ABSTRACT

Title: **THE FULL MARGINAL COST OF VEHICLE TRAVEL ON US ROADWAYS**

Nicholas Joseph Ferrari, M.S., 2011

Directed by: **Assistant Professor Lei Zhang, Department of Civil and Environmental Engineering**

In this research, models primarily based on the Highway Economic Requirements System (HERS) are retrofitted to calculate six component marginal costs: Safety, Travel Time, Vehicle Operations, Agency, Emissions, and Noise. Each of these marginal costs is separately obtained for both peak and off-peak periods for seven different vehicle types. By combining these component costs, the true marginal cost to society of each vehicle is obtained for each roadway segment reported in the Highway Performance Monitoring System. This full marginal cost can be applied in future policy analysis in defining appropriate vehicle miles traveled (VMT) fee structures.

In addition to calculating segment marginal costs, this report conducts a section level revenue analysis that compares the revenue generated by the current gas tax system employed by the United States versus a revenue system based on vehicle mile fees developed from marginal vehicle cost analyses.

THE FULL MARGINAL COST OF VEHICLE TRAVEL ON US ROADWAYS

By

Nicholas Joseph Ferrari

Thesis submitted to the Faculty of the Graduate School of the

University of Maryland, College Park, in partial fulfillment

of the requirements for the degree of

Master of Science

2011

Advisory Committee:

Professor Lei Zhang, Chair

Professor Paul M. Schonfeld

Professor Naijun Zhou

Dedication

This thesis is dedicated to my family: parents, grandparents, sister, nephew and, most importantly, my wife.

Acknowledgements

I would like to thank all of the distinguished faculty members who served on my committee: Dr. Lei Zhang (chair), Dr. Paul M. Schonfeld, and Dr. Naijun Zhou. Their support, patience, and suggestions helped guide me in creating a thorough study on marginal cost analysis.

Special thanks to my advisor, Pr. Lei Zhang: without your vision this research would not be possible.

Table of Contents

List of Figures

List of Tables

1. Introduction

Obtaining an accurate estimate for the full marginal cost of vehicles is a principle step towards designing and maintaining a sustainable highway transportation facility for the entirety of the United States. Similar to the Greenroads initiative developed by the University of Washington (which focuses on the sustainable design of roadways according to environment, energy, economic and social equity goals) the proper identification of total marginal costs must consider all potential damages associated with highway vehicles. Thus, the final results of this research define vehicle user fees that will provide the necessary compensation for maintaining a sustainable highway transportation system.

Road pricing, throughout the United States, typically focuses on either revenue generation for infrastructure maintenance or congestion pricing for demand management. Expanding road pricing applications to account for all societal costs is fundamental in creating sustainable transportation systems. The Federal Highway Administration’s Highway Cost Allocation (HCA) study conducted in 1997 and updated in 2000 evaluates several highway cost categories to identify the cost responsibility of different vehicle classifications and the extent and equity of their user fees. While existing policies, such as gas taxes and congestion pricing, are used to separately address some of the infrastructure, environment and traffic costs associated with vehicles; obtaining a value that encompasses all of these costs will enable policy makers to craft vehicle fee systems that correctly recoup these expenses from individual vehicles.

Beyond the development of vehicle fee systems, component marginal costs by vehicle type can also be used to update the existing HCA study. Detailed section level cost data can further augment existing methodologies, which are currently based on applications of various Passenger Car Equivalencies (PCEs), and will help to provide a more accurate representation of vehicle marginal costs on a more refined geographic scale. Updating the HCA will equip policy makers and researchers with the information needed for future studies regarding infrastructure investment and various vehicle fee systems.

Another key use for marginal cost data is the direct analysis of highway infrastructure investment. Geospatial analysis of section level marginal cost data could potentially identify areas where infrastructure investment is required. Sections with significantly high marginal costs may be associated with inadequate capacity or maintenance systems. Furthermore, combining the marginal vehicle cost data (costs from adding one more vehicle) from this report with marginal infrastructure cost data (costs from adding one more unit of roadway capacity) provides a means for conducting benefit cost analyses on infrastructure investment.

This paper proposes methodology for estimating marginal costs to society of vehicle transit on roadways within the United States. The analysis obtains values for several component marginal costs, including: infrastructure, safety, environment, travel, noise and vehicle operations. These costs estimated for seven different vehicles categories (small automobiles, medium-large automobiles, pickups and vans, six-tire single-unit trucks, three and four axle single-unit trucks, four axle combined trucks, and five axle combined trucks) for the peak and off-peak periods use retrofitted models primarily based on the Highway Economic Requirements System (HERS) in conjunction with the Highway Performance Monitoring System (HPMS) database.

While this methodology relies on engineering cost models formulated within the existing core of HERS, the overall goal of calculating marginal vehicle costs requires a redesign of the existing input system, recreation of existing core models, and further manipulation of basic total cost outputs from models to derive marginal costs. Both estimates of total marginal cost to society as well as estimates of component marginal costs are then produced to allow for future analysis of current policies as well as development of road pricing strategies. As shown through the simple analysis of the current gas tax revenue system, knowing the full marginal cost of individual vehicle types on roadways at various geographic scales empowers decision makers with the knowledge necessary for crafting more sustainable and socially equitable transportation revenue systems.

2. Data

The methodology proposed in this research uses the Highway Performance Monitoring System (HPMS) to estimate marginal costs on individual segments of roadway. This database contains yearly reported performance and design characteristics for all major roadways within the United States from 1978 to 2008. Each roadway is broken down into smaller segments by mile marker and is identified by route, state, county and functional classification identification codes. All roadways are represented in this system except for rural and urban local roadways.

The HPMS database is further broken down into the Universe database and the Sample database. The Universe database contains general roadway information for every roadway represented in the HPMS, which includes location, general geometry and the Average Annual Daily Traffic Volume (AADT) data. The Sample database is a more refined dataset comprised of only a subsection of national roadways that have conducted additional data collection; gathering information regarding vertical and horizontal alignments, paving conditions and maintenance, truck percentages, intersection controls, peaking factors, etc.. In conjunction, these two HPMS datasets are used by the Federal Highway Administration, the US Department of Transportation and the US Congress to conduct system condition, performance and investment analysis (as provided by the HERS and other analysis frameworks).

As the methodology proposed in this study is based on HERS cost models, which rely on numerous performance and design measurements only contained within the HPMS sample database, marginal costs are only calculated for the portion of roadways that were sampled. These roadways were then expanded using HPMS sample expansion factors. Future analysis will merge the HPMS sample and universe databases to obtain marginal cost estimates on all roadways.

3. Methodology

3.1 Implementation Overview

The Highway Economic Requirements System (HERS) provides a strong framework for calculating the marginal cost of U.S. roadways by interfacing directly with the Highway Performance Monitoring System database. While HERS is specifically designed for analyzing small portions of the nation's highways for planning and improving purposes, the economic and engineering models for impact estimation can be readily retooled to calculate total and average costs for every roadway segment. These total and average cost equations can be further manipulated to produce marginal costs per vehicle type for every roadway segment reported in the HPMS Sample database.

3.1.1 Fleet Disaggregation System

The key to calculating marginal costs for every roadway segment is the addition of a manual disaggregate fleet input system, which provides a means for both incrementing individual vehicle types as well as iterating the cost analysis process. By design, the HERS uses an automated fleet disaggregation system (which relies on empirically estimated coefficients to break the fleet down into vehicle classes) along with HPMS Average Annual Daily Traffic (AADT) and Truck Percentage data. As this architecture is unable to increment individual vehicle volume types for re-calculating cost conditions under higher vehicle loads, a manual disaggregate approach is used for inputting vehicle volumes. First, the HERS fleet disaggregation coefficients are used to break the traffic flow into separate vehicle categories, which are then re-stored in an expanded HPMS database. These different vehicle volumes are then incremented before separate iterations of the cost models are conducted to obtain total costs under different vehicle volume conditions, which are later used to calculate marginal costs by vehicle types. As the pre-compiled HERS program lacks the enhanced access to the input system needed, the core cost models are redesigned with the proposed disaggregate fleet input system and marginal cost calculations.

3.1.2 Core HERS Cost Models

The HERS system consists of seven principle models: Pavement Condition, Speed Estimation, Vehicle Operation Costs, Emission Costs, Travel Time Costs, Agency Costs and Safety Costs. As shown below in Figure 4-1, HERS first estimates pavement conditions by executing the pavement sub-model. Secondly, estimates of effective speeds for each vehicle are estimated by the Speed sub-model and passed onwards into the Emissions, Vehicle Operation cost, and Travel Time cost models. Thirdly, the Agency cost model uses the forecasted pavement condition to derive costs for resurfacing roadway sections. Lastly, the Safety cost model estimates property damage, injury and fatality costs independently of the other models. In addition to the HERS models shown below, this report implements a Noise cost model based on work conducted by Haling and Cohen, which uses the average effective speeds of vehicles to determine noise damages.

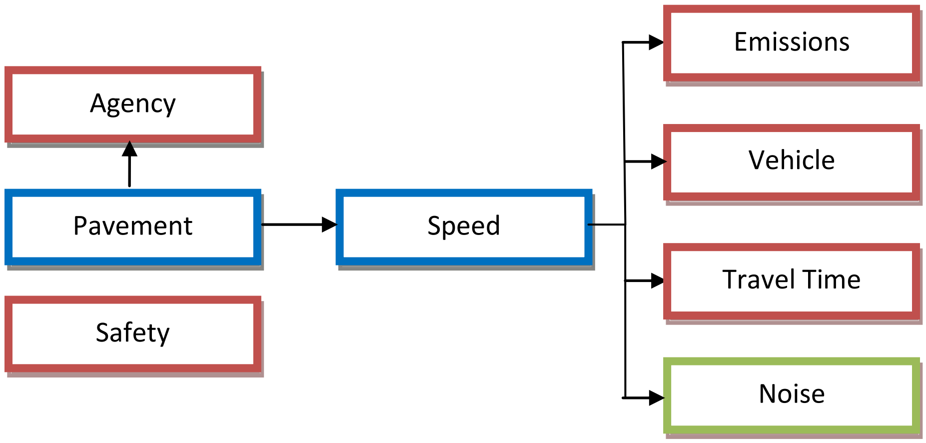


Figure 3.1 Model Relationships

Once each cost model has been used to compute respective total costs, the process can be iterated through the redesigned disaggregate fleet input system with incremented values of different vehicle types to obtain marginal costs without further derivation of the complex formulas employed by HERS.

3.2 Pavement Deterioration Model

The models employed by HERS to forecast pavement conditions consider both the wear due to vehicle traffic as well as the natural deterioration associated with weather conditions. A maximum rate of deterioration is developed according to the structural number (SN) for the respective pavement type reported in HERS. In addition, a minimum deterioration rate is set to reflect only the effects of weather on the roadway surface. The pavement deterioration is then calculated and finally constrained by these minimum and maximum rates to arrive at a forecasted pavement condition.

3.2.1 Pavement Damage by Vehicles

Based on the 1993 AASHTO Pavement Design guide, wear caused by vehicles is only considered significant for vehicles with individual axle loads greater than 18,000 pounds. Thus, HERS assumes pavement damage is only caused by single (6-tire or 3 to 4 axle) trucks and combined (4 and 5+ axle) trucks. Using the reported AADT, Percent Average Daily Single Unit Commercial Vehicles (PADSUC) and Percent Average Daily Combination Commercial Vehicles (PADCC), for each sample segment in HPMS the total number of Equivalent Single Axle Loads per year can be computed as follows:

$$ESALS = 365 * (AADT * PADSUC * ELF_{SU} * LF) * (AADT * PADCC * ELF_{SU} * LF) \quad \text{Eq. 3.2.1}$$

Where:

ELF_{SU}	=	Equivalent load factor for single unit trucks per pavement and functional class type
ELF_{CM}	=	Equivalent load factor for combination trucks per pavement and functional class type

LF = Lane load distribution factor.

Equivalent load factors derived from the AASHTO Pavement design guide are contained within Table 5-1 of the HERS Technical Report. Similarly, Lane load distribution factors are contained within Table 5-2, and are used to describe the usage of individual lanes for single and multi lane roadways. With the number of ESALs computed for each segment, the final end-of-year pavement condition (PSRF) is computed separately for flexible and rigid pavements in terms of pavement serviceability rating (PSR):

$$PSRF = 5 - 3.5 * 10^{XG} \qquad \text{Eq. 3.2.2}$$

Flexible Pavement $XG = XB * (LOG(ESALS) - XA - XO - XM)$ Eq. 3.2.3

Rigid Pavement $XG = XB * (LOG(ESALS) - XA - XO - XN - XC)$ Eq. 3.2.4

Where:

XA = Function of the pavement's structural number

XO = Function of the pavement's reliability

XM = Function of the pavement's modulus of resistance

XN = Function of the pavement's terminal serviceability index (3.42 by default)

XC = Function of the pavement's modulus of rupture, load transfer coefficient, drainage coefficient, modulus of elasticity, modulus of subgrade reaction and pavement thickness

For further technical documentation regarding component equations for flexible and rigid pavement, see the HERS Technical Report Section 5.1.2

3.2.2 Pavement Damage by Weather

The minimum deterioration rate for both flexible and rigid pavements is a product of the time spent exposed to natural elements. Regardless of the amount of traffic on the roadway, the pavement surface will still deteriorate over time thereby constraining the forecasted pavement condition with an upper bound. Using the last reported resurfacing date and condition, contained in the HPMS sample database, the following equation is used to obtain the maximum possible pavement condition (PSRMAX):

$$PSRMAX = PSR_{t_0} * \left((1/NPSRAI)\right)^{(t-t_0)/ML} \qquad \text{Eq. 3.2.5}$$

Where:

t_O	=	Time at which the section was last resurfaced
t	=	Time of interest (for this study pavement conditions are forecasted for 2009)
PSR_{to}	=	Condition of pavement after last resurfacing
NPSRAI	=	Normal PSR after improvement for respective pavement type
ML	=	Maximum pavement life for respective pavement type (Table 5-6 HERS Technical Report)

This maximum possible pavement condition (PSRMAX) is then used in conjunction with the previously forecasted pavement condition (PSRF):

$$PSRMX = MIN\begin{cases} PSRMAX \\ PSRF \end{cases} \qquad \text{Eq. 3.2.6}$$

Where PSRMX is the pavement condition after enforcing the minimum deterioration due to natural weathering.

3.2.3 Maximum Deterioration Rate

The deterioration of the section's pavement is also constrained by a maximum deterioration rate (by default 0.3 per year). This maximum rate provides a worst case pavement condition which further constrains the previously calculated PSRMX as follows:

$$PSR = MAX\begin{cases} PSR_{t_O} - MAXPDR * (t - t_O) \\ PSRMX \end{cases} \qquad \text{Eq. 3.2.7}$$

Where:

t_O = Time at which the section was last resurfaced

t = Time of interest (for this study pavement conditions are forecasted for 2009)

PSR_{to} = Condition of pavement after last resurfacing

MAXPDR = Maximum deterioration rate per year (0.3)

3.2.4 Final Pavement Condition and Uses

Once the forecasted and constrained pavement condition is calculated, it is then incorporated into the Speed model for estimating the impacts of roadway roughness on average effective speed (AES). In addition, the pavement condition is directly used for estimating Agency Pavement Maintenance Costs.

3.3 Speed Model

The HERS speed model considers the impacts of roadway roughness, curvature, the posted speed limit, grades, number and control types of intersections, and volume to capacity ratios when determining the speeds of individual vehicle types during three periods of the day: off-peak, peak when driving in the peak-direction, and peak when driving in the off-peak direction. Using models based on the Texas Research and Development (TRD) foundations "Aggregate Probabilistic Limiting Velocity Model" (APLVM) in conjunction with algorithms from both Science Applications International Corporation (SAIC) and Cambridge Systematics, Inc. average effective speeds are derived for later use in calculating vehicle operating costs, travel time costs, and emission costs.

3.3.1 Free-Flow Speed Computation (APLVM)

Similar to the APLVM created by TRD, HERS uses four steps to estimate the free flow speed of all vehicles on roadway segments. The first three steps deal with estimating the respective limiting velocities associated with curves, pavement roughness and speed limits. The final step combines these limiting velocities to produce the sections free-flow speed.

Originally developed by the World Bank, the APLVM's estimation of maximum allowable speed on a curve (VCURVE) is calculated using HPMS roadway geometry data and a constant established by TRDF in accounting for the maximum perceived friction ratio (FRATIO) or the ratio of lateral force on a horizontal curve to the normal force.

$$VCURVE = 292.5 * \sqrt{(FRATIO + SP)/DC} \quad \text{Eq. 3.3.1}$$

Where:

FRATIO	=	0.155 for Autos, 0.1055 for Single-Unit Trucks and 0.103 for Combination Trucks
SP	=	Super elevation (estimated from HPMS degree of curvature)
DC	=	Degree of curvature

Estimation of maximum allowable ride-severity speed (VROUGH) is a function of the pavement condition, which is measured in terms of PSR. Equations for HERS were developed based on descriptions of pavement conditions and possible speeds according to various values of PSR. Using the final pavement condition (PSRF) obtained from the previous sub-model, VROUGH is evaluated according to following functions:

When PSRF>1.0 $\quad VROUGH = VR2 + VRSLOP * (PRSF - 1.0)$ $\quad$ Eq. 3.3.2

When PSRF<=1.0 $\quad VROUGH = VR1 + (VR2 - VR1) * PSRF$ $\quad$ Eq. 3.3.3

Where:

VR1	=	Value of VROUGH when PSRF is zero (5 mph by default)
VR2	=	Value of VROUGH when PSRF is equal to 1 (20 mph by default)
VRSLOP	=	Slope of the function when PSRF>1.0 (32.5 by default)

The last limiting velocity; the effects of speed limits on free flow speed (VSPLIM) is assumed to be 9.323 mph (for urban freeways or rural multilane access controlled roads) or 6.215 mph (for all other roadway segments) greater than the speed limit.

The three limiting speeds are combined using the following APLVM equation based on World Bank and TRDF studies:

$$FFS = \left(\left(\frac{1}{VCURVE}\right)^{10} + \left(\frac{1}{VROUGH}\right)^{10} + \left(\frac{1}{VSPLIM}\right)^{10}\right)^{-0.1} \qquad \text{Eq. 3.3.4}$$

3.3.2 The Effects of Grades

HERS calculates the effects of uphill grades on free-flow speed for single and combined unit trucks using an algorithm proposed by SAIC. Personal vehicles (small, medium and large cars, as well as vans and pickups) are assumed to be unaffected by uphill grades for the purpose of HERS estimations. The equation shown below is used to obtain estimates of crawl speed (CRAWLS) in mph for the different commercial vehicle types:

$$CRAWLS = \frac{1}{0.0090 + k * GRADE} \qquad \text{Eq. 3.3.5}$$

Where:

k = Grade constant for specific commercial vehicle type

(0.0815 for 6-Tire Trucks, 0.2755 for all others)

GRADE = The average grade of the section (as a fraction)

The crawl speed is then used to calculate the delay in hours due to uphill grades (DGRADE):

$$DGRADE = \begin{cases} a * (1 - e^{b/a}) + b & if\ CRAWLS < FFS \\ 0 & otherwise \end{cases} \qquad \text{Eq. 3.3.6}$$

$$a = -0.05 * \left(\frac{1}{CRAWLS} - \frac{1}{FFS}\right)^{0.6} \qquad \text{Eq. 3.3.7}$$

$$b = SLEN * \left(\frac{1}{CRAWLS} - \frac{1}{FFS}\right) \qquad \text{Eq. 3.3.8}$$

Where:

SLEN = length of the section (miles)

The delay due to uphill grades is then combined with free-flow speed to obtain free-flow speed uphill (FFSUP) for each separate commercial vehicle type:

$$FFSUP = 1/(\frac{1}{FFS} + \frac{DGRADE}{SLEN}) \quad \text{Eq. 3.3.9}$$

3.3.3 The Effects of Congestion and Traffic Control Devices

HERS develops six classifications of highways, using existing SAIC algorithms, to account for effects of traffic control types (signals and stop-signs), and number of lanes per direction. These six classifications are summarized in Table 3.1 below, with references to equation tables used from the HERS Technical Report:

Table 3.1 HERS Highway Classifications for Speed Analysis

#	HERS Classification	Algorithms Used	HERS Table
1	Sections with Stop Signs	Urban Arterials with Unsignalized Intersections	5-16
2	Sections with Traffic Signals	Urban Arterials with Signalized Intersections	5-17,18,19,20
3	Sections with Stop Signs and Traffic Signals	Both: Urban Arterials with Unsignalized Intersections and Urban Arterials with Signalized Intersections	5-16,17,18,19,20
4	Free-Flow Sections, One Lane per Direction	Two-Lane Rural Sections	5-21
5	Free-Flow Sections, Three-Lane Two-Way	Two-lane Rural Sections and modified Freeways and Multilane Rural Highways	5-21,22,23,24,25
6	Free-Flow Sections, Two or More Lanes per Direction	Freeways and Multilane Rural Highways	5-22,23,24,25

Each algorithm is comprised of multiple equations which are conditioned on the roadway section's ratio of Annual Average Daily Traffic (AADT) to two-way peak hour capacity, also referred as the sections ACR. These algorithms produce values for congestion, incident and traffic control delay in terms of hours per 1000 vehicle miles. These delays are then converted into the average effective speed (AES) for each vehicle type on the roadway according to the following equation:

$$AES = 1/(\frac{1}{FFS} + \frac{D}{1000}) \qquad \text{Eq. 3.3.10}$$

Where:

FFS	=	Free-Flow Speed or Free-Flow Speed Uphill (FFSUP) for commercial vehicles
D	=	Average delay in hours per 1000 vehicle miles, considering delay due to incidents, congestion, and traffic control devices

The average effective speed for each vehicle on each roadway is then used to calculate disaggregated fleet vehicle operating costs, travel time costs, and emission costs.

3.4 Safety Model

The HERS Safety Cost model uses a three-step procedure to first estimate the number of crashes, then to apply crash ratios for injuries and fatalities, and, lastly, to estimate the costs per crashes in term of injuries, fatalities, property damage and delay.

3.4.1 Crash Estimation

HERS uses modified versions of crash rate equations recommended by Richard Margiotta's report to FHWA *Incorporating Traffic Crash and Incident Information into the Highway Performance Monitoring System Analytical Process* along with Vogt and Bared's "Accident Models for Two-Lane Rural Segments and Intersections". Estimation of crash rates is broken down into six procedures based on urban or rural facility types: freeways, multi-lane roads and two-lane roads.

3.4.1.1 Rural Two-Lane Roads

According to Vogt and Bared's work, HPMS segments of rural two-lane roads are first broken down into roadway sections and intersections for individual crash estimation. The roadway (non-intersection) crash equations were developed using Highway Safety Information (HSIS) for Minnesota and Washington, and are a function of section length, lane width, shoulder width, grades and curves as displayed below:

$$\begin{aligned} CNINT = {} & 100 * ADJSL/SLEN \\ & * EXP(0.72 - 0.085 * LW - 0.059 * SHW + 0.067 * RHR + 0.0085 * DD + 0.44 * CCGR) \\ & * (\textstyle\sum_i \mathrm{LCURV}_i * \mathrm{EXP}(0.045 * \mathrm{CURV}_i)/\mathrm{SLEN} \\ & * (\textstyle\sum_i \mathrm{LGRD}_i * \mathrm{EXP}(0.011 * \mathrm{GRD}_i)/\mathrm{SLEN} \end{aligned} \qquad \text{Eq. 3.4.1}$$

Where:

SLEN = Section length (miles)

ADJSL	=	Adjusted section length excluding 250ft segments surrounding intersections.
LW	=	Lane width (feet)
SHW	=	Shoulder width (feet)
RHR	=	Roadside hazard rating (default 3.0 for rural roadways)
DD	=	Driveway density (per mile) (default of 3.7 for rural development)
$CURV_i$	=	Average degrees of curvature in HPMS curve class i
$LCURV_i$	=	Total length of all curves in curve class i
GRD_i	=	Average percent grade in HPMS grade class i
$LGRD_i$	=	Total length of all grades in grade class i
CCGR	=	Crest curve grade rate (0 for flat terrain, 0.03 for hilly and mountainous terrain)

The use of the ratio of adjusted section length ADJSL to SLEN reduces roadway crash estimates to segments outside of the 250 foot buffer of intersections, to obtain non intersection crashes per 100 million VMT.

Crash rates at intersections are estimated separately for signalized and "other" (neither signalized nor stop-signed controlled) intersections using the following equations derived from Vogt and Bared's analysis of Minnesota HSIS data:

$$CSINT = 0.2 * NSIG * FSICAS * EXP(-7.74 + 0.64 * LN(ADT1) + 0.58 * LN(ADT2) + 0.33 * CCGR - 0.053 * ADJLA + 0.11 * ND) \quad \text{Eq. 3.4.2}$$

$$COINT4 = 0.2 * 0.45 * NOINT * EXP(-7.74 + 0.64 * LN(AADT) + 0.58 * LN(ADT2) + 0.33 * CCGR - 0.053 * ADJLA + 0.11 * ND) \quad \text{Eq. 3.4.3}$$

$$COINT3 = 0.2 * 0.55 * NOINT * EXP(-11.48 + 0.82 * LN(AADT) + 0.51 * LN(ADT2) + 0.26 * CCGR + 0.036 * DC + 0.027 * SPDLIM + 0.18 * RHR3LI + 0.24 * PRTL) \quad \text{Eq. 3.4.4}$$

Where:

VMT	=	Vehicle Miles traveled on the section over one year
CSINT	=	Annual crashes at signalized intersections
COINT4	=	Annual crashes at "other" four-legged intersections
COINT3	=	Annual crashes at "other" three-legged intersections
NSIG	=	Number of signalized intersections
FSICAS	=	Fraction of total AADT on the reported HPMS section AADT/(ADT1+ADT2)
ADT1	=	At signalized intersections, the AADT of the road with the highest volume
ADT2	=	At "other" intersections, the AADT of the road with the lowest volume
ADJLA	=	Adjusted intersection angle (default 2.0)
NOINT	=	Number of "other" intersections
AADT	=	Average annual daily traffic reported for the segment in HPMS
ND	=	Number of driveways within 250 feet of intersection = (500/5280)*DD
DC	=	Average degree of curvature on the section

SPDLIM	=	Speed limit (mph)
RHR3LI	=	Roadside hazard rating for three-legged intersections (default 2.1)
PRTL	=	Probability that a three-legged intersection has a right-turn lane (default 0.42)

ADT1 and ADT2 are set based on the functional classification of the roadway:

- Rural principle arterials - assumed that intersecting roadways carry less, ADT1 = AADT and ADT2 = 0.5 *AADT
- Rural major collectors - assumed intersecting roadways carry more, ADT1 = AADT and ADT2 = 2 * AADT
- Rural minor arterials - assumed volume on both roadways is equal, ADT1 = AADT and ADT1 = AADT

Further technical documentation on HERS process of selecting default values for adjusted intersection angles, roadside hazard ratings and presence of right-turn lane probabilities can be found in the HERS Technical Report, Section 5.3.1.1.

$$CRASH = 1.056 * (CNINT + CINT) \quad \text{Eq. 3.4.5}$$

Combining the crash rates from equations 3.4.2 through 3.4.4, using the above equation, produces an estimate of the number of intersection crashes per 100 million vehicle miles along a particular segment.

3.4.1.2 Rural Multilane Roads

Based on work done by Wang, Hughes and Stewart with the Minnesota HSIS data for rural four-lane roads HERS calculates crash estimates per 100 million vehicle-miles for rural multilane roads using the following equation:

$$CRASH = 132.2 * AADT^{0.073} * EXP(0.131 * RHRRML - 0.151 * AC + 0.034 * DDRML + 0.078 * INTSPM - 0.572 * RPA + 0.0082 * (12 - LW) - 0.094 * SHLDW - 0.003 * MEDW) \quad \text{Eq. 3.4.5}$$

Where:

RHRRML	=	Roadside hazard rating for rural multilane roads (default 2.45)
AC	=	Access control (1 for full or partial control, 0 otherwise)
DDRML	=	Driveway density for rural multilane roads (default 0.41 for rural development)
INTSPM	=	Intersections per mile (maximum of 10)
RPA	=	Binary for rural principle arterial and interstate (1 if rural principle arterial or rural interstate, 0 otherwise)
LW	=	Lane width (feet)
SHLDW	=	Shoulder width (feet)
MEDW	=	Median width (feet)

3.4.1.3 Rural Freeways

The equation for rural freeway crash rate estimation relies on work done by Persaud in estimating four-lane highway crash rates for Ontario, with minor adjustments proposed by HERS to account for lane width (LW) and calibration for all configurations of rural freeways contained in HPMS.

$$CRASH = 17.64 * AADT^{0.155} * EXP(0.0082 * (12 - LW)) \qquad \text{Eq. 3.4.6}$$

The effect of lane width on freeway crash rates is assumed to be the same as that of other rural multilane roadways, as shown in the previous equation 4.4.5

3.4.1.4 Urban Two-Lane Streets

The equation for estimating the crash rates for urban two-lane streets was obtained using ordinary least squares regression (r^2 of 0.99) and calibration factors obtained by Margiotta using HSIS data from Illinois, Maine, Minnesota and Utah and 1994 HPMS data. As shown below this crash rate, in crashes per 100 million vehicle-miles, is a function of only segment AADT:

$$CRASH = -19.6 * LN(AADT) + 7.93 * (LN(AADT))^2 \qquad \text{Eq. 3.4.7}$$

3.4.1.5 Urban Multilane Surface Streets

Again based on work completed by Margiotta, using data developed by Bowman and Vecellio in 1994, the estimation of crash rates for urban multilane surface streets and urban expressways without full access control is as follows:

$$CRASH = A * AADT^{B} * NSIGPM^{C} \qquad \text{Eq. 3.4.8}$$

Where:

NISGPM = Number of signals per mile

A, B and C = Constants dependent on type of surface street section Obtained from the HERS Technical Report Table 5-9, as shown below in Table 3.2

Table 3.2 Parameters for Urban Multilane Surface Street Crash Estimation

Type of Section	A	B	C
Two-way Left-Turn Lanes	95.1	0.1498	0.4011
One-Way, or Two-Way with a median: 1) wider than 4 feet 2) curbed, or 3) a positive barrier	82.6	0.1749	0.2515
Otherwise	115.8	0.1749	0.2515

3.4.1.6 Urban Freeways

The last of the six procedures for estimating crash rates uses equations developed by Margiotta from 1994 results in Tedesco's report to IVHS America and Margiotta and Cohen's *Roadway Usage Patterns: Urban Case Studies*. HERS further incorporated a lane width factor similar to equations 3.4.5 and 3.4.6 as shown below:

$$CRASH = (154.0 - 1.203 * ACR + 0.258 * ACR^2 - 0.00000524 * ACR^5) * EXP(0.0082 * (12 - LW)) \qquad \text{Eq. 3.4.9}$$

Where:

ACR = AADT divided by two-way hourly capacity contained in HPMS

3.4.2 Fatality and Injury Rates

The estimated numbers of fatalities and injuries due to crashes are assumed to be proportional to the number of crashes on specific roadway functional classes. HERS used fatality and injury estimates from the 1995 Highway Statistics, along with the number of crashes per 100 million vehicle-miles to obtain fatality and injury ratios per crashes by functional classification. As shown in the HERS technical report (Table 5-12) Table 3.3, below, summarizes these ratios:

Table 3.3 Fatality and Injury Rates by Functional Classification

Functional Classification	Fatalities per Crash	Injuries per Crash
Rural		
Interstate	0.01408	0.4546
Other Principle Arterial	0.01685	0.6317
Minor Arterial	0.01362	0.5610
Major Collector	0.0137	0.6261
Urban		
Interstate	0.00382	0.4908
Other Freeway or Expressway	0.00396	0.3640
Other Principle Arterial	0.00273	0.4113
Minor Arterial	0.00237	0.3401
Collector	0.00237	0.3496

3.4.3 The Cost of Crashes

HERS uses crash rates per 100 million vehicle-miles along with injury and fatality rates per crashes to obtain the number of crashes, fatalities, and injuries along a segment of roadway per 100 million vehicle-miles. The third, and final, step of the safety model merges these estimates with unit costs to produce a total safety cost.

Injury costs are derived from Ted Miller's study in 1991 and were later updated with the 1994 National Highway Traffic Safety Administration's (NHTSA) Maximum Abbreviated Injury Scale (MAIS), which are based on principles of willingness to pay. Estimates of property damage costs and travel delay cost were also derived from the NHTSA and HERS crash estimation and calibration procedure. Finally, using U.S. Department of Transportation 1994 estimates on the value of life, HERS found the cost of fatal injury to be $2.7 million (current value of life estimates from studies concluding in 2004 show the estimated value of life at $5.8 million). Using the value of life, MAIS and estimates of crashes per each MAIS level, HERS produces average injury costs per injury, along with property damage costs per crash in 1994 dollars, as shown below in Table 3.4 by functional classification. These costs are then indexed from 1994 to future years using the Consumer Price Index (1.126 to 1997) for property damage, and the Bureau of Labor Statistics Employment Cost Index (1.089 to 1997) for delay costs and injuries.

Table 3.4 Injury and Property Damage Costs by Functional Classification

Functional Classification	Injury Cost per Injury	Property Damage Cost per Injury
Rural		
Interstate	$52,800	$5,000
Other Principle Arterial	68,300	6,300
Minor Arterial	55,900	6,300
Major Collector	77,650	6,300
Urban		
Interstate	55,900	6,300
Other Freeway or Expressway	46,600	7,500
Other Principle Arterial	49,700	7,500
Minor Arterial	40,400	7,500
Collector	31,300	6,300

Taking these indexed costs and multiplying by the number of injuries, fatalities and crashes, yields safety costs per 100 million vehicle miles in 1997 dollars. Further work is needed to provide proper indexing and safety model improvements for use with the 2008 HPMS.

$$DELCC = \frac{0.0886 * AADT}{LANES} * CRASH \qquad \text{Eq. 3.4.10}$$

Where:

LANES	=	Number of lanes
CRASH	=	The calculated crash rate for the section per 100 million VMT

Additionally, delay costs due to incidents (DELCC) are also calculated for use in the speed model in calculating total delay; however, the delay produced by the safety model is only used in one lane free flow sections, or sections with stop signs, as calibrated equations for incident delay are already contained within speed calculations on other types of roadways. Furthermore, as shown above in equation 3.4.10, HERS assumes a linear relationship between delay cost and traffic volume, which is an oversimplification and results in poor estimates for congested and uncongested roads.

3.5 Vehicle Operations Model

Vehicle operating costs for users is estimated separately for fuel, oil, tires, maintenance and vehicle depreciation. Each of these costs is further broken down into constant-speed operating costs, excess operating costs due to speed changes, and excess operating costs due to curves.

3.5.1 Constant Speed Costs

Constant speed cost estimated relies on the average effective speed (AES), calculated in the previous speed model, average grades and pavement conditions (PSR), calculated in the previous pavement model. In addition, HERS compiles 1997 unit costs of fuel, oil, tires, maintenance and depreciation, which are further adjusted to 2000 unit costs using respective adjustment factors (contained in section 5.2.1.2 of the HERS Technical Report). As shown below equation 3.5.1, constant speed operating costs for a specific vehicle type ($CSOPCST_{vt}$) can be calculated as:

$$\begin{aligned} CSOPCST_{vt} = {} & CSFC * PCAFFC * COSTF_{vt}/FEAF_{vt} \\ & +CSOC * PCAFOC * COSTO_{vt}/OCAF_{vt} \\ & +0.01 * CSTW * PCAFTW * COSTT_{vt}/TWAF_{vt} \\ & +0.01 * CSMR * PCAFMR * COSTMR_{vt}/MRAF_{vt} \\ & +0.01 * CSVD * PCAFVD * COSTVD_{vt}/VDAF_{vt} \end{aligned} \quad \text{Eq. 3.5.1}$$

Where:

CSFC	=	Constant speed fuel consumption rate (gallons/1000 miles)
CSOC	=	Constant speed oil consumption rate (quarts/1000 miles)
CSTW	=	Constant speed tire wear rate (%worn/1000 miles)
CSMR	=	Constant speed maintenance rate (% of avg. cost/1000 miles)

CSVD	=	Constant speed depreciation rate (% of new price/1000 miles)
PCAF (FC,OC,TW,MR,VD)	=	Pavement condition adjustment factors for fuel, oil, tire wear, maintenance and depreciation (Table E-16 through E-11 of HERS Technical Report)
$COST_{vt}$ (F,O,T,MR,VD)	=	Unit cost of fuel, oil, tires, maintenance and depreciation for vehicle type (vt).
AF_{vt} (FE,OC,TW,MR,VD)	=	Fuel efficiency, oil consumption, tire wear, maintenance and depreciation adjustment factors for vehicle type (vt)

Equations for estimating constant speed consumption rates were derived from Zaniewski's 1982 FHWA report: "Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors." HERS used ordinary least squares regression and slight modifications to account for an overall increase of roadway speeds since the 1980s. Below, in Table 3.5, is an example of the produced constant speed consumption rates for small car fuel consumption as a function of both grade and average effective speed:

Table 3.5 Constant Speed Fuel Consumption for Small Auto

Data Need	HERS Table	Source	Equation
AVG Effective Speed (AES), Grade(%),	E-2. Small Auto Constant-Speed Fuel Consumption	J.P. Zaniewski 1982 P.J. Claffey 1971 C. Daniels 1974	GR ≥ 0 CSFC = 100.82 - 4.9713*AES + 0.11148*AES^2 -0.0011161*AES^3 + 5.1089e-06*AES^4 + 3.0947*GR GR < 0 and AES ≤ 40 CSFC = (91.045 - 4.0552*AES + 0.060972*AES^2 + 4.0504*GR + 0.4227*GR^2) / (1 -0.014068*AES + 0.0004774*AES^2 - 0.045957*GR + 0.0054245*GR^2) GR < 0 and AES > 40 CSFC = 23.373 + 3.6374*GR + 0.21681*GR^2+ (72.562 / (1 + exp(-((AES - 81.639) /7.4605))))

Similar to the derivation of constant speed consumption rates, HERS also performed ordinary least squares regression on Zaniewski's pavement condition adjustment factors for oil, tire wear, maintenance, and deprecation. As Zaniewksi did not calculate a pavement condition adjustment factor for fuel, HERS assumes the factor is set to 1.

