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Highway Cost Allocation and Determination of Heavy Freight Truck Permit Fees

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16. Abstract (Limit: 250 words)

Minnesota Department of Transportation (MnDOT) and other state DOTs periodically carry out studies to assess how highway construction and maintenance (HCM) expenditures ought to be attributed to various vehicle classes. In parallel, each vehicle-class' contribution to revenues from fuel and excise taxes and permit fees are calculated. Although, the latter are determined by the state legislature, the cost-to-revenue ratio helps inform MnDOT if changes to policy could be justified. A variety of methods have been developed to apportion HCM costs to different user classes. The purpose of this study was to evaluate pros and cons of different HCA methods and to identify/develop a methodology best suited for conditions in Minnesota. Researchers also carried out a highway cost allocation study (HCAS) using the latest data from Minnesota. In addition, the methodology developed in this project can be used to evaluate damage costs to the road system from permitting more than 80,000-lb gross vehicle weight trucks on Minnesota roads and the users' willingness to pay for such permits.

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Highway Cost Allocation and Determination of Heavy Freight Truck Permit Fees

Final Report

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Table of Contents

List of Figures

List of Tables

Executive Summary

Minnesota Department of Transportation (MnDOT) and other state DOTs periodically carry out studies to assess how highway construction and maintenance (HCM) expenditures ought to be attributed to various vehicle classes. In parallel, each vehicle-class' contribution to revenues from fuel and excise taxes and permit fees are calculated. Although, the latter are determined by the state legislature, the cost-to-revenue ratio helps inform MnDOT if changes to policy could be justified. A variety of methods have been developed to apportion HCM costs to different user classes. The purpose of this study was to evaluate pros and cons of different highway cost allocation methods and to identify/develop a methodology best suited for conditions in Minnesota.

Researchers first carried out a highway cost allocation study (HCAS) using the latest data from the state. The initial study utilized a HCAS tool developed by the Federal Highway Administration. Researchers also developed a customized HCAS tool for use by the state. The customized HCAS tool can be used to evaluate damage costs to the road system from permitting more than 80,000-lb gross vehicle weight trucks on Minnesota roads. The researchers also proposed and tested several auction based mechanisms for the sale of special permits. The recommended mechanism is easy to implement, and its use will allow MnDOT to learn how much users would be willing to pay for such permits.

Chapter 1

Introduction

The project described in this report had the following broader goals.

- To perform a highway cost allocation study (HCAS) using MnDOT data.
- To critically evaluate HCAS methodologies and develop a customized HCAS tool for MnDOT.
- To evaluate different tax structures in terms of their impact on efficiency and equity.
- To develop a methodology by which MnDOT could estimate freight operators' willingness to pay for special permits - i.e. exceeding weight or size thresholds specified by Federal and State regulations.

The project was successful in achieving all of its goals. A highway cost allocation study was first performed with the help of the Federal Highway Administration's (FHWA) HCAS tool. This tool is not customized to a particular state. Therefore, researchers also developed a customized tool for MnDOT data. The customized tool is designed to work with Minnesota-specific data and it also fixes several known bugs in the FHWA tool. Researchers developed a stylized model to show that efficiency and equity cannot be both achieved with the help of fuel taxes or registration fees by themselves. In contrast, the model showed that weight-distance taxes are able to realize both objectives. Finally, the project proposed and tested an auctions based system for selling special permits that would help MnDOT estimate the price-demand relationship for such permits.

The key findings of this project are as follows. The highway cost allocation studies show that heavy trucks are not paying taxes proportional to the damage they cause to the pavement. This is consistent with findings in other state highway cost allocation studies. The project used mathematical arguments to prove that by themselves fuel taxes and registration fees are not enough to realize the twin objectives of greater efficiency and equity. For these reasons, it recommends the use of weight-distance fees in the future. The project identified and tested auctions based strategies for selling special permits that can generate greater revenue for the state and allow state agencies to learn the freight companies' willingness to pay for such permits.

Chapter 2

Highway Cost Allocation Study (HCAS) for the State of Minnesota

2.1 Introduction

This chapter presents the results of a Highway Cost Allocation Study (HCAS) for the state of Minnesota based on financial and traffic data for the period 07/01/2003 to 06/30/2007 (denoted by 2004-07). The main purposes of this study were the following:

1. To calculate highway revenue and cost responsibilities by highway user class.
2. To identify tax equity issues for different user classes and estimate the possible impact of changes in tax structure through what-if analyses.

Highway cost allocation studies provide detailed information on the fairness of tax/fee structure for different vehicle classes based on type (e.g., passenger vehicle, truck) and registered gross weight (RGW). A HCAS is based on a series of calculations to approximate revenue collected and expenditure allocated to each vehicle class using the following data for the state in question: total revenue, total expenditure, highway design parameters, and vehicle miles travelled (VMT) by vehicle class. After the first HCAS was performed in Oregon in 1937, more than 84 HCAS have been conducted by 30 states. A summary of the findings of these HCAS can be found in Balducci and Stowers (2008). It is recommended that HCAS should be performed on a regular basis to examine how different policy changes affect tax equity. Consistent with this recommendation, Oregon conducts HCAS every two years (ECONorthwest 2009) and Idaho performs HCAS every four years (Casavant and Jessup 2007). However, Minnesota has performed HCAS only once in 1989. It was conducted by Cambridge Systematics, Inc. (Cambridge Systematics 1990).

For the results reported in this section, the researchers used Excel worksheets provided by Federal Highway Administration (FHWA). In the remainder of this chapter, the aforementioned software developed by FHWA is referred to as the HCASP (short for highway cost allocation study program). HCASP has been used by several other states (Balducci et al. 2009a; Casavant and Jessup 2007). HCASP allows users to input a series of state-specific data and calculate cost, revenue, and tax equity ratios for each vehicle class. HCASP also comes with default data, based on national averages, which can be used when state-specific data is not readily available. The data requirements for performing HCAS are presented in Section 2.2. Guidelines for carrying out HCAS and for using HCASP are available from FHWA in the form of two publications (Federal Highway Administration 2000a,b).

A key finding of the HCAS reported in this document is that the state of Minnesota does not collect sufficient revenue from truck users to cover their cost responsibility. Calculations also show that the tax equity ratio is decreasing in registered grow weight (RGW). That is, the ratio of revenue to cost responsibility of heavier vehicles is smaller and this ratio decreases in RGW. Three what-if scenarios are also analyzed. The first scenario is a targeted approach in which weight fees for vehicles weighing more than 16,000 lbs are increased by 25%. The second scenario increases diesel tax by 25%. Both improve revenue-to-cost ratios for trucks; however, the impact is not large. This suggests that a different mechanism may be needed to achieve equitable revenue-to-cost ratios. In the third scenario, weight-distance taxes are applied to trucks weighing more than 57,000 lbs. The result of this analysis shows that revenue-to-cost ratios can be significantly improved if Minnesota were to collect weight-distance taxes.

This chapter is organized as follows. Section 2.2 presents the data requirements for HCASP. In Section 2.3 actual data used in the study is provided. Section 2.4 presents the results of the HCAS and Section 2.5 reports the results of what-if analyses. Finally, Section 2.6 concludes the chapter.

2.2 Data Requirements

HCASP relies on four types of user data input: revenue data, expenditure data, travel data, and highway data. Each data type is described in detail below. HCASP comes pre-loaded with default inputs for several other components that are not described in this section. Descriptions of default data elements can be found in Federal Highway Administration (2000a,b).

2.2.1 Revenue Data

The required revenue data contains receipts for each type of tax/fee from highway users. It can be disaggregated into Federal revenue and State revenue, however that is not a requirement for carrying out a HCAS. The Federal revenue includes fuel taxes (gasoline, diesel, gasohol, others), heavy vehicle use tax, vehicle sales tax, and tire tax. The State revenue for Minnesota includes, fuel taxes, weight fee (commercial vehicle), ad valorem tax (passenger vehicle), and vehicle sales tax. Weight fee is determined based on each vehicle's RGW and ad valorem tax is based on its base value.

2.2.2 Expenditure Data

Expenditure data includes expenses related to construction, preservation, maintenance, and administration of state highway programs. Specifically, HCASP requires users to provide expenditure for each type of work performed for each highway functional class. Types of work categories and highway functional class (HFC) categories are listed in Table 2.1.

Note that certain types of expenditures cannot be disaggregated by HFC. Table 2.2 lists such expenditures. These are input without HFC attribution.

Similar to revenue data, the user must also categorize expenditure data by the level of government i.e. federal and state.

Table 2.1: Data Requirements – Types of Work & Highway Functional Classes

Types of Work	Highway Functional Classes
• New Flexible Pavement – Costs of asphalt pavement widening or pavements on new locations, not replacing worn out existing pavements • New Rigid Pavement – Costs of concrete or composite pavement widening or pavements on new locations, not replacing worn out existing pavements • Flexible Pavement Repair – Costs of repairing or replacing asphalt pavements, regardless of what type of pavement overlays or replaces the formerly-asphalt pavements • Rigid Pavement Repair – Costs of repairing or replacing concrete or composite pavements, regardless of what type of pavement overlays or replaces the formerly-concrete pavements • New Bridge – Costs of new bridges, not replacing old bridges • Bridge Repair – Costs of deck replacement, girder upgrading, and any other bridge repair (but not replacement) • Special Bridge – User-definable category that can be used for any special state bridge programs • Grading and Drainage – Culverts and box culverts, ditch excavation, roadway grade preparation, and other such items. (Removal of old pavements and incidental grading associated with pavement repair should not be included here. They should be included with pavement repair • General Construction (Residual) – Miscellaneous costs that do not differentially derive from highway usage by any particular class of vehicle. For example, roadway signs • Transit and Rail – Costs spent from highway funds on mass transit	• Rural Interstate • Rural Other Principal Arterials • Rural Minor Arterials • Rural Major Collectors • Rural Minor Collectors • Rural Local • Urban Interstate • Urban Other Freeways and Expressways • Urban Other Principal Arterials • Urban Minor Arterials • Urban Collectors • Urban - Local

Table 2.1 Cont'd: Data Requirements – Types of Work & Highway Functional Classes

<table>
<tr><th>Types of Work</th><th>Highway Functional Classes</th></tr>
<tr><td>

Truck VMT Construction
Weight stations, escape ramps, and any other costs that you can identify in your highway program that apply only to trucks
Travel-related Maintenance
Items such as bridge painting and sign replacement that do not vary directly with travel, but rather derive from the overall need for keeping the road open and serviceable
Wear-related Flexible Pavement Maintenance
Most flexible pavement maintenance related to vehicle usage
Wear-related Rigid Pavement Maintenance
Most rigid pavement maintenance related to vehicle usage
Axle-Related Maintenance
Pavement markings
Truck-mile Maintenance
Weight station maintenance and any other items that you maintenance cost accounting system might identify as exclusively truck responsibilities
Light-vehicle Maintenance
Maintenance activities on facilities used only by light vehicle (two axle vehicles)
Rest Area Maintenance
Costs related to rest area.

</td><td></td></tr>
</table>

Table 2.2: Data Requirements – Not Disaggregated by HFC

- Multi-System Travel-Related
  - Any general construction, maintenance, operations, or administrative costs that cannot be categorized by highway function class
- State Police Traffic Management
  - The portion of state police costs that come from highway funds or that represent traffic management and operation costs
- Truck Related
  - Any truck related costs that cannot break down by highway function class
- Large Truck Related
  - Any large truck related costs that cannot break down by highway function class
- Fuel Consumption
  - Costs of collecting user fees fuel except for gasoline and diesel (It is considered 0 for many states)
- Gasoline Consumption
  - Costs of collecting user fees on gasoline (It is considered 0 for many states)
- Diesel Fuel Consumption
  - Costs of collecting user fees on diesel fuel (It is considered 0 for many states)
- Vehicle Registration
  - Costs of administering vehicle registrations. (Choose to input either all vehicle-registration cost or light-vehicle/heavy-vehicle registration costs)

2.2.3 Travel Data

Travel data plays a key role in HCASP because both revenue attribution and cost allocation rely on Vehicle Miles Travelled (VMT) information. HCASP requires the user to provide VMT for each vehicle configuration on each type of highway functional class. Vehicle configurations used by HCASP and their descriptions are shown in Table 2.3. The user can choose either Highway Performance Monitoring System's (HPMS) 12-vehicle classes or HCASP's 20-vehicle classes. All calculations in HCASP are based on the 20-vehicle classes. That is, if the user chooses to use HPMS 12-vehicle class system, then it will be mapped onto 20-vehicle class system used by HCASP. Therefore, it is recommended that data should be entered in terms of the 20-vehicle class system whenever possible.

