The ideas in the book might not be the solutions, but with a full read you may agree they sweeten the pot and move us toward a better future.

The authors state that government decisions have, for a generation, focused primarily on reducing mobility – managing travel demand in ways that planners hope will steer people out of their cars. In this respect, many Americans may not realize the extent to which current transportation decision makers were treating road congestion as if it were a good thing.

Thus one key message of the book is simply to reframe the debate about transportation's future around mobility. The path forward should simply be to increase the speed of travel. Improved economic competitiveness and a better quality of life are the results of decisions that reduce congestion and increase transport speeds.

Staley and Moore formulate their vision first by analyzing new trends such as the non-traditional commute. Commuting is no longer as simple as people heading to and from a city center. Moreover, focusing only on commutes misses much of the story. Throughout the book, these types of points are backed up with statistics. For example, over three-quarters, 83%, of all trips are non-work. The notion that transportation is patterned along fixed lines is outdated. Thus, a revolution is needed to upend the hub-and-spoke model of cities.

The book hits its heights of visionary and revolutionary transportation thinking in Chapter 5, "A New Approach to Congestion and Road Networks." In one figure in the chapter, Staley and Moore break new ground in advocating for a "3-D spider web approach" to transportation networks. The two-dimensional transport networks should look more like the mesh of a spider web instead of hub-and-spoke. The spider web transportation network is more capable of quickly getting people from all points of origin to all destinations. Staley and Moore then advocate for "new types of roads" to meet these modern travel patterns. The new "3-D transportation infrastructure" perspective layers roads above ground and below ground. Connectors from our current roads would provide access to tunnels, elevated roads, and flyovers. Featured examples include the A86 tunnel in France, which is a two-tier tunnel, doubling traffic throughput along a portion of this Paris beltway. The Crosstown Expressway in Tampa is an elevated, three-lane expressway positioned above the pre-existing Interstate. The lanes are reversible to speed the flow of traffic in the direction it is needed.

Privatization and pricing are two additional concepts not likely to be a surprise in a book by Sam Staley and Adrian Moore. Technology-based solutions, such as fully electronic tolling systems, have eliminated tollbooths, allowing drivers to flow through at highway speeds while the road operator still collects tolls. This innovation already saves time though, more importantly, will provide the incentive for private road operators to build new capacity in the form of additional tolled lanes and roads that otherwise would not be built. Express toll lanes and truck-only toll lanes are explored. high-occupancy toll (HOT) lanes open up the free space in underutilized HOV lanes so that drivers willing to pay a price can travel alongside cars filled with carpoolers. HOT lane prices are calculated by algorithm to ensure that the toll is high enough to only attract enough drivers to still keep cars moving. Another congestion solution which has yet to gain much momentum is tolled flyovers, known as "queue jumps." These short elevated routes would pass over, say, a busy intersection giving those drivers willing to pay the toll a quick ride straight through a typically bottlenecked situation.

The congestion problem calls for big and innovative solutions. Over the next 20 years, the cost of congestion could close in on $1 trillion (actually estimated at $890.5 billion), representing 4.3% of the entire U.S. economy. As one urban example, in Minneapolis congestion was basically nonexistent in the early 1980s. By 2001, residents wasted an average 28 hours per year in congestion, and the number is rising. Much of the book focuses on large urban areas. Staley and Moore devote a full chapter to the bottleneck that is New York City, noting the surprisingly high level of automobile travel in a metro area usually associated with transit ridership.

Yes, transit advocates will find some cream in the book, though not sweetened in the customary way. In a chapter entitled "Transitioning Transit," Staley and Moore advocate for privatization approaches that could spur transit agencies in a more customer-oriented direction. An easy path forward would be to start simply with experiments. Competitive bidding and concession agreements could be used "to unleash competition, innovation and entrepreneurship" in transit agencies. Currently, advocates for increasing transit ridership push largely for ways to force people out of their automobiles. Staley and Moore are essentially saying that if you build a better product, improve speeds, and provide a better service, people will want to ride transit.

Still, the transit chapter ends up back on the road. Buses and bus rapid transit (BRT) in particular, can take advantage of the spider web mesh network as well as flexibly reroute to accommodate changing travel patterns. The authors also point out that in 27 major metropolitan areas, telecommuters outnumber public transit riders. Among them: Orlando, FL, Austin, TX, Denver, CO, San Diego, CA, St. Louis, MO, and Charlotte, NC.