3.5.2 Excess Cost of Speed Changes

For HPMS section with stop signs or signals, HERS calculates excess operating costs due to speed variability. Using a formula similar to that of the constant speed cost equation 3.5.1, along with equations derived from Zaniewski's FHWA report using ordinary least squares regression, the cost of speed variability ($VSOPCST_{vt}$) is shown on the following page:

$$VSOPCST_{vt} = VSFC * COSTF_{vt}/FEAF_{vt}$$ Eq. 3.5.2

$$+VSOC * COSTO_{vt}/OCAF_{vt}$$

$$+VSTW * COSTT_{vt}/TWAF_{vt}$$

$$+VSMR * COSTMR_{vt}/MRAF_{vt}$$

$$+VSVD * COSTVD_{vt}/VDAF_{vt}$$

Where:

VSFC = Variable speed fuel consumption rate (gallons/1000 miles)

VSOC = Variable speed oil consumption rate (quarts/1000 miles)

VSTW = Variable speed tire wear rate (%worn/1000 miles)

VSMR = Variable speed maintenance rate (% of avg. cost/1000 miles)

VSVD = Variable speed depreciation rate (% of new price/1000 miles)

Similar to the speed model, signals and stops signs are assumed to be evenly spaced along the HPMS segment. If a segment has both signals and stop signs, it is also assumed that all signals are placed on one side of the segment, and all stop signs are placed on the other.

3.5.3 Excess Cost of Curves

Two approaches are used in estimating the effects of curves on operating costs. For sections with average effective speeds (AES) less than 55 mph, HERS first uses two dimensional linear interpolation of the Zaniewksi curve tables directly, then, to index values from 1980 to 2000, HERS multiplies by factors representing improvements to fuel consumption, tire wear and maintenance. For sections with AES greater than 55 mph, HERS uses equations fit to Zaniewski's curve data (after indexing to 2000) for speeds between 55 and 70 mph. The resulting component consumption rates for fuel, tires and maintenance produced by these two methods, are then used within the following equation to produce excess operating cost due to curves ($COPCST_{vt}$):

$$COPCST_{vt} = CFC * COSTF_{vt}/FEAF_{vt} \quad \text{Eq. 3.5.3}$$
$$+0.01 * CTW * COSTT_{vt}/TWAF_{vt}$$
$$+0.01 * CMR * COSTMR_{vt}/MRAF_{vt}$$

Where:

CFC	=	Curve fuel consumption rate (gallons/1000 miles)
CTW	=	Curve tire wear rate (%worn/1000 miles)
CMR	=	Curve maintenance rate (% of avg. cost/1000 miles)

Once the constant speed, variable speed and curve operating costs are calculated for each vehicle, the resulting costs are then summed together and multiplied by the estimated fleet composition to obtain a total fleet operating cost.

3.6 Travel Time Model

In estimating travel time costs, HERS uses values of time per person for personal travel and for business based on the U.S. Department of Transportation's Departmental Guidance report from 1997. As summarized below in Table 3.6, (copied from the HERS Technical Report Table 5-27), the catalogued 1995 values produced by HERS for one hour travel time are further indexed to 2000 dollars using separate operations for value of time per person, vehicle cost, and inventory cost.

Table 3.6 Value of One Hour of Travel Time (1995 Dollars)

	Small Auto	Medium Auto	Pickup and Van	6-Tire Truck	3 to 4 Axle Truck	4- Axle Comb.	5- Axle Comb.
Business Travel							
Value per Person	$18.80	$18.80	$18.80	$16.50	$16.50	$16.50	$16.50
Avg. Occupancy	1.43	1.43	1.43	1.05	1.00	1.12	1.12
Vehicle	$1.09	$1.45	$1.90	$2.65	$7.16	$6.41	$6.16
Inventory	-	-	-	-	-	$0.60	$0.60
Personal Travel							
Value per Person	$8.50	$8.50	$8.50	-	-	-	-
Avg. Occupancy	1.67	1.67	1.67	-	-	-	-
Percent Personal	89%	89%	75%	-	-	-	-
Avg. Value Per Vehicle	**$15.71**	**$15.75**	**$17.84**	**$19.98**	**$23.66**	**$25.49**	**$25.24**

These indexes are developed respectively from the U.S. Bureau of Labor Statistics Employment Cost Index for compensation of civilian workers, the U.S. Department of Commerce Bureau of Economic Analysis (BEA) average expenditure per car, and the implicit gross domestic product deflator.

3.6.1 Average Vehicle Occupancy

Average vehicle occupancy is obtained by using both the 1995 National Personal Travel Survey's (NPTS)estimates of vehicle miles and person miles of travel by trip type, and Hertz's crash analysis of trucks involving two-person driver teams. For four-tire vehicles (Small and Medium Autos, Pickups and Vans) the NPTS produces estimates of 1.43 persons per vehicle. For combination and 6-Tire Single Trucks, Hertz estimates average occupancy of 1.12 and 1.05 respectively.

3.6.2 Vehicle Time Related Depreciation Costs

Vehicle costs were estimated as time related depreciation of vehicles, which is different from the previous operating cost depreciation by vehicle use. The estimation process first estimates total annual depreciation by vehicle type, then, by subtracting the depreciation of vehicle use, travel time depreciation can be estimated.

To estimate the total travel time cost per vehicle type, HERS uses the indexed average value of time per vehicle in conjunction with the average effective speed of the vehicle type:

$$TTCST_{vt} = \frac{1000}{AES_{vt}} * TTVAL_{vt} \qquad \text{Eq. 3.6.1}$$

Where:

AES_{vt} = Average effective speed of vehicle type (vt) from the previous speed model

$TTVAL_{vt}$ = Average value of time for occupants and cargo of the vehicle type (vt)

Once the total travel time costs have been estimated for each vehicle type, the costs can then be summed together and multiplied by the estimated fleet composition to obtain a total fleet travel time cost.

3.7 The Agency Cost Model

Agency costs in HERS are primarily based on the maintenance and improvement of roadway facilities: including resurfacing, reconstructing, widening, and realigning. For the purposes of marginal cost research, this report focuses on three of these agency improvements: resurfacing of pavement, reconstruction of roadways and the widening of roads by one lane in either direction. Vertical and Horizontal Realignment is not considered due to the additional requirement of individual section GIS alignment data supplied by the user. These costs are further broken down into short-run (maintenance) versus long-run (capital improvement) costs, where short-run costs are used by this report for further marginal cost analysis of VMT fee structures. For thoroughness, both short-run and long-run models are presented in this report.

3.7.1 Pavement Maintenance Model

As the only short-run marginal cost considered, estimates for per lane-mile maintenance costs are computed for both flexible and rigid pavement types using the same methodology. Based on Witczak and Rada's *Mircocomputer Solution of the Project Level PMS Life Cycle Cost Model* which models the cumulative cost of maintenance as a function of pavement serviceability rating (PSR) and the pavements structural number (SN), HERS used simple regression to obtain the following equation in terms of PSR for maintenance cost in 1988 dollars:

$$MCOST = -(2411 + 4355 * SN) * (PSR_f - PSR_i) + (270.9 + 489.6 * SN) * (PSR_f^2 - PSR_i^2) \quad \text{Eq. 3.7.1}$$

Where:

SN = Structural number

PSR_f = Forecasted PSR from the pavement model (forecasted for year 2009)

PSR_i = PSR at last resurfacing (taken from the HPMS and pavement model)

The per lane-mile maintenance cost equation is then indexed from 1988 dollars to 2001 dollars using a factor of 1.231 for rural sections and 1.242 for urban sections.

3.7.2 Pavement Resurfacing Model

Again based on the PSR value, outputted by the Pavement model mentioned earlier in this report, and a threshold PSR value obtained from the Default Deficiency Pavement Conditions shown in Table 3.7, the resurfacing model designates whether a particular roadway segment requires resurfacing as shown in the following equation:

$$RESIMP = \begin{cases} 1 \; if \; 1.0 < PSR < PSR_{Threshold} \\ 0 \; Otherwise \end{cases} \qquad \text{Eq. 3.7.2}$$

Where:

RESIMP = Section requires resurfacing or not

Table 3.7 Default Deficiency Pavement Condition Thresholds		
Rural	**PSR Resurface**	**PSR Reconstruct**
Interstate	1.8	1.4
Other Principle Arterial AADT > 6000	1.8	1.4
Other Principle Arterial AADT <= 6000	1.5	1.1
Minor Arterial	1.2	0.9
Collector AADT>1000	1.0	0.8
Collector 400<AADT<AADT	0.8	0.6
Collector AADT < 400	0.6	0.5
Urban	**PSR Resurface**	**PSR Reconstruct**
Interstate	2.0	1.5
Other Freeway or Expressway	1.8	1.4
Other Principal Arterial	1.6	1.2
Minor Arterial	1.0	0.8
Collector	0.8	0.6

The long-run resurfacing cost (RS_{Cost}) is then computed for the section using the following equation:

$$RS_{Cost} = SLENGTH * SLANES * \text{RESCOST} * \text{RESIMP} \qquad \text{Eq. 3.7.3}$$

Where:

SLENGTH	=	Section Length in Miles
SLANES	=	Number of Section Lanes
RESCOST	=	Resurfacing Cost for Highway Type (from Table 3.11)

3.7.3 Pavement Reconstruction Model

Similar to the Resurfacing Model in section 437.3, the Reconstruction model relies on the PSR value outputted by the Pavement model and a threshold PSR value also obtained from Default Deficiency Pavement Conditions in Table 3.7. The reconstruction of a roadway is significantly more expensive in comparison to simple resurfacing, and is only required when pavement conditions have become severe enough to cause a significant impact to drivers.

$$RECIMP = \begin{cases} 1 \ if \ PSR < PSR_{Threshold} \\ 0 \ Otherwise \end{cases} \qquad \text{Eq. 3.7.4}$$

Where:

RECIMP	=	Section requires construction or not

The reconstruction cost (RC_{Cost}) is then computed for the section using the following equation:

$$RC_{Cost} = SLENGTH * SLANES * \text{RECCOST} * \text{RECIMP} \qquad \text{Eq. 3.7.5}$$

Where:

SLENGTH = Section Length in Miles

SLANES = Number of Section Lanes

RECCOST = Reconstruction Cost for Highway Type (from Table 3.11)

3.7.4 Capacity Expansion Model

3.7.4.1 Widening Model

The widening model considers the addition of full lanes to the roadway given unacceptable volume to capacity ratios, as well as the widening of lanes and shoulders given sub design standards. The widening/addition of lanes as well as the widening of shoulders are dependent upon the feasibility of widening the roadway segment. This information is provided by the HPMS for each roadway using the Widening Feasibility Code (WDFEAS), which is coded as follows:

Table 3.8 Widening Feasibility Code and Binary Decision Variables				
Code	**Widening Feasibility**	**NLF**	**NWLF**	**WSF**
1	No widening is feasible	0	0	0
2	Partial lane may be added	0	1	1
3	One way lane may be added	1	1	1
4	Two lanes may be added	1	1	1
5	Three or more lanes may be added	1	1	1

Further, Table 3.8 above shows the binary decision variables of feasibility for adding a lane (NLF), widening a lane (WLF) and widening a shoulder (WSF), which are used to determine the type of capacity improvement being applied to the segment.

3.7.4.2 Building an Additional Lane

Providing segment widening is feasible, the volume to capacity ratio for the segment is checked to determine if additional capacity is required. This ratio is obtained for the peak hour congestion period from the Speed methodology previously mentioned in this report. The VC threshold is obtained from the Default Deficiency Volume/Capacity Conditions shown in Table 3.9 below, which details VC thresholds as a function of section terrain, rural or urban location and functional classification.

$$VCIMP = \begin{cases} 1 \ if \ Volume \ to \ Capacity \ ratio > VC_{Threshold} \\ 0 \ Otherwise \end{cases} \qquad \text{Eq. 3.7.6}$$

Where:

VCIMP = Section requires an additional lane or not

Table 3.9 Default Deficiency Volume/Capacity Condition Thresholds			
	VC Threshold for Adding Lane		
Rural	**Flat**	**Rolling**	**Mountainous**
Interstate	0.90	0.95	0.98
Other Principal Arterial	0.90	0.95	0.98
Minor Arterial	0.90	0.95	0.98
Collector AADT>1000	0.90	0.95	0.98
Collector AADT<1000	1.00	1.00	1.00
Urban	**Flat**	**Rolling**	**Mountainous**
All	0.98	0.98	0.98

The construction cost for adding an additional lane (NL_{Cost}) is then obtained by the following equation:

$$NL_{Cost} = SLENGTH * \mathrm{ADLCOST} * NLF \qquad \text{Eq. 3.7.7}$$

Where:

SLENGTH = Section Length in Miles

ADCOST = Adding a Lane Cost for Highway Type (from Table 3.11)

NLF = New Lane Widening Feasibility (from Table 3.8)

3.7.4.3 Building an Additional Lane and Widening Lanes

If widening is feasible for a lane, based on the binary WLF from Section 3.7.5.1, the widening lane model then considers the current section lane width versus a design threshold obtained from Table 3.10 below.

Table 3.10 Default Deficiency Lane and Shoulder Width Condition Thresholds

Rural	Lane Width Threshold	Shoulder Width Threshold
Interstate	11	6
Other Principal Arterial	10	6
Minor Arterial AADT > 2000	8	6
Minor Arterial AADT < 2000	8	4
Collector AADT > 1000	8	2
Collector AADT < 1000	8	0
Urban	**Lane Width Threshold**	**Shoulder Width Threshold**
Interstate	11	6
Other Freeway or Expressway	10	6
Other Principal Arterial	9	0
Minor Arterial	8	0
Collectors	8	0

$$WLIMP = \begin{cases} 1 \; if \; Lane\ Width < \; Lane\ Width_{Threshold} \\ 0 \; Otherwise \end{cases} \qquad \text{Eq. 3.7.8}$$

Where:

WLIMP = Section requires lane widening

The cost to construct a lane and widen existing lanes is then computed using the following equation:

$NWL_{Cost} = SLENGTH * \text{ADWLCOST} * WLF$ Eq. 3.7.9

Where:

ADWLCOST = Adding and Widening Lanes Cost for Highway Type (from Table 3.11)

WLF = Lane Widening Feasibility (from Table 3.8)

3.7.4.4 Widening Shoulders

Similar to the construction of a new lane and widening of existing lanes, the shoulder widening model again looks at a threshold design width for shoulders (again found in table X) versus the current segments condition. If the shoulder is considered inadequate, the improvement cost model will include a cost for widening existing shoulders, using the following equations:

$$WSIMP = \begin{cases} 1 \; if \; Shoulder\ Width < \; Shoulder\ Width_{Threshold} \\ 0 \; Otherwise \end{cases}$$ Eq. 3.7.10

Where:

WLIMP = Section requires lane widening

The cost to improve the sections shoulder width is then computed below using the cost term taken from table X:

$SW_{Cost} = SLENGTH * \text{SWCOST} * WSF * WSIMP$ Eq. 3.7.11

Where:

SWCOST = Cost to improve Shoulder Width Highway Type (from Table 3.11)

WSF = Shoulder Widening Feasibility (from Table 3.8)

3.7.4.5 Final Capacity Improvement Cost

The final capacity improvement cost is computed after considering the feasibility for widening, the current volume to capacity conditions and the lane width and shoulder width conditions. This determines both if an improvement will be applied, and to what extent. The final capital improvement cost ($CIMP_{Cost}$) is computed as follows:

$$L_{Cost} = \begin{cases} NL_{Cost} & if\ VCIMP = 1 \\ NWL_{Cost} & if\ VCIMP = 1\ AND\ WLIMP = 1 \end{cases} \quad \text{Eq. 3.7.12}$$

$$CIMP_{Cost} = L_{COST} + SW_{Cost} \quad \text{Eq. 3.7.13}$$

Where:

L_{Cost}	=	The additional lane cost
NL_{Cost}	=	The cost of adding just one lane
NWL_{Cost}	=	The cost of adding a lane and widening existing lanes
VCIMP	=	The binary variable for needed capacity expansion
WLIMP	=	The binary variable for needed lane widening

Table 3.11 Capital Improvement Costs in 2002 $/Lane-Mile (Summarized from HERS Table 6-1)

Location	Functional Classfication	Terrain/ Urban Size	Reconstruct Pavement	Resurface Pavement	Improve Shoulders	Add Lane	Add and Widen Lanes
Rural	Interstate	Flat	772	274	51	1899	2633
		Rolling	792	292	84	2059	3331
		Mountainous	916	322	129	2638	8315
	Other Principle Arterials	Flat	618	220	34	1521	2178
		Rolling	635	245	57	1629	2629
		Mountainous	720	267	89	1981	7368
	Minor Arterials	Flat	543	195	32	1383	1941
		Rolling	601	210	59	1585	2500
		Mountainous	687	232	90	1951	7368
	Major Collectors	Flat	575	199	41	1436	1436
		Rolling	584	211	55	1468	1468
		Mountainous	662	231	87	1730	6911
Urban	Interstate/ Other Freeways	Small Urban	1376	334	61	3116	11094
		Small Urbanized	1388	395	81	3405	12121
		Large Urbanized	2272	530	306	5699	60000
	Other Principle Arterials	Small Urban	1169	280	62	2649	9430
		Small Urbanized	1183	331	83	2870	10218
		Large Urbanized	1734	416	267	4200	14953
	Minor Arterials and Collectors	Small Urban	883	205	45	1956	6964
		Small Urbanized	893	233	55	2061	7338
		Large Urbanized	1194	286	150	2858	10173

3.7.5 Total Agency Costs

As the improvement of pavement conditions, additions of lanes and widening of shoulders and lanes are not mutually exclusive; a combination of improvements can be completed on the same segment of roadway. The Total Agency Cost Short-Run Cost (TAS_{Cost}) for short-run costs is obtained directly from the pavement maintenance cost. Additionally, the Total Agency Long-run Cost (TAL_{Cost}) is obtained by summing all of the capital improvement costs together.

$$TAS_{Cost} = MCOST \qquad \text{Eq. 3.7.14}$$

$$TAL_{Cost} = CIMP_{Cost} + RS_{Cost} + RC_{Cost} \qquad \text{Eq. 3.7.15}$$

Where:

MCOST	=	Pavement Maintenance Cost from Section 3.7.2
$CIMP_{Cost}$	=	Capacity Improvement Cost from Section 3.7.5
RS_{Cost}	=	Pavement Resurfacing Cost from Section 3.7.3
RC_{Cost}	=	Pavement Reconstruction Cost from Section 3.7.4

As already stated, further marginal cost analysis will only make use of short-run agency costs in the form of basic pavement maintenance. The reason for this selection: is that the long-run agency marginal cost of vehicles only burdens the single vehicle which breaks capacity or pavement thresholds. Because these long-run costs cannot be easily charged to every vehicle in the fleet, they cannot be considered when developing a marginal cost VMT fee structure. Based on the FHWA's Highway Cost Allocation study, capital improvement costs are spread to various vehicle categories simply based on Passenger Car Equivalent vehicle volumes. Future marginal cost analysis should include ways to better incorporate these long-run costs to capture capital improvements.

3.8 Emissions Model

HERS estimates the total emissions cost by vehicle type using the average effective speed (AES) from the speed model. Separate estimates for each functional classification of roadway are conducted to account for the change in driving behavior associated with each roadway functional system. Additionally estimates for rural and urban areas differ, as the increase in population exposure for urban areas over rural, produce and increased cost.

HERS used the Environmental Protection Agency's MOBILE6 to first estimate emission rates by speed for different pollutant types and different vehicles (pollutants considered include: carbon monoxide, sulfur oxides, nitrogen oxides and particulate matter less than 2.5 microns). Estimates were taken for both the year 2000 and 2015 to allow for the indexing of years in between.

Per ton damage costs for each pollutant were scaled based on the rural or urban identifier contained in HERS, which provides some information on the density of the surrounding development. Thus, urban areas of the highest densities would have their base costs scaled up, while less dense urban areas would have their base costs scaled down.

Exampled on the following page in Table 3.12, the final 2008 per-mile emission damage costs by speed and vehicle type are contained within nine tables representing the various rural and urban functional classifications. Total emission cost estimates are achieved by multiplying the selected emission cost per vehicle by the respective volume of vehicles and then summing across all total vehicle costs.

Table 3.12 Emission Damage Costs by Vehicle Class: Rural Other Principle Arterial

Speed	Emission Damage Cost (2008 $ per veh.-mile)		
	Auto	Single Truck	Combination Truck
5	$0.02174	$0.02930	$0.04885
6	$0.01922	$0.02689	$0.04643
7	$0.01742	$0.02517	$0.04470
8	$0.01607	$0.02389	$0.04340
9	$0.01502	$0.02288	$0.04239
10	$0.01418	$0.02208	$0.04158
11	$0.01351	$0.02122	$0.04025
12	$0.01295	$0.02049	$0.03914
13	$0.01249	$0.01988	$0.03820
14	$0.01209	$0.01936	$0.03739
15	$0.01174	$0.01890	$0.03670
16	$0.01140	$0.01843	$0.03587
17	$0.01110	$0.01802	$0.03514
18	$0.01084	$0.01765	$0.03450
19	$0.01060	$0.01732	$0.03392
20	$0.01039	$0.01702	$0.03340
21	$0.01023	$0.01679	$0.03290
22	$0.01009	$0.01657	$0.03245
23	$0.00995	$0.01637	$0.03203
24	$0.00983	$0.01619	$0.03165
25	$0.00972	$0.01602	$0.03130
...	...	...	...

3.9 The Noise Model

HERS does not contain any cost models for estimating the damage of noise produced by vehicles on surrounding land uses. Turning to previous research, to calculate the marginal cost of vehicles with respect to noise, this analysis combines noise generation and hedonic cost modeling based on models developed by Haling and Cohen in 1997. First, the total noise output of individual vehicle types is calculated at three different ranges and then aggregated together for the entire fleet. Second, these total hourly noise levels are then transformed into noise costs by using hedonic price computations.

When using Passenger Car Equivalencies for Noise (shown below in Table 3.13) the Equivalent Hourly Noise Level per vehicle type can be expressed as:

$$L_{eqi} = 10 * LN\left(\frac{V_i}{D * AES_i}\right) + SL + 2 - 5 * LN\left(\frac{D}{50}\right) \qquad \text{Eq. 3.9.1}$$

Where:

V_i	=	Passenger Car Equivalent Volume of vehicle type i
D	=	Distance between receiver and source (40 ft, 60 ft, and 80 ft)
AESi	=	Average Effective Speed of vehicle type i
SL	=	Adjusted Noise Emission level (assumed 4 dBA for use with PCEs)

Table 3.13 Noise Passenger-Car Equivalents for Single and Combined Trucks									
Vehicle Type	**Miles per Hour**								
	20	25	30	35	40	45	50	55	>=60
Light Vehicles									
Small Auto	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Large-Medium Auto									
Pickup and Van									
Single Unit Trucks									
6 Tire Truck	47.3	32.9	24.4	19.0	15.3	12.6	10.6	9.1	7.9
3 to 4 Axle Truck	75.5	53.5	39.0	30.3	24.4	20.1	17.0	14.5	12.6
Combined Trucks									
4 Axle Trucks	102.2	71.0	52.8	41.1	33.0	27.3	23.0	19.7	17.0
5 Axle Trucks	131.6	91.4	67.9	52.9	42.5	35.1	30.0	25.3	22.0

The Total Noise Level at a specific distance from the road segment is then computed by taking the log sum of the vehicles individual Hourly Noise Levels:

$$NL_D = 10 * LOG(\sum_i^N 10^{Leqi/10}) \quad \text{Eq. 3.9.2}$$

The number of housing units effected within the three noise ranges (D):

$$HU_D = SLEN * \frac{W_R}{5280} * DEN * 2 \quad \text{Eq. 3.9.3}$$

Where:

W_R = Width of noise range (40, 60 and 80 ranges) from roadway (20 ft)

DEN = Density of housing units (from Table 3.14)

Table 3.14 - Residential Housing Unit Densities per Acre			
Land Development Type	30-50ft Units per m^2	50-70ft Units per m^2	70-90ft Units per m^2
Rural	192	192	192
Small Urban Area	1280	1280	1280
Small Urbanized Area	2560	2560	2560
Large Urbanized Area	2560	9600	16640

The change in property value per decibel is based on a number of studies conducted in the 1970s and 1980s, which captured consumer's willingness to pay for lower noise levels. Based on these previous studies, Haling and Cohen obtained a damage approximation of 4% of the housing value for every decibel above the threshold level.

$$NOISE\ COST = \sum_{D=1}^{3}[HU_D * (NL_D - NT)] * P * PROP \qquad \text{Eq. 3.9.4}$$

Where:

HU_D	=	Housing units affected by roadway noise at range D
NL_D	=	Total noise level produced by vehicles at range D (dBA)
NT	=	Noise threshold (assumed to be 55 dBA)
P	=	Percentage housing value per decibel
PROP	=	Average property value ($) for county (American Community Survey)

3.10 The Marginal Cost

Once component total costs for each HPMS Sample segment have been computed using the retrofitted HERS methodology summarized in this report, the marginal costs of adding one additional vehicle from one of the seven types of vehicles can be iteratively calculated. An increase of any single or combined truck volume will yield a change in the pavement condition that in turn creates change in the average effective speed for users (both from increased congestion and deterioration of pavement). Similarly, an increase in auto volume will create more congested roadways while causing no impact to the pavement condition. These changes within the sub-models will then effect each of the cost equations. The marginal cost can then be derived by simply taking the difference between the initial base costs and the incremented volume costs.

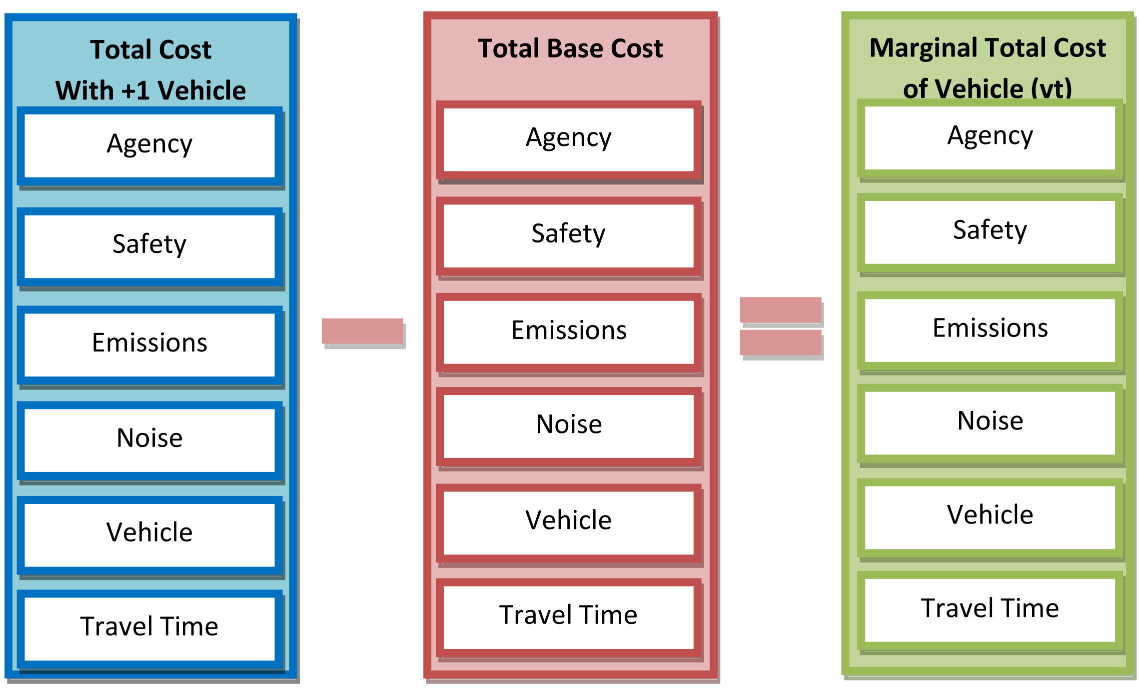


Figure 3.2 Marginal Cost Calculations

The correct application of a mileage based fee system on US roadways requires a true estimate of the burden of one additional vehicle on the roadway system and all other users. This dollar value can be captured by computing the Marginal Cost to Society (MCS) as follows below in equation 3.10.1. The total marginal cost (including all of its principle cost components shown above in Figure 3.2) provides estimates of the impact to the entire system; however, as the additional user already pays some of the burden (in the forms of auto insurance, vehicle part maintenance and travel time), we must subtract these pre-paid average user costs. Our MCS, for each vehicle type, provides an appropriate estimate of per-mile fees for each user.

$$Marginal\ Cost\ to\ Society = Total\ Marginal\ Cost - Average\ Cost\ of\ User \qquad \text{Eq. 3.10.1}$$

$$MCS_{VT} = (MAC_{VT} + MSC_{VT} + MEC_{VT} + MNC_{VT} + MVOC_{VT} + MTTC_{VT}) - (ASC_{VT} + ATTC_{VT} + AVOC_{VT})$$

Where:

MCS_{VT}	=	Marginal cost to society for vehicle type (vt) in dollars
MAC_{VT}	=	Marginal agency cost for vehicle type (vt) in dollars
MSC_{VT}	=	Marginal safety cost for vehicle type (vt) in dollars
MEC_{VT}	=	Marginal emissions cost for vehicle type (vt) in dollars
MNC_{VT}	=	Marginal noise cost for vehicle type (vt) in dollars
$MVOC_{VT}$	=	Marginal vehicle operations cost for vehicle type (vt) in dollars
$MTTC_{VT}$	=	Marginal travel time cost for vehicle type (vt) in dollars
ASC_{VT}	=	Average safety cost for vehicle type (vt) in dollars
$ATTC_{VT}$	=	Average travel time cost for vehicle type (vt) in dollars
$AVOC_{VT}$	=	Average vehicle operations cost for vehicle type (vt) in dollars

4. Results

While the final results of this report's methodology produce section level marginal component costs by vehicle type for every roadway segment, with complete input information contained in the HPMS Sample database, this report provides a summary of results aggregated to the state, county and functional classification levels for each vehicle type during the off-peak and peak periods.

4.1.1 State Level Marginal Costs

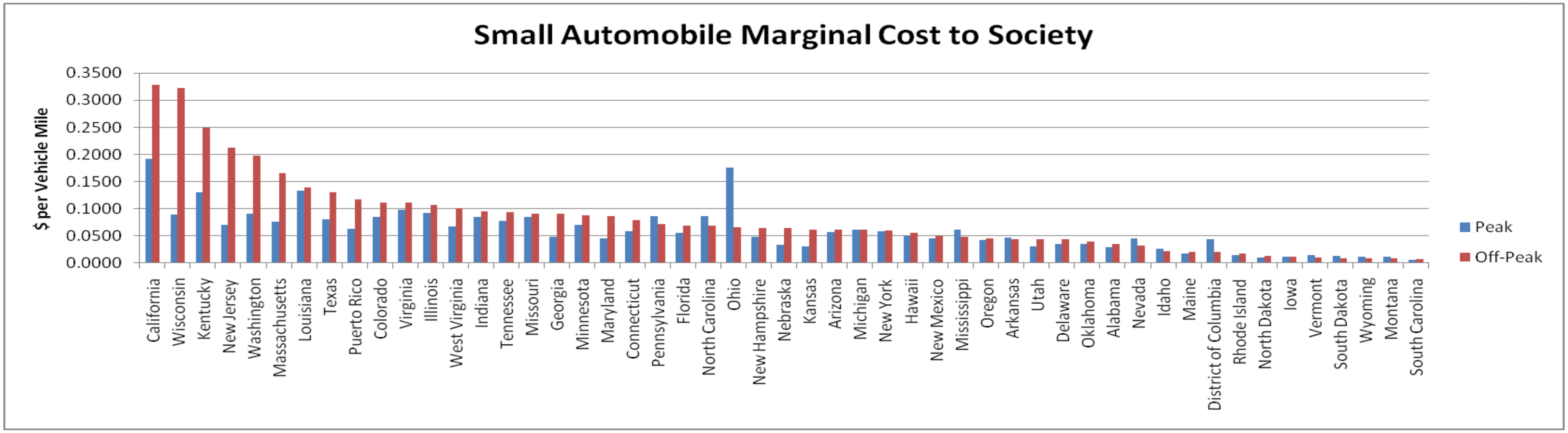
Weighted average marginal costs were calculated at the state level by aggregating HPMS sample section costs grouped by the roadway's state identifier and weighting by the product of the section's length, average annual daily traffic and sample expansion factor. This expansion factor, derived from proportions of sample segment lengths to lengths of segments contained in the HPMS universe database within individual volume groups and functional classifications, is used by the HPMS sample database to expand results to represent the entirety of US roadways reported in HPMS.

4.1.2 Marginal Costs to Society by Vehicle Type

As the methodology for computing individual component costs (including safety, pavement, emissions, travel time, noise and vehicle operating costs) calculates values for each vehicle type, a direct comparison of total marginal cost to society can be conducted. The graphs shown on the following page in Figure 5.1 provide two good examples of the differences of vehicle type in producing total marginal costs to society (additional state graphs are contained in Appendix B).

The state level marginal costs to society (in dollars per vehicle mile) are shown sorted in order of highest costs to lowest costs with respect to off-peak costs. In general, states that are comprised of large urbanized areas (such as New York, California, Florida, etc.) tend to have higher marginal costs across all vehicle classes; however, as the computations for the marginal cost to society are not comprised solely of congestion costs, a large number of predominantly rural states (such as Wisconsin and Kentucky) also appear as high cost states. Overall, California has the highest marginal cost to society for every vehicle class, with approximate small automobile costs of 32 and 18 cents during the off peak and peak periods respectively. Similarly, California's approximate combined five axle truck costs of 2.20 and 1.75 dollars during the off peak and peak periods are also the highest overall.

Counter-intuitive to what we would expect to find when computing off-peak and peak costs, marginal vehicle costs for the peak period are not always greater than the off-peak period. Furthermore, as shown in both of the aggregated state and county level data (shown in section 4.2), often off-peak period costs exceed peak period costs. As the differentiation of off-peak/peak period vehicle impacts relies primarily on the change in overall speed when one additional vehicle is added to the roadway, what the results show is that many roadways during the peak period suffer little slow-down due to the added presence of one vehicle as the roadway is already congested. Conversely, roadways during the off peak period are rarely congested, and the change in overall speed is higher as drivers are no longer able to travel at their desired free-flow speed with the additional presence of one more vehicle. These greater changes to speed are then translated into greater marginal costs of travel time, emissions, vehicle operations, and noise: thus, marginal costs to society can be greater in either the off-peak or peak period depending on the actual performance conditions of sampled roadways.



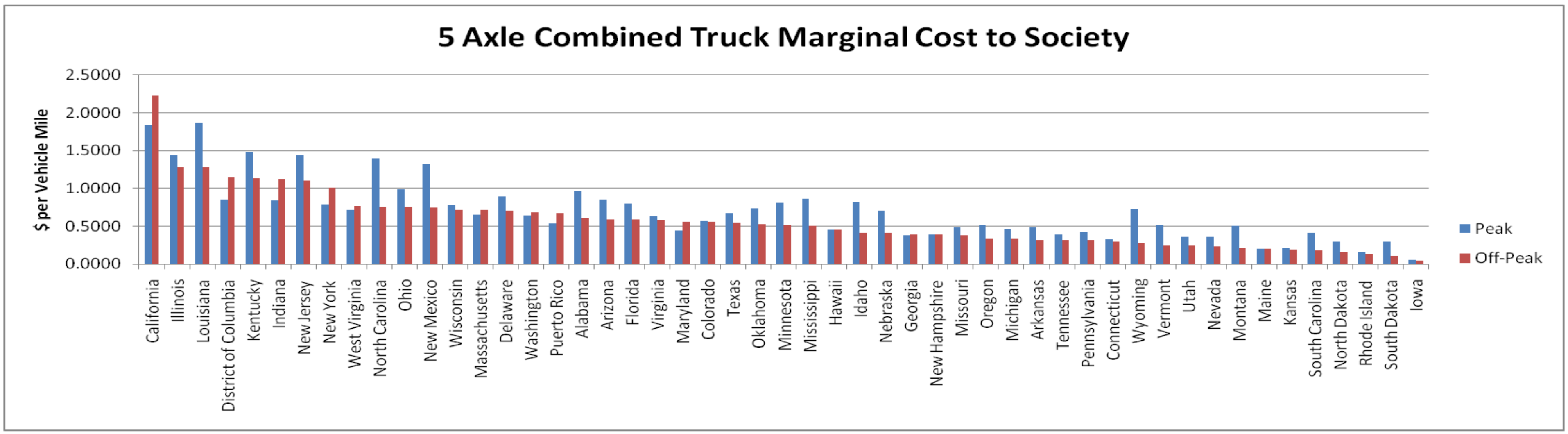


Figure 4.1 State Marginal Cost to Society by Vehicle Types

4.1.3 Marginal Cost to Society of Small Automobiles

As shown in Figures 4.2 and 4.3, maps of the state aggregated marginal costs to society for small automobiles during the peak and off-peak periods are respectively displayed. State marginal costs maps for additional vehicle types can be found in Appendix B. These geographical representations help to further identify regions of higher marginal costs: the east coast, mid-west and west coast as well as several southern states have higher per mile costs compared to states in the central United States. Overall, Figure 4.2 shows peak marginal costs for small automobiles ranging from less than 2 to 15 cents per vehicle mile; similarly, the off-peak marginal costs shown in Figure 4.3 range from 2 to 30 cents. Major changes between peak and off-peak costs also appear to be associated with these high cost regions. Issues with relying only on state aggregated marginal cost data for analysis arise when we compare this information with the finer level of county aggregation in section 4.2.