Table 2.3: HPMS and HCAS Vehicle Classifications

HPMS	**HCAS**	**Description**
AUTO	AUTO	Automobiles and Motorcycles
LT4s	LT4	Light trucks with 2-axles and 4 tires (Pickup Trucks, Vans, Minivans, etc.)
SU2	SU2	Single unit, 2-axle, 6 tire trucks (includes SU2 pulling a utility trailer)
SU3	SU3	Single unit, 3-axle trucks (includes SU3 pulling a utility trailer)
SU4	SU4+	Single unit trucks with 4- or more axles (includes SU4+ pulling a Utility trailer)
CB3&4	CS3	Tractor-semitrailer combinations with 3-axles
	CS4	Tractor-semitrailer combinations with 4-axles
	CT4-	Truck-trailers combinations with 3- or 4-axles
CB5	3S2	Tractor-semitrailer combinations with 5-axles, two rear tandem axles
	CS5	Tractor-semitrailer combinations with 5-axles, two split (¿8 feet) rear axles
	CT5	Truck-trailers combinations with 5-axles
CB6+	CS6	Tractor-semitrailer combinations with 6-axles
	CS7+	Tractor-semitrailer combinations with 7- or more axles
	CT6	Truck-trailers combinations with 6- or more axles
DS5	DS5	Tractor-double semitrailer combinations with 5-axles
DS6	DS6	Tractor-double semitrailer combinations with 6-axles
DS7+	DS7	Tractor-double semitrailer combinations with 7-axles
	DS8+	Tractor-double semitrailer combinations with 8- or more axles
	TS	Tractor-triple semitrailer or truck-double semitrailer combinations
BUS	BUS	Buses (all types)

2.2.4 Highway Data

Highway data include the total mile length for each highway functional class and the minimum thickness (zero traffic thickness) for rigid and flexible pavements. These parameters help determine the allocation of highway maintenance and construction costs to different vehicle classes.

2.3 Data Inputs

In this section, researchers present the actual data used in this study. Unless mentioned otherwise, the data shown in this section are the annual averages between 07/01/2003 and 06/30/2007.

2.3.1 Revenue Data

Table 2.4 shows the federal revenue attributed to Minnesota. The data are collected from Highway Statistics 2004-2007. Federal tax rate information is provided in the software as default. Therefore, details are omitted.

Table 2.5 shows Minnesota state revenue. The data are obtained from Highway Users Tax Distribution Fund. The original data does not provide the breakdown between gasoline tax and diesel tax and between ad valorem tax and weight fee. Therefore, these proportions are approximated based on information provided

Table 2.4: Federal Revenue Attributed to Minnesota (in thousands of dollars)

	2004	2005	2006	2007	Average
Gasoline Tax	360,754	371,111	383,805	390,315	376,496
Diesel/Other Tax	132,715	140,060	137,654	151,909	140,584
Heavy Vehicle Use Tax	17,206	19,490	23,882	17,537	19,528
Vehicle Sales Tax	33,637	53,517	61,579	64,742	53,368
Tires Tax	8,121	8,353	8,307	7,834	8,153

in the document Minnesota's Highway Finances, which states that 79% of fuel taxes comes from gasoline tax and 80% of registration fees comes from ad valorem tax.

Table 2.5: State Revenue Information (in thousands of dollars)

	2004	2005	2006	2007	Average
Fuel Taxes	643,626	655,887	655,010	650,589	651,278
Gasoline Tax	508,465	618,151	517,458	513,965	514,510
Diesel/Other Tax	135,161	137,736	137,552	136,624	136,768
Registration Fees	505,565	499,841	479,000	478,184	490,647
Ad Valorem Tax	101,113	99,968	95,800	95,637	98,129
Weight Fee	404,452	399,873	383,200	382,547	392,518
Sales Tax	184,087	165,235	165,060	153,750	167,033
Permit Fee	2,601	2,854	3,216	3,438	3,027

The tax rates information for Minnesota during 6/1/2003 to 7/30/2007 were as follows. Both gasoline and diesel tax was 20 cents per gallon. The ad valorem tax for passenger vehicle was $10+1.25% of vehicle base value. The vehicle sales tax was 6.5%. Registration fee for commercial vehicle was based primarily on registered gross weight (RGW). The weight fees for commercial vehicles, shown in Table 2.6, was from section 168.013 of 2007 Minnesota Statutes. Average permit fee was approximately $45/permit. This estimate was based on data provided by Roger Clauson of MnDOT.

2.3.2 Expenditure Data

Lynn Poirier of MnDOT provided the expenditure data. Federal and state expenditures by type of work are shown in Tables 2.7 and 2.8, respectively. Note that the breakdown between rigid and flexible pavement is approximated based on relative value of paving projects shown in Table 2.9. In addition, the breakdown for travel-related maintenance is based on overall breakdowns calculated from Highway Statistics (see, Table 2.10). Information in Table 2.10 is excerpted from Table SF-12 of Highway Statistics 2004-2007.

2.3.3 Travel Data

Thomas Nelson of MnDOT provided Vehicle Miles Travelled (VMT) data shown in Table 2.11. Note that VMT for vehicle class TS is 0 because these type of vehicles are not allowed on Minnesota roads. However, a value of 0 as VMT data input triggers an error in HCASP. Therefore, researchers entered a small number (0.00001) to avoid this error.

Table 2.12 shows summary of operating gross weight distributions for selected vehicle configurations. The data were collected from 11 weight stations and provided to researchers by MnDOT's Scott Hedger. The raw data did not map well to all vehicle configurations. For example, the joint distribution for CS3 and CS4 was known but not their individual distributions. Therefore, researchers used HCASP default data for those vehicle classes, i.e. for classes CS3, CS4, 3S5, CS5, CS6, CS7+, DS7, DS8+, for which OGW data were not available.

Table 2.6: Registration Fees for Commercial Vehicles

RGW Range	**Weight Fees**
0-1500	15
1501-3000	20
3000-4500	25
4501-6000	35
6001-10000	45
10001-12000	70
12001-15000	105
15001-18000	145
18001-21000	190
21001-26000	270
26001-33000	360
33001-39000	475
39001-45000	595
45001-51000	715
51001-57000	865
57001-63000	1,015
63001-69000	1,186
69001-73280	1,325
73281-78000	1,595
78001-80000	1,760
Above 80000	1,760 + 50 per ton

Table 2.7: State Expenditures by Highway Functional Class and Type of Work (in thousands of dollars)

Vehicle Class	Rur Int	Rur OPA	Rur MA	Rur MajC	Rur MnC	Rur Loc	Urb Int	Urb OFE	Urb OPA	Urb MA	Urb Coll	Urb Loc
New Flexible Pavement	1079.7	11271.3	7235.2	96.6	51.3	107.1	16206.0	12360.6	24210.3	2746.0	8.6	0.0
New Rigid Pavement	989.1	8975.5	6147.4	86.0	39.2	141.3	13463.3	11851.2	20095.4	2358.8	11.4	0.0
Flexible Pavement Repair	2756.7	13823.2	10744.9	234.2	372.8	1053.0	2389.6	4684.8	5947.8	755.6	248.6	0.0
Rigid Pavement Repair	2306.5	11346.3	9467.3	386.6	276.7	1347.9	1798.5	3928.7	4808.3	608.6	187.5	0.0
New Bridge	1414.7	5949.6	4986.6	549.0	109.7	5143.7	8621.4	3842.2	7974.9	1003.7	0.0	0.0
Replacement Bridge	675.7	2029.6	1303.5	239.1	107.9	1525.1	3332.3	786.8	933.3	139.3	0.0	0.0
Bridge Repair	1410.0	434.5	261.7	28.4	5.1	109.7	1519.3	1207.6	1323.5	208.4	0.0	0.0
General Construction (Residual)	2516.6	32041.8	18840.7	719.3	111.7	1395.2	24770.9	45443.2	45888.6	6515.8	42.8	0.0
Travel-Related Maintenance	19399.6	76734.6	5506.7	216.0	56255.2	0.0	68564.4	56255.2	70112.1	7450.3	0.0	0.0
Rest Area Maintenance	5566.0											
Multi-System Travel-Related	102073.0											
State Police Traffic Management	100784.0											
Fuel Consumption	17.0											
Vehicle Registration	6311.0											
Total	1029713.1											

Table 2.8: Federal-Aid Expenditures by Highway Functional Class and Type of Work (in thousands of dollars)

Vehicle Class	**Rur Int**	**Rur OPA**	**Rur MA**	**Rur MajC**	**Rur MnC**	**Rur Loc**	**Urb Int**	**Urb OFE**	**Urb OPA**	**Urb MA**	**Urb Coll**	**Urb Loc**
New Flexible Pavement	115.4	15849.0	6474.1	0.0	0.0	0.0	31724.8	30168.0	16104.2	3278.5	0.0	0.0
New Rigid Pavement	119.0	13128.0	5348.8	0.0	0.0	0.0	26374.9	23547.7	13422.8	2477.7	0.0	0.0
Flexible Pavement Repair	8510.2	18036.1	8020.0	1135.4	8.2	1.1	1210.0	2603.0	1685.6	277.6	0.0	0.0
Rigid Pavement Repair	8056.3	16332.5	7194.7	767.9	5.0	2.9	832.3	2129.2	1476.6	217.5	0.0	0.0
New Bridge	562.3	8663.4	4211.7	1473.3	1.2	22.8	31121.5	12855.1	9133.6	1313.4	0.0	56.3
Replacement Bridge	330.1	2349.0	905.7	598.4	1.0	9.5	180.3	804.1	560.2	83.9	0.0	0.0
Bridge Repair	82.0	489.3	182.0	0.0	0.0	0.0	665.6	1151.3	936.9	106.5	0.0	0.0
General Construction (Residual)	1612.0	3522.4	1626.5	197.2	0.6	3.0	2841.2	4025.1	3099.6	415.7	0.0	33.9
Multi-System Travel-Related	16310.0											
State Police Traffic Management	3702.0											
Total	382874.6											

Table 2.9: Relative Value of Paving Projects

	2004	**2005**	**2006**	**2007**
Flexible Pavement	57%	62%	43%	55%
Rigid Pavement	43%	38%	57%	45%

Table 2.10: General Cost Breakdown for Highway Functional Classes

Interstate	**Principal Arterials**	**Minor Arterial**	**Major Collectors**	**Minor Collectors**	**Local**	**Interstate**	**Other Freeways/ Expressways**	**Other Principle Arterials**	**Minor Arterials**	**Collectors**	**Local**
5.39%	21.32%	15.46%	1.53%	0.06%	0.00%	19.05%	15.63%	19.48%	2.07%	0.00%	0.00%

Table 2.11: VMT by Vehicle Class and Highway Functional Class (in millions of dollars)

Vehicle Class	Interstate	Principal Arterials	Minor Arterial	Major Collectors	Minor Collectors	Local	Interstate	Other Freeways/ Expressways	Other Principle Arterials	Minor Arterials	Collectors	Local
Auto	3363.2	4709.2	3558.9	2561.7	897.3	1879.6	4712.8	2067.1	2598.0	5039.8	1577.9	2655.3
LT4	1011.3	2095.3	1524.7	1413.0	384.6	805.6	2537.7	1113.0	1398.9	2713.7	849.7	1429.8
SU2	125.3	231.5	147.0	123.8	55.0	115.2	142.0	62.5	74.2	156.4	20.4	25.1
SU3	28.8	96.2	68.5	43.7	14.2	29.6	31.0	15.5	19.8	47.8	1.6	0.3
SU4+	3.7	38.5	1.8	8.1	2.9	6.0	15.5	7.7	10.1	25.1	0.9	0.1
CS3	21.6	12.6	10.4	3.4	2.0	4.1	7.0	3.0	4.6	5.7	1.0	1.2
CS4	40.1	23.5	19.3	6.3	4.6	9.5	13.2	5.4	7.2	8.9	0.2	0.4
3S2	281.8	459.6	238.0	140.9	25.5	53.5	150.6	40.3	48.5	42.5	0.7	1.1
CS5	70.5	114.9	59.5	36.1	6.4	13.4	37.3	10.4	11.8	10.7	0.2	0.3
CS6	13.3	116.2	15.4	42.3	1.6	3.3	69.1	16.8	20.2	16.2	0.3	0.4
CS7+	1.5	12.9	1.7	4.7	0.2	0.4	15.5	4.4	6.7	7.7	0.1	0.2
CT4	0.9	1.9	0.5	0.8	2.0	4.1	3.1	1.7	1.7	5.2	0.5	0.7
CT5	3.9	8.0	2.0	3.4	3.3	6.8	1.9	1.0	1.3	1.6	0.2	0.2
CT6+	0.4	0.7	0.2	0.3	1.3	2.7	1.2	0.7	0.8	2.4	0.2	0.3
DS5	21.7	0.7	0.5	0.4	1.8	3.7	2.0	0.3	1.3	0.3	0.1	1.0
DS6	0.2	0.7	0.3	0.3	1.1	2.4	0.7	0.2	0.6	0.2	0.0	0.8
DS7	0.4	0.9	0.3	0.3	0.4	0.8	0.6	0.1	0.4	0.2	0.0	0.4
DS8+	0.2	0.5	0.3	0.3	0.8	1.6	0.5	0.1	0.3	0.1	0.0	0.2
TS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BUS	17.6	35.8	9.0	15.0	4.3	8.9	18.6	9.7	10.5	21.6	2.1	2.1