The book closes with a typical refrain familiar to Washington, DC, transportation lobbyists—asking for more money. The pitch has a twist, focused on a call for a direct user fee system that would more clearly link "what people pay to what they use." This concept expanded and combined with private investment would provide the sustainable funding necessary for the long-term commitment needed to implement the envisioned dramatic overalls.

Mobility First preaches solutions aimed toward getting people around. Travelers value mobility because it saves time. The many thoughts and ideas built around discussions of supply are a welcome contrast to the more typical reframes seeking to change behavior and "manage" demand. The book envisions the U.S. transportation network upgraded to reflect the dynamic patterns and complexities of modern day travel. Staley and Moore state that "our transportation system is becoming harder and harder to use." Commutes are less important to the layout of an effective transportation system. "We're not willing to think big enough" and "no one is thinking about the dramatic redesign of our transportation networks necessary to ensure that mobility continues to be a cornerstone of the U.S. economy's competitive advantage."

Mobility First is written for a professional audience with data, visuals and bold ideas to keep the most astute transportation minds fully engaged. Thorough knowledge and extensive experience are demonstrated as the book broadly and innovatively covers our complex, interconnected transportation system. Fans may wish for more. Critics will surely be challenged to pull through many parts. Still, readers are likely to be glad they read *Mobility First*.

Marcus Bowman *manages corporate compliance and intellectual property at Standard Furniture Manufacturing, Mobile, Alabama. He is also founder of 3G Mobility, LLC, which does strategic consulting and publishing in promoting, designing, and building into the next generation of transportation. From August 2008 to October 2012, Bowman was director of research at Japan International Transport Institute, an independent research think tank coordinating and sharing transportation policy approaches between Japan and the United States. He served as director at International Access Corporation from December 2004 to October 2012 and as research analyst at ChangeWave Research from June 2004 to February 2006, where he developed surveys for business executives to assess industry trends and new technology developments; then correlated the responses with secondary research of supply chains to develop targeted lists of successful companies. He has a master's in public policy from George Mason University (2005) and a B.S. from Iowa State University in finance and economics (1996). He is currently on the TRF Washington Chapter Council.*

Transportation Research Forum

Statement of Purpose

The Transportation Research Forum is an independent organization of transportation professionals. Its purpose is to provide an impartial meeting ground for carriers, shippers, government officials, consultants, university researchers, suppliers, and others seeking an exchange of information and ideas related to both passenger and freight transportation. The Forum provides pertinent and timely information to those who conduct research and those who use and benefit from research.

The exchange of information and ideas is accomplished through international, national, and local TRF meetings and by publication of professional papers related to numerous transportation topics.

The TRF encompasses all modes of transport and the entire range of disciplines relevant to transportation, including:

Economics	Urban Transportation and Planning
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History and Organization

A small group of transportation researchers in New York started the Transportation Research Forum in March 1958. Monthly luncheon meetings were established at that time and still continue. The first organizing meeting of the American Transportation Research Forum was held in St. Louis, Missouri, in December 1960. The New York Transportation Research Forum sponsored the meeting and became the founding chapter of the ATRF. The Lake Erie, Washington D.C., and Chicago chapters were organized soon after and were later joined by chapters in other cities around the United States. TRF currently has about 300 members.

With the expansion of the organization in Canada, the name was shortened to Transportation Research Forum. The Canadian Transportation Forum now has approximately 300 members.

TRF organizations have also been established in Australia and Israel. In addition, an International Chapter was organized for TRF members interested particularly in international transportation and transportation in countries other than the United States and Canada.

Interest in specific transportation-related areas has recently encouraged some members of TRF to form other special interest chapters, which do not have geographical boundaries – Agricultural and Rural Transportation, High-Speed Ground Transportation, and Aviation. TRF members may belong to as many geographical and special interest chapters as they wish.

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In addition to monthly meetings of the local chapters, national meetings have been held every year since TRF's first meeting in 1960. Annual meetings generally last three days with 25 to 35 sessions. They are held in various locations in the United States and Canada, usually in the spring. The Canadian TRF also holds an annual meeting, usually in the spring.

Each year at its annual meeting the TRF presents an award for the best graduate student paper. Recognition is also given by TRF annually to an individual for Distinguished Transportation Research and to the best paper in agriculture and rural transportation.

Annual TRF meetings generally include the following features:

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