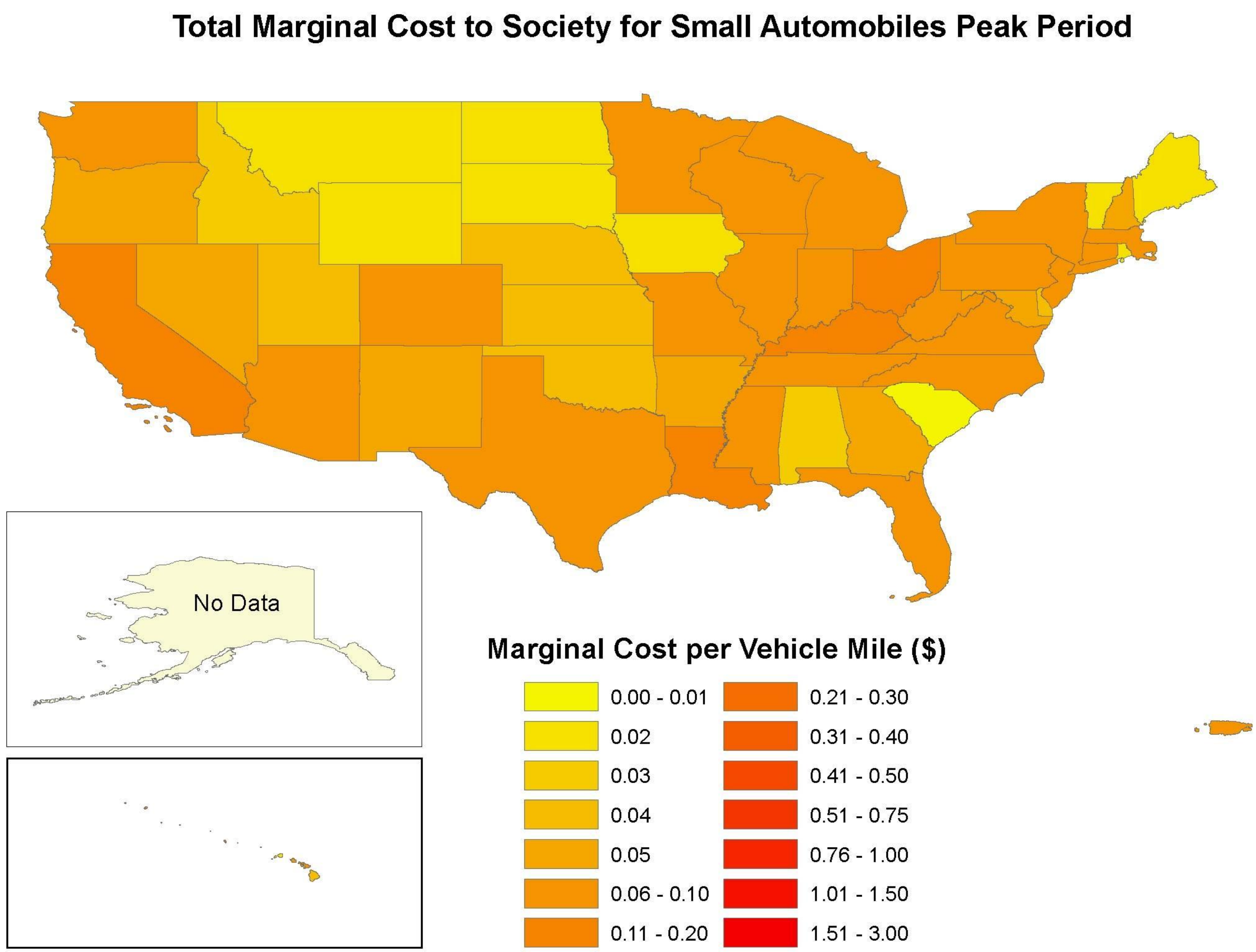


Figure 4.2 Marginal Cost to Society of Small Automobiles (Peak)

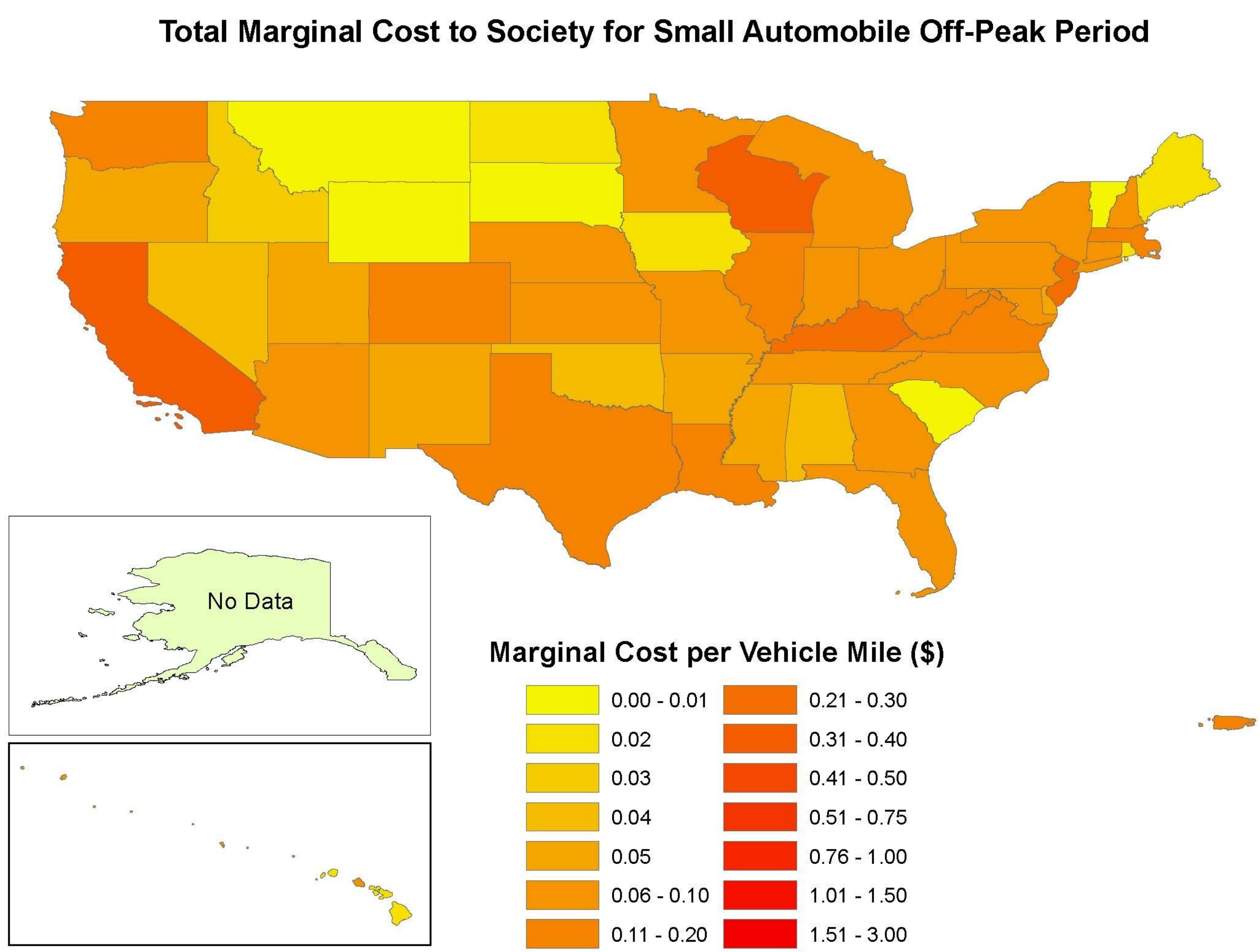


Figure 4.3 Marginal Cost to Society of Small Automobiles (Off Peak)

4.1.4 Component Marginal Costs for Small Automobiles

For purposes of comparing state level data and determining the breakdown of marginal costs to society, component marginal costs are presented for three to four axle single unit trucks during the peak period on the following page in Table 4.1. Overall, the aggregated data shows marginal Vehicle Operations and Pavement costs to be the most significant for three to four axle single unit trucks with a national average of 27 and 26 cents per vehicle mile respectively. Marginal Travel Time costs are also reasonably high with an average of 15 cents per vehicle mile; however, marginal costs for Safety, Emissions and Noise are much lower at roughly 1 cent per vehicle mile. Taking a closer look at high cost states such as California and Ohio, we see that states with higher marginal costs to society tend to have much larger marginal Pavement costs, in comparison to their other component costs.

Table 4.1 - Three to Four Axle Single Unit Truck Marginal Costs								
State	Peak Costs $ per Mile							
	Marginal Safety Cost	Marginal Pavement Cost	Marginal Travel Cost	Marginal Emissions Cost	Marginal Vehicle Operating Cost	Marginal Noise Cost	Total Marginal Cost	Marginal Cost to Society
Alabama	0.0119	0.4522	0.2197	0.0147	0.2318	0.0037	0.9195	0.6131
Arizona	0.0118	0.3160	0.1338	0.0162	0.1830	0.0053	0.8303	0.5307
Arkansas	0.0112	0.1671	0.1228	0.0148	0.1819	0.0015	0.5935	0.3303
California	0.0181	0.6568	0.3729	0.0151	0.2506	0.1216	1.4142	1.0228
Colorado	0.0132	0.2158	0.1764	0.0151	0.2289	0.0127	0.6860	0.3423
Connecticut	0.0058	0.1035	0.0938	0.0148	0.1092	0.0053	0.3509	0.2429
Delaware	0.0077	0.3657	0.1246	0.0150	0.1426	0.0099	0.7771	0.5751
District of Columbia	0.0041	0.4864	0.1596	0.0181	0.0599	0.0504	0.6434	0.5178
Florida	0.0149	0.3294	0.2271	0.0148	0.2093	0.0179	0.9425	0.6457
Georgia	0.0111	0.1605	0.1085	0.0148	0.1921	0.0041	0.5150	0.2455
Hawaii	0.0117	0.2045	0.1462	0.0155	0.2557	0.0147	0.6390	0.2751
Idaho	0.0205	0.2233	0.1698	0.0152	0.3798	0.0021	1.0723	0.5350
Illinois	0.0106	0.7208	0.1263	0.0087	0.1313	0.0072	1.1359	0.9417
Indiana	0.0151	0.7904	0.1398	0.0158	0.4214	0.0032	1.1924	0.6210
Iowa	0.0029	0.0072	0.0297	0.0151	0.0390	0.0002	0.0927	0.0295
Kansas	0.0167	0.0720	0.1367	0.0150	0.4537	0.0015	0.7277	0.1426
Kentucky	0.0331	0.6021	0.3507	0.0166	0.5214	0.0113	1.8757	1.0716
Louisiana	0.0241	0.7407	0.3253	0.0146	0.3806	0.0156	1.8702	1.2756
Maine	0.0033	0.1102	0.0280	0.0160	0.0631	0.0002	0.2292	0.1312
Maryland	0.0056	0.2339	0.0780	0.0147	0.0923	0.0102	0.3972	0.2608
Massachusetts	0.0092	0.2446	0.1189	0.0158	0.0663	0.0128	0.5263	0.3862
Michigan	0.0186	0.1529	0.1843	0.0174	0.3364	0.0041	0.7935	0.3069
Minnesota	0.0218	0.2143	0.2276	0.0158	0.4374	0.0086	1.1650	0.5500
Mississippi	0.0160	0.2730	0.1805	0.0151	0.3529	0.0039	1.0506	0.5637
Missouri	0.0148	0.1795	0.1873	0.0147	0.2491	0.0304	0.7154	0.3332
Montana	0.0237	0.1188	0.1775	0.0151	0.5905	0.0000	1.1218	0.3362
Nebraska	0.0214	0.2319	0.2039	0.0151	0.4743	0.0011	1.1760	0.5160
Nevada	0.0116	0.0924	0.1215	0.0152	0.1934	0.0062	0.5014	0.2135
New Hampshire	0.0116	0.1832	0.1214	0.0151	0.1723	0.0037	0.5097	0.2614
New Jersey	0.0082	0.1410	0.1446	0.0163	0.7055	0.0208	1.0987	0.9442
New Mexico	0.0203	0.4529	0.1969	0.0153	0.3154	0.0035	1.2877	0.7940
New York	0.0092	0.1921	0.2183	0.0155	0.2454	0.0182	0.7748	0.5775
North Carolina	0.0181	0.4170	0.2808	0.0149	0.2949	0.0173	1.4127	0.9820
North Dakota	0.0241	0.0813	0.1696	0.0152	0.7501	0.0001	1.1300	0.1901
Ohio	0.0103	0.4634	0.1086	0.0135	0.0257	0.0026	0.7011	0.7249
Oklahoma	0.0127	0.3214	0.1282	0.0151	0.2345	0.0019	0.8020	0.4659
Oregon	0.0151	0.1696	0.1537	0.0153	0.2534	0.0060	0.7201	0.3522
Pennsylvania	0.0055	0.1501	0.1232	0.0204	0.0472	0.0096	0.3983	0.2994
Rhode Island	0.0018	0.0556	0.0192	0.0146	0.0239	0.0007	0.1369	0.0997
South Carolina	0.0245	0.1077	0.1341	0.0150	0.8488	0.0001	1.2556	0.2509
South Dakota	0.0261	0.0422	0.2298	0.0150	0.5943	0.0002	1.0377	0.1990
Tennessee	0.0087	0.1538	0.1145	0.0148	0.0948	0.0044	0.4392	0.2745
Texas	0.0110	0.2498	0.1713	0.0133	0.2354	0.0059	0.8055	0.4608
Utah	0.0086	0.0907	0.0839	0.0167	0.1377	0.0064	0.4359	0.2284
Vermont	0.0160	0.1296	0.1243	0.0151	0.2865	0.0003	0.7214	0.3104
Virginia	0.0116	0.2037	0.1460	0.0155	0.3308	0.0258	0.7268	0.3595
Washington	0.0191	0.2226	0.2146	0.0151	0.3613	0.0184	0.9155	0.3845
West Virginia	0.0102	0.4884	0.1414	0.0153	0.1054	0.0012	0.6682	0.4735
Wisconsin	0.0069	0.2485	0.1369	0.0149	0.0904	0.0237	0.7165	0.5604
Wyoming	0.0167	0.1506	0.1396	0.0150	0.3377	0.0001	0.9320	0.4528
Puerto Rico	0.0080	0.3336	0.1312	0.0182	0.1065	0.0098	0.5484	0.3551

4.2.1 County Level Marginal Costs

Similar to state level aggregation, the weighted average marginal costs to society were calculated at the county level by aggregating HPMS sample section costs grouped by the roadway's state and county identifiers and again weighting by the product of the section's length, average annual daily traffic and sample expansion factor. While both state and county level summaries of marginal cost information are useful in comparisons, the application/deployment of marginal cost pricing becomes more apparent at the county level.

4.2.2 Marginal Cost to Society of Small Autos

The aggregation to the county level provides a slightly more disaggregate view of the marginal costs of individual vehicles. A complete set of county level marginal costs maps is contained in Appendix C. As shown in Figure 4.4, the map of US counties with regards to the marginal cost to society of small automobiles during the peak period again shows the relationship of more urbanized regions to higher marginal costs. Marginal costs, in cents per vehicle mile, ranged from 0 to 30 cents with city centers like Las Angeles, Miami, New York, and Houston all having high marginal costs versus surrounding rural regions. This level of analysis combined with the results obtained from the state level aggregation show the discrepancies created by relying on HPMS sample expansion to represent the entire state. Considerable bias is created when samples are unevenly taken from higher urban versus lower rural level functional classifications. Furthermore, many counties are poorly represented by the information solely contained within the HPMS sample database, which causes considerable trouble when aggregating to state level.

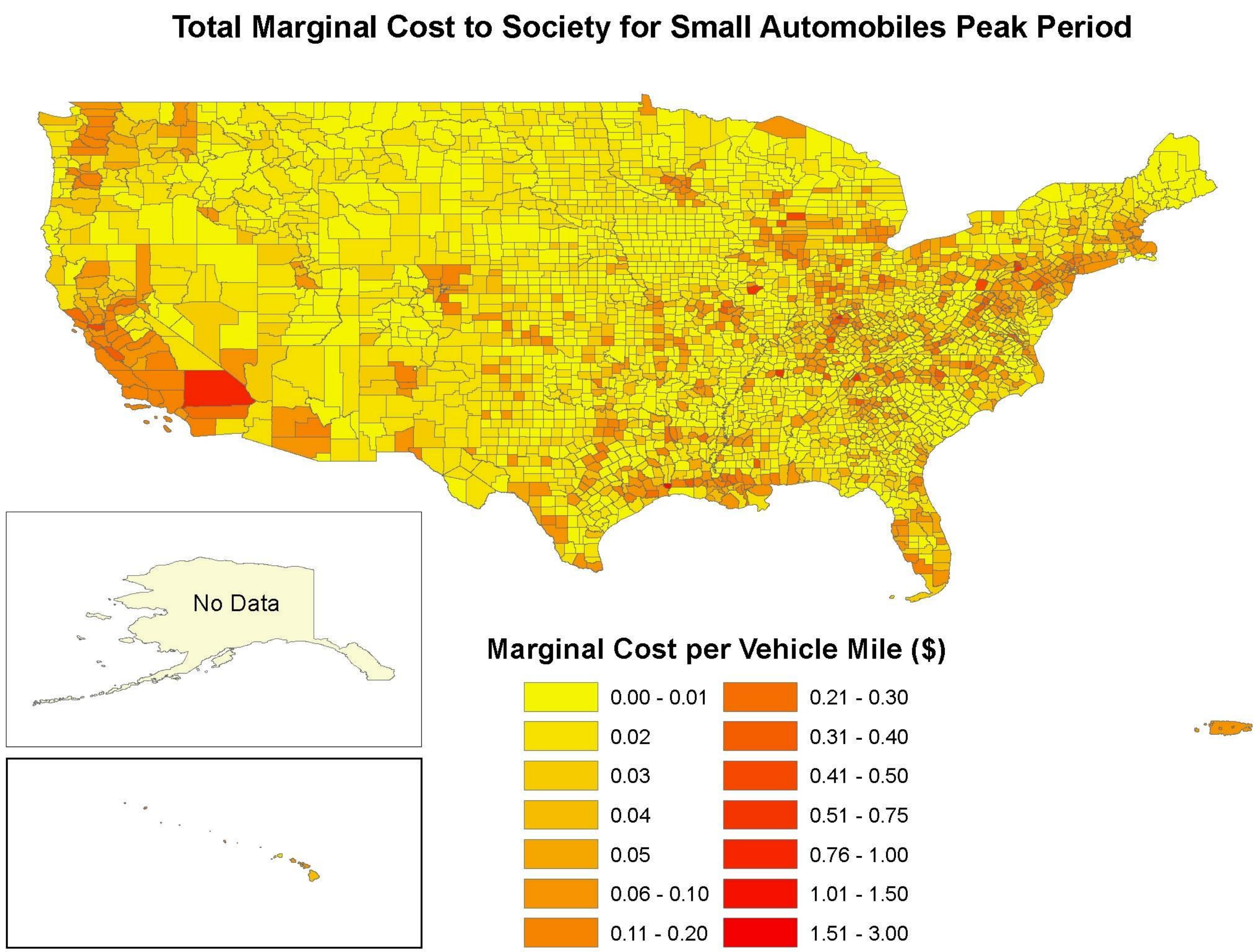


Figure 4.4 County Level Marginal Cost to Society of Small Autos (Peak)

4.3.1 Functional Classification Marginal Costs

As the final level of aggregation in this study, the national weighted average marginal costs to society were calculated for different functional classifications by aggregating HPMS sample section costs grouped by the roadway's rural/urban identifier and the sections functional classification. The information within each group was then weighted by the product of the section's length, average annual daily traffic and sample expansion factor. While marginal cost information for the nation's different functional classifications in rural and urban areas is a more aggregate level than either state or county aggregation, this information allows for useful comparisons in determining to what extent urban areas and roadway types play in marginal costs allocation.

4.3.2 Marginal Costs to Society of 3 to 4 Axle Single Unit Trucks

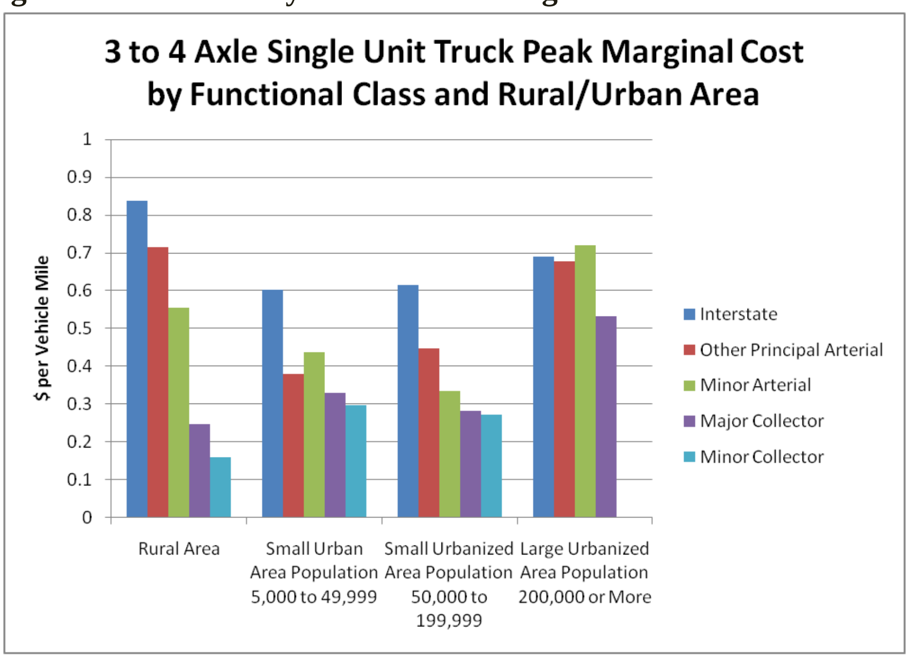


Figure 4.5 Functional Classification Level Marginal Cost to Society of 3 to 4 Axle Single Unit Trucks (Peak)

As shown in Figure 4.5 and below in Figure 4.6, relationships between both rural/urban areas as well as the individual differences in functional classifications are evident. Similar to the other calculated marginal vehicle costs (Contained in Appendix A), the costs of 3 to 4 axle single unit trucks are generally higher for functional classifications in rural and large urbanized city areas, versus sections in small urban or town areas. Additionally, marginal costs decrease in descending order of functional classification: with interstates having the highest marginal costs, arterials having lower costs and finally collectors having the lowest marginal cost.

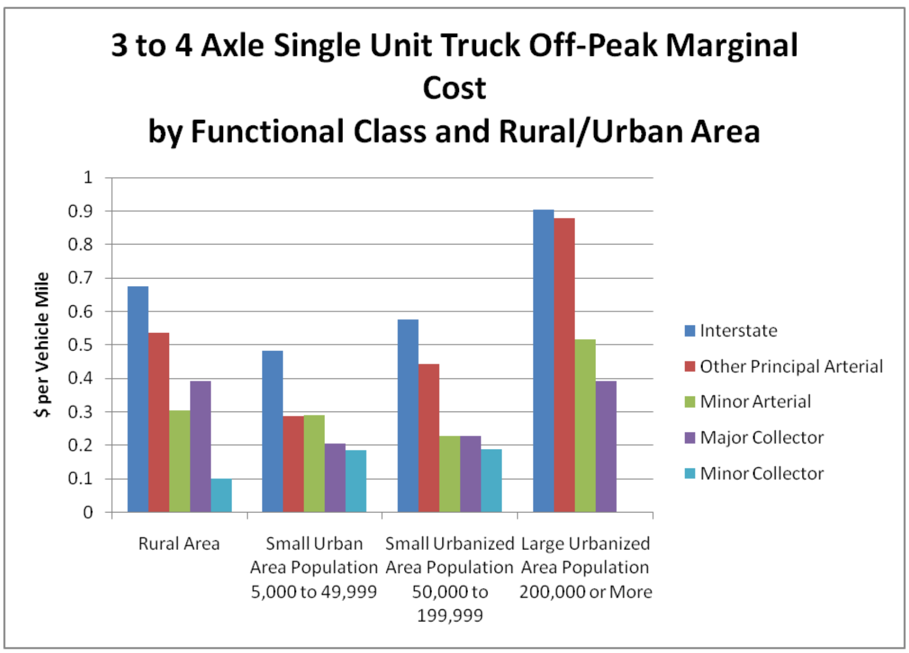


Figure 4.6 Functional Classification Level Marginal Cost to Society of 3 to 4 Axle Single Unit Trucks (Off-Peak)

The differences between peak and off peak costs, shown respectively in Figures 4.5 and 4.6, display marginal cost changes averaging around ten cents within each functional classification. As the analysis moves from the peak to the off-peak period, we generally see 3 to 4 axle single unit truck marginal cost increases in Large Urbanized

Areas, a decrease in Small Urban Area costs, and a decrease in Rural Areas. While the relationships of rural/urban areas as well as individual functional classifications within each area are similar across all vehicles, the changes between peak to off-peak periods are different for each major vehicle classification: all personal automobiles, single unit trucks, and combined trucks display different changes, while finer vehicle classification within each major vehicle type display similar changes.

5. Revenue Analysis

By obtaining marginal cost information for each roadway segment by each vehicle classification further studies can be conducted to determine the validity of vehicle mile fees (VMFs) based on respective marginal costs to society. This report conducts a simple analysis on each segment by computing the ratio of the revenue generated by marginal cost VMFs versus the revenue generated by the existing gas tax within each state.

5.1 State Gas Taxes

State gas taxes were obtained from the American Petroleum Institute's publication of state gas and diesel taxes in 2005 combined with a reported federal gas tax of 18.4 cents per gallon.

5.2 Gas Tax Revenue per Mile

The daily revenue generated by combined state and federal gas tax as a per mile charge to vehicles is calculated as:

$$REV_{GAS} = \sum\left(\frac{CSFC_{VEH}}{1000} * \frac{1}{FEAF_{VEH}} * AADT_{VEH}\right) * GASTAX \qquad \text{Eq. 5.1}$$

Where:

$CSFC_{VEH}$ = The Constant Speed Fuel Consumption rate obtained from the Vehicles Operating Cost Model during the Base Case scenario (Gallons/1000 miles)

$FEAF_{VEH}$ = Fuel Efficiency Adjustment factor from the vehicles Operating Cost Model

$AADT_{VEH}$ = The Average Annual Daily Traffic of a particular type of vehicle

GASTAX = The combined federal and state gas tax.

This produces a total per-mile revenue from the current gas tax system for every segment contained within the HPMS sample database, which can be directly compared with the total per mile revenue generated by the marginal cost to society of all vehicles on the segment.

5.3 Marginal Cost to Society Revenue per Mile

The total revenue generated by the VMF based on the Marginal Cost to Society (REV_{MARG}) is calculated by summing across the peak and off-peak periods respective revenues, which consists of the marginal cost to society of each vehicle times the number of vehicles using the roadway segment during that period:

$$REV_{MARG} = \sum(MCS_{VEH,PEAK} * AADT_{VEH,PEAK}) + \sum(MCS_{VEH,OFFPEAK} * AADT_{VEH,OFFPEAK})$$

Eq. 5.2

Where:

$MCS_{VEH,PEAK}$ = The Marginal Cost to Society of Vehicle type VEH during the Peak Period

$AADT_{VEH,PEAK}$ = The Average Annual Daily Traffic of Vehicle type VEH during the Peak Period

$MCS_{VEH,OFFPEAK}$ = The Marginal Cost to Society of Vehicle type VEH during the Off Peak Period

$AADT_{VEH,OFFPEAK}$ = The Average Annual Daily Traffic of Vehicle type VEH during the Off-Peak Period

5.4 Revenue Ratio

The final step of the revenue analysis takes the revenue generated by the gas tax and divides by the revenue generated by the marginal cost VMF to produce a revenue ratio ($RATIO_{REV}$). When this ratio is less than one, the gas tax revenue generated by the segment is less than the revenue generated by the marginal cost VMF, and, by extension, the actual damage caused to society by the vehicles on the roadway. Conversely, if the revenue ratio is greater than one then the gas tax revenue is greater than marginal cost VMF revenue, showing a charge to vehicles exceeding the actual damage caused by those vehicles. As the VMF based on Marginal Cost considers external costs such as Noise and Emissions, the revenue ratio will typically be less than one, except for those segments where gas taxes significantly overcharge users. Again this revenue ratio is calculated for every segment with complete input data in the HPMS sample database, and results are further aggregated to the state, county and functional classification geographic levels.

$$RATIO_{REV} = \frac{REV_{GAS}}{REV_{MARG}} \qquad \text{Eq. 5.3}$$

Where:

REV_{GAS} = the sections Gas Tax Revenue obtained from Eq. 5.1

REV_{MARG} = the sections Marginal Cost VMF Revenue obtained from Eq. 5.2

5.5 State Level Revenue Analysis

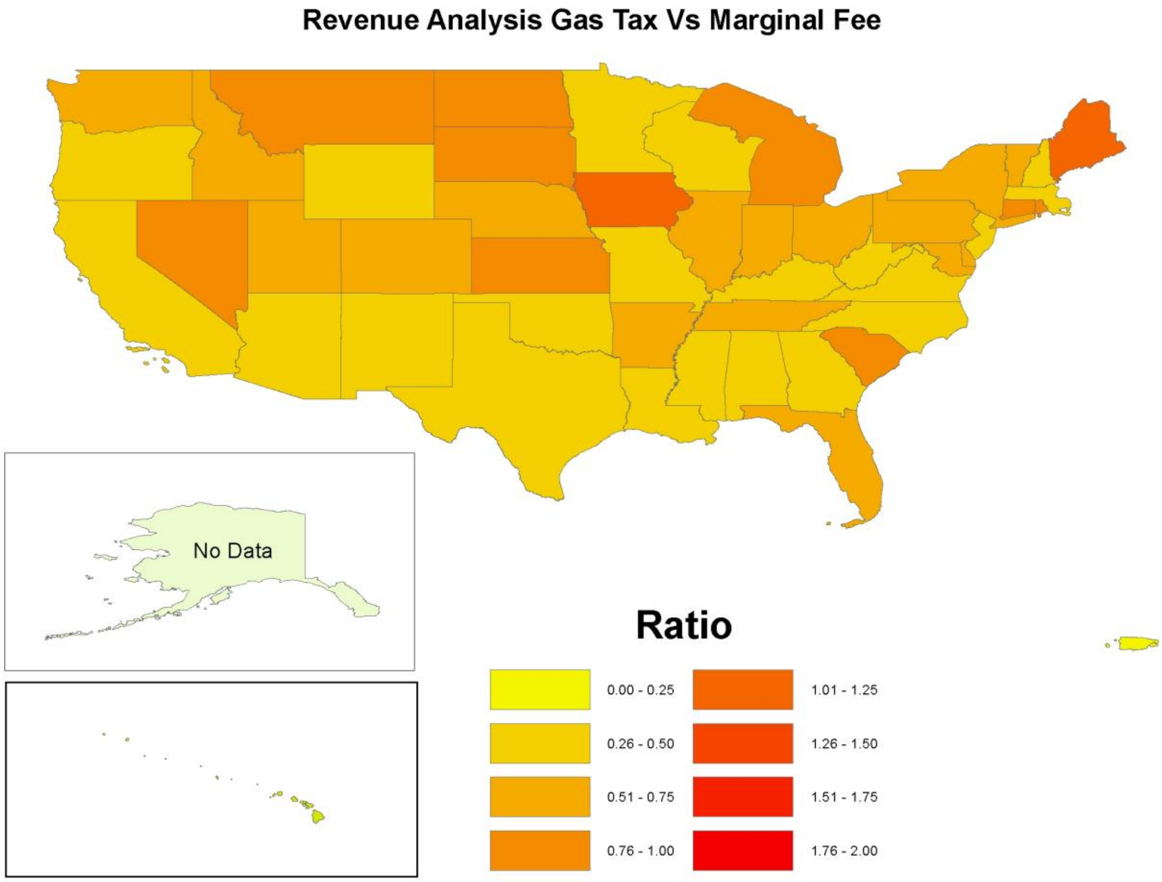


Figure 5.1 State Level Revenue Analysis

After aggregating the revenue ratio to the state level using the similar steps taken in obtaining weighted state averages for marginal costs in Section 4.1.1, several regional relationships become apparent. The state map displayed above in Figure 5.1, shows most states have an average revenue ratio less than one, with the exception of Maine and Iowa, which are slightly over one. Regionally, states located in the south, north east and west coast have revenue ratios less than a quarter: these states also correspond to areas of high marginal costs identified in Figures 4.2 and 4.3. Areas in central and mid west states have revenue ratios close to or above one, signifying areas that are being overcharged by the gas tax system.

5.6 County Level Revenue Analysis

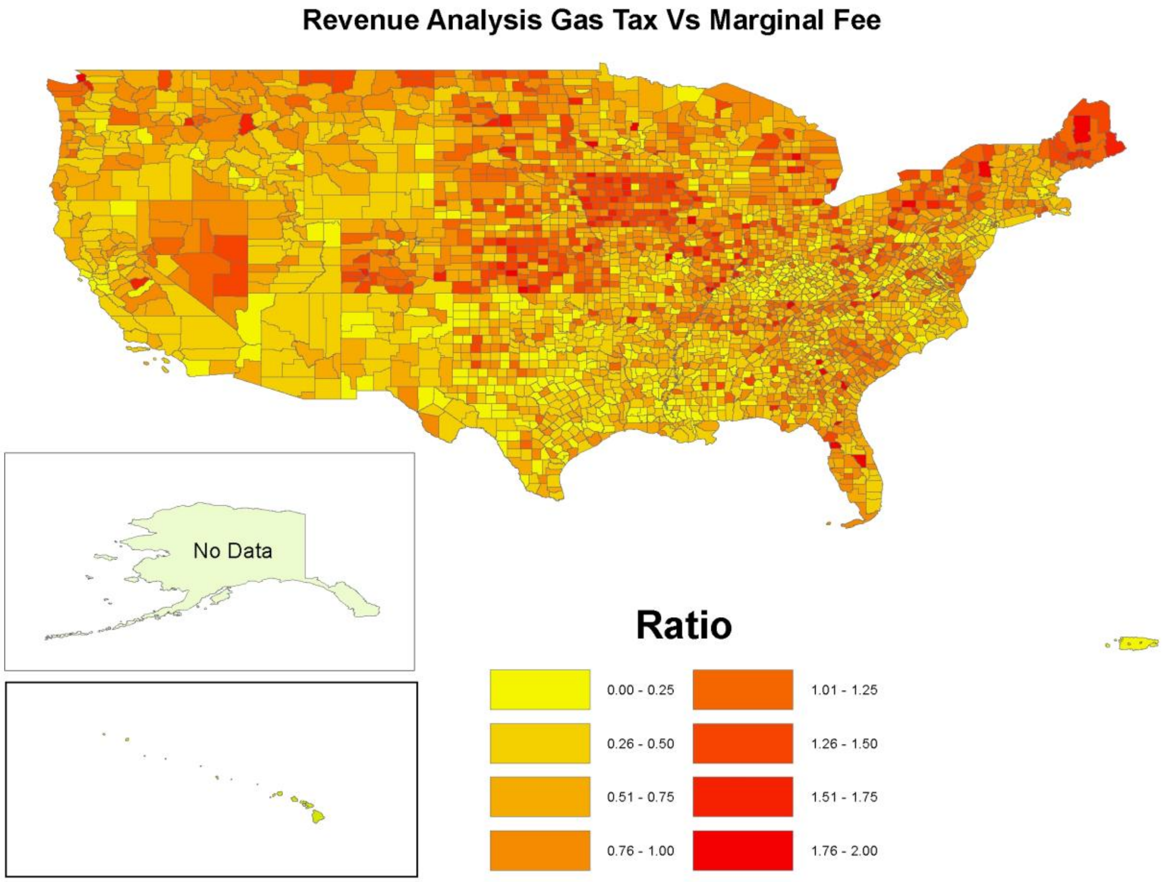


Figure 5.2 County Level Revenue Analysis

As a finer level of aggregation for revenue analysis, the county weighted average revenue ratio is obtained using similar steps conducted in Section 4.2 and is displayed above in Figure 5.2. The revenue ratios are considerably high (corresponding to excessively high gas taxes versus marginal vehicle costs) in rural areas of Nevada, Colorado, Kansas, Nebraska, Iowa, South Dakota, North Dakota, New York, Pennsylvania and Maine. In contrast, urban areas in California and states along the eastern and southern coast of the US have low revenue ratios (corresponding to inadequate gas tax revenue versus marginal vehicle costs). Noticeably, the results in

Maine show that the gas tax revenue is significantly higher than marginal revenue; as the marginal costs per vehicle mile are very similar to rural regions in the US, while the gas tax is significantly higher and similar to other east coast urban states. This detailed county level information combined with state level data shows that, while the state gas tax system provides, on average, a total revenue which is reasonably proportional to the marginal vehicle costs (when excluding external costs, and only considering those costs already covered by the gas tax), these gas tax costs are poorly distributed leaving many counties paying too much and others paying too little.

5.7 Functional Classification Revenue Analysis

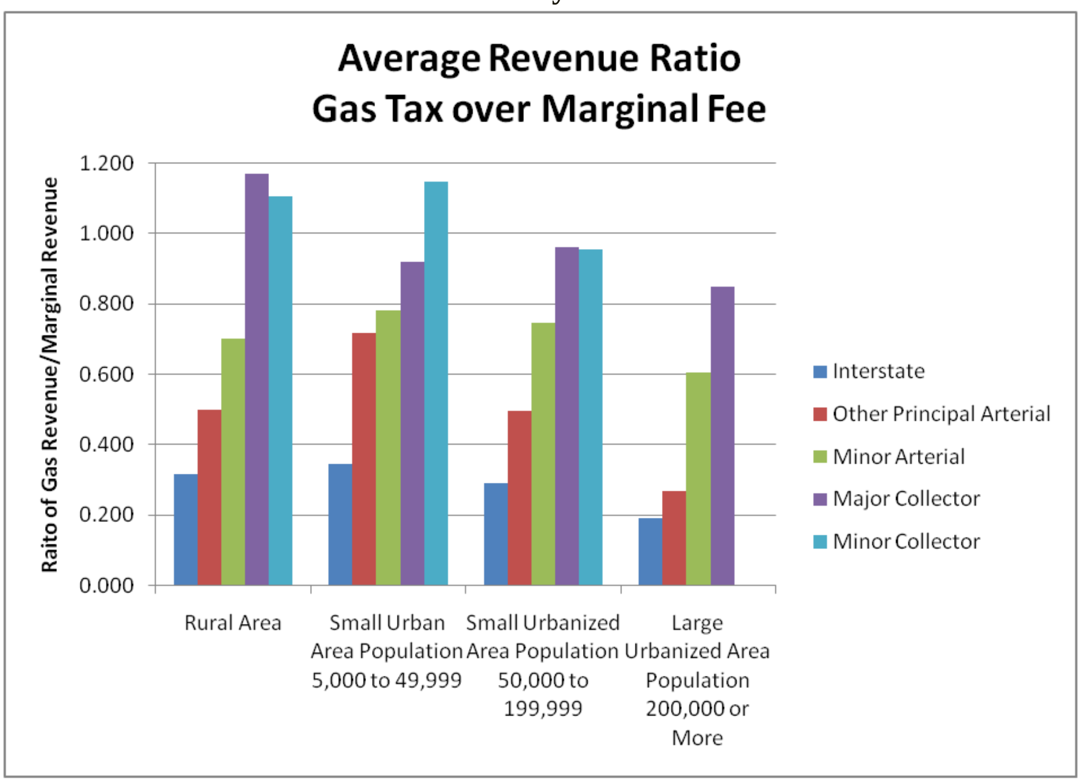


Figure 5.3 Functional Class Level Revenue Analysis

The last aggregation level of the revenue analysis is developed similar to the marginal cost aggregation in Section 4.3. As shown above in Figure 5.3, there is a distinct relationship between the revenue ratio, functional classification and rural/urban area.