Table 2.12: Vehicle OGW Distribution

RGW (000) lbs	AUTOS	LT4	SU2	SU3	SU4+	DS5	DS6
0-3	21.4%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%
4-6	76.8%	68.1%	1.1%	0.0%	0.0%	0.0%	0.0%
7-9	1.8%	26.0%	20.3%	0.3%	1.0%	0.0%	0.0%
10-12	0.1%	3.1%	20.1%	1.0%	4.9%	0.0%	0.0%
13-15	0.0%	0.9%	15.3%	2.8%	6.8%	0.2%	0.1%
16-18	0.0%	0.4%	15.0%	8.2%	6.6%	0.6%	0.2%
19-21	0.0%	0.2%	12.6%	12.6%	6.0%	0.6%	0.3%
22-24	0.0%	0.1%	7.4%	10.6%	6.0%	0.4%	0.4%
25-27	0.0%	0.1%	4.2%	9.9%	5.1%	0.4%	0.3%
28-30	0.0%	0.0%	2.2%	9.1%	4.5%	0.8%	0.5%
31-33	0.0%	0.0%	1.1%	8.5%	4.1%	2.1%	0.9%
34-36	0.0%	0.0%	0.4%	7.7%	3.5%	3.7%	1.9%
37-39	0.0%	0.0%	0.2%	6.9%	2.8%	3.6%	2.5%
40-42	0.0%	0.0%	0.1%	5.9%	2.4%	4.0%	2.9%
43-45	0.0%	0.0%	0.0%	5.3%	1.8%	5.1%	3.9%
46-48	0.0%	0.0%	0.0%	3.9%	1.6%	6.5%	4.8%
49-51	0.0%	0.0%	0.0%	2.7%	2.1%	7.9%	5.9%
52-54	0.0%	0.0%	0.0%	1.8%	3.0%	9.5%	7.3%
55-57	0.0%	0.0%	0.0%	1.2%	4.1%	10.0%	8.5%
58-60	0.0%	0.0%	0.0%	0.7%	5.5%	9.9%	9.0%
61-63	0.0%	0.0%	0.0%	0.4%	8.3%	9.3%	9.6%
64-66	0.0%	0.0%	0.0%	0.2%	7.5%	8.1%	9.5%
67-69	0.0%	0.0%	0.0%	0.1%	5.1%	6.1%	9.5%
70-72	0.0%	0.0%	0.0%	0.1%	2.9%	4.3%	7.3%
73-75	0.0%	0.0%	0.0%	0.0%	2.2%	3.1%	5.8%
76-78	0.0%	0.0%	0.0%	0.0%	1.3%	1.9%	3.9%
79-81	0.0%	0.0%	0.0%	0.0%	0.6%	0.9%	2.0%
82-84	0.0%	0.0%	0.0%	0.0%	0.2%	0.5%	1.1%
85-87	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.6%
88-90	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%
91-93	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%
94-96	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%
97-99	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%
100 +	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%

2.3.4 Highway Data

Total highway miles listed in Table 2.13 are obtained from Highway Statistics 2004 2007 (Table HM-20). Minimum (zero-traffic) pavement Thickness in Table 2.14 is provided by Curtis Turgeon of MnDOT.

Table 2.13: Total Highway Miles

Rur Int	**Rur OPA**	**Rur MA**	**Rur MajC**	**Rur MnC**	**Rur Loc**	**Urb Int**	**Urb OFE**	**Urb OPA**	**Urb MA**	**Urb Coll**	**Urb Loc**
662	3696	6911	16215	12789	79637	252	161	593	2289	2005	13083

Table 2.14: Minimum Pavement Thickness

Flexible Pavement Minimum SN	**Rigid Pavement Minimum Slab Thickness**
1.86	7.0

2.4 Results

Total revenues and expenditures attributed to each type of vehicle are shown in Table 2.15. Observe that approximately 81% of revenues come from passenger vehicles and light trucks. However, passenger vehicles and light trucks are only responsible for approximately 63% of total expenditures. Among heavy trucks, CB5 has the largest share of the total revenues and expenditures. Specifically, approximately 8% of total revenues come from CB5 and 21% of total expenditures are allocated to CB5. (Recall that CB5 includes 3S2, CT5, CS5.)

Next, to evaluate tax equity, the researchers calculate two ratios. The first ratio, called revenue-to-cost (R-C) is defined as follows.

$$\text{R-C ratio (for a particular vehicle class)} = \frac{\text{revenue from a particular vehicle class}}{\text{cost allocated to a particular vehicle class}}$$

When revenues match expenditures (i.e. when revenues from all sources and true costs (not expenditures) are considered), the ideal R-C ratio is 1. That is, the revenue collected should equal the cost responsibility. If the ratio is greater than 1 for a particular vehicle class, then it means that the vehicle class pays more compared to their cost responsibility. Similarly, if the ratio is less than 1, then the vehicle class pays too little. However, in practice, expenditures in a given year do not reflect the cost of damage to roadways. Therefore, in addition to R-C ratio, adjusted R-C ratio is also calculated. This ratio is defined as follows.

$$\text{Adjusted R-C ratio} = \frac{\text{revenue from a particular vehicle class / total revenue}}{\text{cost allocated to a particular vehicle class / total cost}}$$

The relationship between (unadjusted) R-C ratio and adjusted R-C ratio can be explained as follows. Let r_i and c_i be the revenue and cost allocated to vehicle class $i = 1, \cdots, n$, respectively. Clearly, total revenue

Table 2.15: Revenue and Expenditure by Vehicle Class (in thousands of dollars)

Vehicle Class	Federal Revenue	State Revenue	Total Revenue	Federal Expenditure	State Expenditure	Total Expenditure
AUTO	274,241 -45.85%	726,090 -55.34%	1,000,331 -52.37%	75,271 -19.66%	472,218 -45.86%	547,501 -38.76%
LT4	133,151 -22.26%	414,604 -31.60%	547,754 -28.68%	68,677 -17.94%	267,901 -26.02%	336,582 -23.83%
SU2	36,600 -6.12%	39,522 -3.01%	76,122 -3.99%	16,487 -4.31%	35,029 -3.40%	51,516 -3.65%
SU3	21,990 -3.68%	21,026 -1.60%	43,016 -2.25%	12,077 -3.15%	19,144 -1.86%	31,221 -2.21%
SU4+	6,803 -1.14%	6,560 -0.50%	13,363 -0.70%	8,969 -2.34%	10,429 -1.01%	19,398 -1.37%
CB3&4	9,732 -1.63%	9,000 -0.69%	18,733 -0.98%	6,103 -1.59%	9,798 -0.95%	15,901 -1.13%
CB5	74,848 -12.51%	69,545 -5.30%	144,393 -7.56%	140,376 -36.66%	154,784 -15.03%	295,150 -20.89%
CB6+	32,691 -5.47%	14,548 -1.11%	47,239 -2.47%	47,995 -12.54%	48,569 -4.72%	96,560 -6.84%
DS5*	1,340 -0.22%	1,244 -0.09%	2,585 -0.14%	1,303 -0.34%	2,396 -0.23%	3,699 -0.26%
DS6*	573 -0.10%	288 -0.02%	861 -0.05%	401 -0.10%	848 -0.08%	1,250 -0.09%
DS7+*	2,134 -0.36%	400 -0.03%	2534 -0.13%	1,376 -0.36%	2,357 -0.23%	3,732 -0.26%
BUS	4,025 -0.67%	9,158 -0.70%	13,183 -0.69%	3,840 -1.00%	6,240 -0.61%	10,079 -0.71%
TOTAL	598,129	1,311,986	1,910,115	382,875	1,029,713	1,412,588
*VMT for these vehicle classes are not negligible						

and cost are $r = \sum_{i=1}^{n} r_i$ and $c = \sum_{i=1}^{n} c_i$, respectively. Define ρ_i and $\hat{\rho}_i$ as unadjusted and adjusted ratios for vehicle class i. Then, the following two equations can be obtained.

$$\rho_i = \frac{r_i}{c_i}, \tag{2.1}$$

and

$$\hat{\rho}_i = \frac{r_i/r}{c_i/c} = \frac{\rho_i}{\rho}, \tag{2.2}$$

where $\rho = r/c$. There are two main reasons for using adjusted R-C ratio. Adjusted ratios account for the fact that ρ does not equal 1 in many instances of problem. Second, adjusted ratios can be compared across states and across time for the same state regardless of when the damage occurs and when the repair/reconstruction takes place.

Table 2.16 shows both unadjusted and adjusted ratios for different vehicle classes. It includes ratios for state only and ratios when both federal and state data are considered. Observe that AUTO and LT4 have adjusted ratio greater than 1. However, all truck categories have adjusted ratio less than 1. In other words, trucks are not paying what they are responsible for. Especially for combination trucks with five or more axles, the state adjusted ratios range from 0.13 to 0.41 and federal-plus-state adjusted ratios are from 0.36 to 0.51.

Table 2.16: Revenue/Cost per Mile and Tax Equity Ratios by Vehicle Class

RGW			**State Ratio**		**Federal+State Ratio**	
	Revenue/Mile	**Cost/Mile**	**Unadjusted**	**Adjusted**	**Unadjusted**	**Adjusted**
AUTO	2.04	1.32	1.54	1.21	1.83	1.35
LT4	2.40	1.55	1.55	1.22	1.63	1.20
SU2	3.09	2.73	1.13	0.89	1.48	1.10
SU3	5.30	4.82	1.10	0.86	1.38	1.02
SU4+	5.44	8.63	0.63	0.50	0.69	0.51
CB3&4	3.78	4.11	0.92	0.72	1.18	0.87
CB5	3.68	8.18	0.45	0.35	0.49	0.36
CB6+	3.80	12.67	0.30	0.24	0.49	0.36
DS5*	3.68	7.08	0.52	0.41	0.70	0.52
DS6*	3.77	11.09	0.34	0.27	0.69	0.51
DS7+*	4.20	24.71	0.17	0.13	0.68	0.51
BUS	5.90	4.01	1.47	1.16	1.31	0.97
TOTAL	2.29	1.80	1.27	1.00	1.35	1.00
*VMT for these vehicle classes are not negligible						

Table 2.17 shows the state R-C ratios and federal-plus-state R-C ratios for vehicles with different ranges of registered gross weights. In this table, vehicles that weigh no more than 16,000 lbs have adjusted ratios greater than 1. For vehicles above 16000 lbs, the adjusted ratios are less than 1. Especially for vehicles weighing more than 40,000 lbs, the adjusted state ratio can be lower than 0.35. In addition, although state ratios for vehicles weighing more than 75,000 lb are lower than 0.15, the federal taxes make federal-plus-state ratios for these vehicle classes close to 1. This is because heavy vehicles pay significantly more federal taxes than light vehicles. However, for vehicles that weigh between 40,000 and 75,000 lbs, the adjusted federal-plus-state ratios are still relatively low.

Table 2.17: Tax Equity Ratios Summarized by RGW

RGW Range	State Ratio Unadjusted	State Ratio Adjusted	Federal+State Ratio Unadjusted	Federal+State Ratio Adjusted
0 -8,000	1.46	1.15	1.64	1.21
8,001 -16,000	1.56	1.23	1.77	1.31
16,001 -26,000	1.19	0.94	1.52	1.12
26,001 -40,000	1.09	0.86	1.30	0.97
40,001 -54,999	0.43	0.34	0.49	0.36
55,000 -75,000	0.22	0.17	0.54	0.40
75,001 -80,000	0.17	0.14	0.84	0.62
80,001 -90,000	0.18	0.14	0.98	0.73
90,001 -100,000 *	0.18	0.14	1.16	0.86
100,001 -105,500 *	0.19	0.15	1.22	0.91
105,501 above *	0.12	0.10	1.09	0.81
Total	1.27	1.00	1.35	1.00

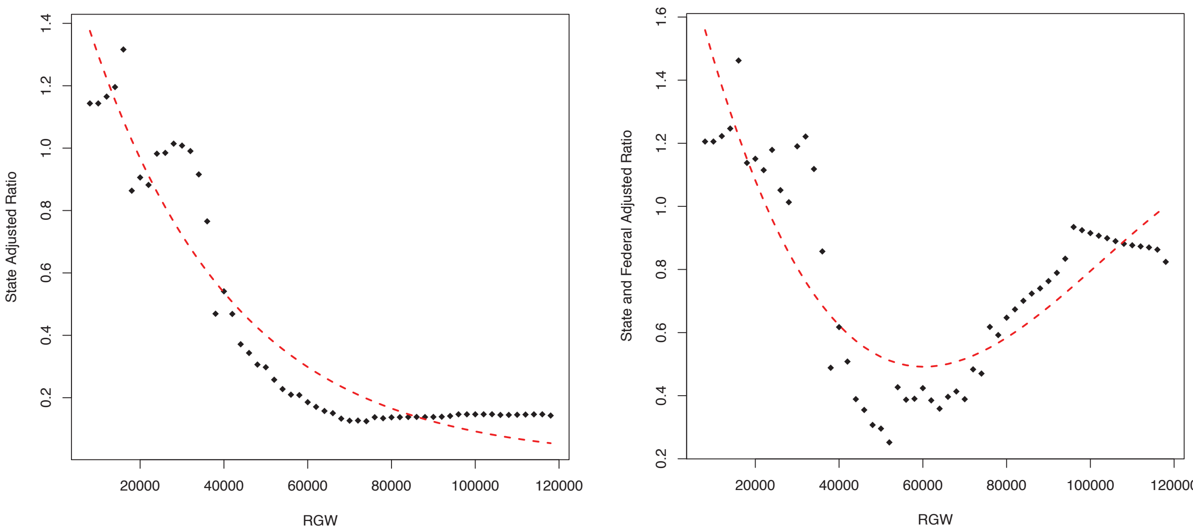
*VMT for these vehicle classes are not negligible

Figure 2.1 shows adjusted ratios for different registered-gross-weight vehicles in 2000 lb increments. Each dot indicates the adjusted ratio for each 2000 lb RGW increments. The dotted line indicates the regression line using actual adjusted ratios as the dependent variable and the upper bound of RGW as explanatory variable. As shown in this figure, the state adjusted ratio has a generally decreasing trend in registered gross weight. This suggests that heavy vehicles pay relatively less state taxes than light vehicles. However, the federal government charges heavy trucks more on sales taxes and tire fees. Therefore, after considering both state and federal revenues, only trucks between 30,000 and 90,000 have adjusted ratios significantly lower than 1.