First, the revenue ratio increases as functional classification decreases from Interstate segments (which pay too little) on down to Collector segments (which pay too much). Second, revenue ratio decreases as roadway segments go from rural areas to large urbanized areas. Concluding from these national averages, vehicle users who drive predominantly on minor rural roadways, are paying an excessive amount due to gas taxes versus their urban counterparts who make use of major roadways.

Developing an effective means of recouping vehicle damages to roadways, environment and other drivers proportional to the actual damages a user incurs is essential in creating a revenue system that is socially equitable. While the task of creating and implementing a standard system that is able to measure and collect these vehicle mile fees is a difficult task, having one user subsidize another user’s damages is socially disproportional.

6. Conclusions

This report provides methods for calculating the marginal costs of vehicles on US roadways. Based on total cost calculations developed by the FHWA for use in the Highway Economic Requirements System, this analysis produces component marginal costs of safety, pavement damage, travel time, emissions, and vehicle operating costs for seven vehicle types. There are several areas of improvement for both existing models contained in this report, as well as additional cost models not currently considered.

This report also conducts a simple analysis of the revenue generated by a vehicle mile fee based on the marginal costs per vehicle derived using the methodology outlined in this report. By comparing this generated revenue versus revenue generated by current gas tax fees, states, counties and functional classification results show areas where gas taxes charge either too little or too much for the actual damage being caused by vehicles. While this analysis shows the shortcomings in social equity of state level gas tax revenue, developing a system which directly and proportionally recoups all of the costs associated with vehicle travel is difficult to deploy across the entire infrastructure system.

6.1 Model Improvements

Future model improvements include the expansion and updating of existing models alongside the implementation of models for costs not already considered. Adjustments to current models include:

1. Emissions model updates to use vehicle emission rates from the EPA's MOVES model.
2. Safety model updates using the 2010 Highway Safety Manual.

3. Vehicle operating model indexes to 2008 fuel, oil, tire, maintenance, and depreciation costs
4. Pavement model disaggregation of single-unit and combined truck categories

Future work will also include the creation of several new models to account for additional costs that should be captured in the total marginal cost to society calculations:

1. Agency model expansion to include more maintenance as well as capital improvement costs
    a. Bridge and tunnel maintenance, realignment, lane construction
    b. Additional methods for computing short-run agency costs from capital improvement options

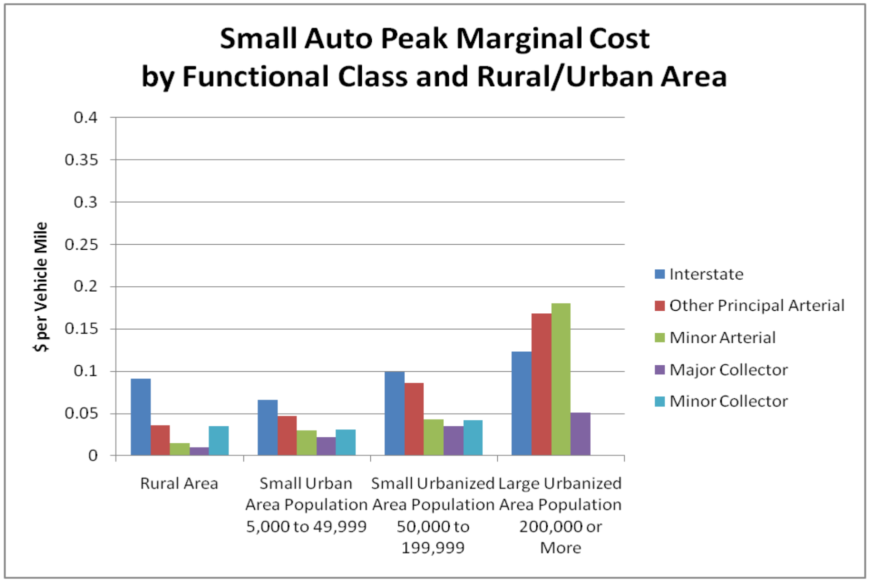
6.2 Data Improvements

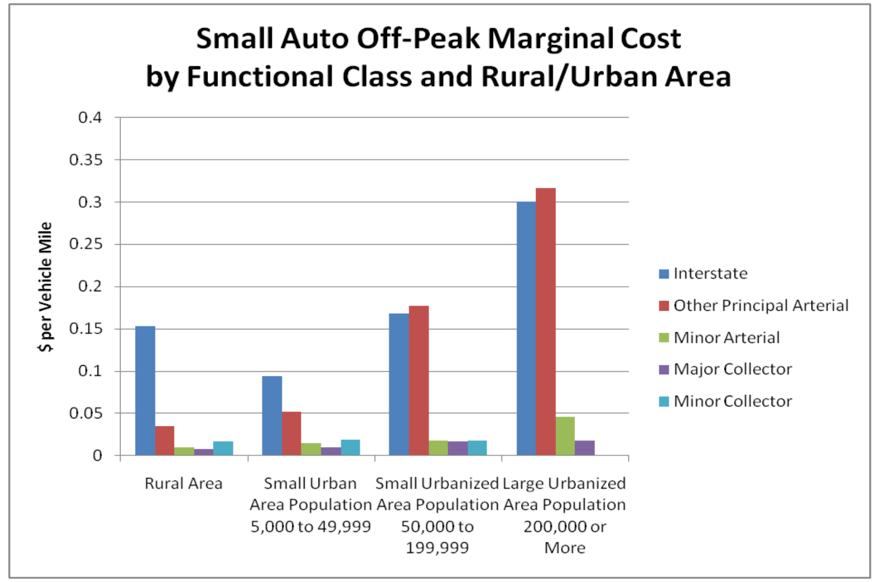
Currently these cost models rely on the HPMS sample database as it reports numerous roadway performance and geometry characteristics. While the HPMS sample database does contain detailed information on over 120,000 roadway segments, the HPMS universe database contains over 1,000,000 segments. In order to represent, and finally calculate marginal costs, on every roadway, detailed sample information can be integrated with the universe database by first aggregating sample information to functional classifications within specific volume groups, counties, and states. With these aggregated performance data joined together with the universe database complete database can be produced and successfully used with the marginal cost models contained within this report.

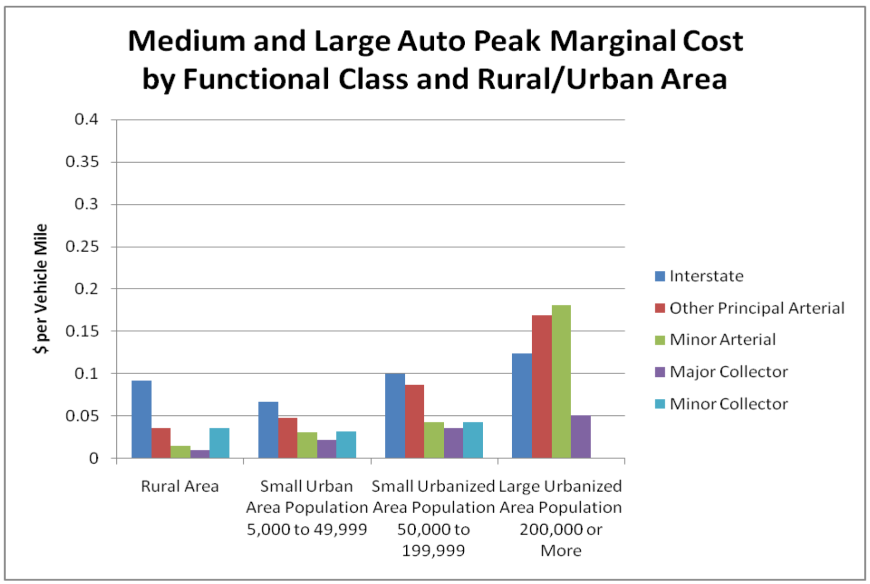
6.3 Future Uses

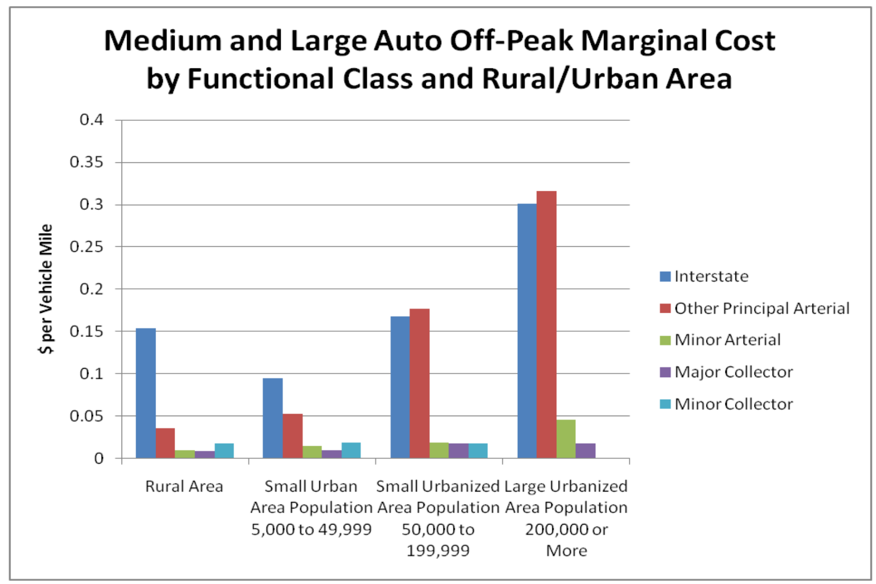
The evaluation of uses and deployment strategies for vehicle miles traveled (VMT) pricing according to marginal cost to society calculations should be further considered in the future. While examples of cordon/tolling congestion pricing have been deployed throughout the US, having detailed marginal cost information for every roadway provides a huge resource for both calibration of existing practices as well as development of large scale VMT fee structures. The advent of electronic-tolling technology for vehicles (such as EZ-Pass) and the evolution of in car GPS provide two potential points for marginal cost integration in road pricing. Allowing state agencies to recoup the true costs of providing public roadways while showing planners exactly where these costs arise from is a necessary step towards creating sustainable transportation infrastructure.

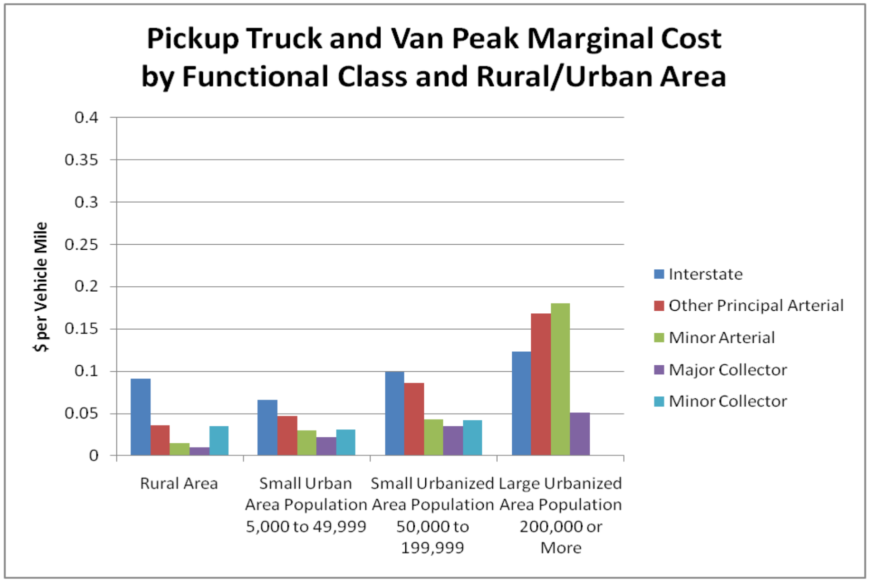
Appendix A: Functional Classification Data

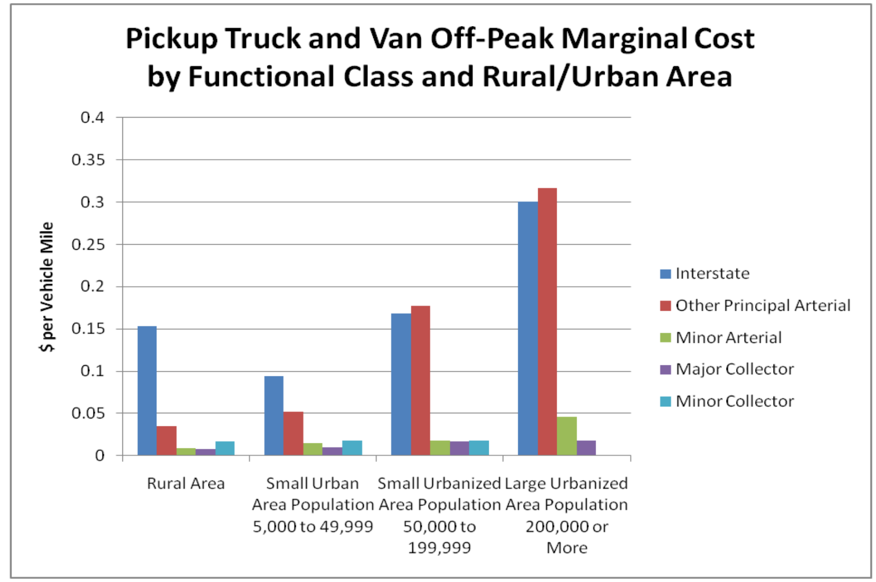

Small Auto Peak Marginal Cost
by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

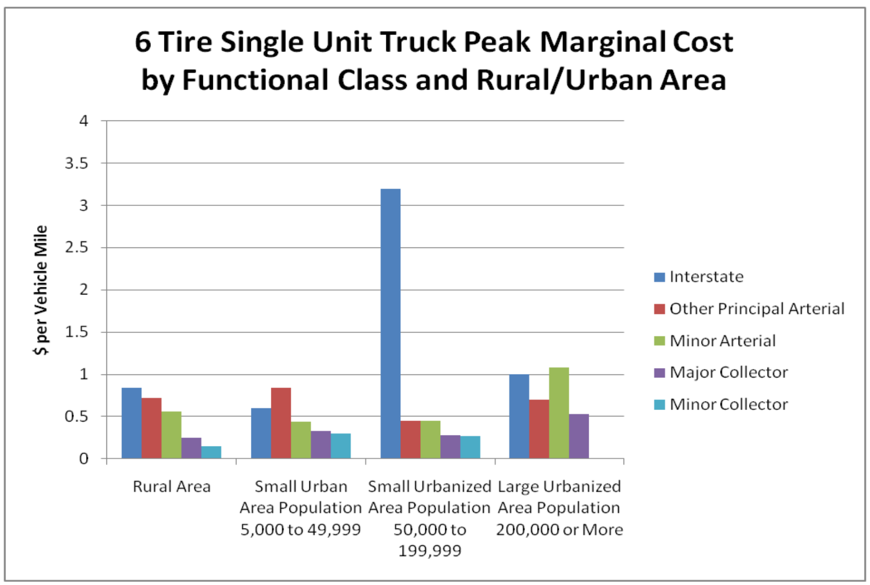

Small Auto Off-Peak Marginal Cost
by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

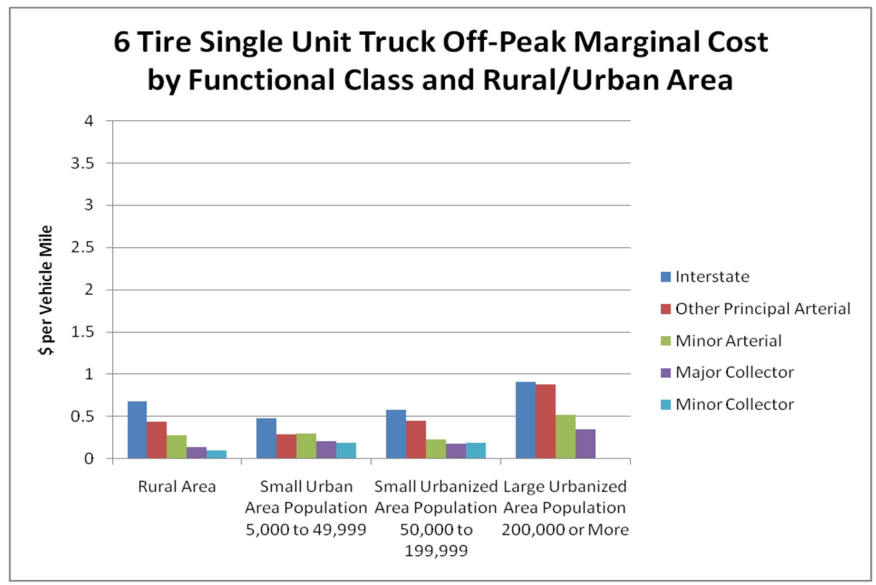

Medium and Large Auto Peak Marginal Cost
by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

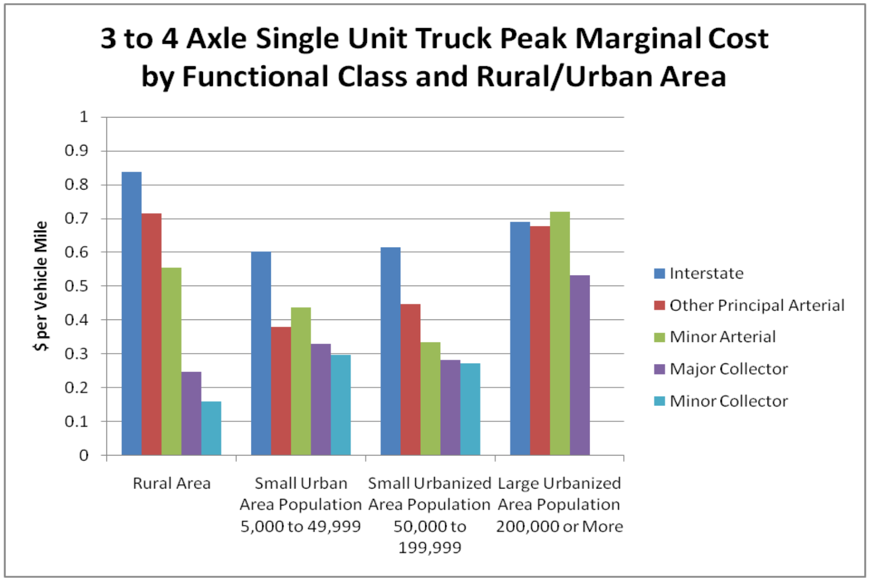

Medium and Large Auto Off-Peak Marginal Cost
by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

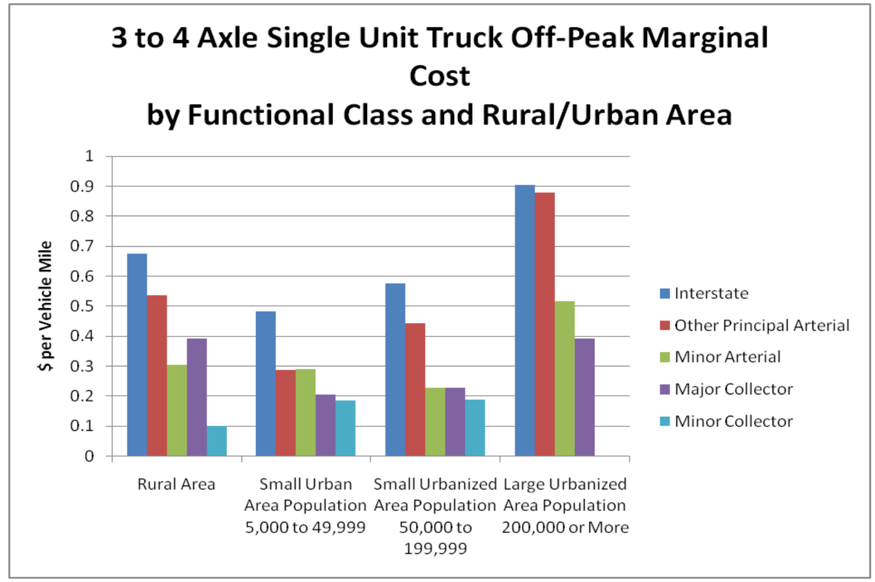

Pickup Truck and Van Peak Marginal Cost by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

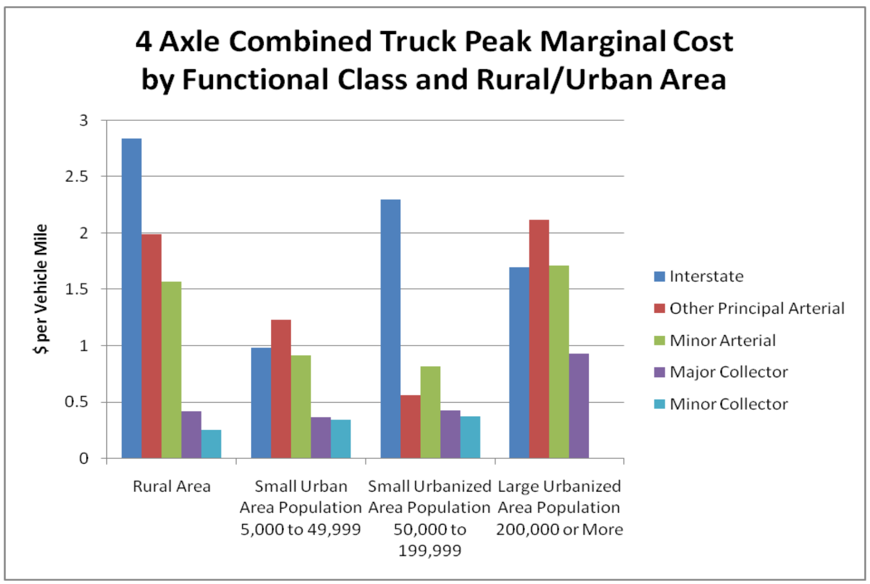

Pickup Truck and Van Off-Peak Marginal Cost by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

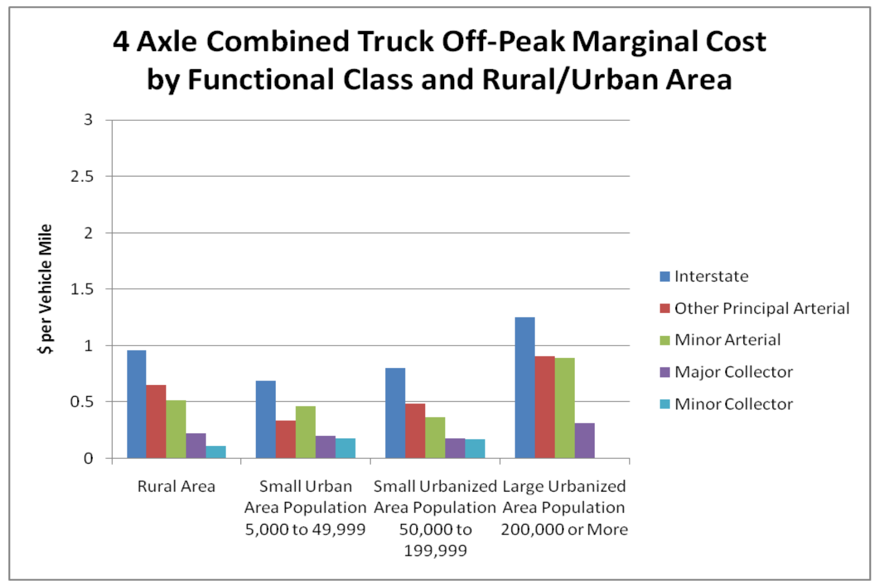

6 Tire Single Unit Truck Peak Marginal Cost by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.5
1
1.5
2
2.5
3
3.5
4
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

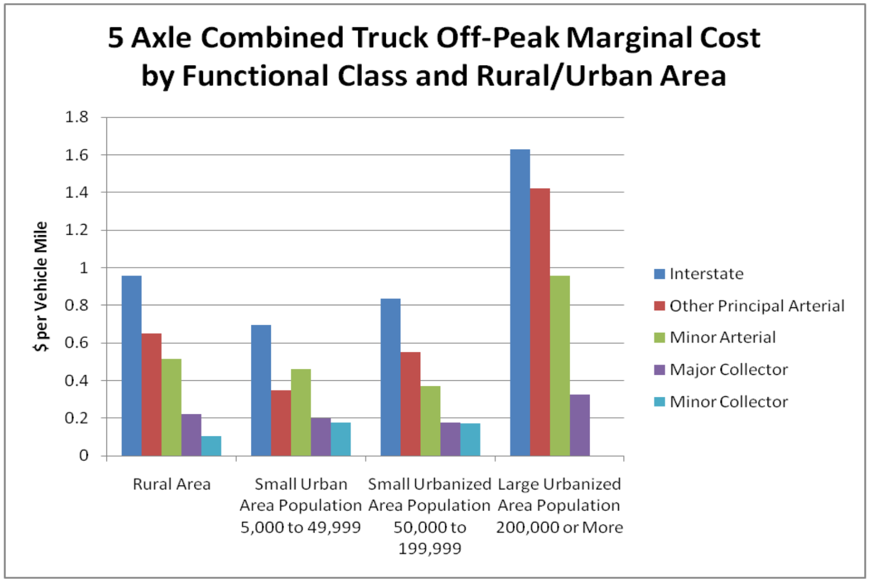

6 Tire Single Unit Truck Off-Peak Marginal Cost by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.5
1
1.5
2
2.5
3
3.5
4
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

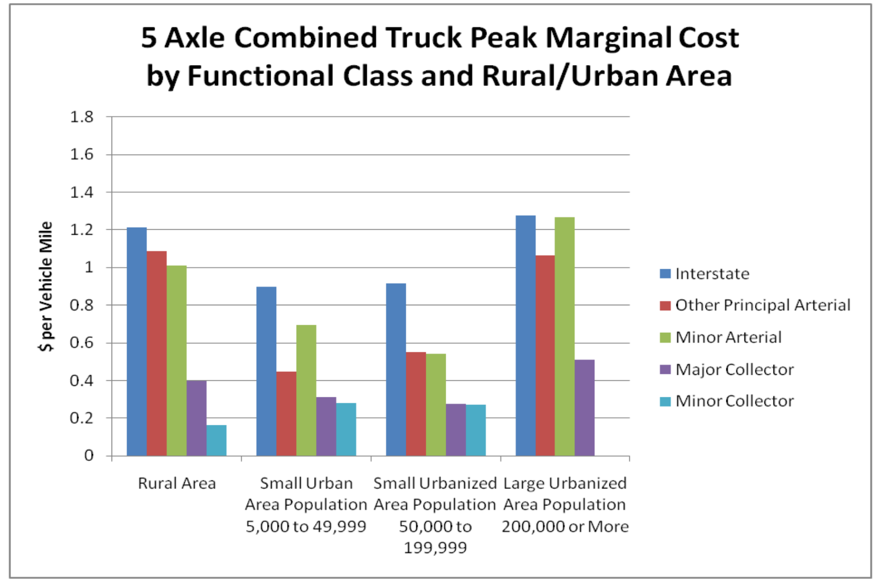

3 to 4 Axle Single Unit Truck Peak Marginal Cost by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

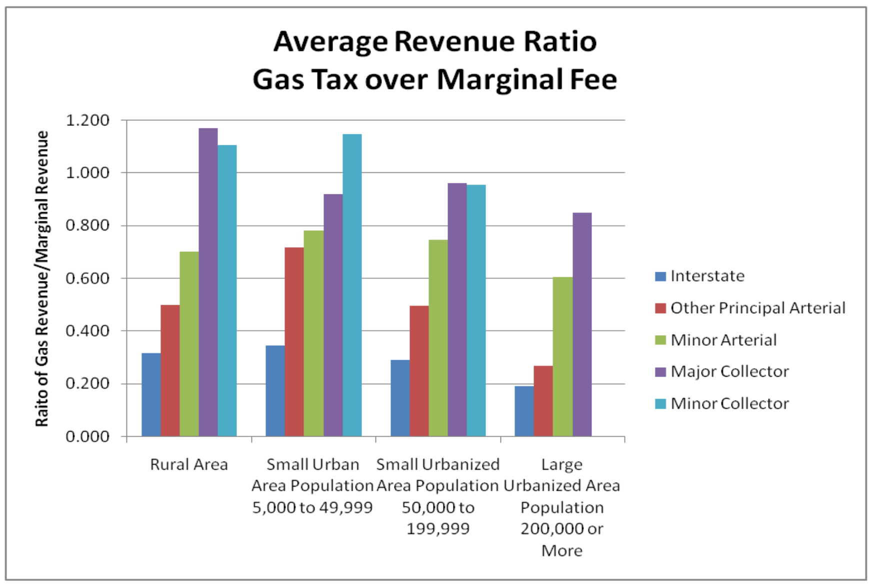

3 to 4 Axle Single Unit Truck Off-Peak Marginal Cost by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector


4 Axle Combined Truck Peak Marginal Cost by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.5
1
1.5
2
2.5
3
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector


4 Axle Combined Truck Off-Peak Marginal Cost by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.5
1
1.5
2
2.5
3
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector


5 Axle Combined Truck Off-Peak Marginal Cost
by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector


5 Axle Combined Truck Peak Marginal Cost
by Functional Class and Rural/Urban Area
$ per Vehicle Mile
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector


Average Revenue Ratio
Gas Tax over Marginal Fee
Raito of Gas Revenue/Marginal Revenue
0.000
0.200
0.400
0.600
0.800
1.000
1.200
Rural Area
Small Urban Area Population 5,000 to 49,999
Small Urbanized Area Population 50,000 to 199,999
Large Urbanized Area Population 200,000 or More
Interstate
Other Principal Arterial
Minor Arterial
Major Collector
Minor Collector

Functional Codes		
Code	**Description**	
	Rural	**Urban**
1	Interstate	Interstate
2	Other Principal Arterial	Other Freeways and Expressways
3	Minor Arterial	Other Principal Arterial
4	Major Collector	Minor Arterial
5	Minor Collector	Collector
6	Local	Local

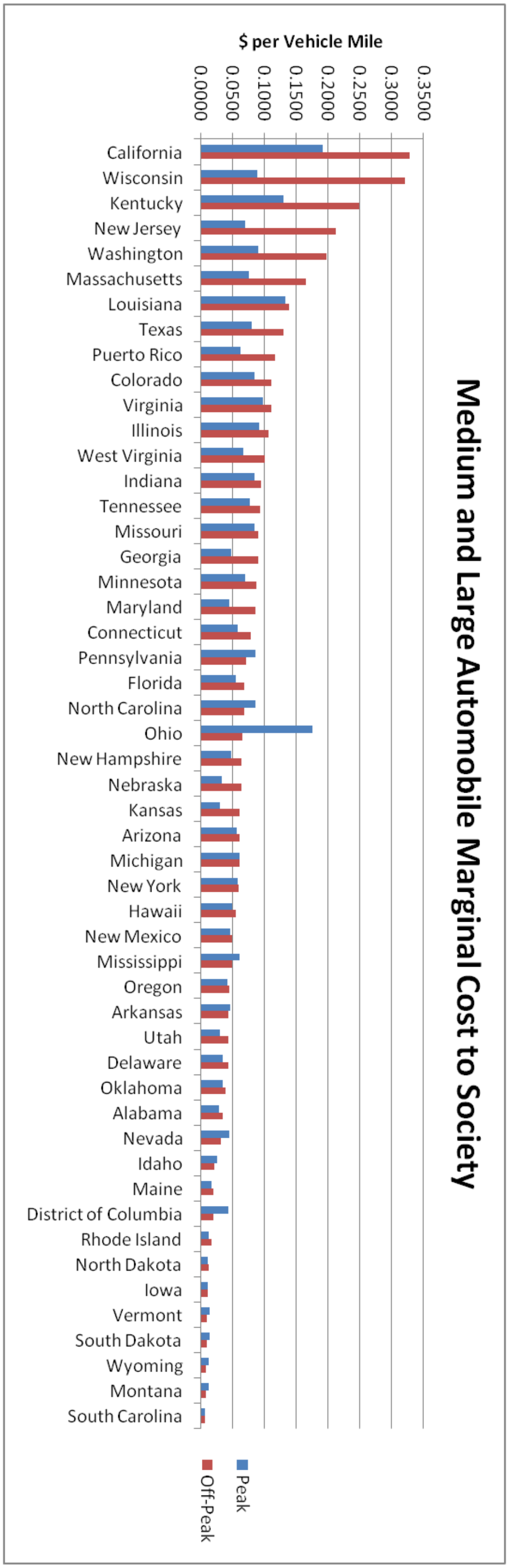
Rural/Urban Codes	
Code	**Description**
1	Rural Area
2	Small Urban Area Population 5,000 to 49,999
3	Small Urbanized Area Population 50,000 to 199,999
4	Large Urbanized Area Population 200,000 or More

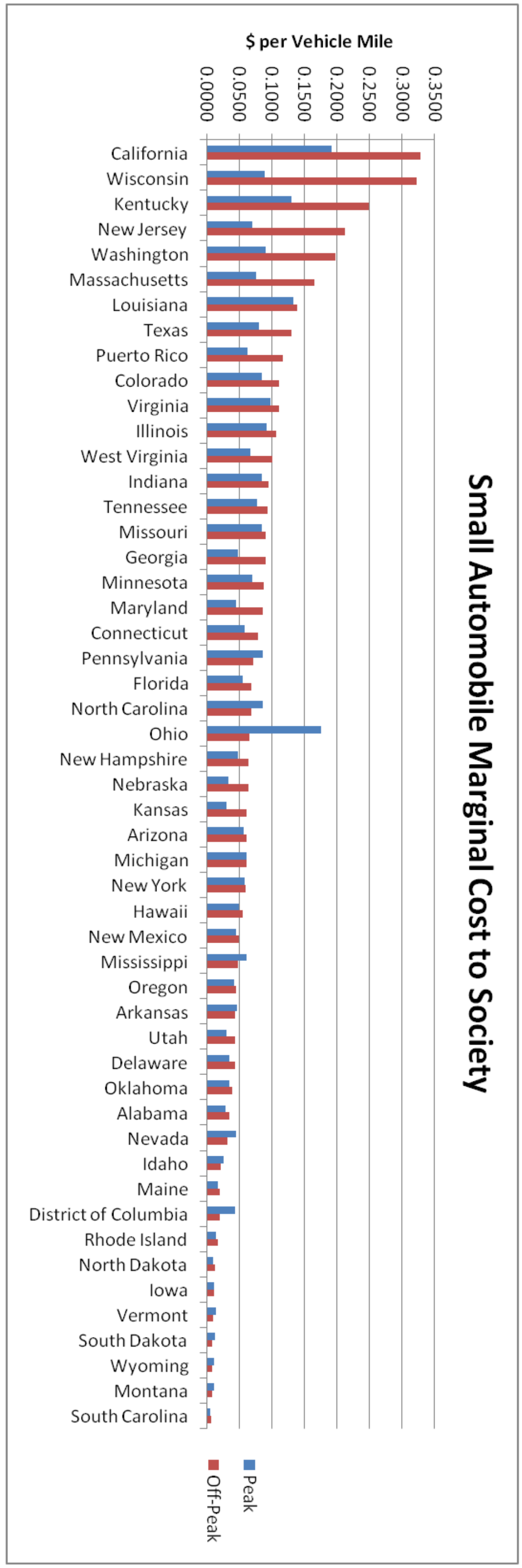
Off-Peak Marginal Cost to Society by Functional Classification								
Functional Classifcation	Rural/Urban Area	Small Auto ($)	Medium and Large Auto ($)	Pickup Truck and Van ($)	Six Tire Single Unit Truck ($)	Three to Four Axle Single Unit Truck ($)	Four Axle Combined Unit Truck ($)	Five Axle Combined Unit Truck ($)
1	1	0.1534	0.1538	0.1534	0.6753	0.6744	0.9548	0.9577
1	2	0.0941	0.0942	0.0941	0.4811	0.4811	0.6861	0.6954
1	3	0.1681	0.1682	0.1681	0.5761	0.5749	0.7986	0.8346
1	4	0.3006	0.3007	0.3006	0.9043	0.903	1.2502	1.627
2	1	0.035	0.0352	0.035	0.4347	0.5354	0.6509	0.6517
2	2	0.0523	0.0524	0.0523	0.2861	0.2859	0.3355	0.3474
2	3	0.1768	0.1769	0.1768	0.4435	0.4427	0.4818	0.5514
2	4	0.3162	0.3163	0.3162	0.8808	0.8792	0.9078	1.4233
3	1	0.0093	0.0095	0.0093	0.2805	0.3048	0.5158	0.5158
3	2	0.0144	0.0145	0.0144	0.294	0.2912	0.459	0.4605
3	3	0.0182	0.0182	0.0182	0.227	0.2262	0.3636	0.3716
3	4	0.0455	0.0455	0.0455	0.5154	0.5157	0.8909	0.9573
4	1	0.0079	0.0081	0.0079	0.1362	0.3927	0.2227	0.2227
4	2	0.0094	0.0095	0.0094	0.2055	0.2057	0.1976	0.1983
4	3	0.0173	0.0174	0.0173	0.1802	0.2288	0.1768	0.1787
4	4	0.0179	0.018	0.0179	0.3445	0.3904	0.3094	0.3263
5	2	0.0173	0.0173	0.0173	0.0974	0.1009	0.1065	0.1067
5	3	0.0184	0.0184	0.0184	0.1861	0.1853	0.1779	0.1793
5	4	0.0175	0.0176	0.0175	0.1865	0.1882	0.1677	0.1712