In Table 2.18, results obtained from using 2004-07 and HCASP are compared with the 1989 HCAS results. Because both the tax/fee structure and the cost allocation methods have changed since 1989, the ratios for 1989 and 2004-07 are not expected to be close. For AUTO and LT4, the ratios for 2004-07 are higher than those for 1989. For single unit trucks with three or more axles, the 1989 HCAS shows that the ratio is significantly greater than 1 (state: 1.31 and federal-plus-state: 1.89). However, for 2004-07, the ratios are much closer to 1 (state: 0.91 and federal-plus-state: 1.08). In addition, results for 1989 HCAS show that combination trucks with four or less axles were paying too much whereas trucks with five or more axles are paying too little. However, in the current study, all combination trucks are found to have adjusted ratios less than 1.

2.5 Scenario Analysis

In this section, researchers investigate how different tax rates affect tax equity. The results in Section 2.4 show that, in general, trucks are paying less than what they should pay. Therefore, the researchers considered three alternatives that may be used to make R-C ratios closer to 1 for trucks. For the first two scenarios, researchers consider cases in which the current tax rate is increased, whereas in the last scenario, they consider the effect of adopting a new weight-distance tax. In the first scenario (Scenario A), researchers



(a) State Adjusted Ratio (b) State+Federal Adjusted Ratio

Figure 2.1: Tax Equity Ratios and Trend by RGW

Table 2.18: Tax Equity Ratios for 1989 and 2004-07

	State Ratio		**Federal+State Ratio**	
	1989	**2004-07**	**1989**	**2004-07**
AUTO	1.05	1.21	0.94	1.35
LT4	1.06	1.22	1.09	1.20
Single Unit Trucks	-	-	-	-
2 Axle	0.99	0.89	1.02	1.10
3+ Axle	1.31	0.74	1.89	0.83
Combinations	-	-	-	-
3 Axle	1.13	0.72	1.49	0.87
4 Axle	1.04		1.41	
5 Axle	0.66	0.35	0.93	0.36
6+ Axle	0.50	0.24	0.76	0.36
BUS	0.85	1.16	0.72	0.97
All Vehicles	1.00	1.00	1.00	1.00

increased weight fees for vehicle weighing more than 16,000 lbs by 25%. Because the adjusted ratios for vehicles that weigh more than 16,000 lbs were significantly lower than 1, researchers suspected that higher weight fees might increase the ratios for heavy vehicles. For the purpose of this simulation, it was assumed that truck traffic and VMTs were not affected upon changing the weight fee. This additional tax increased revenue from weight fee by $106,878K. In the second scenario (Scenario B), researchers increased diesel tax by 25% (extra 5 cents/gallon). Because most trucks run on diesel fuel and passenger cars on gasoline, it was believed that this change would largely affects trucks. Again, researchers assumed that truck traffic and VMTs were not affected by the additional fuel tax. The 5-cent per gallon increase in diesel tax increased state revenues by $170,960K.

Table 2.19: State Tax Equity Ratios by Vehicle Type for Different Scenarios

RGW	**Original**		**Scenario A**		**Scenario B**	
Vehicle Class	**Unadjusted**	**Adjusted**	**Unadjusted**	**Adjusted**	**Unadjusted**	**Adjusted**
AUTO	1.54	1.21	1.54	1.20	1.55	1.19
LT4	1.55	1.22	1.55	1.21	1.56	1.20
SU2	1.13	0.89	1.20	0.93	1.20	0.92
SU3	1.10	0.86	1.17	0.92	1.25	0.95
SU4+	0.63	0.50	0.67	0.52	0.72	0.55
CB3&4	0.92	0.72	0.96	0.75	1.06	0.81
CB5	0.45	0.35	0.46	0.36	0.53	0.40
CB6+	0.30	0.24	0.32	0.25	0.36	0.27
DS5*	0.52	0.41	0.54	0.42	0.61	0.47
DS6*	0.34	0.27	0.36	0.28	0.41	0.31
DS7+*	0.17	0.13	0.18	0.14	0.19	0.15
BUS	1.47	1.16	1.59	1.24	1.57	1.20
Total	1.27	1.00	1.28	1.00	1.31	1.00

*VMT for these vehicle classes are not negligible

Table 2.19 shows the tax equity ratios by vehicle type for Scenarios A and B as well as the original results. Observe that Scenario A does increase the ratios for trucks, especially for single unit trucks. However, the overall improvement is relatively small. The improvement is greater in Scenario B. Similar effects can also be observed in Table 2.20, where tax equity ratios are shown by RGW for the two scenarios and with the original taxes. Both scenarios increase the ratio for vehicles above 16,000 lbs. However, the improvements for vehicles above 55,000 lbs are limited. This is because the number of vehicles in these categories is relatively small although VMTs are not small for all weight categories. Therefore, the changes in tax rate do not significantly affect the ratios in these ranges.

Although increasing tax rates improves the tax equity for highway users, its effect is small. Perhaps for these reasons, the State of Oregon (ECONorthwest 2009) uses weight-distance taxes to achieve better tax equity. In addition, a recent study (Balducci et al. 2009b) shows that weight-distance fees can significantly improve tax equity in Nevada. Although Minnesota does not have a weight-distance tax in its current tax system, it is worthwhile to investigate the impact of weight-distance taxes on tax equity. In the third scenario (Scenario C), researchers assumed that the weight-distance taxes shown in Table 2.21 were applied to trucks weighing more than 57,000 lbs. The values of the tax rates in terms of cents/mile in Table 2.21 were obtained by fitting a segmented regression model that regresses the difference between revenue/mile and cost/mile on RGW category. In other words, the tax rates in Table 2.21 are designed to increase the ratios for vehicle with low ratios in the current tax system. As before, researchers assumed that truck traffic and VMTs did not change as a result of charging weight-distance fees. Then, the state could collect an additional $174,879K from weight-distance taxes under Scenario C. Table 2.22 compares the R-C ratios under the current system and scenario C. The results show that applying weight-distance tax can significantly improve the tax equity. Passenger vehicles (AUTO), light trucks (LT4), and buses (BUS) under Scenario C have adjusted ratios close to 1. Combination trucks (CB and DS) all have significant improvement on R-C ratios. Note that the ratios for single unit trucks (SU) in this example are worse than the current tax structure because the

Table 2.20: State Tax Equity Ratios by RGW for Different Scenarios

RGW	Original		Scenario A		Scenario B	
Upper Bound	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
8,000	1.46	1.15	1.46	1.14	1.47	1.12
16,000	1.56	1.23	1.56	1.21	1.57	1.20
26,000	1.19	0.94	1.26	0.98	1.25	0.95
40,000	1.09	0.86	1.17	0.90	1.23	0.94
55,000	0.43	0.34	0.45	0.35	0.51	0.39
75,000	0.22	0.17	0.23	0.18	0.26	0.20
80,000	0.17	0.14	0.19	0.15	0.20	0.15
90,000	0.18	0.14	0.19	0.15	0.20	0.15
100,000 *	0.18	0.14	0.20	0.15	0.21	0.16
105,500 *	0.19	0.15	0.21	0.16	0.21	0.16
150,000 *	0.12	0.10	0.20	0.16	0.14	0.11
Total	1.27	1.00	1.28	1.00	1.31	1.00

*VMT for these vehicle classes are not negligible

weight-distance taxes do not apply to trucks below 57,000 lbs. However, a carefully designed tax policy can certainly make improvement on all vehicle categories.

2.6 Conclusions and Recommendations

This chapter contains the results of a highway cost allocation study for the State of Minnesota based on average revenue and expenditure data collected between 2004 and 2007. The calculations are performed with the help of software developed by FHWA. The researchers found that both automobiles and light trucks have adjusted state R-C ratio greater than 1, which means the revenues from those vehicles exceed the cost responsibility. However, other truck categories have adjusted state R-C ratios significant less than 1 and the adjusted R-C ratio is decreasing in RGW. This suggests that heavy vehicles pay too little relative to their cost responsibilities. Researchers carried out three what-if scenario analyses. The purpose of this exercise was to study how tax equity ratios will change if either weight fees or diesel tax are increased or weight-distance fees are introduced. All three improve tax equity, but weight-distance taxes have the most significant effect on these ratios for heavy trucks.

Table 2.21: Weight-Distance Tax Rates for Scenario C

RGW Range	Cents/mile	RGW Range	Cents/mile
57000-63000	1.67	112001-114000	21.79
63001-69000	3.61	114001-116000	21.88
69001-78000	6.04	116001-118000	21.97
73281-78000	7.02	118001-120000	22.06
80000-82000	7.99	120001-122000	22.14
82001-84000	8.96	122001-124000	22.23
84001-86000	9.93	124001-126000	22.32
86001-88000	10.91	126001-128000	22.41
88001-90000	11.88	128001-130000	22.5
90001-92000	12.85	130001-132000	22.59
92001-94000	13.83	132001-134000	22.68
94001-96000	14.8	134001-136000	22.77
96001-98000	15.77	136001-138000	22.86
98001-100000	16.74	138001-140000	22.95
100001-102000	17.72	140001-142000	23.04
102001-104000	18.69	142001-144000	23.13
104001-106000	19.22	144001-146000	23.22
106001-108000	20.63	146001-148000	23.31
108001-110000	21.61	148001-150000	23.4
110001-112000	21.7	150001-152000	23.49

Table 2.22: State Tax Equity Ratios by Vehicle Type for Scenario C

	Original		Scenario C	
Vehicle Class	**Unadjusted**	**Adjusted**	**Unadjusted**	**Adjusted**
AUTO	1.54	1.21	1.54	1.07
LT4	1.55	1.22	1.55	1.07
SU2	1.13	0.89	1.13	0.78
SU3	1.10	0.86	1.10	0.76
SU4+	0.63	0.50	0.63	0.44
CB3&4	0.92	0.72	1.06	0.73
CB5	0.45	0.35	1.28	0.89
CB6+	0.30	0.24	1.09	0.76
DS5*	0.52	0.41	1.48	1.03
DS6*	0.34	0.27	1.19	0.82
DS7+*	0.17	0.13	0.88	0.61
BUS	1.47	1.16	1.47	1.02
TOTAL	1.27	1.00	1.44	1.00

*VMT for these vehicle classes are not negligible

Chapter 3

HCA Methodology Evaluation

3.1 Introduction

In this chapter, we investigate the issues of equity and efficiency in Minnesota's road-use tax structure. Equity depends on how welfare or costs are distributed across different groups. Efficiency is measured by the ratio of maximum outputs for a given set of inputs. We critically appraise methods proposed in the literature to achieve or enhance equity and efficiency, and develop several avenues for future research in this area.

Tax equity in this context can be divided into two broad categories — horizontal equity and vertical equity. Horizontal equity is concerned with the distribution of benefits and costs among individuals or groups based on their usage. In other words, users with similar characteristics and profiles should receive equal share of resources and bear equal portion of costs. Highway cost allocation study is an example of a technique that focuses on achieving horizontal equity for allocating road user costs to different user classes defined by vehicle types.

Vertical equity (or social equity) is concerned with the distribution of benefits and costs among individuals or groups based on their income or social class. This approach creates a progressive tax policy that does not cause a higher cost burden (relative to ability to pay) on disadvantaged groups. An example of progressive tax in transportation is value-based registration fee (ad valorem tax) according to which the vehicle registration fee is based on the base value of each vehicle.

Different types of equity goals may sometimes conflict with each other. For example, to achieve vertical equity, some subsidies are usually provided to disadvantaged groups, which violate the principle of horizontal equity that requires people to pay an amount based on their usage. Unlike horizontal equity, vertical equity is usually more visible on issues related to welfare benefits, such as mass transit and public health. In this chapter, we discuss only horizontal equity because our main concern is the allocation of the construction, maintenance, and repair expenditures, and external costs to road users according to how much each user contributes to these costs.

Efficiency is another important issue that affects the design of a tax policy. Minnesota requires certain vehicles to obtain special permits on certain trips because these vehicles (usually overweight and/or oversize vehicle) may cause excess damage to roads and bridges or disrupt traffic flow. However, the prices charged for special permits may not reflect the truck industry's willingness to pay for these special dispensations. Therefore, the design of a pricing mechanism for special permits, which affect tax efficiency, is also a focus of this study.

Minnesota's revenue sources for the state's highway investments are fuel taxes, graduated registration fees, and vehicle sales taxes, of which fuel taxes are a significant source of funds. An advantage of charging fuel taxes is that these taxes are approximately proportional to the distance traveled. That is, the state collects more in fuel taxes from users with greater vehicle miles travelled. However, relying on fuel taxes as the primary financing source is not desirable for the following reasons. First, fuel taxes typically do not achieve tax equity because heavy vehicles that cause significantly greater damage to the road do not pay proportionally more in taxes. Gronau (1994) shows that a single diesel tax rate on all vehicles causes misallocations because heavy vehicles can lead to at least five times more damage than light trucks or buses. Also, revenue from fuel taxes is likely to decrease in the future because the new generation of vehicles will probably not be gasoline or diesel powered (Forkenbrock 2005) and because of ongoing improvements in fuel efficiency of automobiles.