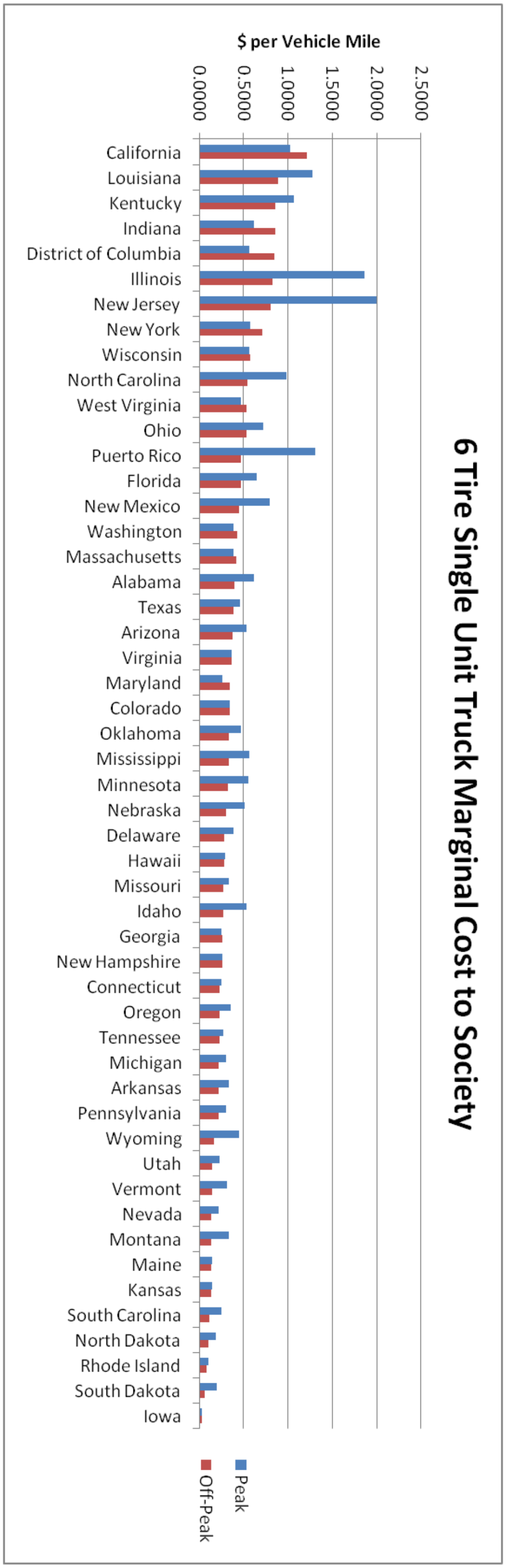
Peak Marginal Cost to Society by Functional Classification								
Functional Classifcation	Rural/Urban Area	Small Auto ($)	Medium and Large Auto ($)	Pickup Truck and Van ($)	Six Tire Single Unit Truck ($)	Three to Four Axle Single Unit Truck ($)	Four Axle Combined Unit Truck	Five Axle Combined Unit Truck
1	1	0.0912	0.0921	0.0912	0.8378	0.8371	2.8398	1.2119
1	2	0.066	0.0663	0.066	0.6007	0.6027	0.9828	0.8979
1	3	0.099	0.0993	0.099	3.1966	0.6145	2.2967	0.9178
1	4	0.1234	0.1235	0.1234	1.0008	0.6908	1.6941	1.2779
2	1	0.0358	0.036	0.0358	0.7168	0.7144	1.9898	1.087
2	2	0.0475	0.0477	0.0475	0.8408	0.3807	1.2294	0.4487
2	3	0.0862	0.0864	0.0862	0.4491	0.4483	0.5635	0.5503
2	4	0.1686	0.1687	0.1686	0.6986	0.6775	2.1179	1.0629
3	1	0.0149	0.0149	0.0149	0.5559	0.5559	1.5661	1.0111
3	2	0.0301	0.0301	0.0301	0.4408	0.4367	0.913	0.695
3	3	0.0428	0.0429	0.0428	0.4493	0.335	0.8136	0.5395
3	4	0.1803	0.1804	0.1803	1.0806	0.7196	1.7112	1.2668
4	1	0.0095	0.0098	0.0095	0.2471	0.2459	0.4186	0.3968
4	2	0.0215	0.0215	0.0215	0.3321	0.3305	0.3646	0.3115
4	3	0.0351	0.0351	0.0351	0.2834	0.2813	0.427	0.2771
4	4	0.051	0.051	0.051	0.5287	0.5332	0.9268	0.5122
5	2	0.0354	0.0354	0.0354	0.1498	0.1594	0.2501	0.1619
5	3	0.031	0.0311	0.031	0.2979	0.2965	0.3397	0.2779
5	4	0.0422	0.0423	0.0422	0.2722	0.2719	0.3727	0.2693

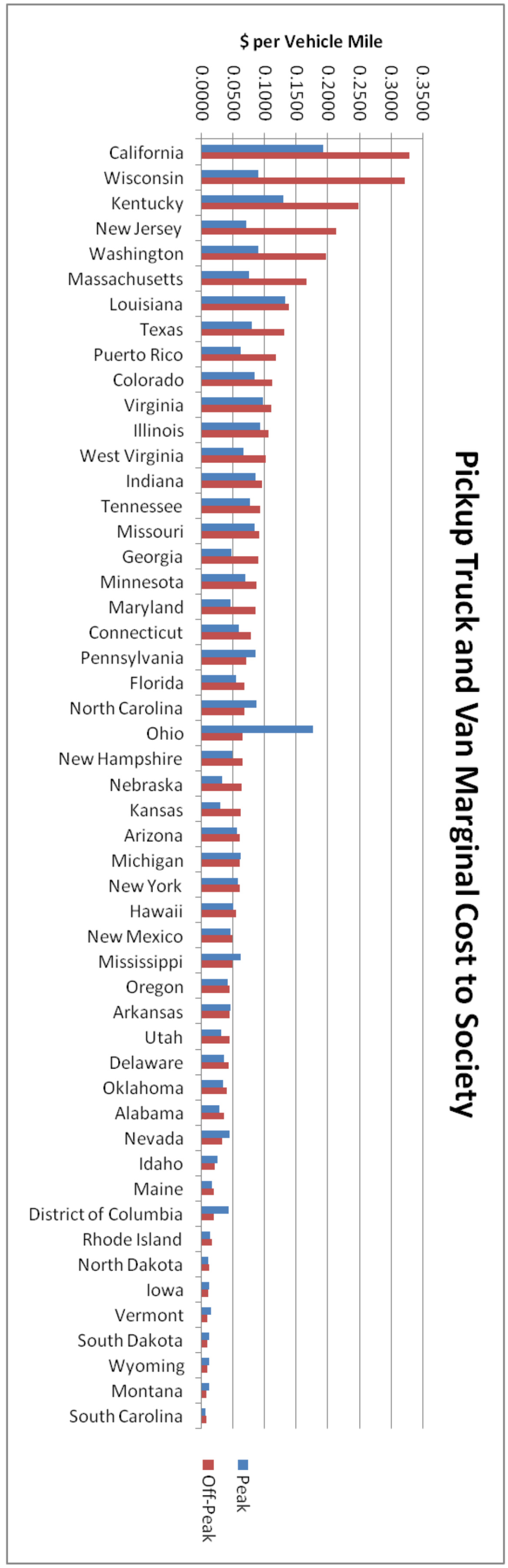
Revenue Comparison of Gas Tax versus Marginal Vehicle Mile Charge by Functional Classification		
Functional Classification	Rural/Urban Area	Average Ratio for Gas Tax to Marginal Fee
1	1	0.315
1	2	0.344
1	3	0.292
1	4	0.190
2	1	0.499
2	2	0.716
2	3	0.495
2	4	0.267
3	1	0.701
3	2	0.781
3	3	0.747
3	4	0.607
4	1	1.171
4	2	0.921
4	3	0.960
4	4	0.850
5	2	1.105
5	3	1.147
5	4	0.956

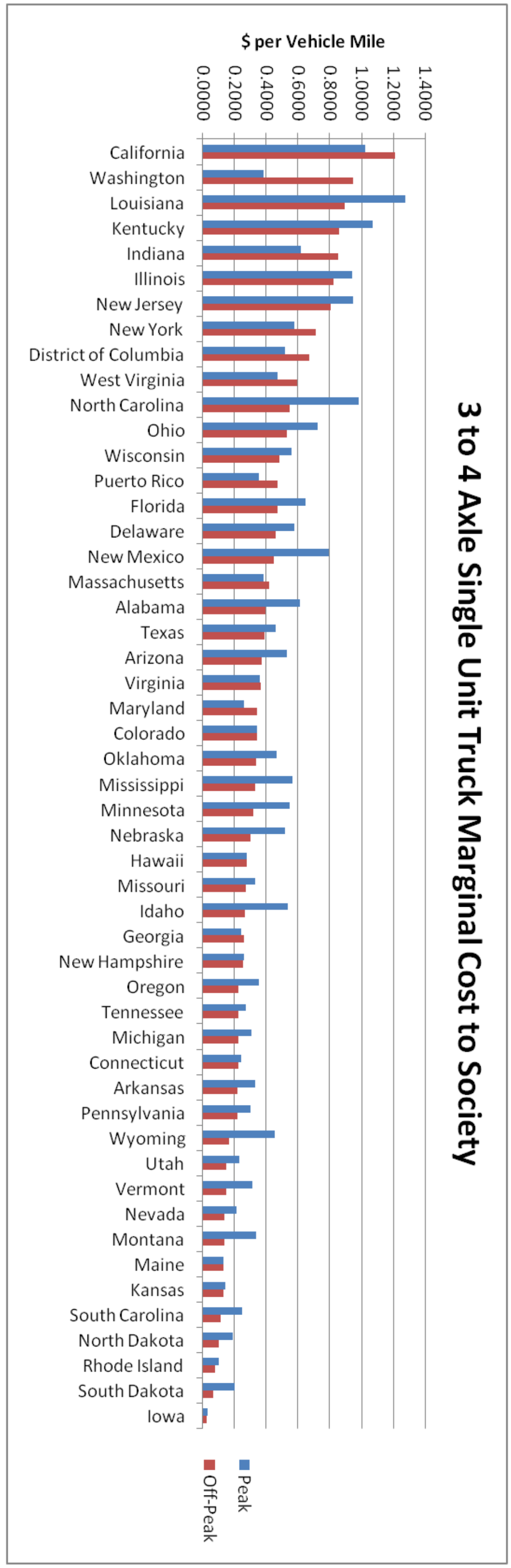
Appendix B: State Data

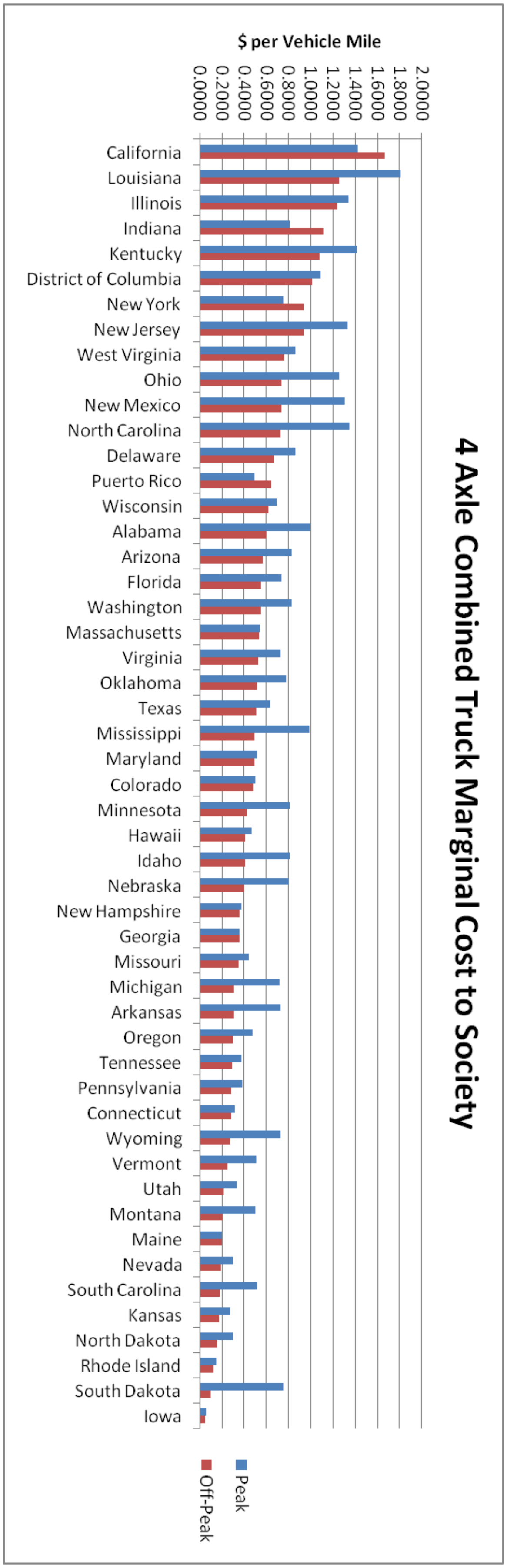

Medium and Large Automobile Marginal Cost to Society
$ per Vehicle Mile
0.0000
0.0500
0.1000
0.1500
0.2000
0.2500
0.3000
0.3500
California
Wisconsin
Kentucky
New Jersey
Washington
Massachusetts
Louisiana
Texas
Puerto Rico
Colorado
Virginia
Illinois
West Virginia
Indiana
Tennessee
Missouri
Georgia
Minnesota
Maryland
Connecticut
Pennsylvania
Florida
North Carolina
Ohio
New Hampshire
Nebraska
Kansas
Arizona
Michigan
New York
Hawaii
New Mexico
Mississippi
Oregon
Arkansas
Utah
Delaware
Oklahoma
Alabama
Nevada
Idaho
Maine
District of Columbia
Rhode Island
North Dakota
Iowa
Vermont
South Dakota
Wyoming
Montana
South Carolina
Peak
Off-Peak

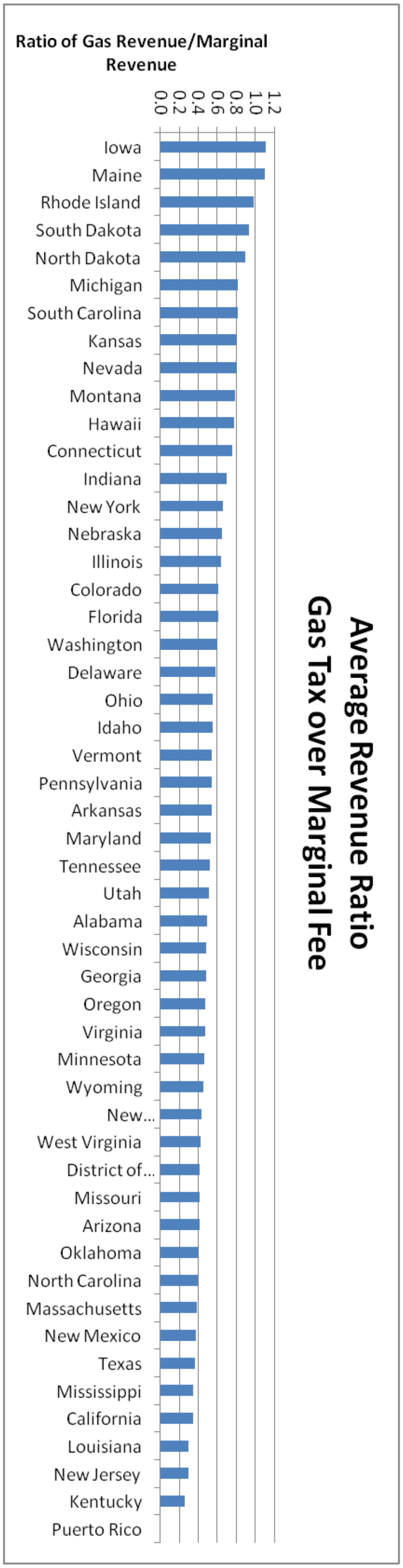

Small Automobile Marginal Cost to Society
$ per Vehicle Mile
0.0000
0.0500
0.1000
0.1500
0.2000
0.2500
0.3000
0.3500
California
Wisconsin
Kentucky
New Jersey
Washington
Massachusetts
Louisiana
Texas
Puerto Rico
Colorado
Virginia
Illinois
West Virginia
Indiana
Tennessee
Missouri
Georgia
Minnesota
Maryland
Connecticut
Pennsylvania
Florida
North Carolina
Ohio
New Hampshire
Nebraska
Kansas
Arizona
Michigan
New York
Hawaii
New Mexico
Mississippi
Oregon
Arkansas
Utah
Delaware
Oklahoma
Alabama
Nevada
Idaho
Maine
District of Columbia
Rhode Island
North Dakota
Iowa
Vermont
South Dakota
Wyoming
Montana
South Carolina
Peak
Off-Peak

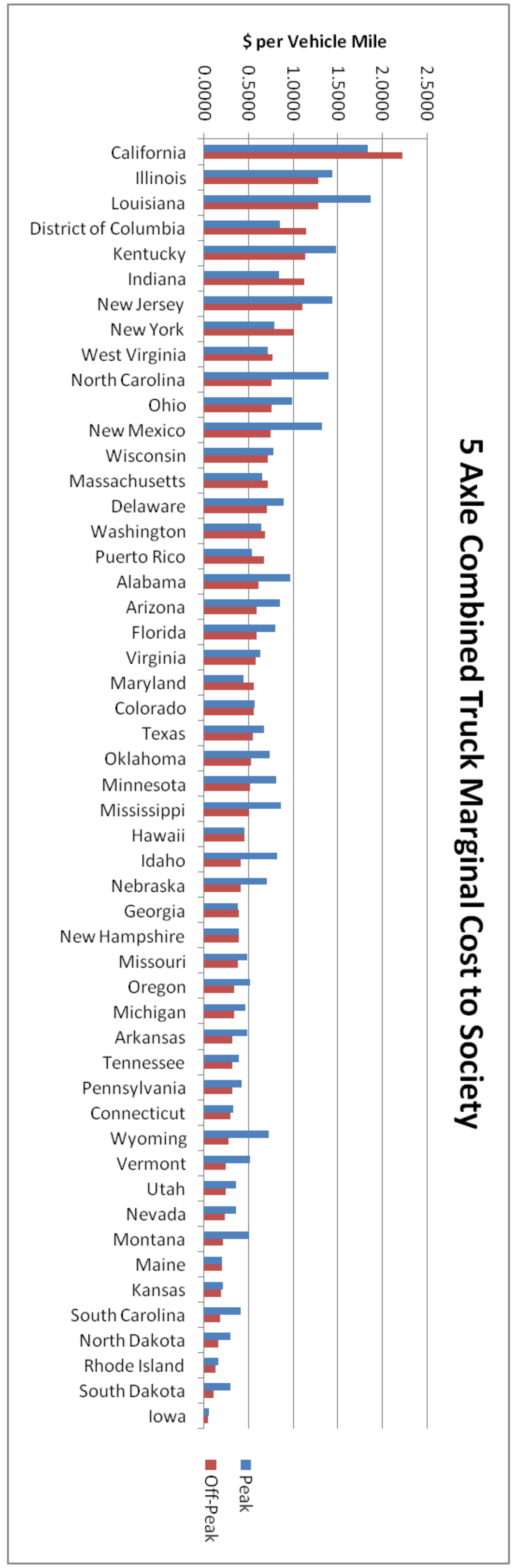

6 Tire Single Unit Truck Marginal Cost to Society
$ per Vehicle Mile
0.0000
0.5000
1.0000
1.5000
2.0000
2.5000
California
Louisiana
Kentucky
Indiana
District of Columbia
Illinois
New Jersey
New York
Wisconsin
North Carolina
West Virginia
Ohio
Puerto Rico
Florida
New Mexico
Washington
Massachusetts
Alabama
Texas
Arizona
Virginia
Maryland
Colorado
Oklahoma
Mississippi
Minnesota
Nebraska
Delaware
Hawaii
Missouri
Idaho
Georgia
New Hampshire
Connecticut
Oregon
Tennessee
Michigan
Arkansas
Pennsylvania
Wyoming
Utah
Vermont
Nevada
Montana
Maine
Kansas
South Carolina
North Dakota
Rhode Island
South Dakota
Iowa
Peak
Off-Peak


Pickup Truck and Van Marginal Cost to Society
$ per Vehicle Mile
0.0000
0.0500
0.1000
0.1500
0.2000
0.2500
0.3000
0.3500
California
Wisconsin
Kentucky
New Jersey
Washington
Massachusetts
Louisiana
Texas
Puerto Rico
Colorado
Virginia
Illinois
West Virginia
Indiana
Tennessee
Missouri
Georgia
Minnesota
Maryland
Connecticut
Pennsylvania
Florida
North Carolina
Ohio
New Hampshire
Nebraska
Kansas
Arizona
Michigan
New York
Hawaii
New Mexico
Mississippi
Oregon
Arkansas
Utah
Delaware
Oklahoma
Alabama
Nevada
Idaho
Maine
District of Columbia
Rhode Island
North Dakota
Iowa
Vermont
South Dakota
Wyoming
Montana
South Carolina
Peak
Off-Peak


3 to 4 Axle Single Unit Truck Marginal Cost to Society
$ per Vehicle Mile
0.0000
0.2000
0.4000
0.6000
0.8000
1.0000
1.2000
1.4000
California
Washington
Louisiana
Kentucky
Indiana
Illinois
New Jersey
New York
District of Columbia
West Virginia
North Carolina
Ohio
Wisconsin
Puerto Rico
Florida
Delaware
New Mexico
Massachusetts
Alabama
Texas
Arizona
Virginia
Maryland
Colorado
Oklahoma
Mississippi
Minnesota
Nebraska
Hawaii
Missouri
Idaho
Georgia
New Hampshire
Oregon
Tennessee
Michigan
Connecticut
Arkansas
Pennsylvania
Wyoming
Utah
Vermont
Nevada
Montana
Maine
Kansas
South Carolina
North Dakota
Rhode Island
South Dakota
Iowa
Peak
Off-Peak


4 Axle Combined Truck Marginal Cost to Society
$ per Vehicle Mile
0.0000
0.2000
0.4000
0.6000
0.8000
1.0000
1.2000
1.4000
1.6000
1.8000
2.0000
California
Louisiana
Illinois
Indiana
Kentucky
District of Columbia
New York
New Jersey
West Virginia
Ohio
New Mexico
North Carolina
Delaware
Puerto Rico
Wisconsin
Alabama
Arizona
Florida
Washington
Massachusetts
Virginia
Oklahoma
Texas
Mississippi
Maryland
Colorado
Minnesota
Hawaii
Idaho
Nebraska
New Hampshire
Georgia
Missouri
Michigan
Arkansas
Oregon
Tennessee
Pennsylvania
Connecticut
Wyoming
Vermont
Utah
Montana
Maine
Nevada
South Carolina
Kansas
North Dakota
Rhode Island
South Dakota
Iowa
Peak
Off-Peak

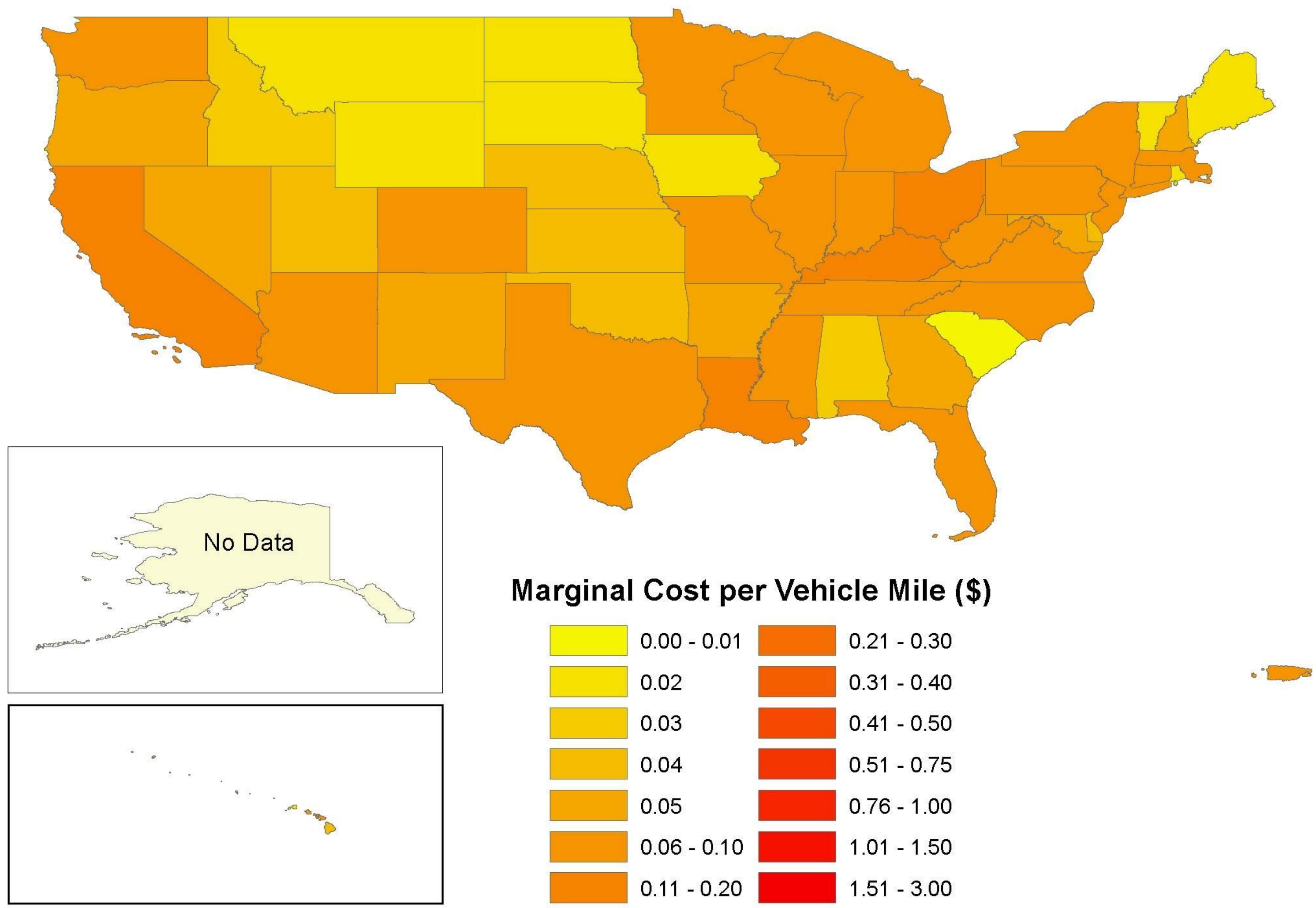

Average Revenue Ratio
Gas Tax over Marginal Fee
Ratio of Gas Revenue/Marginal Revenue
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Iowa
Maine
Rhode Island
South Dakota
North Dakota
Michigan
South Carolina
Kansas
Nevada
Montana
Hawaii
Connecticut
Indiana
New York
Nebraska
Illinois
Colorado
Florida
Washington
Delaware
Ohio
Idaho
Vermont
Pennsylvania
Arkansas
Maryland
Tennessee
Utah
Alabama
Wisconsin
Georgia
Oregon
Virginia
Minnesota
Wyoming
New...
West Virginia
District of...
Missouri
Arizona
Oklahoma
North Carolina
Massachusetts
New Mexico
Texas
Mississippi
California
Louisiana
New Jersey
Kentucky
Puerto Rico


5 Axle Combined Truck Marginal Cost to Society
$ per Vehicle Mile
0.0000
0.5000
1.0000
1.5000
2.0000
2.5000
California
Illinois
Louisiana
District of Columbia
Kentucky
Indiana
New Jersey
New York
West Virginia
North Carolina
Ohio
New Mexico
Wisconsin
Massachusetts
Delaware
Washington
Puerto Rico
Alabama
Arizona
Florida
Virginia
Maryland
Colorado
Texas
Oklahoma
Minnesota
Mississippi
Hawaii
Idaho
Nebraska
Georgia
New Hampshire
Missouri
Oregon
Michigan
Arkansas
Tennessee
Pennsylvania
Connecticut
Wyoming
Vermont
Utah
Nevada
Montana
Maine
Kansas
South Carolina
North Dakota
Rhode Island
South Dakota
Iowa
Peak
Off-Peak

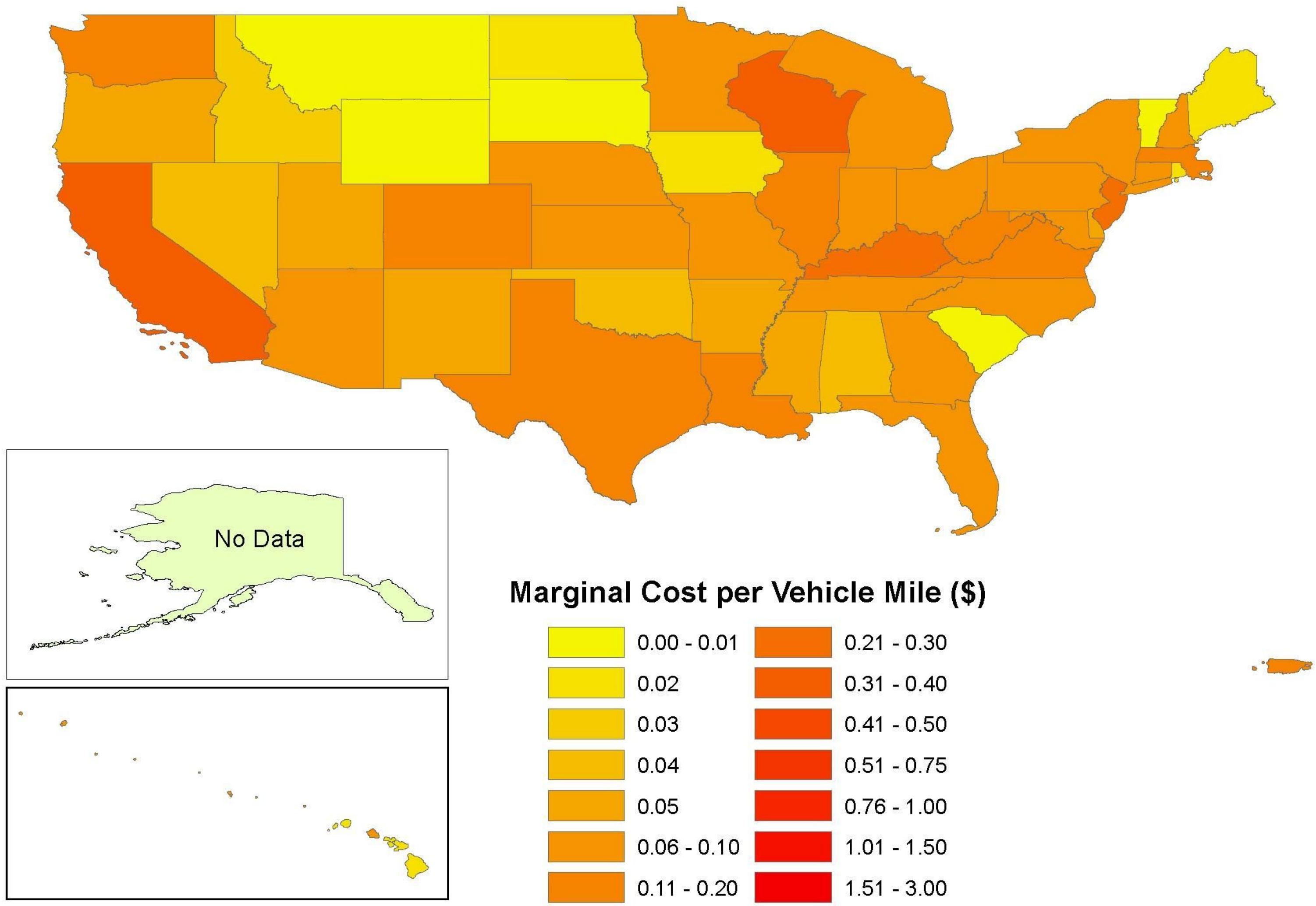
Off-Peak Marginal Cost to Society by State								
State Code	State	Small Auto ($)	Medium and Large Auto ($)	Pickup Truck and Van ($)	Six Tire Single Unit Truck ($)	Three to Four Axle Single Unit Truck ($)	Four Axle Combined Unit Truck ($)	Five Axle Combined Unit Truck ($)
1	Alabama	0.0351	0.0352	0.0351	0.3941	0.394	0.6051	0.6118
4	Arizona	0.0607	0.0609	0.0607	0.3737	0.3737	0.5649	0.5897
5	Arkansas	0.0443	0.0444	0.0443	0.2189	0.2189	0.3086	0.3182
6	California	0.3288	0.3289	0.3288	1.2149	1.2135	1.6661	2.2268
8	Colorado	0.1115	0.1116	0.1115	0.3406	0.3406	0.4853	0.556
9	Connecticut	0.0785	0.0786	0.0785	0.2289	0.2225	0.2795	0.3014
10	Delaware	0.0436	0.0437	0.0436	0.2812	0.4608	0.6677	0.7013
11	District of Columbia	0.0196	0.0196	0.0196	0.844	0.6712	1.0089	1.1469
12	Florida	0.0686	0.0686	0.0686	0.4673	0.47	0.5544	0.5869
13	Georgia	0.0906	0.0907	0.0906	0.2607	0.2606	0.3584	0.3929
15	Hawaii	0.0554	0.0554	0.0554	0.2804	0.2798	0.4069	0.4578
16	Idaho	0.0215	0.0218	0.0215	0.2671	0.2671	0.4054	0.4129
17	Illinois	0.1061	0.1062	0.1061	0.8227	0.8225	1.2382	1.2845
18	Indiana	0.0954	0.0955	0.0954	0.8543	0.8543	1.1119	1.1213
19	Iowa	0.0112	0.0113	0.0112	0.0254	0.0254	0.0467	0.0474
20	Kansas	0.0618	0.062	0.0618	0.1295	0.1295	0.1735	0.1914
21	Kentucky	0.2485	0.2488	0.2485	0.8574	0.8573	1.0824	1.137
22	Louisiana	0.139	0.1392	0.139	0.8932	0.8931	1.2535	1.2806
23	Maine	0.0196	0.0196	0.0196	0.1302	0.1302	0.1987	0.2013
24	Maryland	0.0862	0.0862	0.0862	0.3414	0.3411	0.4929	0.5569
25	Massachusetts	0.1656	0.1657	0.1656	0.4189	0.4187	0.5379	0.7129
26	Michigan	0.0606	0.0608	0.0606	0.223	0.2229	0.3111	0.3358
27	Minnesota	0.0875	0.0877	0.0875	0.3199	0.3199	0.4226	0.5158
28	Mississippi	0.0488	0.049	0.0488	0.3312	0.3311	0.4957	0.5045
29	Missouri	0.091	0.0911	0.091	0.2727	0.2726	0.3532	0.3832
30	Montana	0.0082	0.0084	0.0082	0.1358	0.1358	0.21	0.21
31	Nebraska	0.0636	0.0639	0.0636	0.3033	0.3032	0.4027	0.4118
32	Nevada	0.0325	0.0326	0.0325	0.1372	0.1372	0.1907	0.2308
33	New Hampshire	0.0646	0.0646	0.0646	0.2562	0.2563	0.3632	0.3926
34	New Jersey	0.2127	0.2127	0.2127	0.8039	0.8036	0.935	1.1058
35	New Mexico	0.0489	0.0493	0.0489	0.4497	0.4497	0.7324	0.743
36	New York	0.0602	0.0602	0.0602	0.7106	0.7102	0.9401	1.0114
37	North Carolina	0.0684	0.0685	0.0684	0.5456	0.5456	0.7292	0.7589
38	North Dakota	0.0121	0.0126	0.0121	0.1005	0.1005	0.161	0.1617
39	Ohio	0.0655	0.0656	0.0655	0.5294	0.5294	0.7327	0.7566
40	Oklahoma	0.0395	0.0397	0.0395	0.3344	0.3344	0.5192	0.5261
41	Oregon	0.0448	0.045	0.0448	0.2277	0.2276	0.3045	0.3359
42	Pennsylvania	0.0716	0.0717	0.0716	0.2178	0.2178	0.2839	0.3132
44	Rhode Island	0.0172	0.0172	0.0172	0.0807	0.0807	0.1245	0.1298
45	South Carolina	0.0071	0.0075	0.0071	0.1116	0.1116	0.1853	0.1853
46	South Dakota	0.009	0.0093	0.009	0.065	0.065	0.1031	0.1039
47	Tennessee	0.093	0.093	0.093	0.2273	0.2273	0.2959	0.3154
48	Texas	0.1304	0.1305	0.1304	0.388	0.388	0.5101	0.544
49	Utah	0.0441	0.0442	0.0441	0.149	0.1489	0.2182	0.24
50	Vermont	0.0093	0.0095	0.0093	0.1465	0.1465	0.2476	0.2476
51	Virginia	0.1105	0.1105	0.1105	0.3632	0.363	0.5293	0.5812
53	Washington	0.1971	0.1972	0.1971	0.4311	0.9463	0.5479	0.6871
54	West Virginia	0.1014	0.1015	0.1014	0.532	0.5935	0.7635	0.767
55	Wisconsin	0.3217	0.3218	0.3217	0.5763	0.4831	0.6213	0.7188
56	Wyoming	0.009	0.0092	0.009	0.1688	0.1688	0.2774	0.278
72	Puerto Rico	0.1172	0.1173	0.1172	0.4733	0.4732	0.6436	0.6791

Revenue Comparison of Gas Tax versus Marginal Vehicle Mile Charge by State		
State Code	State	Average Ratio for Gas Tax to Marginal Fee
1	Alabama	0.497
4	Arizona	0.4102
5	Arkansas	0.5371
6	California	0.3478
8	Colorado	0.6143
9	Connecticut	0.7593
10	Delaware	0.5817
11	District of Columbia	0.4152
12	Florida	0.6122
13	Georgia	0.4829
15	Hawaii	0.7806
16	Idaho	0.5486
17	Illinois	0.6361
18	Indiana	0.6943
19	Iowa	1.1132
20	Kansas	0.8091
21	Kentucky	0.2575
22	Louisiana	0.2966
23	Maine	1.1047
24	Maryland	0.5355
25	Massachusetts	0.3862
26	Michigan	0.8209
27	Minnesota	0.4657
28	Mississippi	0.3501
29	Missouri	0.4129
30	Montana	0.7864
31	Nebraska	0.6459
32	Nevada	0.8045
33	New Hampshire	0.4295
34	New Jersey	0.2936
35	New Mexico	0.3789
36	New York	0.6604
37	North Carolina	0.3978
38	North Dakota	0.8961
39	Ohio	0.5527
40	Oklahoma	0.401
41	Oregon	0.4761
42	Pennsylvania	0.5446
44	Rhode Island	0.9801
45	South Carolina	0.8126
46	South Dakota	0.9363
47	Tennessee	0.5242
48	Texas	0.3611
49	Utah	0.5101
50	Vermont	0.5456
51	Virginia	0.4749
53	Washington	0.6019
54	West Virginia	0.423
55	Wisconsin	0.4848
56	Wyoming	0.4569
72	Puerto Rico	0

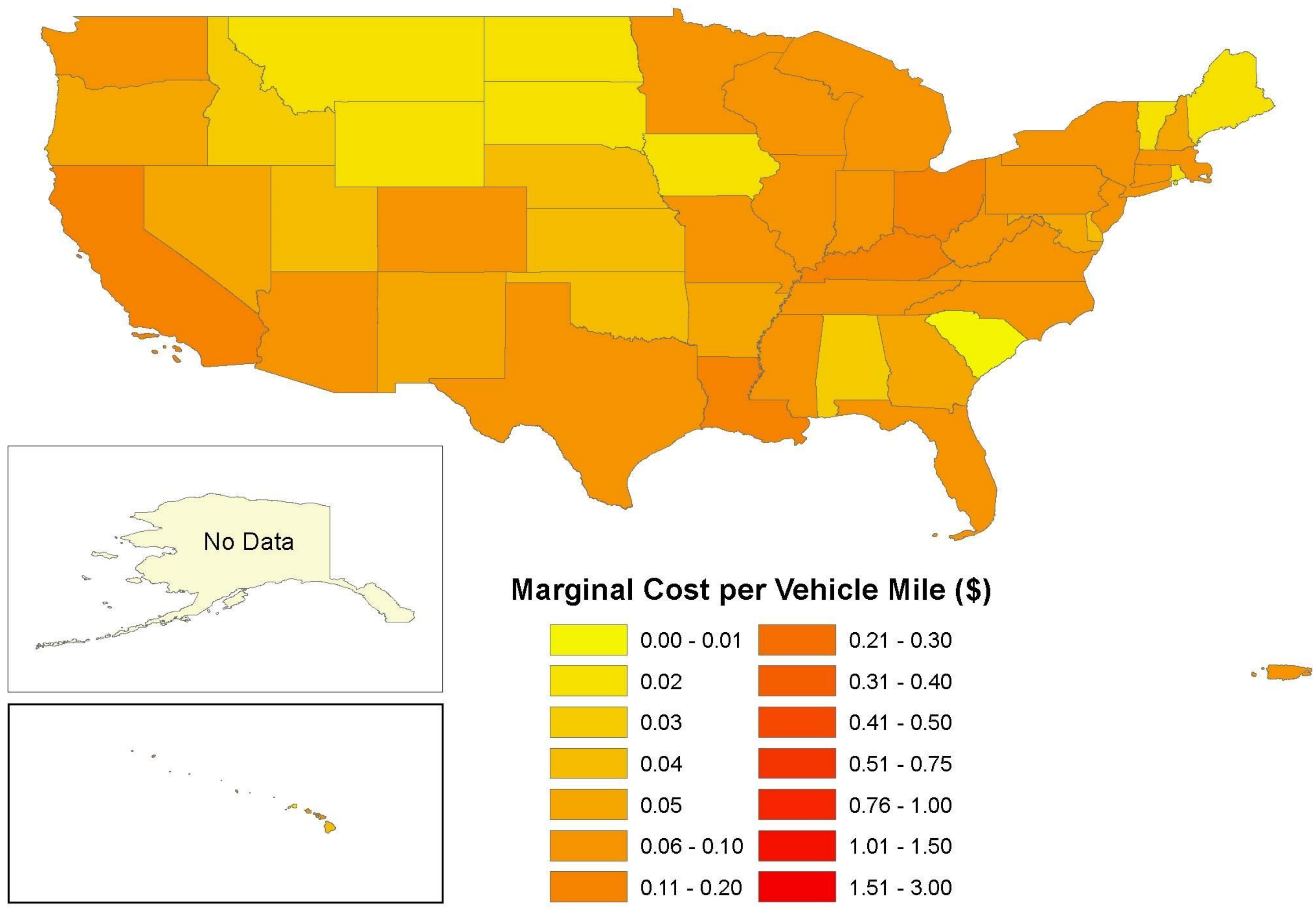
Total Marginal Cost to Society for Small Automobiles Peak Period



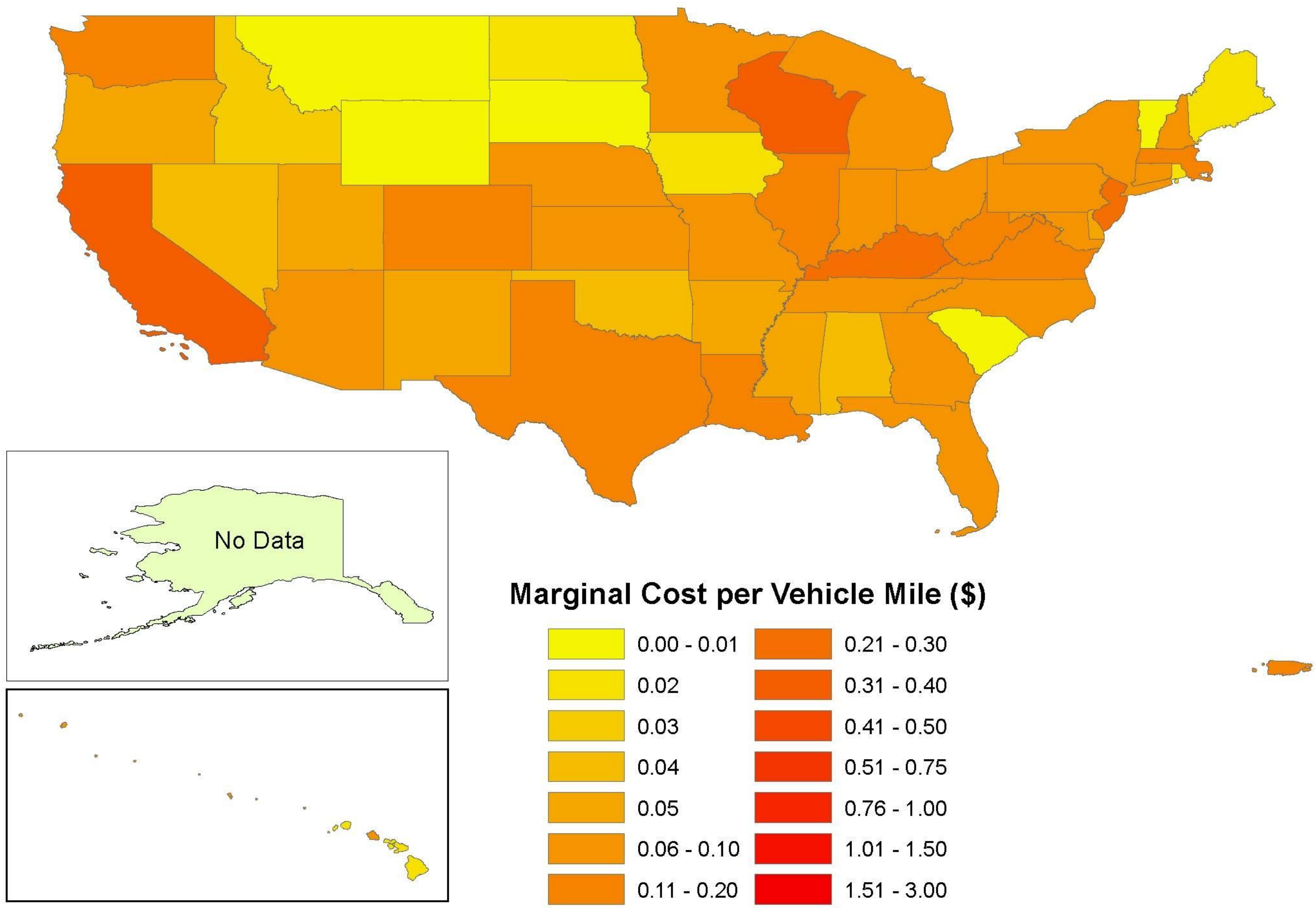
Total Marginal Cost to Society for Small Automobile Off-Peak Period



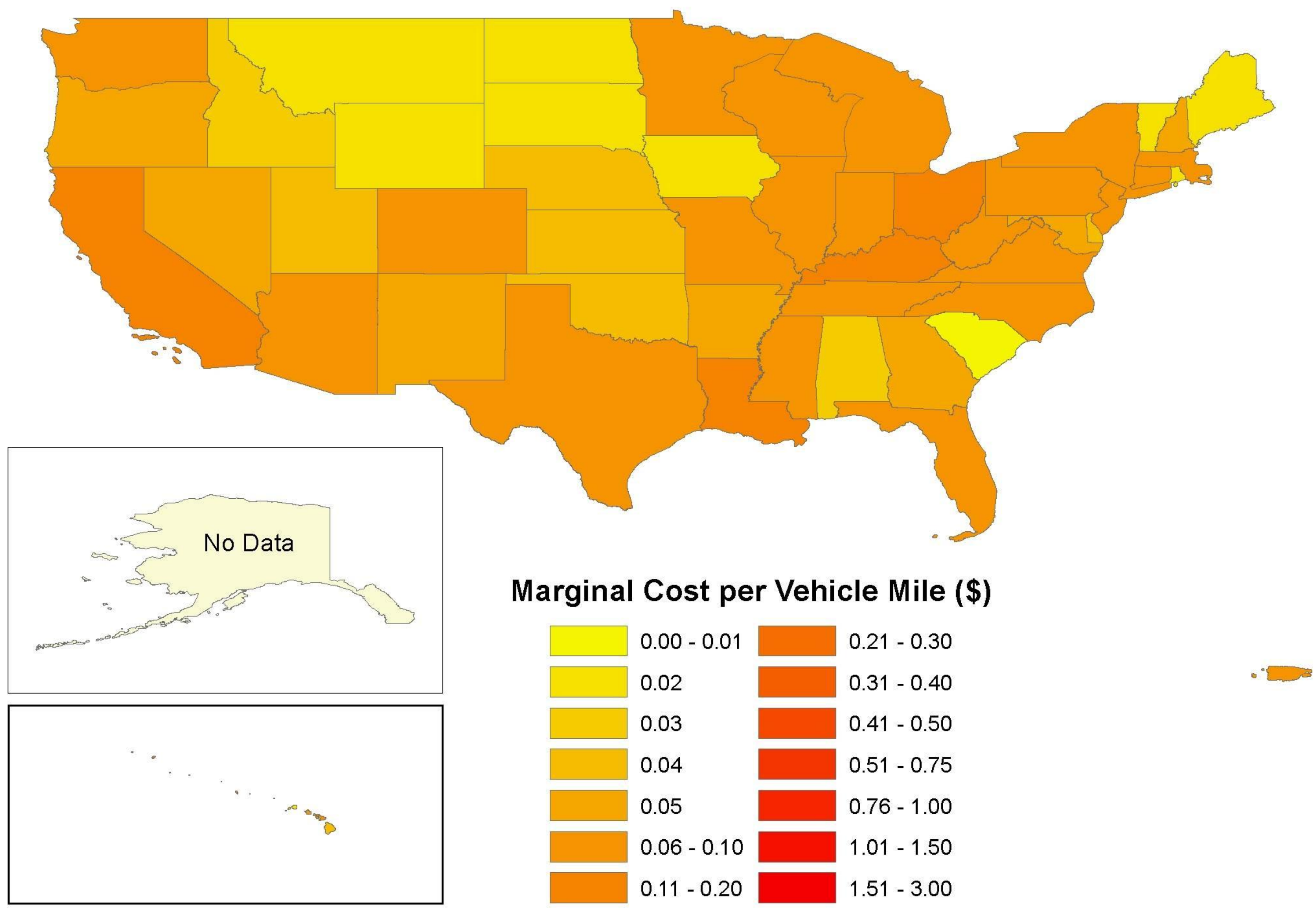
Total Marginal Cost to Society for Medium and Large Automobiles Peak Period



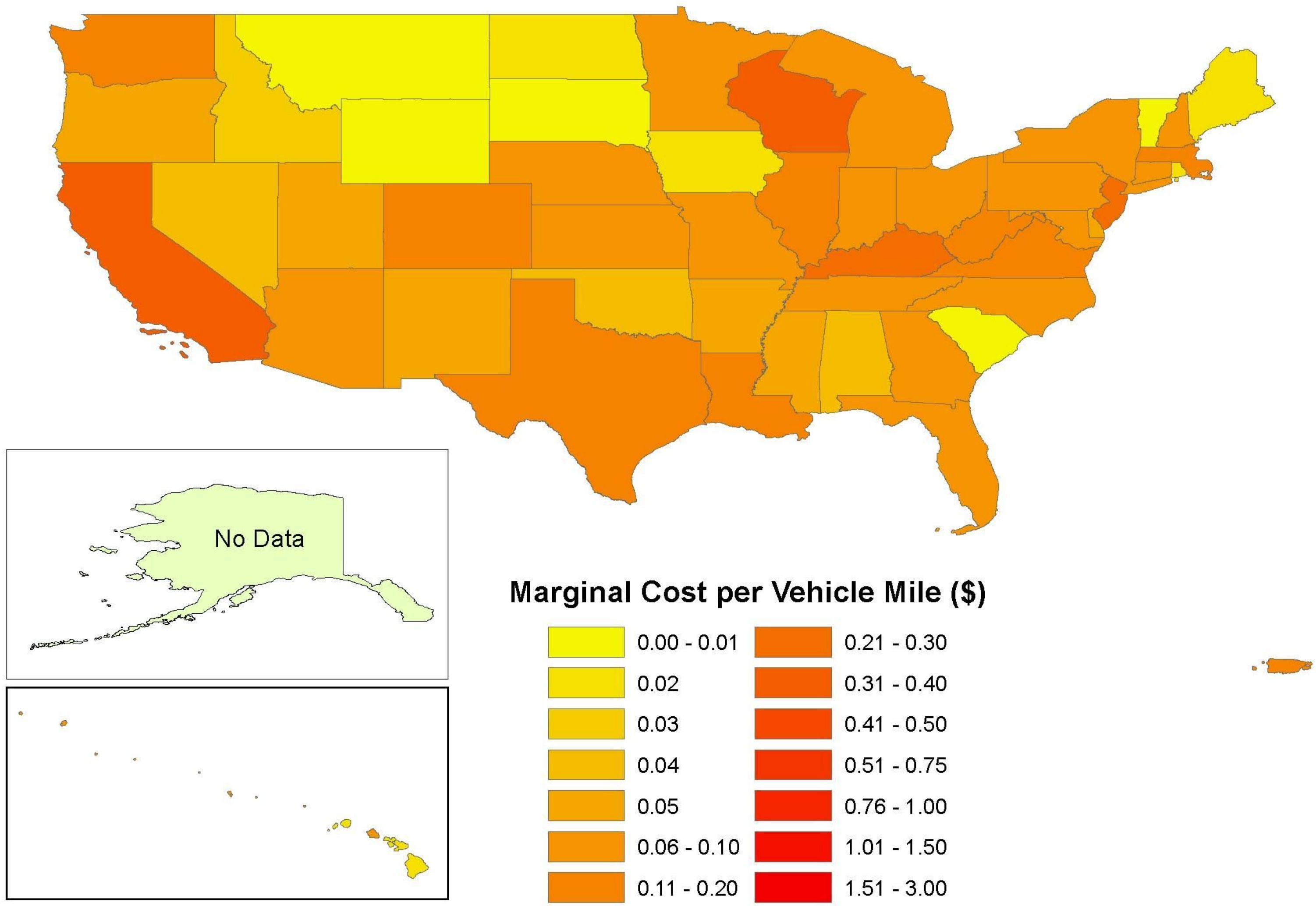
Total Marginal Cost to Society for Medium and Large Automobile Off-Peak Period



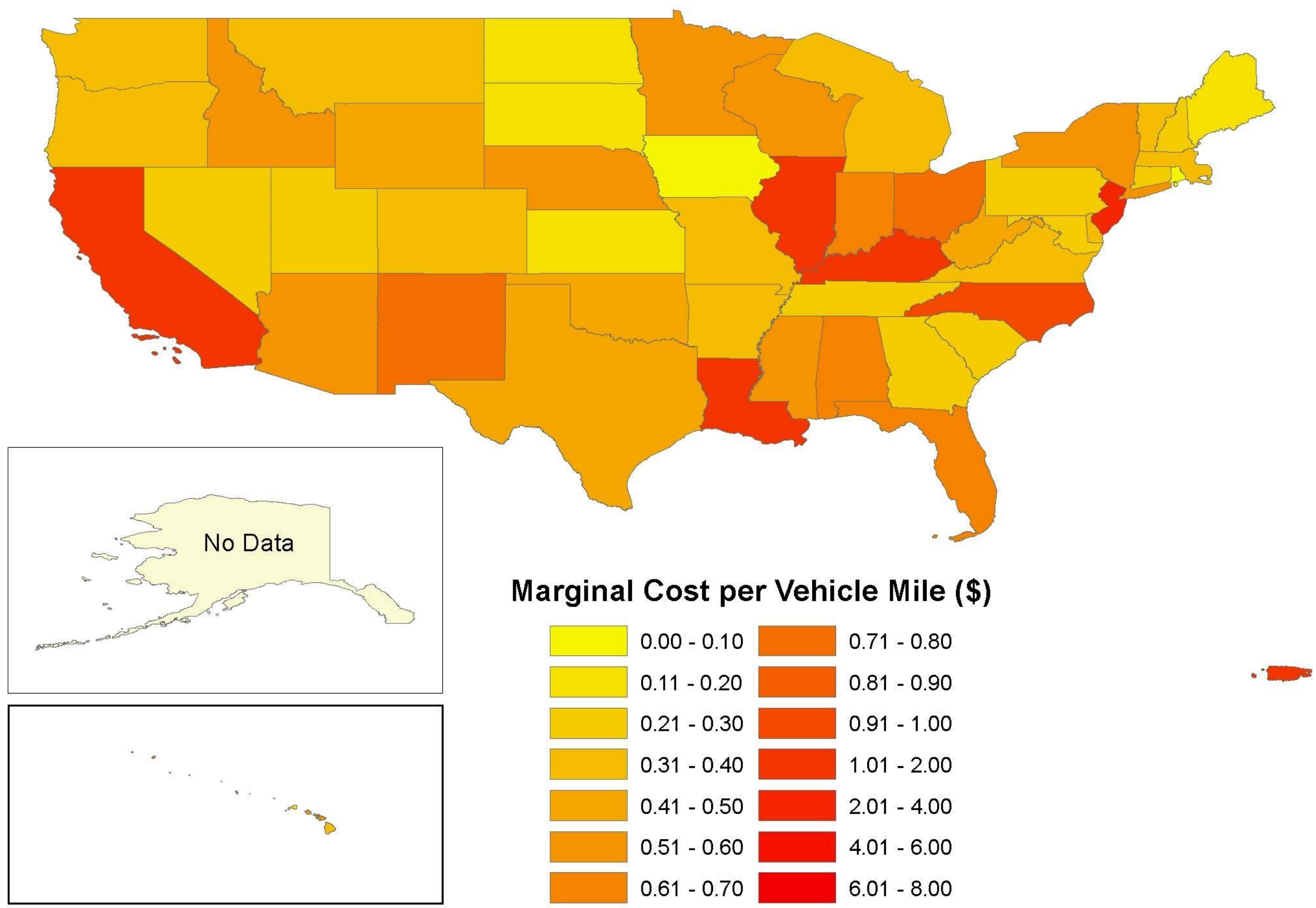
Total Marginal Cost to Society for Pickup Truck and Van Peak Period



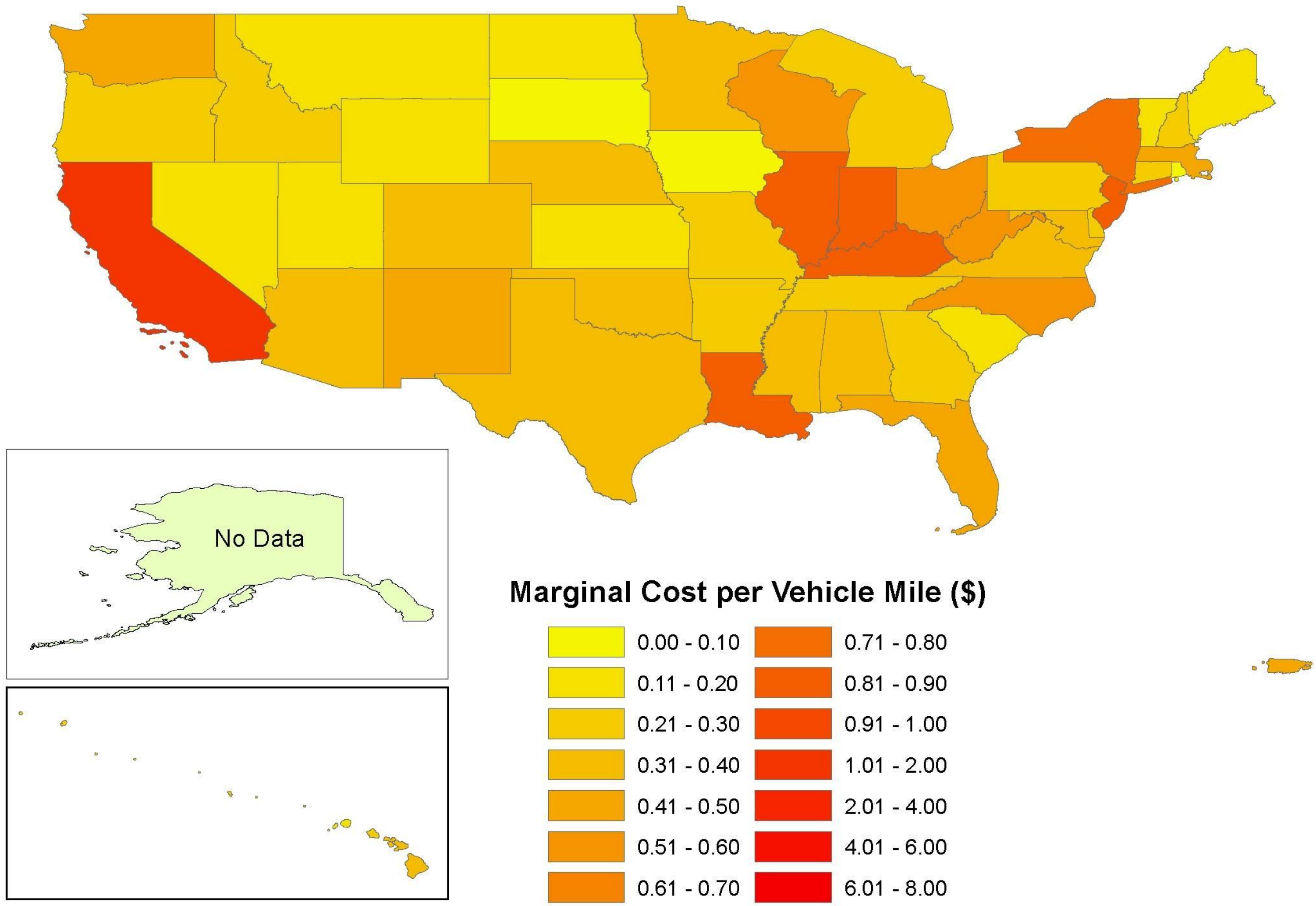
Total Marginal Cost to Society for Pickup Truck and Van Off-Peak Period



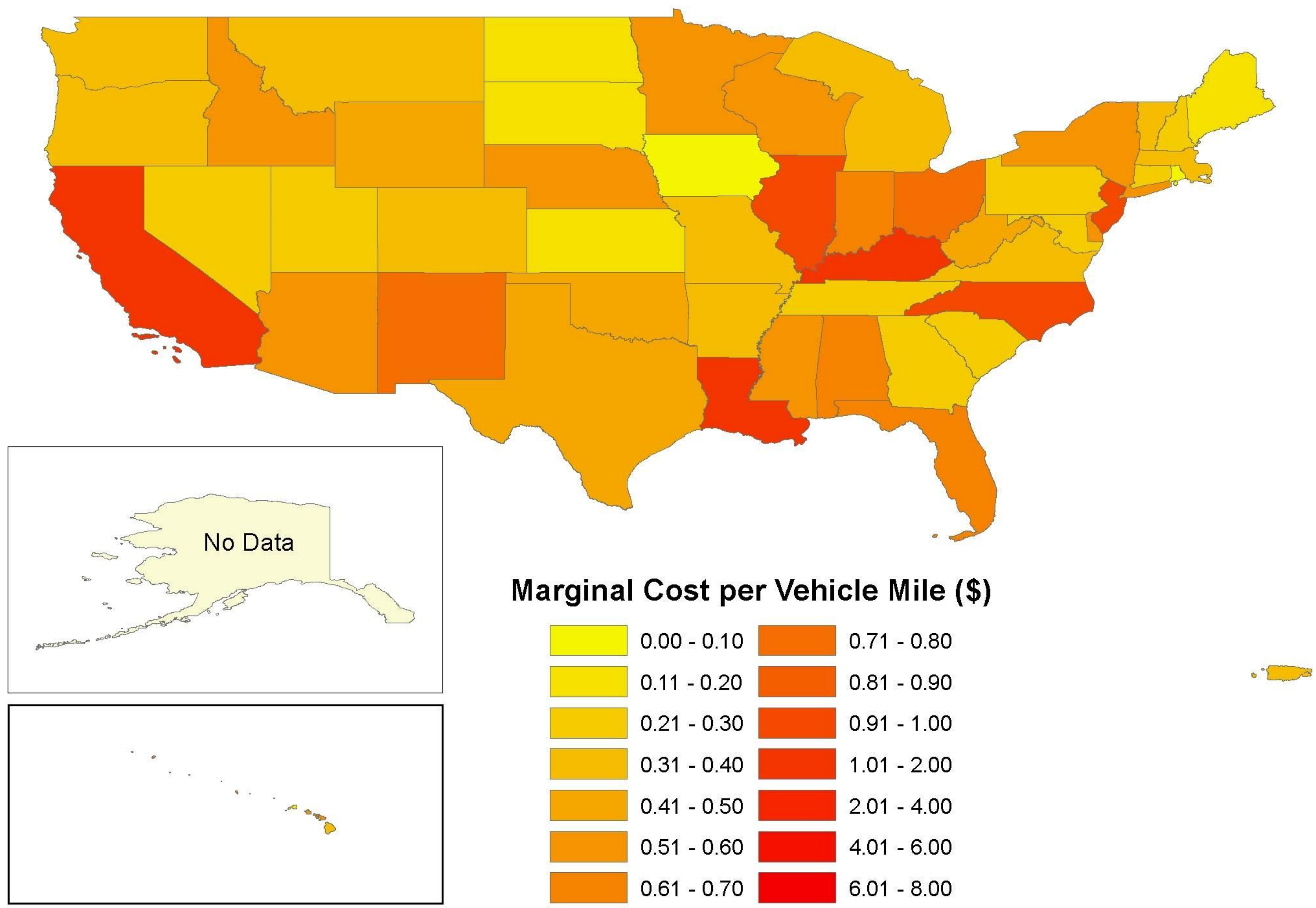
Total Marginal Cost to Society for 6 Tire Single Unit Truck Peak Period



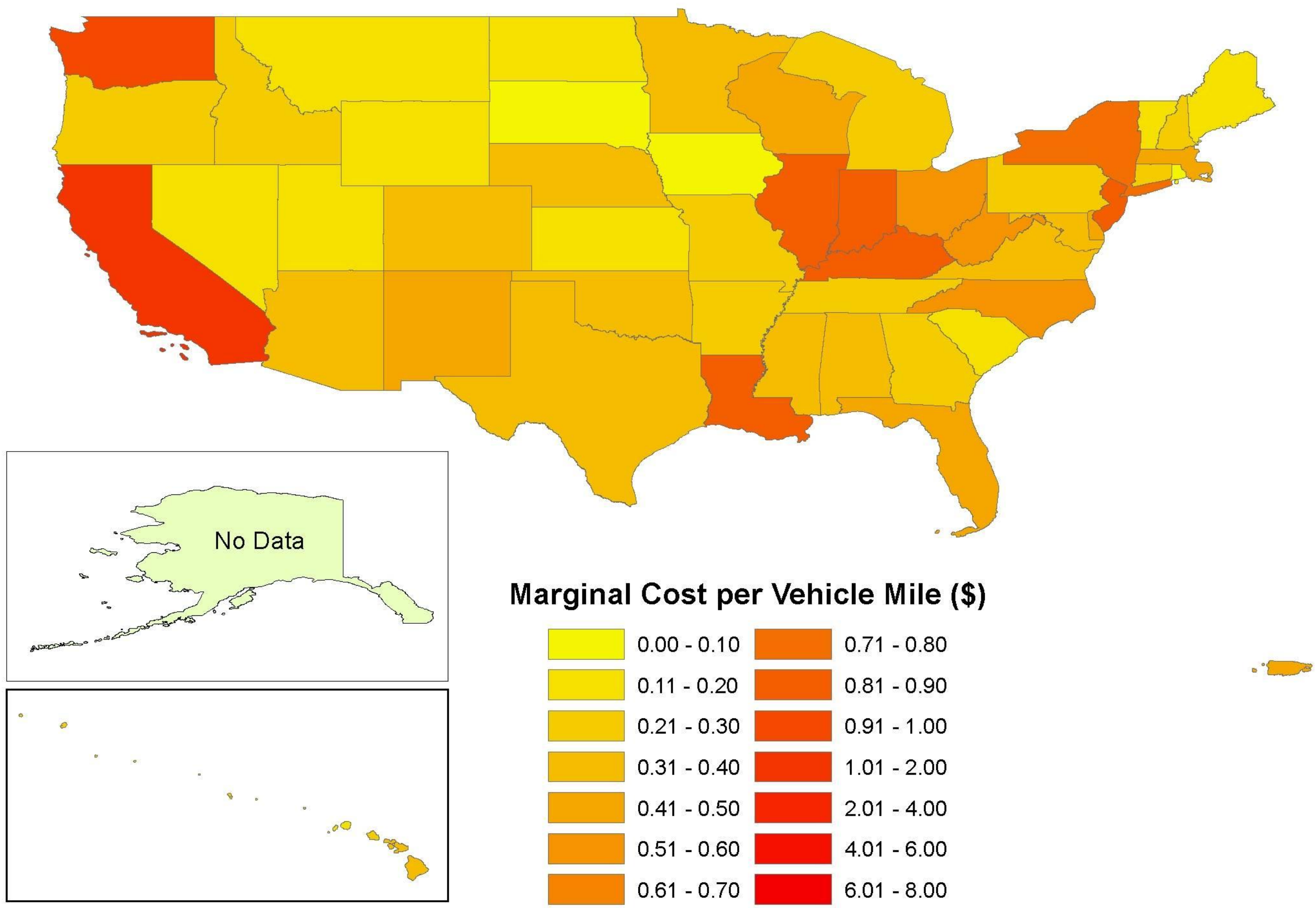
Total Marginal Cost to Society for 6 Tire Single Unit Truck Off-Peak Period



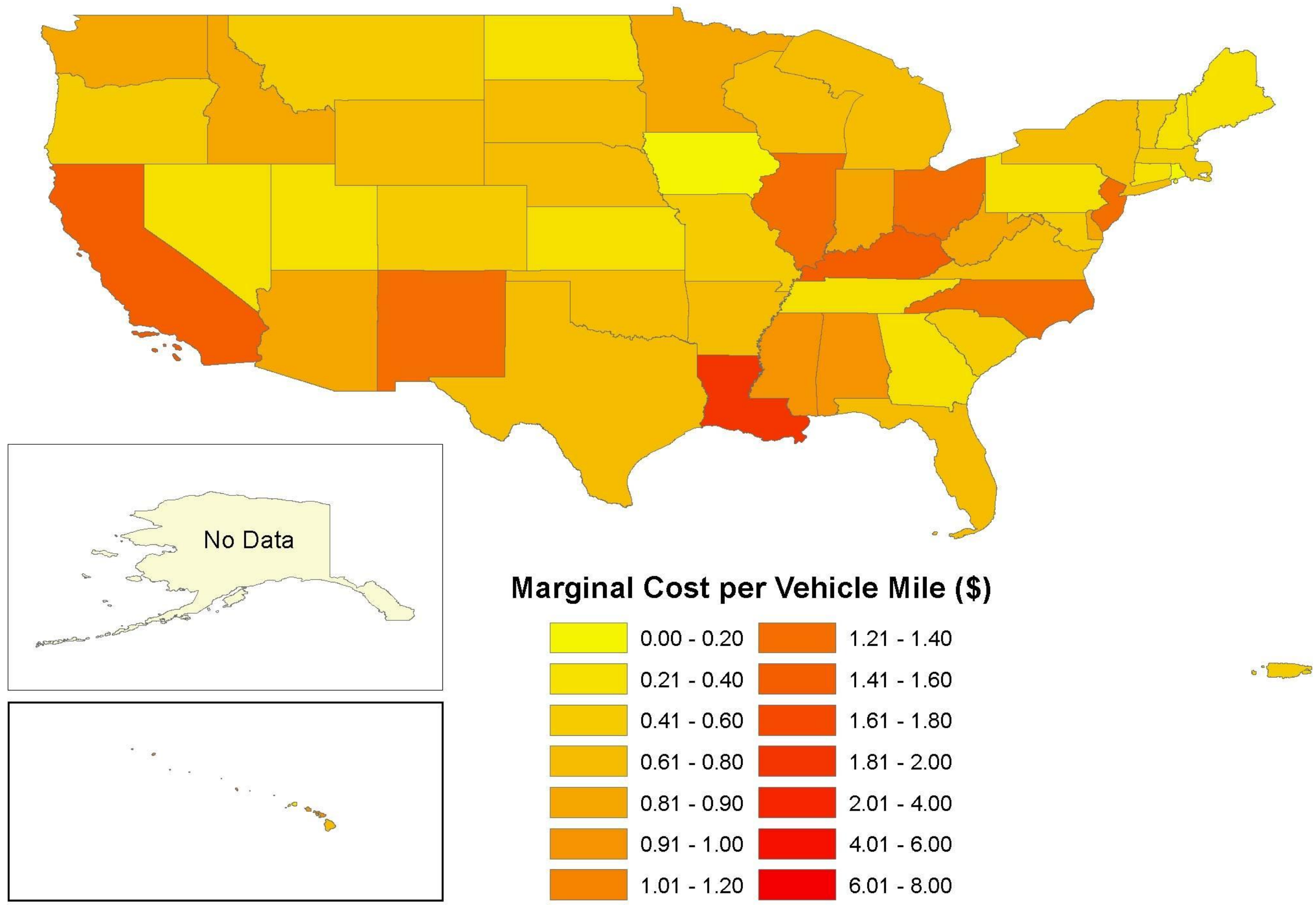
Total Marginal Cost to Society for 3 to 4 Axle Single Unit Truck Peak Period



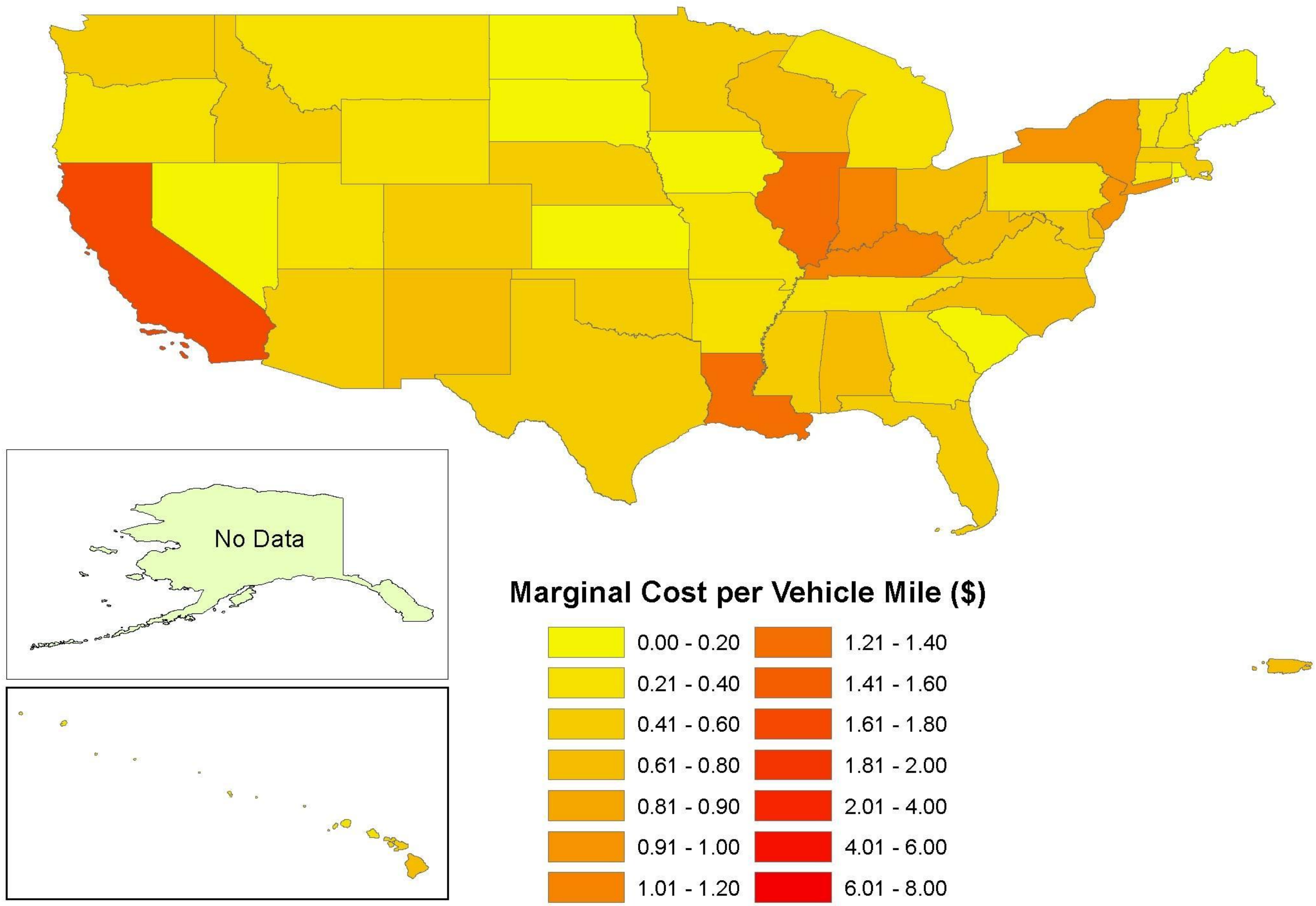
Total Marginal Cost to Society for 3 to 4 Axle Single Unit Truck Off-Peak Period