It has been shown that the fuel tax rates in the United States are lower than they should be. For example, Parry and Small (2005) show that the optimal gasoline tax in the US should be more than twice the current rate. However, because of economic and political pressures, adjustments in fuel taxes are usually difficult to enact. Another disadvantage of charging fuel taxes is that they do not provide incentives to drivers to change their road-use behavior. Parry and Small (2005) show that when fuel taxes increase, the reduction in fuel consumption mainly comes from changes in fuel efficiency (such as buying a more-efficient/newer car). In other words, people typically do not drive less in response to a higher tax rate. Also, higher fuel taxes provide little help to mitigate congestion problems (Forkenbrock 2005).

Many authors have suggested that mileage-based user charges are more appropriate to directly address highway costs (see, for example, Forkenbrock 2005; Glaister and Graham 2005; Gronau 1994; Parry and Small 2005; Verhoef et al. 1995). An effective mileage-based user charge should be differentiated according to multiple dimensions, such as type-of-vehicle, length-of-trip, route-of-trip, and time-of-driving (Verhoef et al. 1995). However, Forkenbrock (2005) points out that a state government may face a variety of challenges when implementing highly differentiated mileage-based road user charges. We summarize these challenges in Section 4.11.

Partly in response to the difficulty of implementing a highly differentiated mileage-based road user fee structure, some states have been experimenting with a simpler version, which is sometimes referred to as the second-best method. In this simpler version, weight-distance taxes are based on actual miles of travel per vehicle and tax rates are determined by each vehicles' gross weight and number of axles. However, the route chosen by the vehicle and time of travel do not affect the taxes. That is, weight-distance tax rates do not dynamically change based on time of travel and trip route, with the result that weight-distance taxes are much easier to implement. Kentucky, New Mexico, New York, and Oregon, have imposed weight-distance taxes for truck users. Weight-distance taxes not only help achieve equity among groups, they also help achieve equity within each group. This means that weight-distance charges for trucks in the same category can be differentiated based on their actual travel distances.

Mileage-based user charge can also avoid moral hazard and adverse selection. Moral hazard occurs when individuals or parties face a perverse incentive to act inappropriately because they do not bear responsibility for their actions. For example, if road users pay the same amount regardless of the miles travelled, there is not only no reason to travel fewer miles, but in fact having paid the fixed fee, each user may wish to maximize its utility by traveling more. Similar moral hazard is observed when customers purchase health insurance. Once they pay the insurance premium, they often maximize their utilization of the health care resources.

Adverse selection (or negative selection) refers to a process in which costly customers are more likely to be selected. For example, suppose road user fee is based on vehicle-type and weight but not travel distance. Each vehicle class consists of both high utilization users and low utilization users. Because the tax rate for each class is determined by its overall characteristic and usage, the determined tax rate for a class is usually preferred by high utilization users but not by low utilization users. As a result, low utilization users may change to other groups, which makes the original vehicle class have a larger portion of high utilization users and consequently induce a higher cost. This effect may force the government to increase the tax rate to recover its costs and consequently make equity within a group more difficult to achieve.

The remainder of this chapter is organized as follows. In Section 3.2, we present a stylized mathematical model to demonstrate the impacts of fuel and weight-distance taxes in terms of cost recovery and tax equity. In Section 3.3, we describe the shortcomings of the FHWA's State HCAS Tool used in Chapter 2 and explain why it may not be the best tool for analyzing tax policy. In Section 3.4, we propose four possible research directions that may help improve current highway tax structure in the State of Minnesota.

3.2 Fuel vs. Weight-Distance Taxes

In this chapter we construct a stylized mathematical model to demonstrate how different tax structures may affect the truck industry's response and corresponding revenue-cost ratios for the State. In particular, this model helps explain why mileage-based taxes can improve equity and how universal fuel taxes may help achieve equity by encouraging truck industry to utilize trucks that cause less damage to roads and bridge.

In the model, we represent the entire truck industry as a single decision maker that determines its equilibrium fleet design. In reality, each transport company makes its individually-optimal decisions and the decisions of the trucking industry as a whole are an aggregation of these individual decisions. However, this process (though not the outcome) is identical for all individual decision makers. In fact, a company that deviates from the equilibrium solution will not be viable in the long run because its costs will be higher than other companies that follow the equilibrium solution, all other things being equal. Therefore, an equilibrium solution extrapolated to the entire trucking industry is a reasonable approach to take at this level of abstraction.

We use $\mathcal{N} = \{1, 2, \cdots, n\}$ to denote a set of available truck classes and X_i to denote the demand (measured in pound-miles) for class $i \in \mathcal{N}$ truck. Note that the demand for smaller trucks can be carried by larger trucks (demand X_i can be carried by any truck class $j \geq i$). The truck industry needs to decide $y_{i,j}$, which denotes a portion of demand X_j that is carried by truck class i, to maximize its profit for each i, j. Furthermore, we use $g_i(y_i)$ to denote the number of class-i trucks required to satisfy y_i, where $y_i = \sum_{j=1}^{i} y_{i,j}$. In the numerical examples, we assume that $g_i(y)$ is an increasing linear function.

Two types of costs are considered in this model. One is mileage-weight related cost, such as operating cost and diesel taxes, and another is truck quantity related cost, such as capital cost and yearly registration fee. We use c_i and t_i to denote the per truck capital cost and yearly tax, respectively, for trucks in class i. In addition, we use θ_i and δ_i to denote the operating cost and diesel tax, respectively, per pound-mile travelled by truck class i. Note that only t_i and δ_i are paid to the State. Finally, r_i is the revenue per pound-mile for satisfied class-i demand.

Assuming the truck industry's goal is to maximize total profit, its objective function can be written as follows

$$\max_{y_{i,j}} \sum_{i=1}^{n} \big[r_i X_i - y_i[\theta_i + \delta_i] - g_i(y_i)[c_i + t_i]\big]. \tag{3.1}$$

Subject to

$$\sum_{i=j}^{n} y_{i,j} \leq X_j \text{ for each } j = 1, 2, \cdots, N, \tag{3.2}$$

$$y_{i,j} \geq 0 \text{ for all } (i, j). \tag{3.3}$$

Constraints (3.2) ensure that actual pound-miles that generate revenue do not exceed X_j for each j. The mathematical formulation shown in (3.1)-(3.3) is also known as a linear program. For such problems, the optimal solutions, $y^*_{i,j}$ can be efficiently calculated using software such as MATLAB (MATLAB is a registered trademark of The MathWorks) and Microsoft Excel (Microsoft Excel is a registered trademark of Microsoft Corporation).

From the State's viewpoint, each truck class is associated with two income sources — t_i (based on the number of trucks) and δ_i (based on pound-miles traveled by each truck). Depending on the class of truck, a truck can cause different levels of damage to the road. We use κ_i to denote maintenance and repair cost induced by each pound-mile traveled by truck i. Let $y^*_{i,j}$ and $y^*_i = \sum_{j=1}^{i} y^*_{i,j}$ denote the truck industry's optimal decisions. We can calculate adjusted-revenue-cost ratio RC_i for truck class i as shown below:

$$RC_i = \frac{[y^*_i \cdot \delta_i + g_i\big(y^*_i\big) \cdot t_i]/[y^*_i \cdot \kappa_i]}{RC}, \tag{3.4}$$

where the denominator

$$RC = [\sum_{i=1}^{n}[y^*_i \cdot \delta_i + g_i\big(y^*_i\big) \cdot t_i]]/[\sum_{i=1}^{n} y^*_i \cdot \kappa_i], \tag{3.5}$$

is the overall revenue-cost ratio for all truck classes. If $RC < 1$, then the State does not collect enough revenue to cover its costs. Similarly, if $RC \geq 1$, then it means that the State collects more revenue than costs. RC_i indicates if truck class i pays a fair share of taxes. If $RC_i > 1$, it means class i pays relatively more than other truck groups. If $RC_i < 1$, it means class i pays relatively less than other truck groups. We are primarily interested in ensuring that RC_i lies in a neighborhood of 1 for all i. Note that the acceptable size of this neighborhood is typically specified by the State. For example, a state may consider its tax policy to be equitable if RC_i lies in the interval $[0.8, 1.2]$ for each i.

3.2.1 Example of Two-Class Truck Configuration

In this section, we use a two-class truck configuration to demonstrate why charging distance-weight taxes is more suitable for achieving tax equity. Based on the optimization model shown in (3.1) – (3.3), a two-class truck model can be simplified as shown below.

$$\begin{aligned} \max \quad & -y_{1,1} \cdot [\theta_1 + \delta_1] - g_1(y_{1,1}) \cdot [c_1 + t_1] + [y_{1,1} + y_{2,1}] \cdot r_1 \\ & -[y_{2,1} + y_{2,2}] \cdot [\theta_2 + \delta_2] - g_2(y_{2,1} + y_{2,2}) \cdot [c_2 + t_2] + y_{2,2} \cdot r_2, && (3.6) \\ \text{s.t.} \quad & y_{1,1} + y_{2,1} \leq X_1, && (3.7) \\ & y_{2,2} \leq X_2, && (3.8) \\ & y_{1,1}, y_{2,1}, y_{2,2} \geq 0. && (3.9) \end{aligned}$$

We next solve this model under two scenarios. In the first scenario, the heavier truck class has less than a certain threshold number of axles with the result that the heavier trucks cause more damage (i.e. $\kappa_2/\kappa_1 > 1$).

In the second scenario, heavier trucks have greater than a threshold number of axles and now lighter trucks cause more damage (i.e. $\kappa_2/\kappa_1 < 1$). In addition, three adjustments to the tax structure are evaluated under each scenario. We check if equity can be achieved by adjusting fuel taxes, or adjusting registration fees, or switching to mileage-based taxes.

Heavier Trucks Cause More Damage: $\kappa_2 > \kappa_1$

Let $X_1 = 20,000$, $X_2 = 40,000$, $g_1(y) = 0.01y$, $g_2(y) = 0.005y$, $\theta_1 = 1$, $\theta_2 = 1.5$, $c_1 = 1$, $c_2 = 1.25$, $r_1 = 5$, $r_2 = 8$, $\kappa_1 = 2$, $\kappa_2 = 6$, and $(t_1, t_2) = (100, 150)$. Note that $\delta_2/\delta_1 < 1$ because trucks that are twice as heavy consume less than twice the amount of fuel per pound-mile of demand served. For example, if a lighter truck with 10000 lbs load can travel 1 mile with 1 gallon of fuel and a heavy truck with 20000 lbs load can travel 1 miles with 1.6 gallon of fuel, then $\delta_2/\delta_1 = 0.8$.

Now, consider an example with fuel taxes $(\delta_1, \delta_2) = (1, 0.8\delta_1)$, where δ_1 can be varied by the state. This leads to the revenue-cost ratios in the following table after we select optimal values of $y_{1,1}$, $y_{2,1}$, and $y_{2,2}$ from the truck industry's perspective.

Table 3.1: Revenue-Cost Ratios — Base Case

$(y^*_{1,1}, y^*_{2,1}, y^*_{2,2})$	RC	RC_1	RC_2
$(20000, 0, 40000)$	0.36	2.75	0.71

In Table 3.1, the adjusted R-C ratio for class-1 trucks is clearly much higher than that for class-2 trucks. That is, in order to achieve equity, some tax adjustments are necessary. In the following experiments, we show how the RC ratios change if we adjust the tax structure/rate. Note that we set $\delta_1 < \delta_2$ because class-2 trucks, on average, carry heavier loads. If we assume that both class-1 and class-2 carry the same amount of loads for each trip, then it is possible to have $\delta_1 > \delta_2$. We only discuss cases when $\delta_1 < \delta_2$ because we obtained similar results when cases with $\delta_1 > \delta_2$ were considered.

Adjusting Fuel Taxes

The current tax structure does not allow different fuel tax rates based on truck classes. Therefore, to simulate changes made to fuel taxes, we increase δ_1 in increments of 0.2 while fixing $\delta_2/\delta_1 = 0.8$. The results are shown in Table 3.2.

Table 3.2: Revenue-Cost Ratios — Effect of Gas Taxes

(δ_1, δ_2)	$(y^*_{1,1}, y^*_{2,1}, y^*_{2,2})$	RC	RC_1	RC_2
$(1.0, 0.8)$	$(20000, 0, 40000)$	0.36	2.75	0.71
$(1.2, 0.96)$	$(20000, 0, 40000)$	0.40	2.74	0.71
$(1.4, 1.12)$	$(0, 20000, 40000)$	0.31	N/A	1.00

From Table 3.2, we observe that increasing gas taxes on all truck classes does not improve tax equity. In fact, it can make the problem worse. When (δ_1, δ_2) increases from $(1, 0.8)$ to $(1.2, 0.96)$, RC_1 decreases about 0.01. Furthermore, if the fuel tax rate becomes higher, i.e. $(1.4, 1.12)$, then the truck industry decides to use heavier trucks only to carry light-weight demand. This is because a high fuel tax rate makes owning lighter trucks less attractive. The truck industry is better off by satisfying light-weight demand using only heavier trucks. This increases road damage and decreases the overall RC ratio although equity is no longer an issue because only one class of trucks are used. Figure 3.1 further illustrates how equity ratios change as a function of fuel tax rate. We can see that the equity cannot be achieved without affecting overall RC ratio. What we learn from this experiment is that adjusting a universal fuel tax cannot help achieve equity without affecting overall efficiency because the revenue per pound-mile does not match cost per pound-mile.