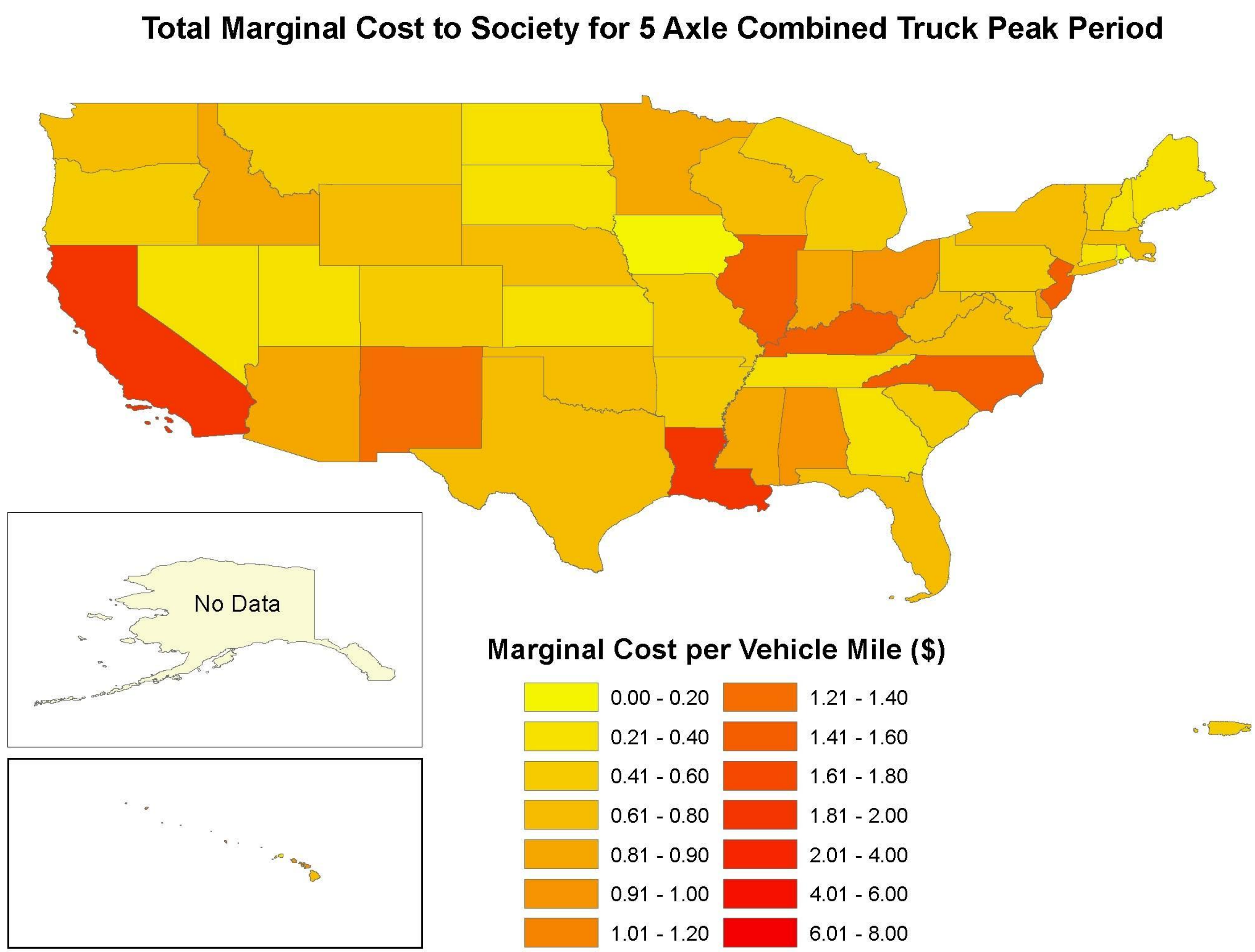


Total Marginal Cost to Society for 4 Axle Combined Truck Peak Period

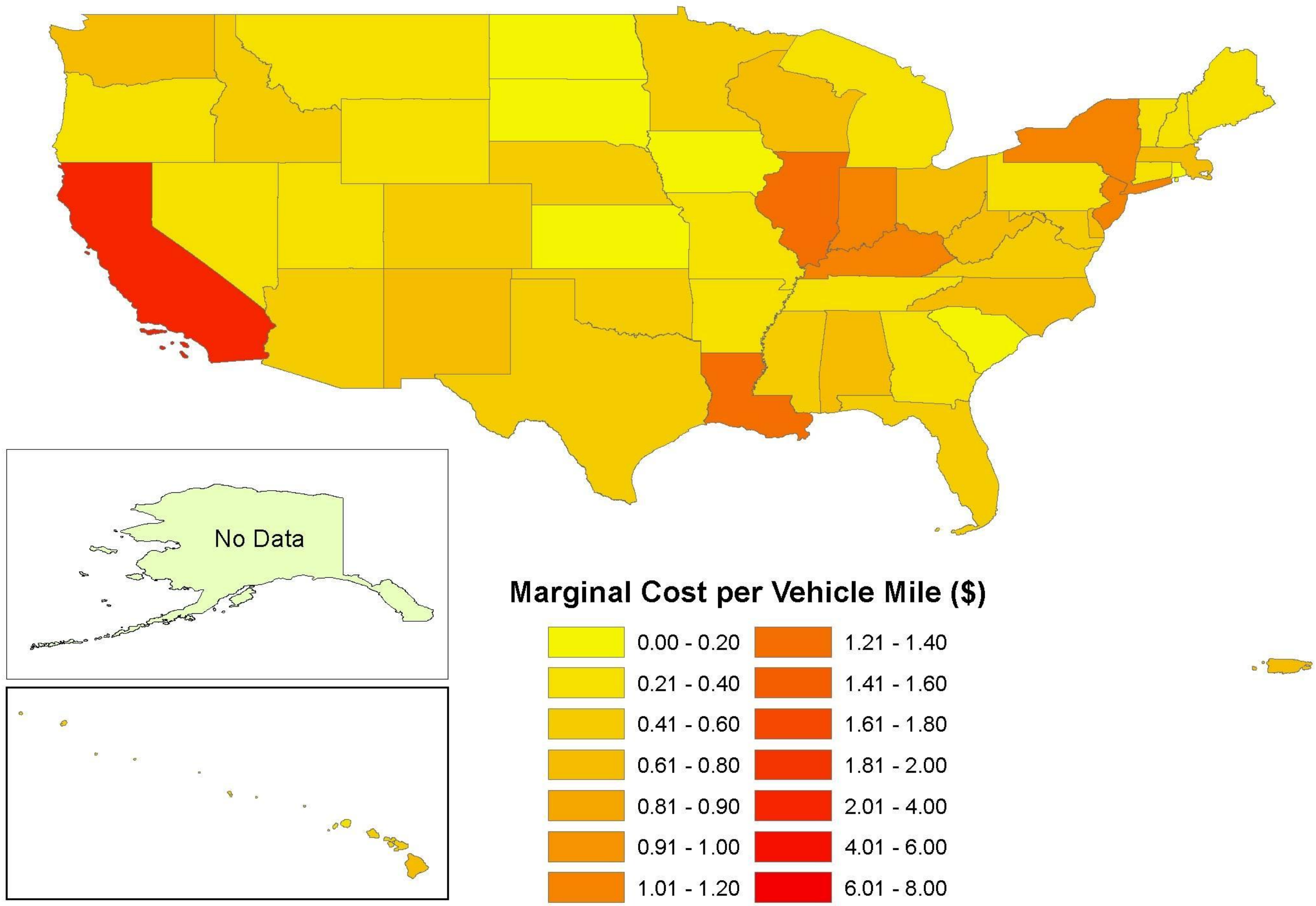


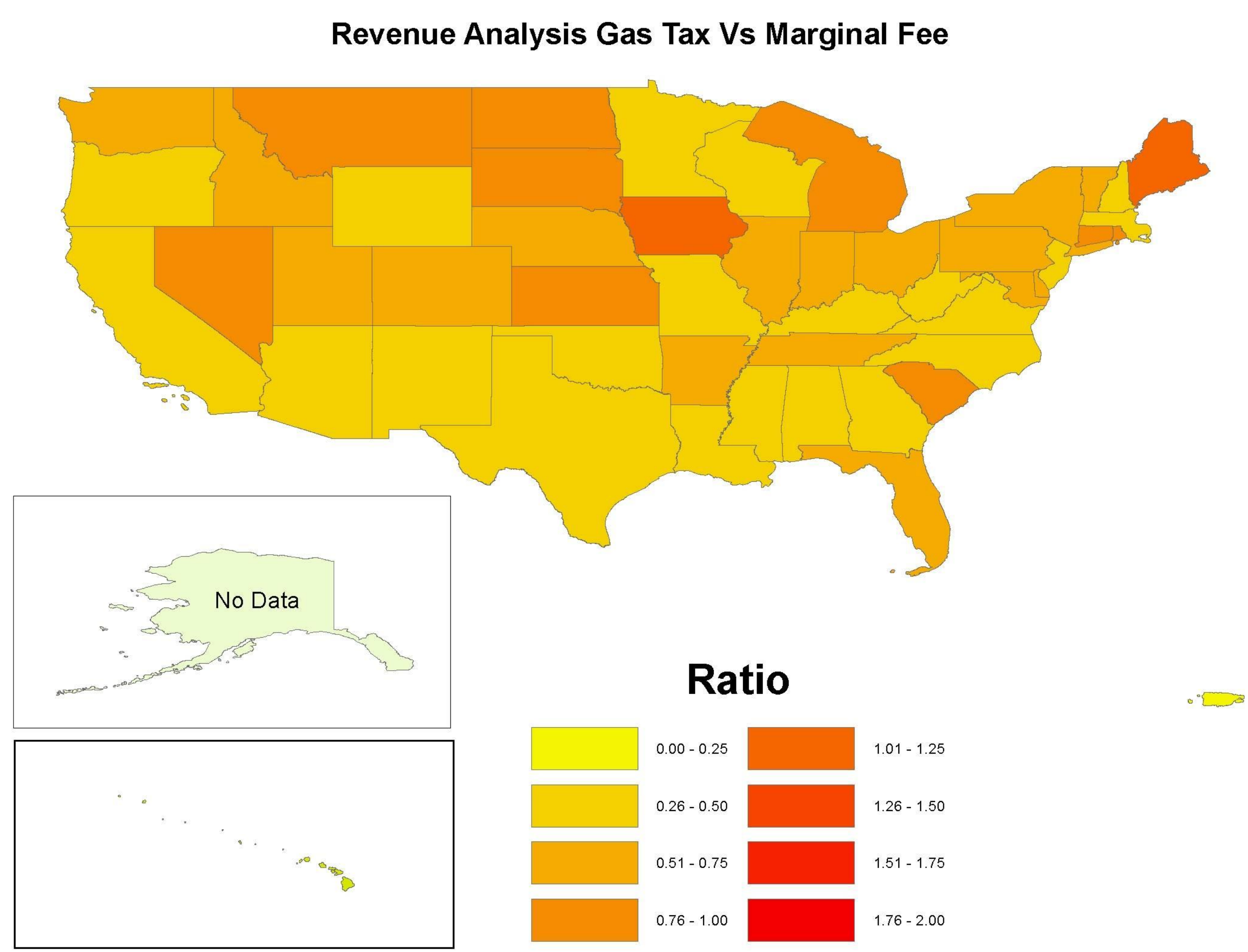
Total Marginal Cost to Society for 4 Axle Combined Truck Off-Peak Period




Total Marginal Cost to Society for 5 Axle Combined Truck Peak Period
No Data
Marginal Cost per Vehicle Mile ($)
0.00 - 0.20
0.21 - 0.40
0.41 - 0.60
0.61 - 0.80
0.81 - 0.90
0.91 - 1.00
1.01 - 1.20
1.21 - 1.40
1.41 - 1.60
1.61 - 1.80
1.81 - 2.00
2.01 - 4.00
4.01 - 6.00
6.01 - 8.00

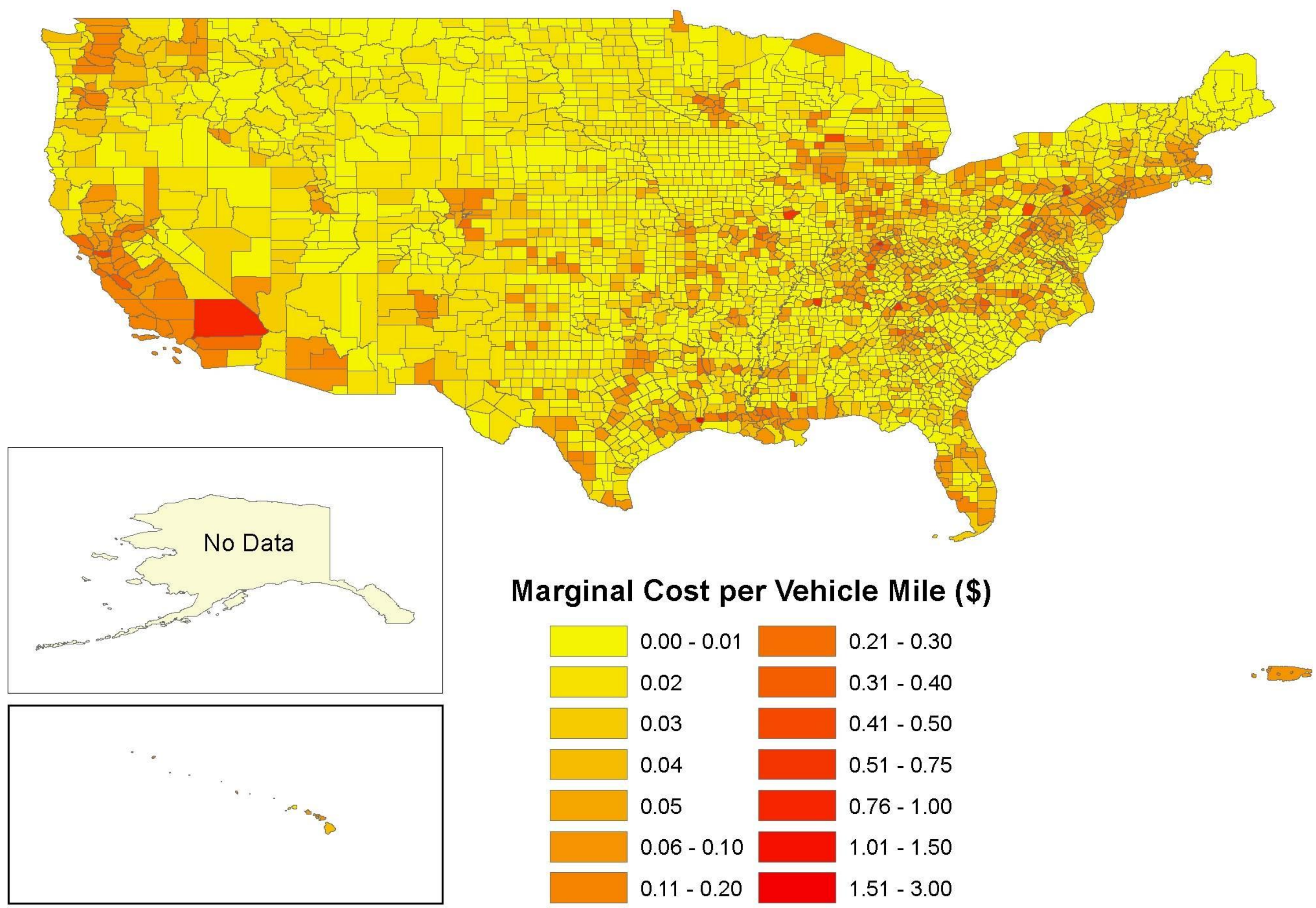
Total Marginal Cost to Society for 5 Axle Combined Truck Off-Peak Period

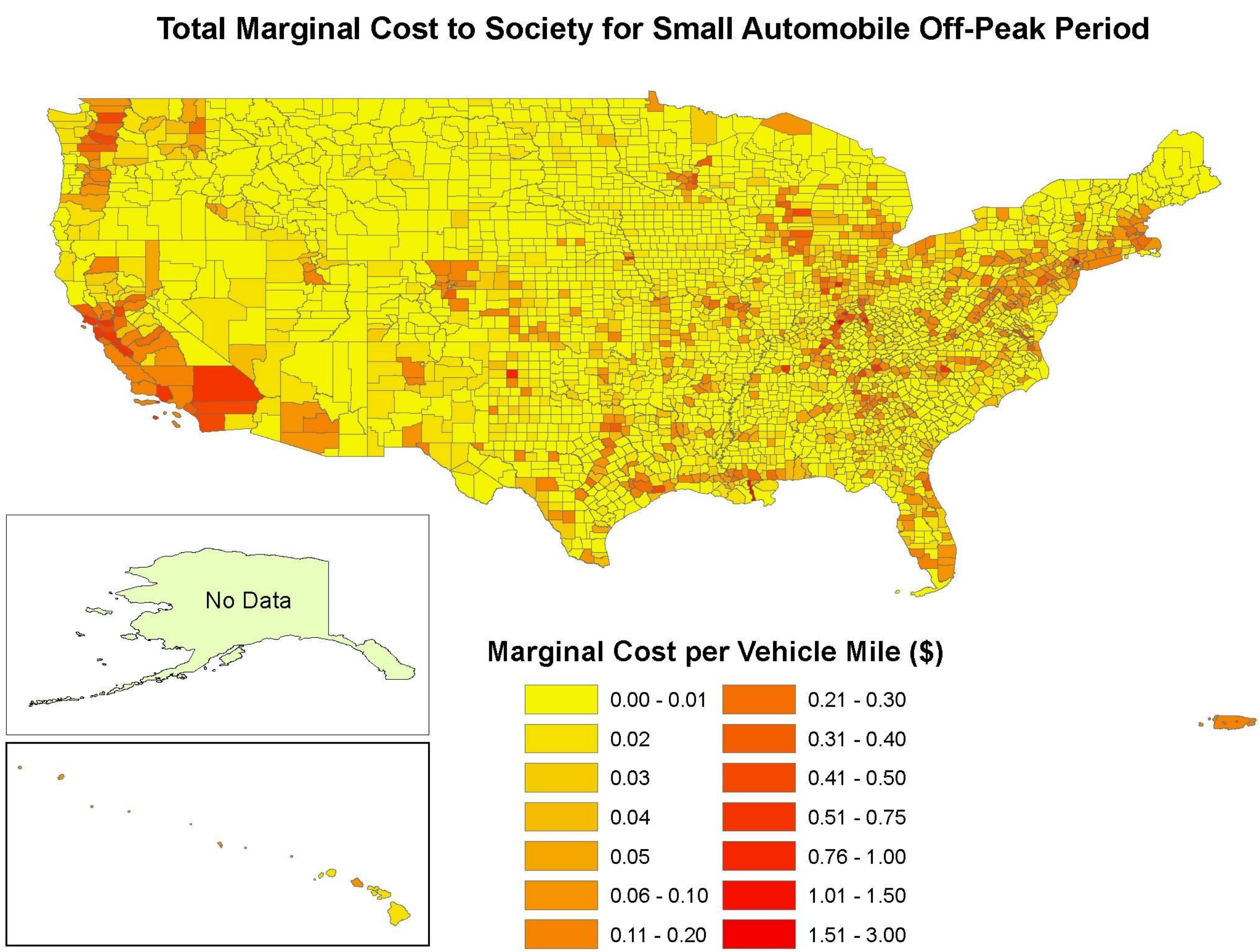



Revenue Analysis Gas Tax Vs Marginal Fee
No Data
Ratio
0.00 - 0.25
0.26 - 0.50
0.51 - 0.75
0.76 - 1.00
1.01 - 1.25
1.26 - 1.50
1.51 - 1.75
1.76 - 2.00

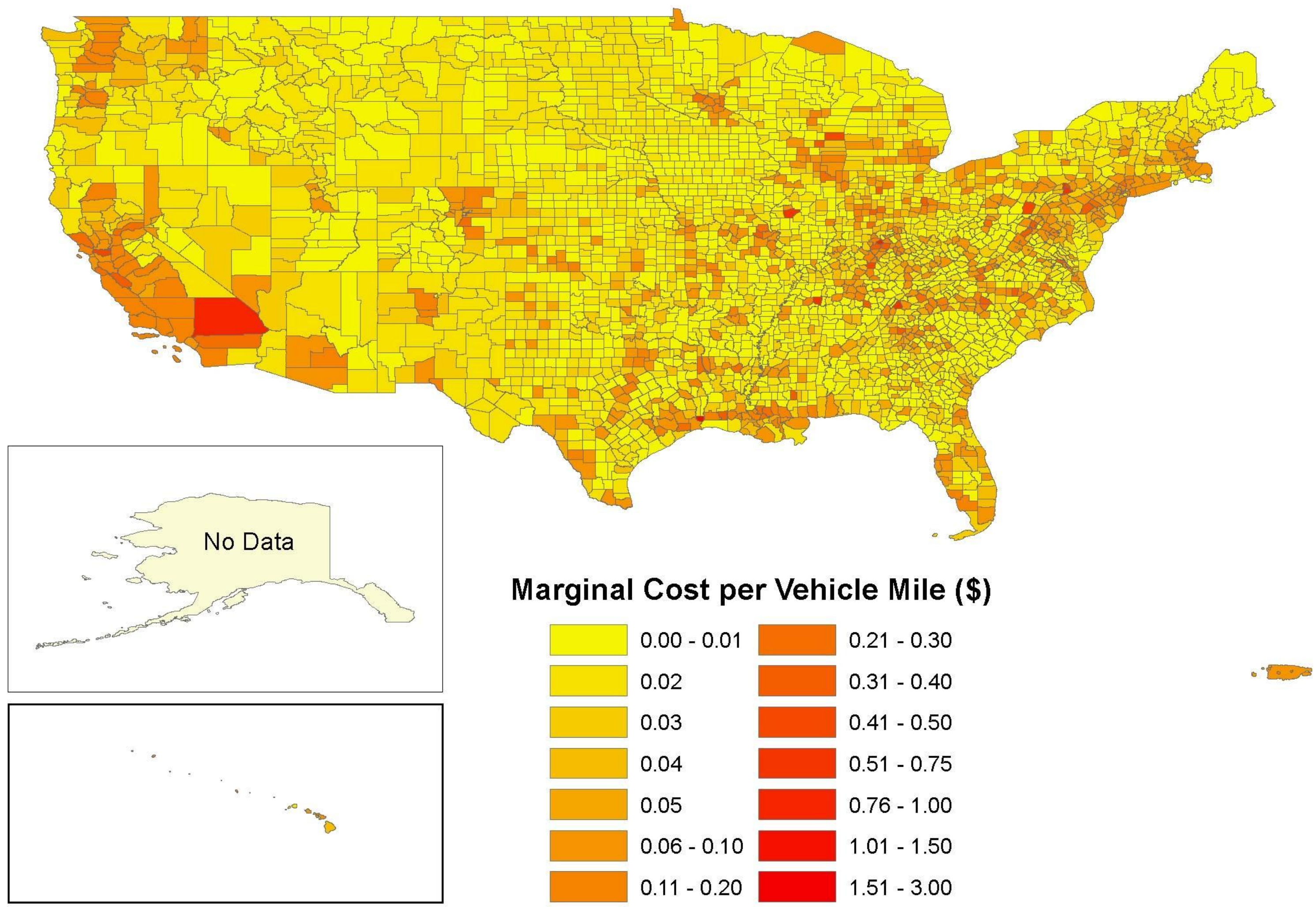
Appendix C: County Data

Total Marginal Cost to Society for Small Automobiles Peak Period

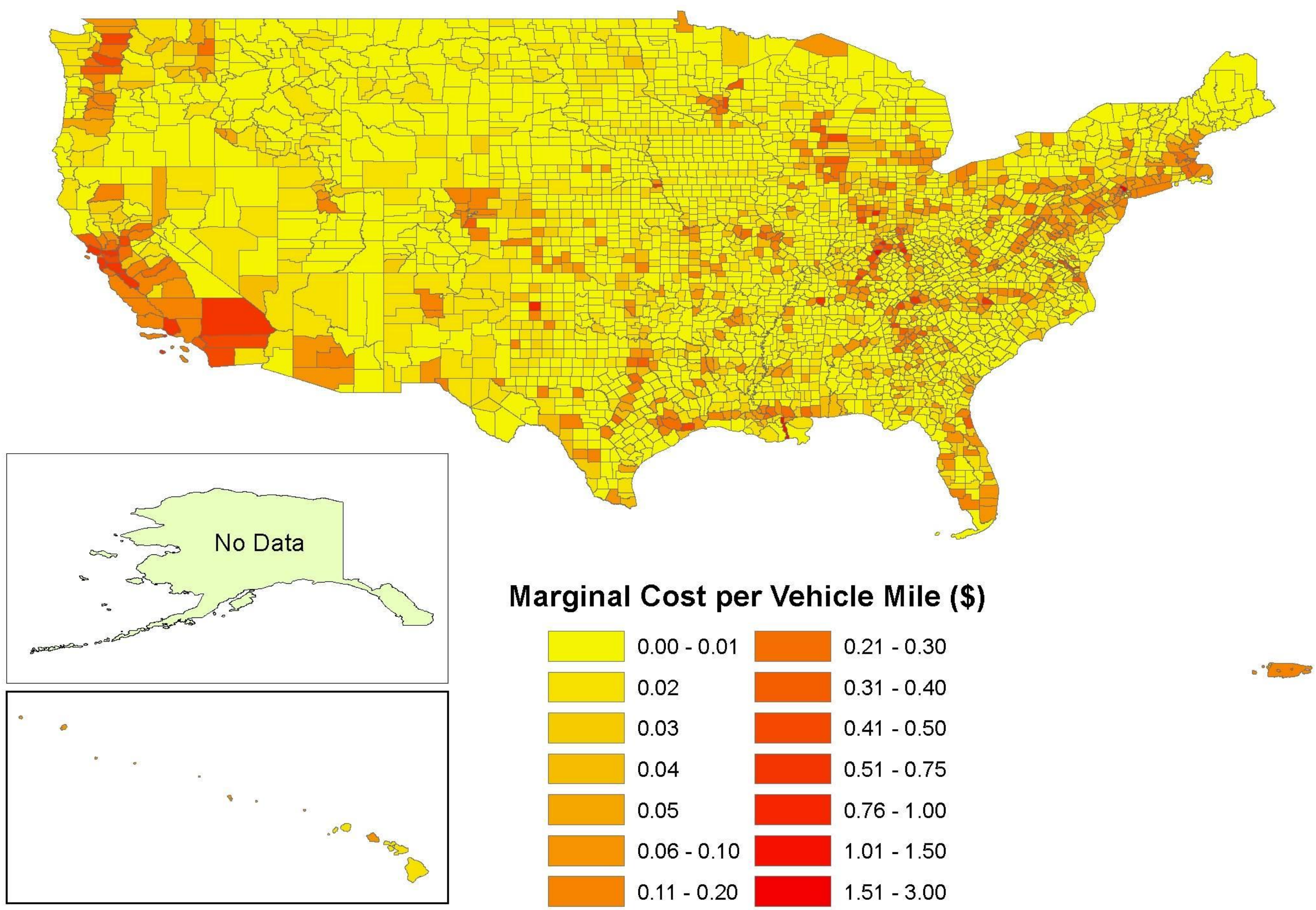



Total Marginal Cost to Society for Small Automobile Off-Peak Period
No Data
Marginal Cost per Vehicle Mile ($)
0.00 - 0.01
0.02
0.03
0.04
0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.30
0.31 - 0.40
0.41 - 0.50
0.51 - 0.75
0.76 - 1.00
1.01 - 1.50
1.51 - 3.00

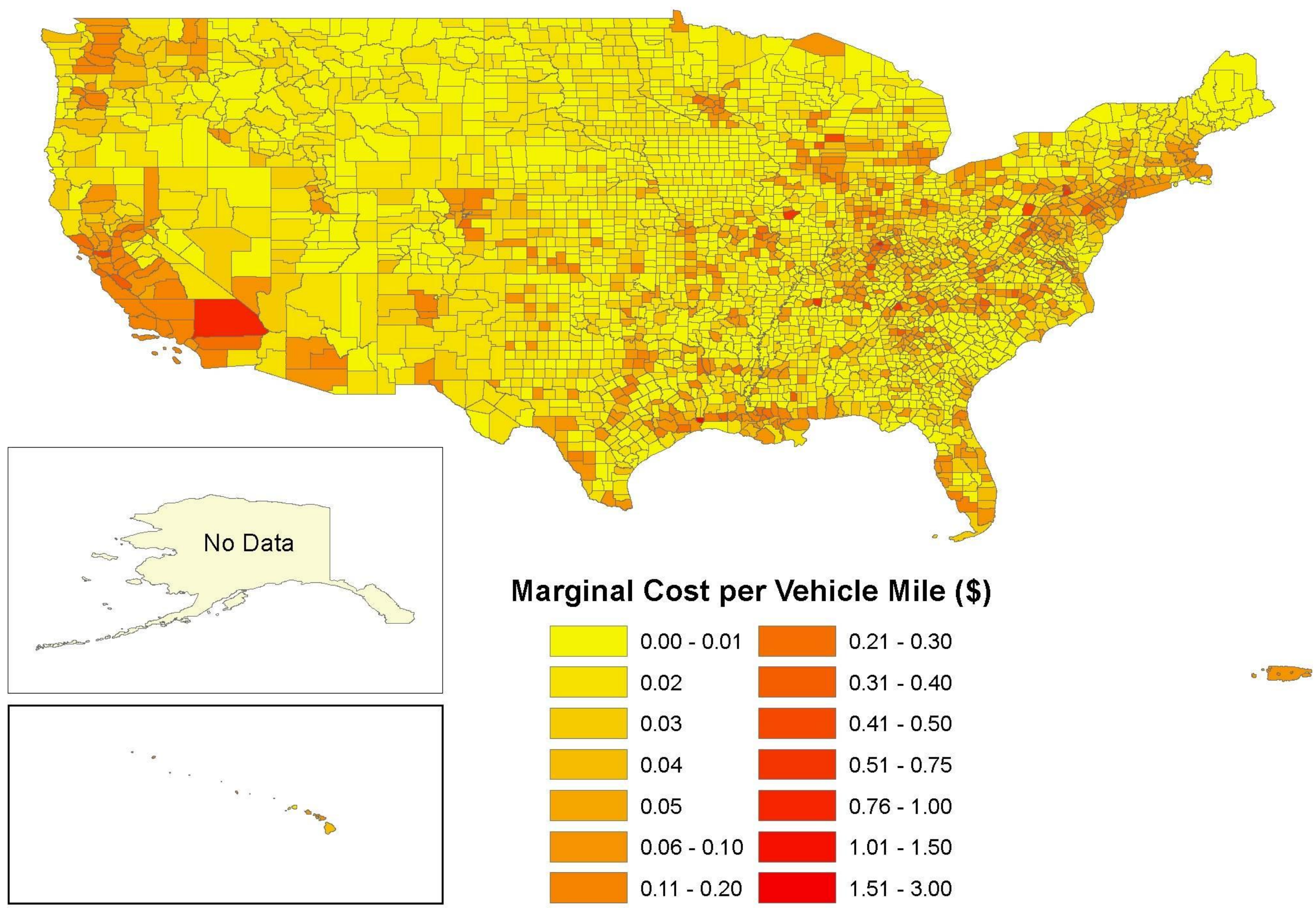
Total Marginal Cost to Society for Medium and Large Automobiles Peak Period



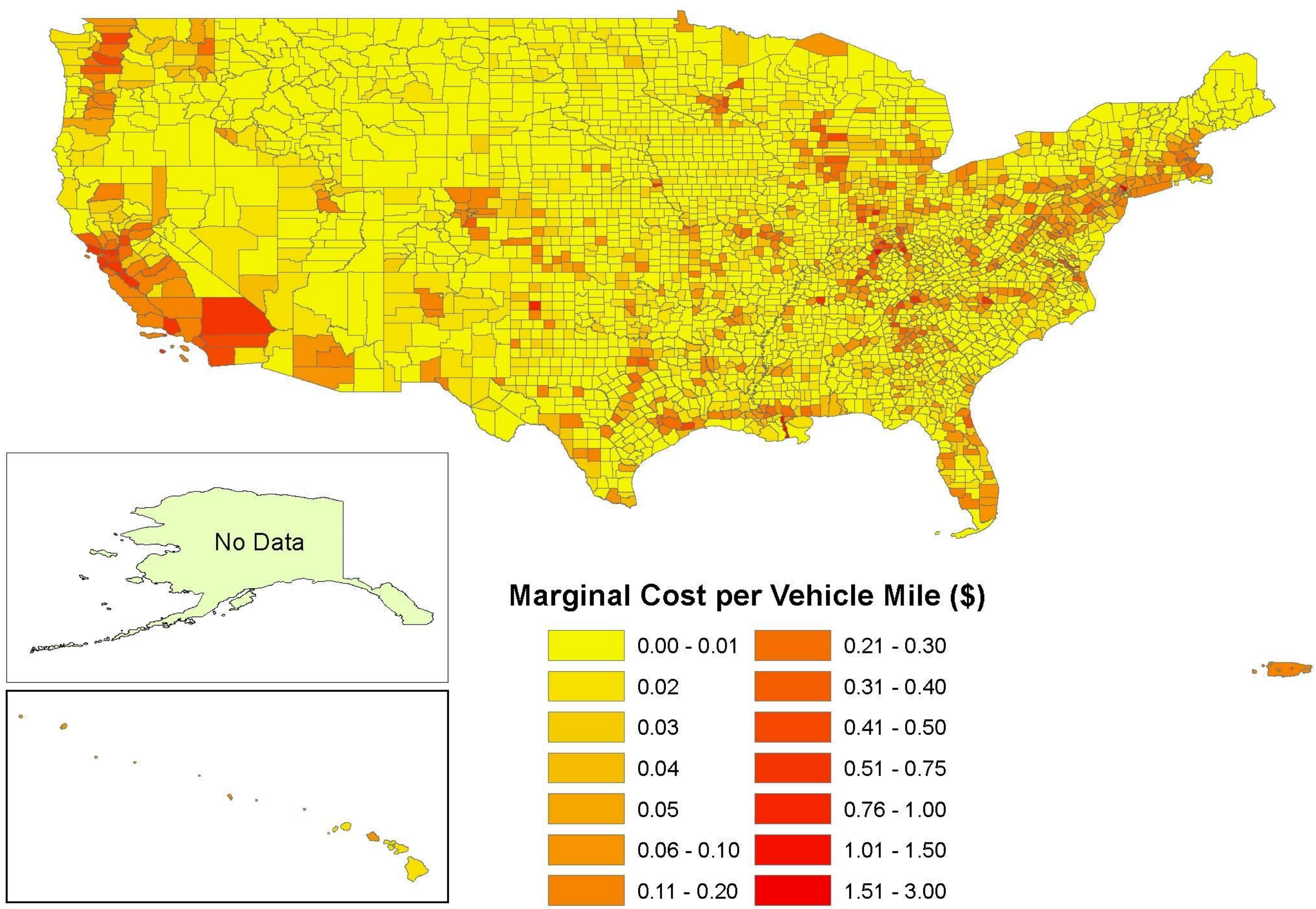
Total Marginal Cost to Society for Medium and Large Automobile Off-Peak Period



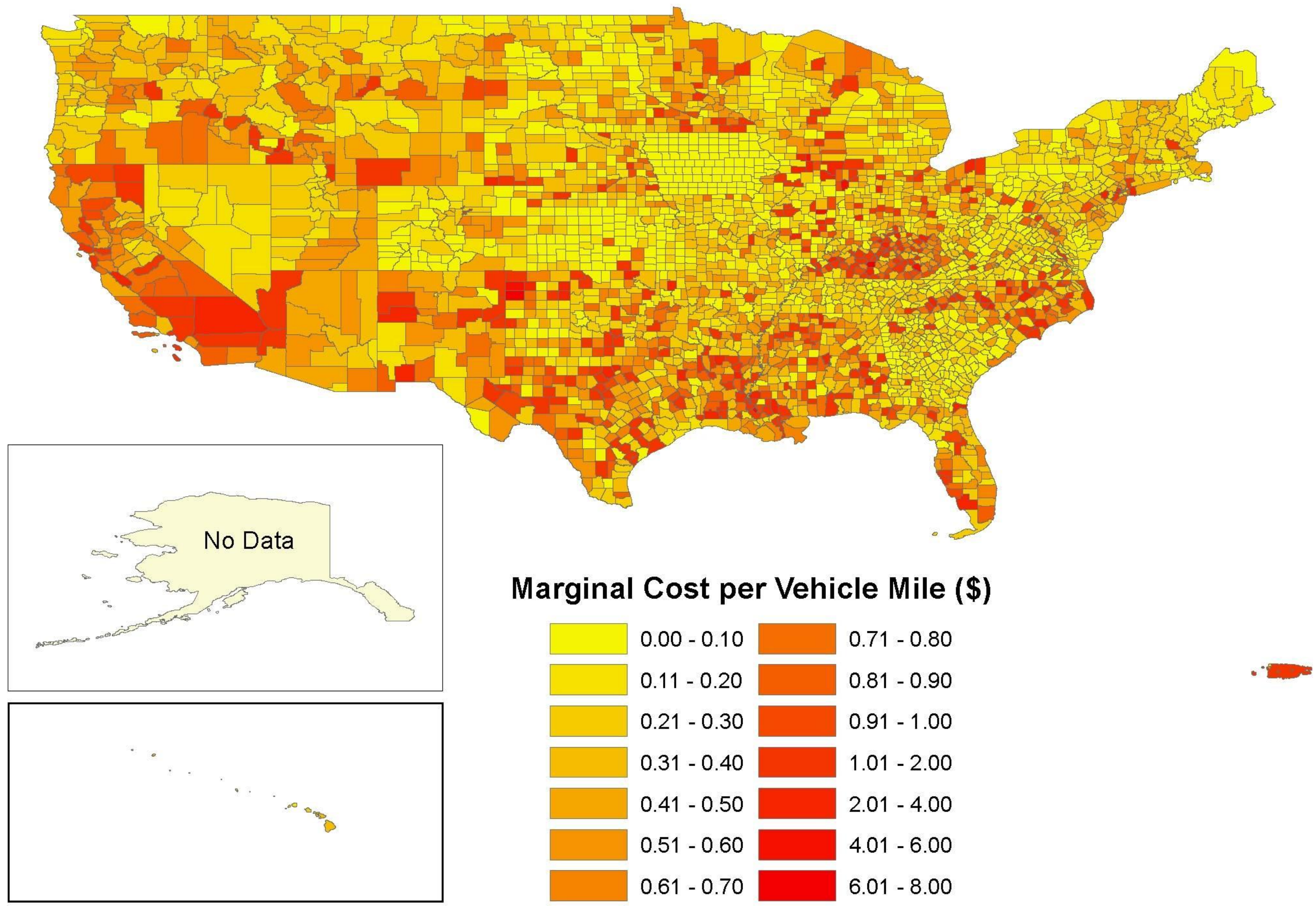
Total Marginal Cost to Society for Pickup Truck and Van Peak Period



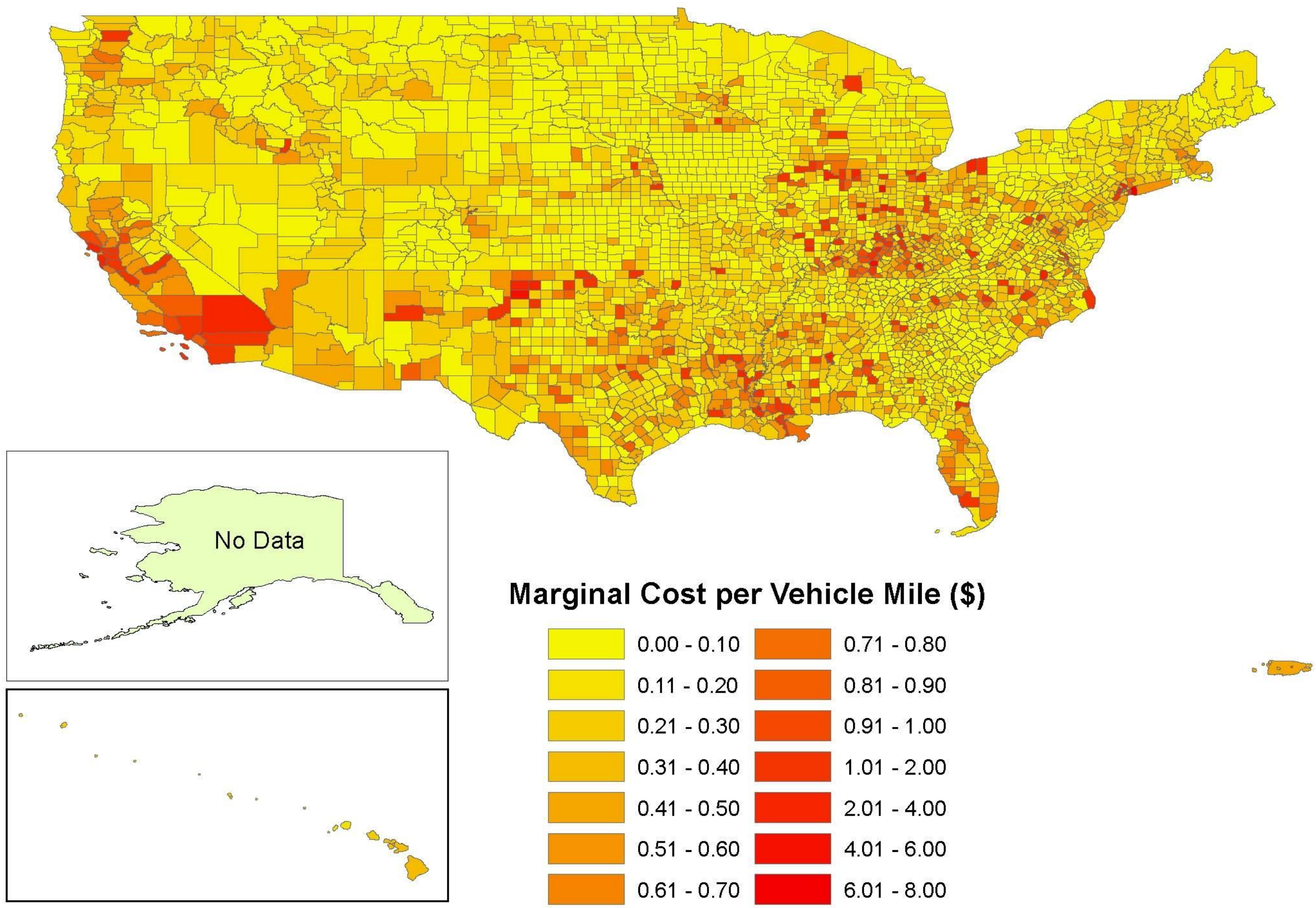
Total Marginal Cost to Society for Pickup Truck and Van Off-Peak Period



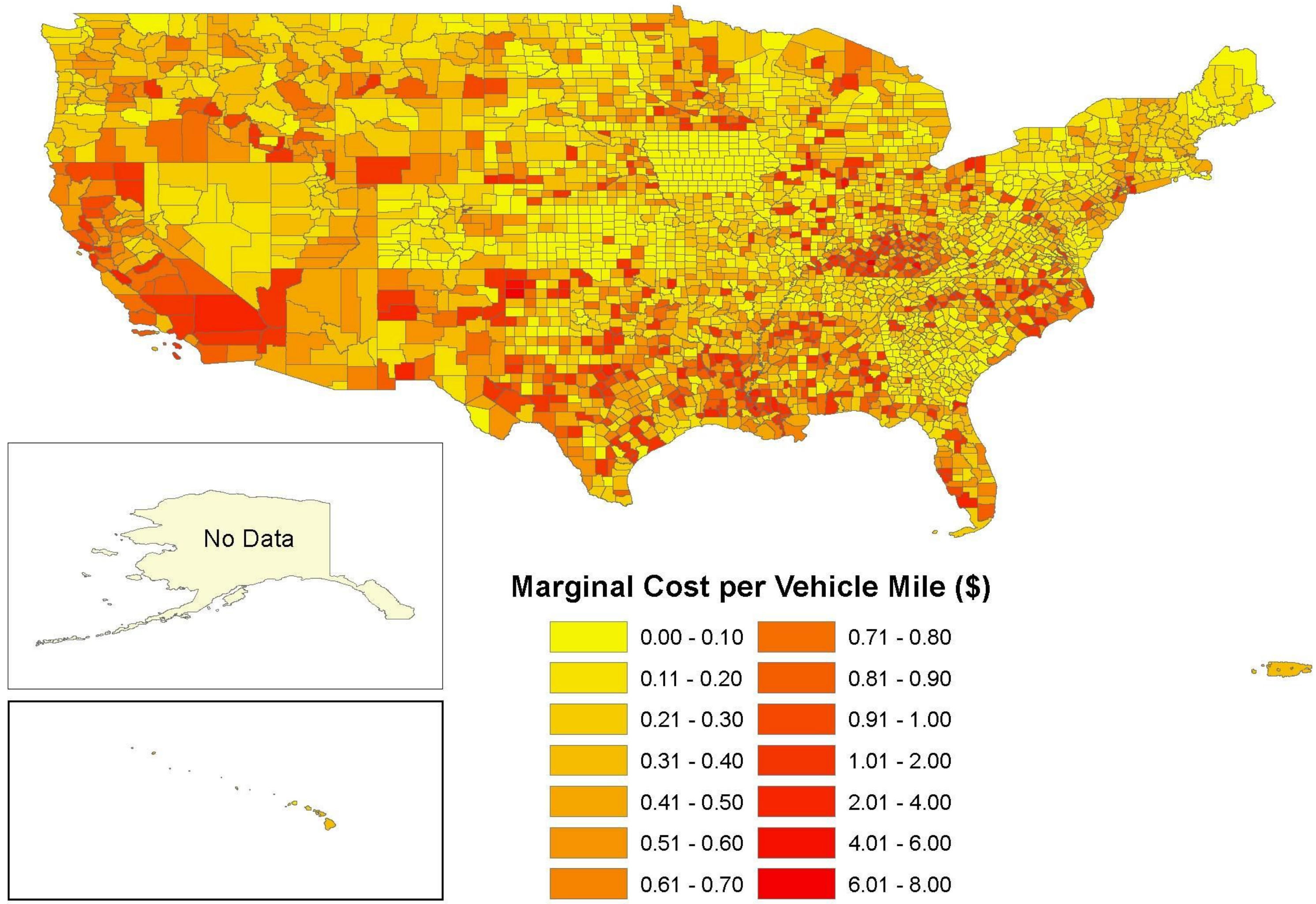
Total Marginal Cost to Society for 6 Tire Single Unit Truck Peak Period



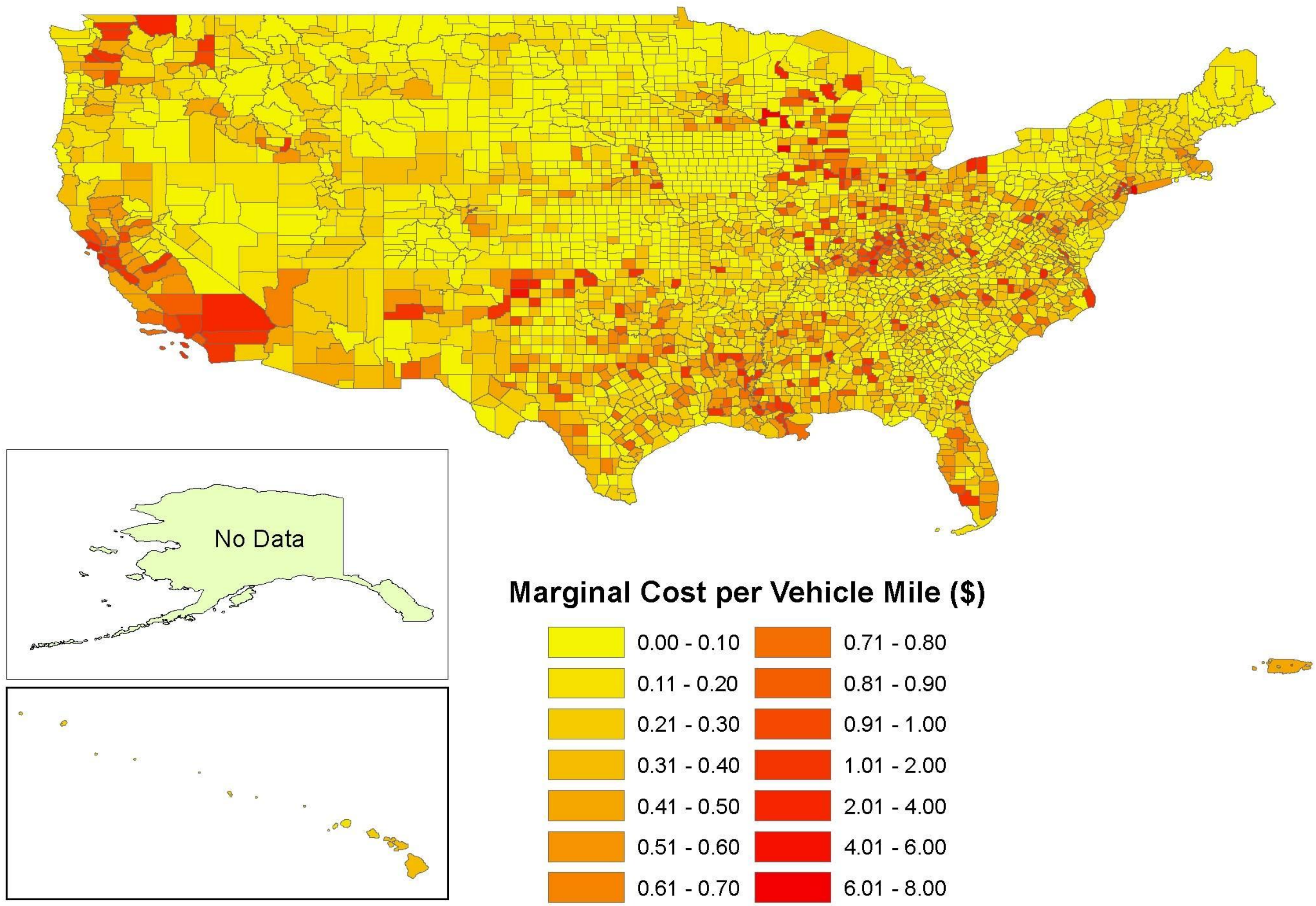
Total Marginal Cost to Society for 6 Tire Single Unit Truck Off-Peak Period



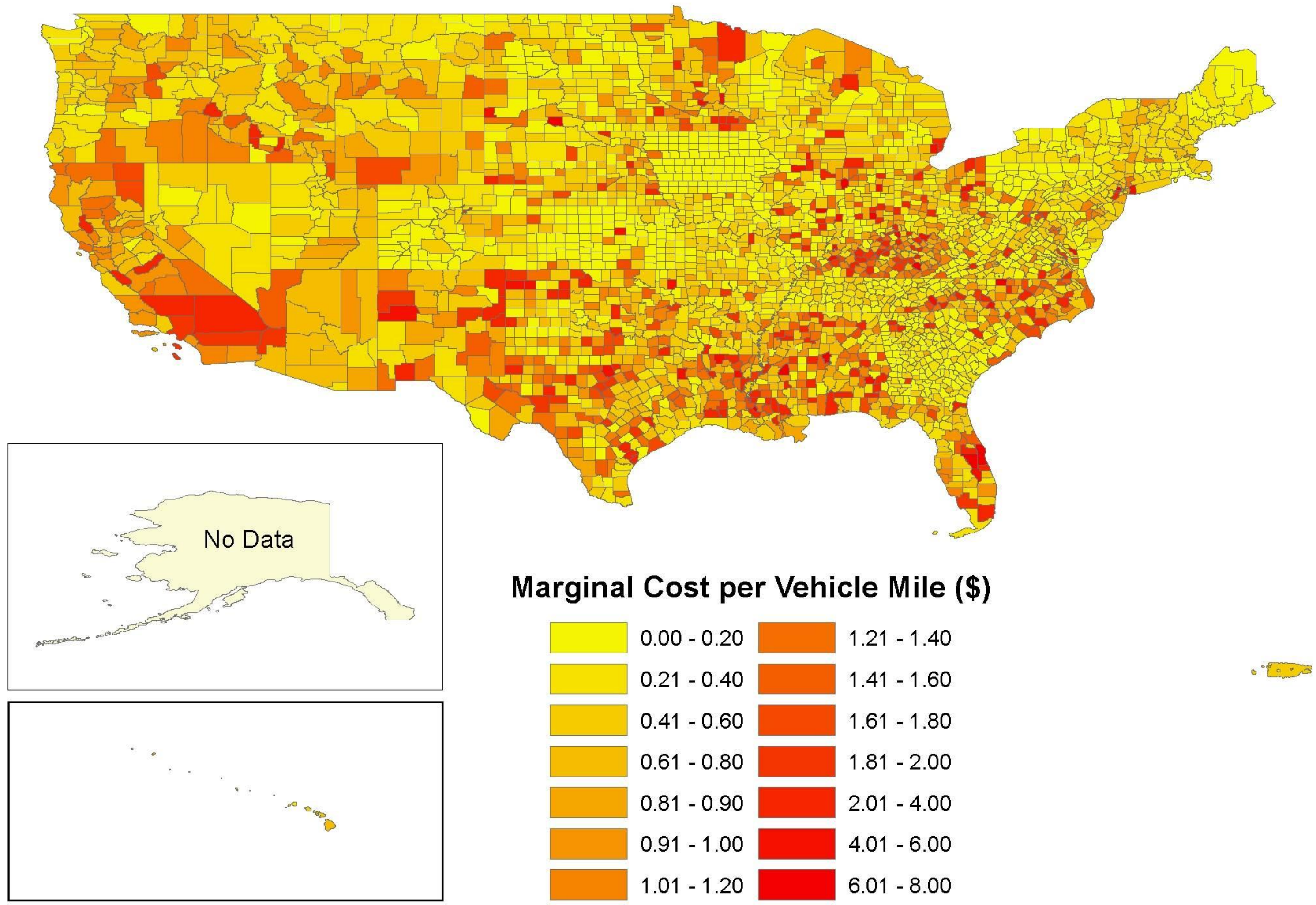
Total Marginal Cost to Society for 3 to 4 Axle Single Unit Truck Peak Period



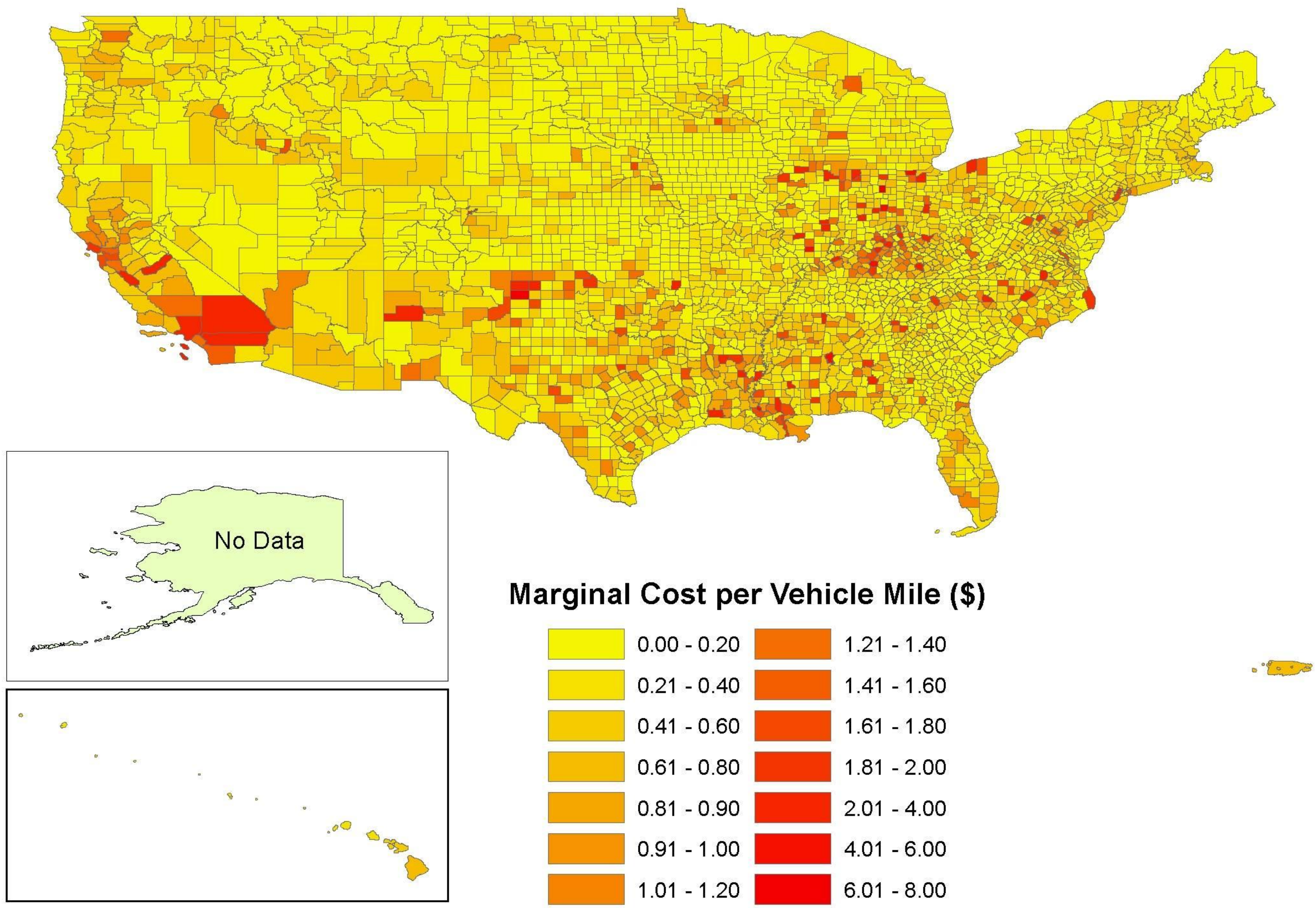
Total Marginal Cost to Society for 3 to 4 Axle Single Unit Truck Off-Peak Period



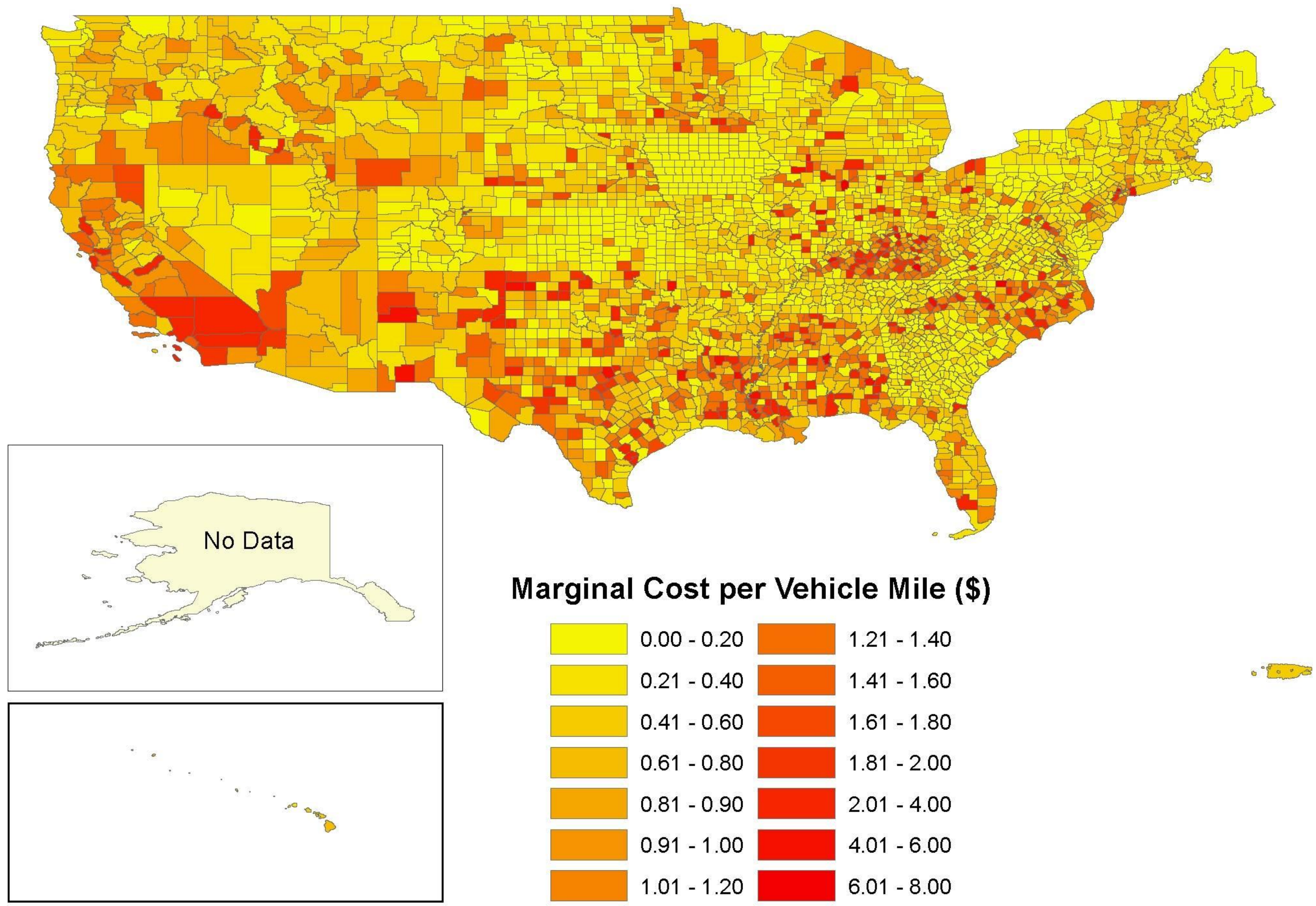
Total Marginal Cost to Society for 4 Axle Combined Truck Peak Period



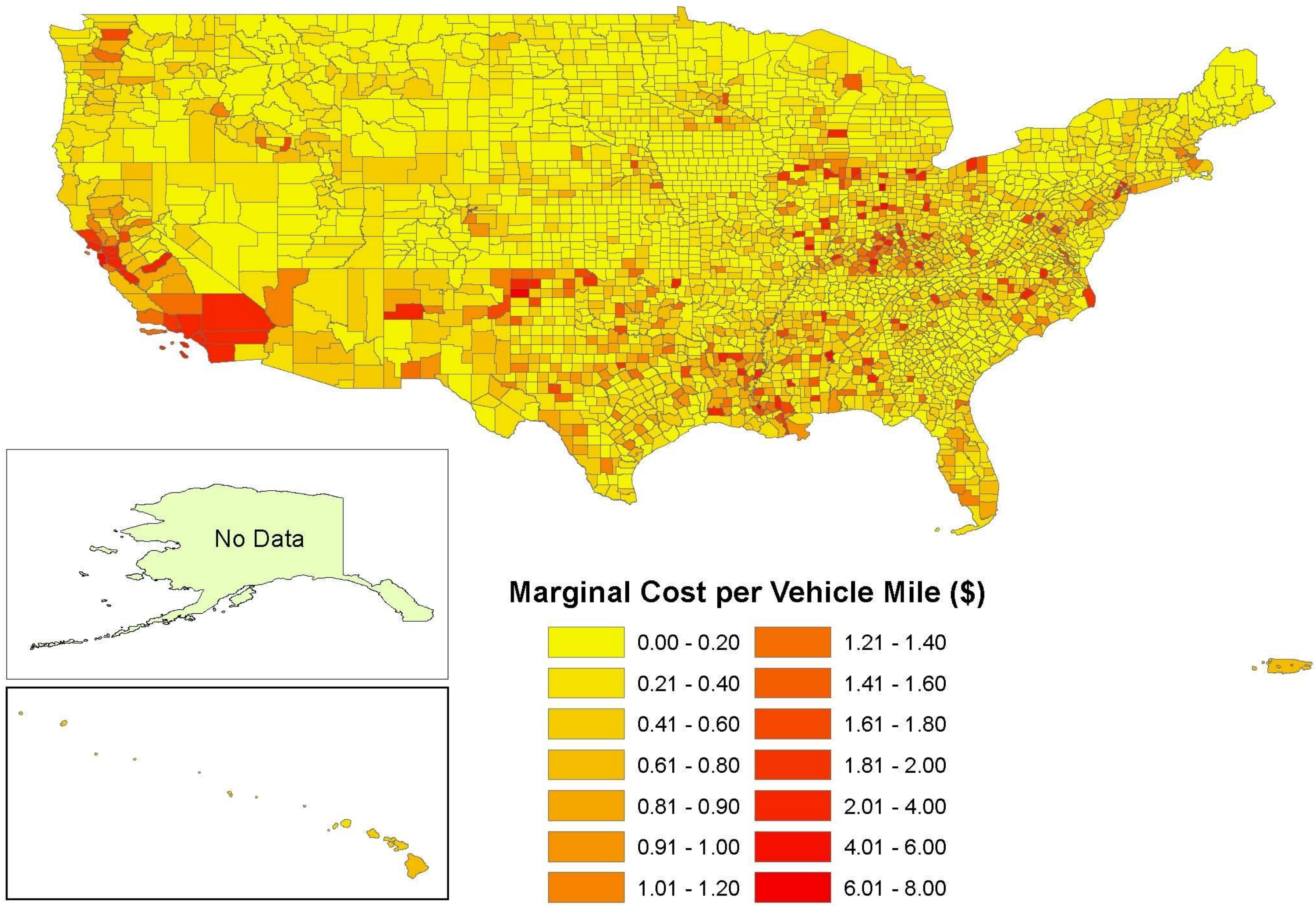
Total Marginal Cost to Society for 4 Axle Combined Truck Off-Peak Period

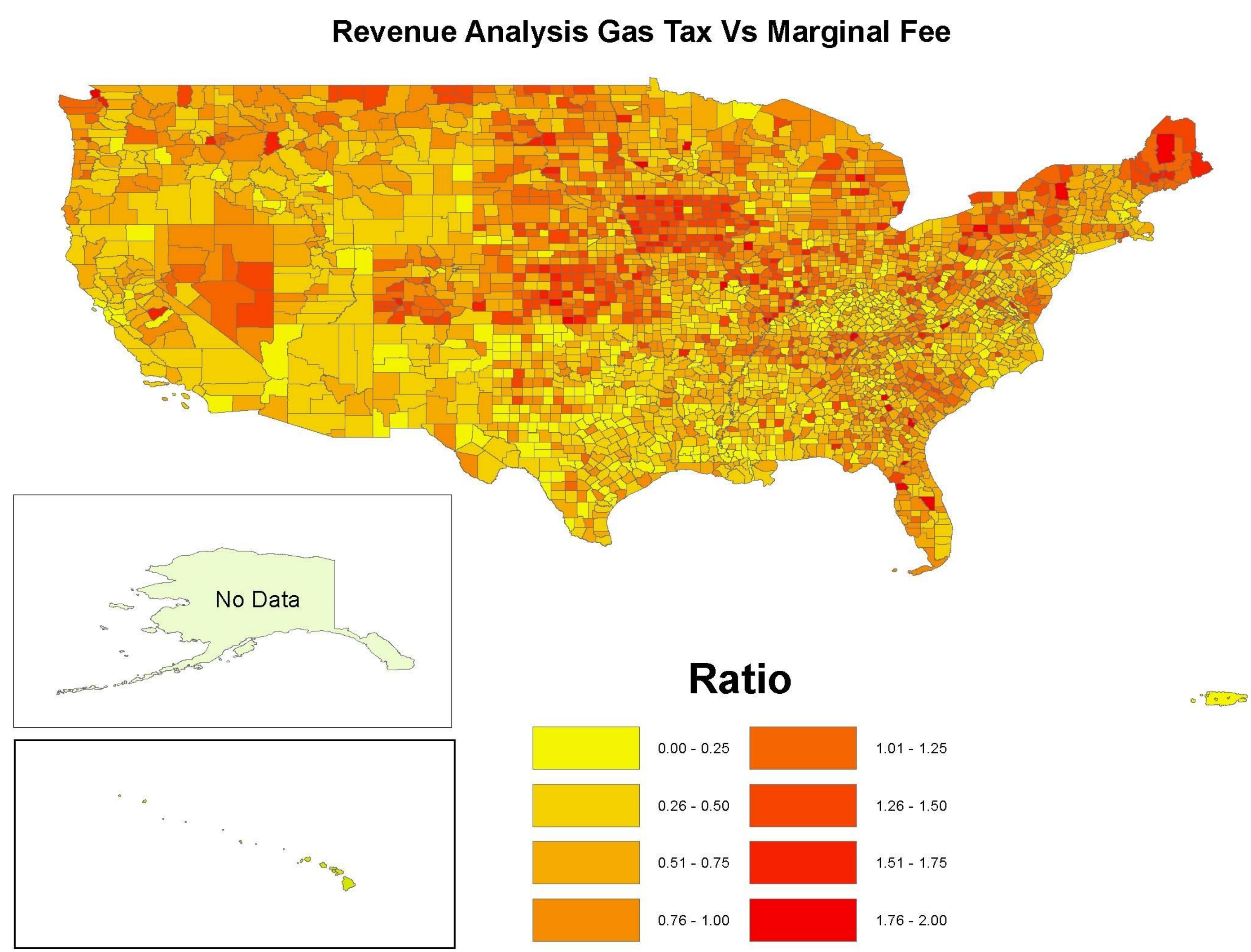


Total Marginal Cost to Society for 5 Axle Combined Truck Peak Period



Total Marginal Cost to Society for 5 Axle Combined Truck Off-Peak Period





Revenue Analysis Gas Tax Vs Marginal Fee
No Data
Ratio
0.00 - 0.25
0.26 - 0.50
0.51 - 0.75
0.76 - 1.00
1.01 - 1.25
1.26 - 1.50
1.51 - 1.75
1.76 - 2.00

References

American Association of State Highway and Transportation Officials, AASHTO Guide for Design of Pavement Structures, Washington, D.C., 1986.

American Automobile Manufacturers Association, Motor Vehicle Facts and Figures, 1996, Detroit, 1996, p. 60

Lawrence J. Blincoe and Barbara M. Faigin, The Economic Cost of Motor Vehicle Crashes, 1990, NHTSA, Report DOT HS 807 876, 1992

Brian L. Bowman and Robert L. Vecellio, "Effect of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety," Transportation Research Record 1445, 1994, pp. 169-179

Cambridge Systematics, Inc., 2000 Revisions to HERS, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., August 2002

Cambridge Systematics, Inc., Harry Cohen, and Science Applications International Corp., Sketch Methods for Estimating Incident-Related Impacts, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., December 1998

Harry Cohen and Daniel Hailing, Residential Noise Damage Costs Caused by Motor Vehicles, Transportation Research Record 1997

G.C. Elkins, et al., Estimating Vehicle Performance Measures, Texas Research and Development Foundation, prepared for the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., July 1987, pp. 128-177

Robin P. Hertz, "Sleeper Berth Use as a Risk Factor for Tractor Trailer Driver Fatality," 31st Annual Proceedings, American Association for Automotive Medicine, September 1987, pp. 215-227

Richard Margiotta and Harry Cohen, Roadway Usage Patterns: Urban Case Studies, prepared by Science Applications International Corporation and Cambridge Systematics for Volpe National Transportation Systems Center, June 1994

Richard Margiotta, Incorporating Traffic Crash and Incident Information into the Highway Performance Monitoring System Analytical Process, prepared by COMSIS Corporation and Science Applications International Corporation for FHWA, September 1996

Oak Ridge National Laboratories, 1995 National Personal Travel Survey, Table NPTS-1, October 1997

B. Persaud and L. Dzbik, "Accident Prediction Models for Freeways," Transportation Research Record 1401, 1993

Science Applications International Corporation, et al., Speed Determination Models for the Highway Performance Monitoring System, pp 78-79.

Shelby A. Tedesco, et. al., "Development of a Safety Model to Assess the Impact of Implementing IVHS User Services," Proceedings of the IVHS America 1994 Annual Meeting, April 1994

U.S. Bureau of Labor Statistics, Consumer Price Index – All Urban Consumers, Series ID CUUR0000SETD01, Motor Vehicle Body Work

U.S. Bureau of Labor Statistics, Employment Cost Index, Series ID: ECS10001I, Total Compensation of All Civilian Workers

U.S. Department of Commerce, Bureau of Economic Analysis, "Average Transaction Price of a New Car," quoted in American Automobile Manufacturers Association, Motor Vehicle Facts and Figures, 1996, Detroit, 1996, page 60

U. S. Department of Transportation, FHWA, 1997 Federal Highway Cost Allocation Study, August 1997

U.S. Department of Transportation, FHWA, 1997 Highway Statistics, November 1999, Table VM-1

U.S. Department of Transportation, FHWA, 2005 Highway Economic Requirements System - State Version: Technical Report, August 2005

U. S. Department of Transportation, "The Value of Saving Travel Time: Departmental Guidance for Conducting Economic Evaluations," April 1997, Table 4

Andrew Vogt and Joe Bared, "Accident Models for Two-Lane Rural Segments and Intersections," presented at the TRB Annual Meeting, January 1998.

Jun Wang, Warren Hughes and Richard Stewart, Safety Effects of Cross-Section Design of Rural Four- Lane Highways, FHWA Report FHWA-RD-98-071, May 1998

Thawat Watanatada, Ashok M. Dhareshwar and Paulo Roberto S. Rezende Lima, Vehicle Speeds and Operating Costs, The World Bank, Johns Hopkins University Press, Baltimore, 1987

Herbert Weinblatt, "The Effects of Grades on Truck Speed," memorandum, Cambridge Systematics, Inc., Feb. 25, 1998

Matthew W. Witczak and Gonzalo R. Rada, Microcomputer Solution of the Project Level PMS Life Cycle Cost Model, University of Maryland, Department of Civil Engineering, prepared for Maryland Department of Transportation, State Highway Administration, Baltimore, Md., December 1984

J.P. Zaniewski, et.al., Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors, Texas Research and Development Foundation, prepared for U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., June 1982

C.V. Zegeer and C. Williams, Calculation of Accident Rates by Roadway Class for HSIS States, University of North Carolina Highway Research Center, June 1994