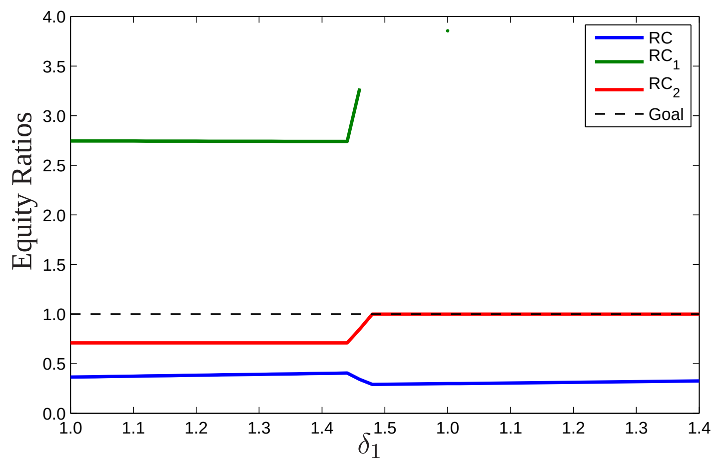


Figure 3.1: Effect of Fuel Taxes

Weight-Distance Taxes

We have shown in the previous section that tax equity may not be achieved without adjusting tax rate for each class independently. In the next experiment, we demonstrate how weight-distance taxes affect equity ratios. Here we assume that δ_1 and δ_2 are weight-distance tax rates. Therefore, now the ratio δ_2/δ_1 may be changed. The results are shown in Table 3.3.

Table 3.3: Revenue-Cost Ratios — Effect of Weight-Distance Taxes

(δ_1, δ_2)	$(y_{1,1}, y_{2,1}, y_{2,2})$	RC	RC_1	RC_2
$(1.0, 0.8)$	$(20000, 0, 40000)$	0.36	2.75	0.71
$(1.0, 2)$	$(20000, 0, 40000)$	0.53	1.87	0.86
$(1.0, 5.25)$	$(20000, 0, 40000)$	1.00	1.00	1.00

We observe that by increasing δ_2/δ_1, RC_is as well as RC approach 1. This is because the new (δ_1, δ_2) can better match costs (κ_1, κ_2), which makes the heavier trucks pay appropriately for the road damage based on their usage. We illustrate the effect of weight-distance taxes in Figure 3.2. We see that as we increase the ratio of δ_2/δ_1, both RC and RC_i move to 1. In addition, if we set $\delta_2/\delta_1 > 5.25$, then the RC ratio can be greater than 1. However, the system again becomes inequitable because class-2 trucks pay more than a fair share in such case. This experiment shows that proper adjusted weight-distance taxes, or other forms of mileage-based taxes that can be differentiated by truck class, can make tax policy more equitable as compared to a universal fuel tax.

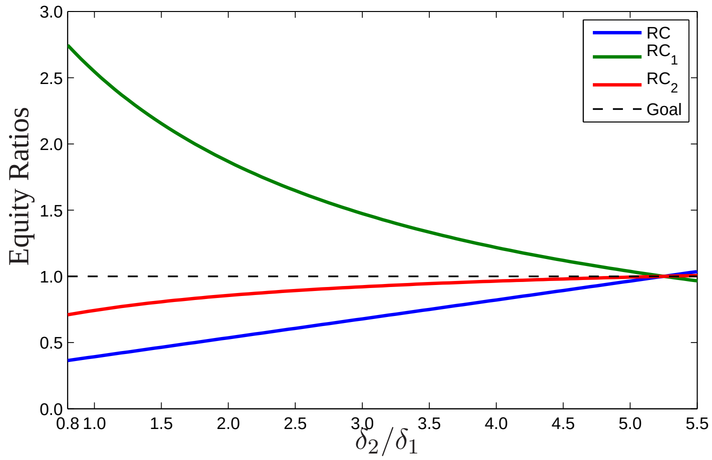


Figure 3.2: Effect of Weight-Distance Taxes

Adjusting Registration Fees

Equity can also be achieved by adjusting registration taxes. In table 3.4, we show that a higher registration tax for heavier truck helps improve overall ratio and equity among truck classes. The effect of registration fees is shown in Figure 3.3 and is similar to Figure 3.2. However, registration tax does not charge road users based on their usage. This creates within-class inequity because amount paid by heavy users and light users within a class are not differentiated.

Table 3.4: Revenue-Cost Ratios — Effect of Registration Fees

(t_1, t_2)	$(y^*_{1,1}, y^*_{2,1}, y^*_{2,2})$	RC	RC_1	RC_2
$(100, 150)$	$(20000, 0, 40000)$	0.36	2.75	0.71
$(100, 200)$	$(20000, 0, 40000)$	0.54	1.84	0.86
$(100, 1040)$	$(20000, 0, 40000)$	1.00	1.00	1.00

Lighter Trucks Cause More Damage: $\kappa_2 \leq \kappa_1$

In this section, we assume that $\kappa_2/\kappa_1 \leq 1$ because the heavier trucks with more axles can cause less damage to the road compared to lighter trucks with fewer axles. The remaining parameter are $X_1 = 20,000$,

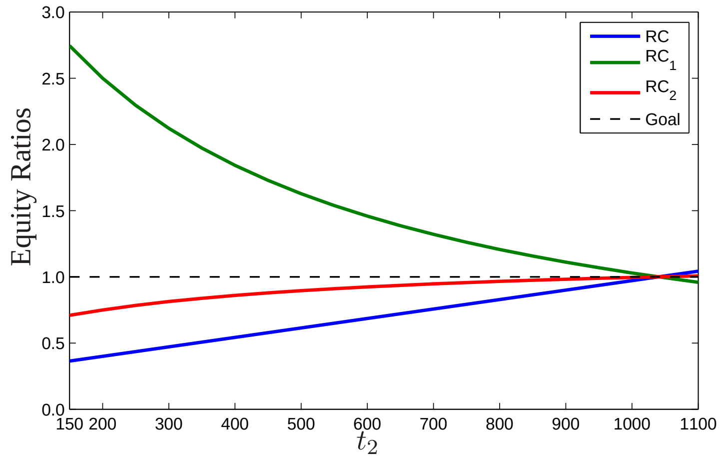


Figure 3.3: Effect of Registration Fees

$X_2 = 40,000$, $\theta_1 = 1$, $\theta_2 = 1.5$, $c_1 = 1$, $c_2 = 1.25$, $r_1 = 5$, $r_2 = 8$, $\kappa_1 = 2$, $\kappa_2 = 1.9$, and $(t_1, t_2) = (100, 150)$.

Adjusting Fuel Taxes

We increase δ_1 in small increments while keeping $\delta_2/\delta_1 = 0.8$. Table 3.5 shows that the equity does not improve by setting $\delta_1 = 1.2$ because a universal fuel tax does not have the ability to match cost share of each truck class. However, when $\delta_1 = 1.4$ or higher, equity is achieved because the truck industry use only the larger truck for all demand. The effect of adjustments is provided in Figure 3.4. This result is similar to Table 3.2 with one difference that higher fuel tax rate helps increase the overall efficiency (RC becomes greater). This is because heavier trucks cause less damage in this setting. Therefore, encouraging truck industry to carry X_1 using class-2 trucks is beneficial.

Table 3.5: Revenue-Cost Ratios — Effect of Fuel Taxes

(δ_1, δ_2)	$(y_{1,1}, y_{2,1}, y_{2,2})$	RC	RC_1	RC_2
$(1.0, 0.8)$	$(20000, 0, 40000)$	0.88	1.14	0.93
$(1.2, 0.96)$	$(20000, 0, 40000)$	0.92	1.14	0.92
$(1.4, 1.12)$	$(0, 20000, 40000)$	0.98	N/A	1

Weight-Distance Taxes

Similar to Table 3.4, Table 3.6 shows that weight-distance taxes help achieve equity. The effect of δ_2/δ_1 ratio is shown in Figure 3.5. In this example, we can reach equity with little adjustment because the difference between κ_1 and κ_2 is less significant.

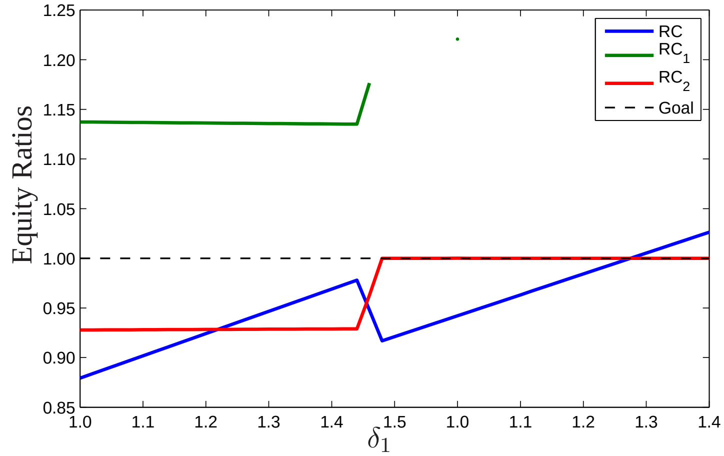


Figure 3.4: Effect of Fuel Taxes

Table 3.6: Revenue-Cost Ratios — Effect of Weight-Distance Taxes

(δ_1, δ_2)	$(y_{1,1}, y_{2,1}, y_{2,2})$	RC	RC_1	RC_2
$(1.0, 0.8)$	$(20000, 0, 40000)$	0.88	1.14	0.93
$(1.0, 1.0)$	$(20000, 0, 40000)$	0.95	1.05	0.97
$(1.0, 1.15)$	$(20000, 0, 40000)$	1.00	1.00	1.00

Adjusting Registration Fees

Table 3.7 and Figure 3.6 show equity can also be achieved by adjusting registration fees. However, as mentioned earlier, this can create within-class inequity because amount paid by heavy users and light users within a class are not differentiated.

Table 3.7: Revenue-Cost Ratios — Effect of Registration Fees

(t_1, t_2)	$(y^*_{1,1}, y^*_{2,1}, y^*_{2,2})$	RC	RC_1	RC_2
$(100, 150)$	$(20000, 0, 40000)$	0.88	1.14	0.93
$(100, 185)$	$(20000, 0, 40000)$	0.94	1.06	0.97
$(100, 220)$	$(20000, 0, 40000)$	1.00	1.00	1.00

3.2.2 General Comments about Results

The examples presented in Section 3.2.1 and 3.2.1 show that adjusting a universal tax rate may help realize equity only if the adjustment can encourage the truck industry to use trucks that cause less damage. Other-

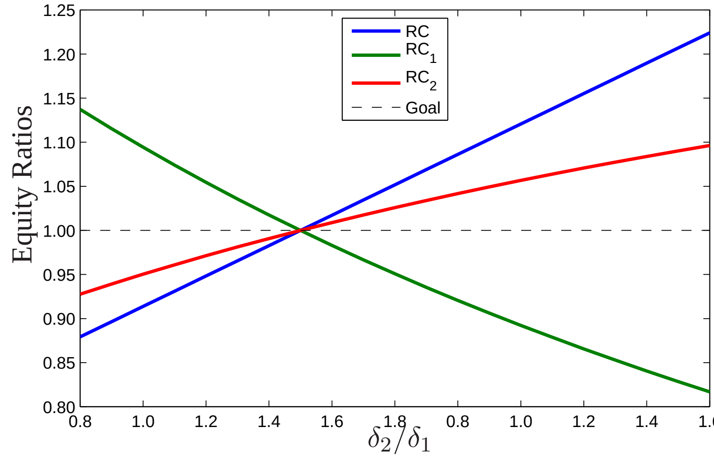


Figure 3.5: Effect of Weight-Distance Taxes

wise, equity can be achieved through a tax policy that can be differentiated by truck classes and their usage. Here we further explain why differentiated tax rates help achieve equity.

From the definition of RC_i shown in (3.4), it follows that equity can be achieved when

$$\frac{[y_1^* \cdot \delta_1 + g_1(y_1^*) \cdot t_1]}{[y_1^* \cdot \kappa_1]} = \frac{[y_2^* \cdot \delta_2 + g_2(y_2^*) \cdot t_2]}{[y_2^* \cdot \kappa_2]}. \tag{3.10}$$

Suppose that in the current system $RC_1 > RC_2$. Then the only reasonable way to achieve equity is to increase (resp. decrease) δ_2 or t_2 (resp. δ_1 or t_1) as we suggested in the previous examples. Note that equity generally cannot be achieved when $\delta_1 : \delta_2 = \kappa_1 : \kappa_2$ because the truck industry is required to pay registration fee for each truck, which is not proportional to their corresponding cost. However, if we completely remove registration fee ($t_1, t_2 = 0$), then $RC_1 = RC_2 = 1$ when $\delta_1 : \delta_2 = \kappa_1 : \kappa_2$.

Inequity Caused by Economical Impacts

Sometimes, equity cannot be achieved without affecting efficiency because the truck industry may reallocate its resources based on the changes made to the tax structure. In the following example, we set $c_1 = 1$, $c_2 = 1.8$, $\kappa_1 = 3$, $r_1 = r_2 = 5$ and keep remaining parameters in Section 2.1.1 unchanged. In Table

Table 3.8: Revenue-Cost Ratios — Effect of Weight-Distance Taxes

(δ_1, δ_2)	$(y_{1,1}, y_{2,1}, y_{2,2})$	RC	RC_1	RC_2
$(1, 1.24)$	$(20000, 0, 40000)$	0.40	1.67	0.83
$(1, 1.25)$	$(20000, 0, 0)$	0.67	1.00	N/A

3.8, we achieve equity when $(\delta_1, \delta_2) = (1, 1.25)$ because heavy trucks are no longer used by the truck industry. However, this is an economically undesirable outcome because demand that can be transported only by

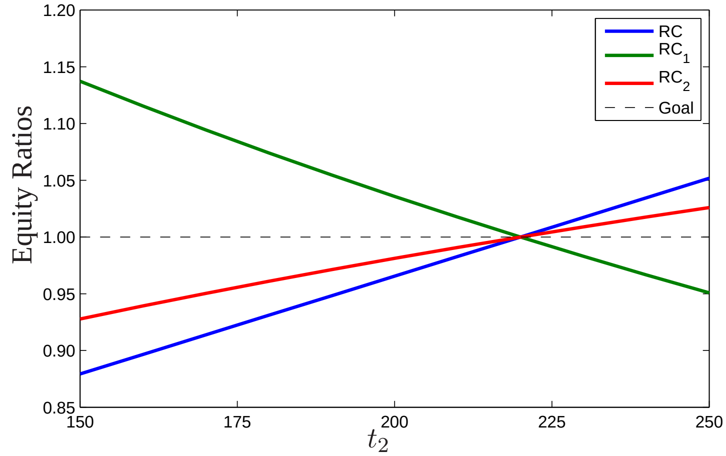


Figure 3.6: Effect of Registration Fees

heavier truck is not satisfied. In this case, the best RC ratios can be obtained by setting $(\delta_1, \delta_2) = (1, 1.24)$, which does not achieve equity. This is an example of the limitation of weight-distance taxes (or any other form of mileage-based taxes), which happens when tax rates cannot be completely adjusted due to low marginal benefit.

Sensitivity Analysis for Equilibrium Solution

One advantage of formulating the problem as a linear program is that there are methodologies and tools available that help predict how equilibrium solution varies if any parameter changes. For example, Table 3.9 shows the range of each parameter so that the equilibrium solution is not affected if we use parameters in Section 2.1.1 as default.

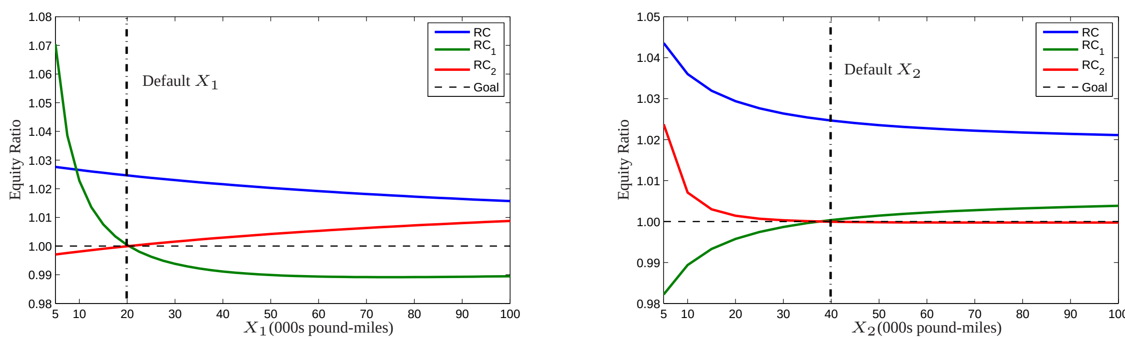
Table 3.9: Sensitivity Analysis

Parameter	Lower Bound	Upper Bound	Equilibrium Solution (Below Lower Bound)	Equilibrium Solution (Above Upper Bound)
t_1	0.00	104.52	N/A	(10005, 9995, 40000)
t_2	140.34	1138.26	(10005, 9995, 40000)	(20000,0, 0)
δ_1	0.00	1.043	N/A	(10005, 9995, 40000)
δ_2	0.76	5.74	(10005, 9995, 40000)	(20000,0, 0)
c_1	0.00	5.43	N/A	(10005, 9995, 40000)
c_2	0.00	989.75	N/A	(20000,0, 0)
r_1	3.02	∞	(0,0,40000)	N/A
r_2	0.06	∞	(20000,0,0)	N/A

In summary, the results show that as the cost for using class-1 trucks increases (or using class-2 trucks decreases), some part of demand X_1 will be carried by class-2 trucks. Similarly, if the cost for using class-2 truck increases, X_2 will no longer be satisfied. Note that if we further increases cost for class-1 trucks, then entire X_1 will be carried by class-2 trucks.

Problems with Random Demand

While we assume that all parameters are known in the model, it is invariable to have some unknown parameters in real world problems. If the demand involves uncertainty, then the model above needs to be solved as a stochastic program and the truck industry's goal will be to find an allocation that maximizes the expected profit. Here, we do not solve this random version of this problem. Instead, we show how demand randomness can affect the equity. In the following example, we set $(\kappa_1, \kappa_2) = (2, 6)$, $g_1(y) = 0.01y + 10$, and $g_2(y) = 0.05y + 10$. If the default demand $(X_1, X_2) = (20000, 40000)$ and keep all other parameters unchanged, then tax equity can be achieved when $(\delta_1, \delta_2) = (1, 5.36)$. Now, we show how changes in demand affect the equity ratio when we keep $(\delta_1, \delta_2) = (1, 5.36)$. In Figure 3.7, we see that the optimal tax rates are no longer equitable when demand changes. The overall RC ratio decreases when demand increases. In addition, if the demand is lower (resp. higher) than the default demand, then the RC_i for the corresponding truck class (trucks that carry class-i demand) is higher (resp. lower) than 1. In other words, if a particular class of trucks carries more demand, then it pays less than a fair share whereas other class of trucks pays more than a fair share.



(a) Changing X_1 (b) Changing X_2

Figure 3.7: The Effect of Demand

Equity with More Than Two Truck Classes

When there are more than two truck classes $(n > 2)$ in the system, equity may still be achieved. However, the difficulty to find the optimal tax rates increases because the truck industry can respond to tax change in a variety of different ways with multiple truck classes to choose from. Next, we use an example to show how this can be done when $n = 4$. Suppose that $D_i = \{20000, 40000, 0, 0\}$, $\kappa_i = \{2, 6, 5, 7\}$, $c_i = \{1.0, 1.8, 1.9, 1.7\}$, $\theta_i = \{1.0, 1.5, 1.6, 1.7\}$, and $t_i = \{100, 150, 170, 170\}$. In addition, we set $g_i(y) = a_i y$, where $y_i = \{0.01, 0.005, 0.007, 0.003\}$. The equity ratios are shown in Table 3.10.

In this example, we see that the equity can be achieved with a more complicated adjustment because the truck industry has more options to adjust allocation. Eventually, we achieve equity by choosing $\delta_i = \{(1.00, 5.05, 3.80, 5.10)\}$. Note that this is a sample solution for this problem. There may be multiple optimal solutions for this particular problem.

Table 3.10: Revenue-Cost Ratios — Effect of Weight Distance Taxes

$(\delta_1, \delta_2, \delta_3, \delta_4)$	RC	RC_1	RC_2	RC_3	RC_4
$(1.00, 5.00, 5.00, 5.00)$	0.81	1.22	N/A	N/A	0.97
$(1.00, 5.00, 5.00, 5.10)$	0.96	1.04	0.99	N/A	N/A
$(1.00, 5.05, 5.00, 5.10)$	0.97	1.03	0.99	N/A	N/A
$(1.00, 5.05, 3.80, 5.10)$	1.00	1.00	N/A	1.00	N/A

Model Extension – Multi-Period Model

Finally, the model introduced earlier in this chapter can be easily extended to multi-period scenario. Suppose that the truck industry is required to make a one-time decision to find the equilibrium solution for the next t periods and let notation with superscript l denote the parameters for period i. The supplier's problem can be formulated as follows:

$$\max_{y_{i,j}} \sum_{l=1}^{t} \sum_{i=1}^{n} \left[r_i^l X_i^l - y_i^l [\theta_i^l + \delta_i^l] - g_i^l(m_i)[c_i^l + t_i^l] \right]. \tag{3.11}$$

Subject to

$$\sum_{i=j}^{n} y_{i,j}^l \leq X_j^l \text{ for each } j = 1, 2, \cdots, N, \text{ and } l = 1, 2, \cdots, t, \tag{3.12}$$

$$\sum_{j=1}^{i} y_{i,j}^l \leq m_i \text{ for each } i, \tag{3.13}$$

$$y_{i,j}^l \geq 0 \text{ for all } (i, j, l). \tag{3.14}$$

Objective function (3.11) maximizes the total profit for the next t period and constraints (3.12) make sure truck load does not excess demand for each period. The main difference between this multi-period model and the previous single-period model is constraint (3.13), where we use m_i to denote the maximum pound-miles can be carried by class-i trucks for each period. Truck industry's decision is to find $y_{i,j}^l$, y_i^l, and m_i that maximize the profit. Again, this model can be solved as a stochastic program when demand X_i^l are random.

3.3 Critique of FHWA's HCAS Tool

In 2002, FHWA State HCAS Tool was created to help states measure the tax equity of their highway finance programs. This tool allows users to input detailed parameters for infrastructure, such as pavement thickness and bridge parameters, and then calculate costs allocated to each vehicle class based on Passenger Car Equivalents (PCE) or Vehicle Miles of Travel (VMT). More details about FHWA State HCAS Tool can be found in Balducci and Stowers (2008); Federal Highway Administration (2000a), and Federal Highway Administration (2000b). Note that the results provided in Chapter 2 were based on this tool. In Chapter 2, we showed that in general the heavy trucks pay less than their cost responsibility.

Data collection is usually the most time-consuming task when performing a HCAS. In each state, data are usually stored in a wide variety of formats and sometimes required data may be missing. For example, some states may not have all required VMT breakdowns. Also, many default parameters may be outdated and lead to inaccurate conclusions. For example, Registered Gross Weight (RGW) breakdowns for each vehicle configurations are based on 2001 representative data. Mapping from VMT for 12-vehicle configurations to 20-vehicle configurations are based on 1997 national VMT data. In addition, Minnesota has its own vehicle configuration standards. As a result, VMTs for the 20-vehicle configurations must be approximated. Therefore, the HCAS results may not have the intended impact on tax policy because doubts are often raised about its accuracy.

Some states develop their own HCA models to simplify the HCA process but still get promising results. For example, the Arizona's Simplified Model for Highway Cost Allocation Studies (Arizona SMHCAS) developed in 1999 allocates costs for urban area based on VMT whereas costs in rural area are based on vehicle axle loads per mile. Carey (2001) shows that the SMHCAS can produce results comparable to the FHWA model without the complexities of data requirements.

Another issue with FHWA State HCAS Tool is the inability to allocate external costs. External costs include environmental impacts, congestion, and crash costs. Those external costs are induced by highway use but are not included in HCAS Tool for the following reasons. External costs do not solely depend on the type of vehicle and the distance traveled. They also depend on the time of travel and the route chosen. Therefore, external cost may be difficult to allocate using a tool that is primarily based on VMT data. However, external costs should not be ignored because they are significant. For example, in 2007 for the Twin Cities area, 58% of VMT during rush hours is congested travel. Due to congestion, 38,534,000 gallons of fuel per year are wasted and 55,287,000 person-hours are delayed (Schrank and Lomax 2009). If those external costs are included in a HCAS, it can be expected that the cost responsibility for private vehicles will be higher than the current estimate.

In addition, equity within a group cannot be examined using FHWA's State HCAS Tool. That is, users who belong to the same group pay the same amount regardless of their actual usage. This may create fairness issues and cause extra tax burden for some road users. For example, suppose a state is able to adjust graduated registration fees to achieve tax equity between vehicle classes, the HCAS Tool is unable to catch the fact that non-mileage-based taxes do not achieve equity within class. For example, residents in rural areas may end up paying as much as residents in urban areas even though rural drivers may drive less and cause less damage, congestion, and pollution than urban drivers.

3.4 Research Directions

In this section, we list four possible directions for this research project that relate to the equity and efficiency of the road-use tax structure. These possibilities were discussed with the TAP members and based on data availability and TAP members' feedback, two of four plans were selected and investigated in the next phase of this project.

3.4.1 Mileage-Based Taxation

As shown in previous sections, mileage-based user charges allocate highway costs more precisely than fuel taxes. Mileage-based charges help achieve equity among different user groups as well as equity among individual road users within each class. Mileage-based user charges can be implemented via either a comprehensive Electronic Road Pricing System (ERPS) or a simpler weight-distance tax system. We introduce these two options and potential implementation issues for each in this section.

Electronic Road Pricing System (ERPS)

ERPS is a new technology that collects differentiated mileage-based taxes based on the particulars of each trip. ERPS requires an on-board computer with Global Positioning System (GPS) on each vehicle to record the details for each trip such as type of vehicle, route of trip, and time of travel. Precise tax rates can be determined based on vehicle weights, number of axles, congestion levels, and the road conditions for chosen routes, for each individual trip. As a result, ERPS makes it easier to achieve equity and can better address congestion problems, as compared to other forms of taxation.

Note that like all other technologies and policies, it may take some time for state governments to switch from fuel taxes to mileage-based taxes. Forkenbrock (2005) identifies four major issues governments may face when implementing this technology: (1) privacy protection, (2) parallel operation with the fuel taxes during the phase-in period, (3) development and operation of an efficient billing center, and (4) cooperation among states. Among those issues, operation during the phase-in period and cooperation among states are more challenging. For example during the phase-in period, because not every vehicle will have ERPS installed, the State will have to keep collecting fuel taxes. This may create a double-payment problem. Users who would have paid mileage-based fees may also pay fuel taxes for some period of time. Similar issues also exist when dealing with payments from out-of-state vehicles, especially for vehicles from states without ERPS. Finding solutions to such issues is not in the scope of the current study.

Weight-Distance Taxes

An alternative is to study the feasibility and impacts of using weight-distance taxes for the State of Minnesota. We will evaluate the impact of switching from fuel taxes to weight-distance taxes while taking congestion-related external cost into consideration. Weight-distance taxes are charged based only on a vehicle's registration weight, distance traveled, and axle configuration. They do not depend on route chosen or time of travel and are applied to commercial vehicles only. Therefore, weight-distance taxes are easier to implement compared to an ERPS. This is one of the reasons that some states have chosen to implement weight-distance taxes. Although weight-distance taxes cannot be tailored to the same extent as an ERPS, it has been shown that weight-distance taxes can still provide promising results in terms of equity.

Among the two options presented above for mileage-based taxation, MnDOT picked the second, i.e., weight-distance taxes. The deliverable will be a customized HCA spread sheet that matches Minnesota's needs and an analysis of potential impacts of weight-distance taxes using this tool.

3.4.2 Special Permits and Willingness-To-Pay

State of Minnesota issues special permits for overloaded or oversized trucks because they can damage or possibly collapse roads and bridges. However, analyzing and issuing special permits can be time-consuming (Chou et al. 1999) and costly. As the number of permit requests increase, it becomes essential for states to design a better pricing mechanism for special permits. Therefore, a potential direction is to evaluate and redesign the pricing mechanism for special permits through either auctions or better estimates of the truck industry's willingness to pay. A carefully designed pricing mechanism can help the State generate higher revenue. We discuss two possible ways of maximizing revenue from special permits: estimating willingness to pay and designing an auction-based permitting system. Note that in this section, we primarily focus on annual/seasonal permits. We do not consider one-time permits because users apply for one-time permits for various purposes. Therefore, the value of each one-time permit is difficult to estimate.

Estimating Willingness-To-Pay

Willingness-To-Pay (WTP) is defined as the maximum amount a customer is willing to pay for a product (Park and MacLachlan, 2008). WTP can be estimated from different sources of information. Because current prices for special permits do not change over time, WTP cannot be estimated from actual market transactions. However, it can be estimated through surveys or experiments (Wertenbroch and Skiera 2002). The process includes two steps: first obtaining responses to carefully constructed surveys from customers (the truck industry), and second, adjusting estimated WTP to account for biases in customer responses.

One methodology for estimating WTP is call contingent valuation, where customers report their willingness to pay for a given product description (in this case, the description for a particular permit). There are two types of contingent valuation methods. Open-ended contingent valuation requires respondents to state their WTP. Closed-ended contingent valuation requires respondents to make purchasing decision for a given price (yes/no questions).

Like many other survey methods, contingent valuations are subject to non-sampling errors. Because some types of surveys provide no incentive for the respondents to reveal their true WTP, the true WTP is likely to be either over- or under-estimated. These issues have been addressed in many papers. For example, Park and MacLachlan (2008) introduced a new method called the exaggeration bias-corrected contingent valuation method (EBC-CVM) to control the tendency to exaggerate over/under report the customer's WTP. Blomquist et al. (2009) designed follow-up questions to calibrate a hypothetical bias. Cooper (1993) constructed a model to select the survey design that minimizes the mean square error of the measure.

Auction-based Permit System (ABPS)

The last proposal is to design and evaluate an auction-based permit system. In an auction-based permit system, each permit is sold at a different price depending on how truck companies value special permits. By carefully controlling the number of permits and setting the reserve price (the minimum acceptable bid), the State may generate a higher profit than from current permit pricing structure. Availability of special permits in this fashion may also benefit the trucking industry because of their ability to weigh costs and benefits of having access to special permits. There are four typical types of auction:

1. First-price sealed-bid auctions — Bidders submit their sealed bids simultaneously. The highest bidder wins and pays a price equal to his bid.

2. Vickrey auctions — Bidders submit their sealed bids simultaneously. The highest bidder wins and pays a price equal to the second highest bid.

3. English auctions — The published price is raised over time until all bidders except for one drop out. The remaining bidder wins the auction and pays the last price.

4. Dutch auctions — The published price is reduced over time until a bidder decides to buy. The winning bidder pays the last price.

Among the two potential directions within the willingness to pay stream, MnDOT picked ABPS. The remainder of this report therefore focuses on

1. developing a customized HCAS for Minnesota and
2. developing an auction based pricing system for sale of special permits for heavy freight trucks.

Chapter 4

Highway Cost Allocation Spreadsheets for Minnesota

4.1 Introduction

In Chapter 2, researchers presented results of a highway cost allocation study for the state of Minnesota. This study used the highway cost allocation tool (HCAT) commissioned by Federal Highway Administration (FHWA). HCAT is not designed for any particular state. Different states need to either modify or massage inputs (e.g. revenues, expenses, and tax structures) to fit their data to HCAT's required formats. This was also the case for state of Minnesota. In particular, data available in the state of Minnesota could not be input directly into HCAT, which resulted in the need to estimate certain parameters, increased difficulty of use, and doubts about the accuracy of the results. Researchers also found that some functions in HCAT did not work properly upon using Minnesota's tax structure. Specifically, certain tax revenues such as registration fees and weight fees were attributed to all vehicle classes even if they were specified to be attributed only to a subset of vehicle classes. Similarly, administrative costs associated with the collection of registration and weight fees were not allocated correctly in HCAT.

For the reasons mentioned above, this chapter presents a Minnesota-centric highway cost allocation tool. We call this tool Minnesota Highway Cost Allocation Tool (MHCAT). MHCAT is a modified version of HCAT that is customized to be consistent with Minnesota's tax structure and data formats. All allocation methods in MHCAT are adapted from HCAT, and many Excel macros used in the new tool are modified versions of those included HCAT. Key differences between MHCAT and HCAT are summarized in Table 5.6 below.

Table 4.1: MHCAT and HCA – A Comparison

Features	MHCAT	HCAT
Vehicle Classification	HPMS 12-class	HCA 20-class
Data Formats	Minnesota-based	Universal Design
Ability to Expand	Up to 8 customized classes	No
Complexity	One file with one step	Multiple files with multiple steps

The first main difference between MHCAT and HCAT is vehicle classification. In HCAT, all calculations are based on Highway Cost Allocation (HCA) 20-class vehicle configuration. Although the user may alternatively enter data based on Highway Performance Monitoring System (HPMS) 12-class system, all calculations in HCAT are based on HCA 20-class vehicle configuration. This is achieved by mapping HPMS classification into HCA classification. Because most data in Minnesota is based on HPMS 12-class configuration, we designed MHCAT and all calculations such that they are based on the HPMS vehicle configuration. This eliminates unnecessary data manipulation and increases accuracy.

In MHCAT, the user also has the option to add up to 8 customized vehicle classes for research purposes. This function is useful when considering changes to tax rules and cost allocation for any particular vehicle configuration. In Section 4.3 of this chapter, we include an example that introduces a hypothetical vehicle class to illustrate this functionality. MHCAT's input requirements match Minnesota data and the new software is also more user-friendly.

The rest of this chapter is organized as follows. In Section 4.2, we present data requirements and how data is used in MHCAT. In section 4.3, we compare the results between HCAT and MHCAT, and analyze the effect of weight-mileage fees on tax equity. Appendix A.1 contains a quick summary of inputs used in MHCAT and Appendix A.2 describes procedures for calculating axle weight distributions from Weight-In-Motion (WIM) data. The revenue attribution and expenditure allocation algorithms used in MHCAT are presented in Appendices A.3 and A.4.

4.2 Inputs/Outputs for MHCAT Spreadsheets

In this section, we present data requirements for carrying out a highway cost allocation study using MHCAT. Before we start, we first list Minnesota's vehicle classes (Table 4.2). The table also shows vehicle miles travelled (VMT) in millions of miles, which is an annual average obtained by averaging annual VMT data for 2003-2007.

Table 4.2: Minnesota's Vehicle Classes

HPMS Class	**FHWA** Class	**Description**	**VMT** (10^6)
AUTO	2	Automobiles	35620
LT4	3	Light trucks with 2 axles and 4 tires	17277
SU2	5	Single unit, 2-axle 6 tires trucks	1278
SU3	6	Single unit, 3-axle trucks	397
SU4	7	Single unit, 4-or-more-axle trucks	120
CB34	8	Tractor-semitrailer / truck-trailer combinations with 3 or 4 axles	215
CB5	9	Tractor-semitrailer / truck-trailer combinations with 5 axles	1888
CB6	10	Tractor-semitrailer / truck-trailer combinations with 6 or more axles	382
DS5	11	Tractor-double semitrailer combinations with 5 axles	33
DS6	12	Tractor-double semitrailer combinations with 6 axles	7
DS7+	13	Tractor-double semitrailer combinations with 7 or more axles	10
BUS	4	Buses (all types)	155

Note that HPMS classification is identical to FHWA's 13-vehicle classes. However, class 1 (motorcycle) in FHWA classification is not included in HPMS. In addition to the 12 classes mentioned in Table 4.2, the user has the option to add up to 8 more classes for research purpose. The reason for choosing Highway Performance Monitoring System's (HPMS) 12-vehicle classes is that most traffic related data, such as vehicle miles travelled (VMT) and weight-in-motion (WIM), in Minnesota are based on FHWA's 13-vehicle classification. In MHCAT, several data inputs are required to be disaggregated based on highway functional classes. We list the highway functional classification in Table 4.3.

Table 4.3: Highway Functional Classes

Abbreviation	Description
Rur Int	Rural - Interstate
Rur OPA	Rural - Other Principal Arterials
Rur MA	Rural - Minor Arterials
Rur MajC	Rural - Major Collectors
Rur MnC	Rural - Minor Collectors
Rur Loc	Rural - Local
Urb Int	Urban - Interstate
Urb OFE	Urban - Other Freeways and Expressways
Urb OPA	Urban - Other Principal Arterials
Urb MA	Urban - Minor Arterials
Urb Coll	Urban - Collectors
Urb Loc	Urban - Local

Similar to HCAT, allocations in MHCAT rely on revenue data, expenditure data, pavement parameters, bridge parameters, and vehicles' features and their travel related data. All required inputs are located in nine different tabs in the MHCAT workbook (see Table 4.4). Details for each input tab are described in separate sections below. A list of cell ranges in which each type of data must be provided in each worksheet can be found in Appendix A. Note that the name of each section is also the name of the worksheet tab in MHCAT workbook.

Table 4.4: Input Tabs in MHCAT Workbook

Input Tab Name	Short Description	Section
INPUT-VMT	Highway length and VMT	Section 4.2.1
INPUT-RGW	Registered weight distribution	Section 4.2.2
INPUT-INPUT-MPG, Distance and Fuel	Vehicle-related information	Section 4.2.3
INPUT-OGW-AXLE DISTRIBUTION	Operating (total or axle) weight distribution	Section 4.2.4
INPUT-TAX	Revenues and tax rates	Section 4.2.5
INPUT-Expenditures	Expenditures by government level	Section 4.2.6
INPUT-Allocation Factor	Expenditure allocation rules	Section 4.2.7
INPUT-BridgeData	Bridge inventory information	Section 4.2.8
INPUT-MomentDist	Vehicle's moment load distribution	Section 4.2.9

4.2.1 INPUT-VMT

In this tab, the user needs to specify the total system miles for each highway functional class and the vehicle miles travelled (VMT) for each highway functional class and each vehicle class.

Total System Miles

The total system miles for each highway functional class is entered in cells **B5:M5**. This information can be found in Highway Statistics. The default total system miles information included in MHCAT is the average of reported values in Highway Statistics from 2004 to 2007.

Vehicle Miles Travelled (VMT) [Two input options are available]

In terms of VMT for each highway functional class and each vehicle class, the user has two options: (1) estimate VMT based on VMT per day and the number of vehicles for each highway functional class and each vehicle class, and (2) supply VMT for each highway functional class and each vehicle class directly. The two options can be chosen by users by entering either "1" (for option 1) or "2" (for option 2) in cell **B2**.

If option 1 is selected, then the average VMT per day for each highway functional class must be entered in cells **B6:M6** and the number of vehicle for each functional class and vehicle class must be entered in cells **B14:M34**. If option 2 is selected, the VMT for each functional class and vehicle class must be entered directly in cells **B38:M57**. The default VMT numbers included in MHCAT were prepared by Thomas Nelson of MnDOT and represent an average of calendar years 2004–2007.

4.2.2 INPUT-RGW

In this tab, the user is required to input the registered gross weight distribution for each vehicle class based on 2000-lb increments going from 8,000 lbs to 152,000 lbs in cells **C3:V75**. Note that the sum of each column needs to be one. The default values included in MHCAT were obtained from Vehicle Inventory and Use Survey of 2002 (VIUS 2002). These data were collected and reported by the U.S. Census Bureau.

4.2.3 INPUT-MPG, Distance and Fuel

This section concerns relevant information for each vehicle class, including miles per gallon, annual distance per vehicle, fuel type, and the average value of vehicles in each class. We discuss each one of these inputs one by one.

Gasoline and Diesel MPG Information [Two input options are available]

Miles per gallon (MPG) for gasoline and diesel vehicles by vehicle class and registered gross weight can be entered in cells **E8:BY27** (gasoline) and **E33:BY52** (diesel). The user also has the option to enter the average MPG for each vehicle class directly in cells **C8:C27**(gasoline) and **C33:C52**(diesel). Note that the default data is calculated from VIUS 2002. The average MPG information is expected to change gradually over time because newer vehicles tend to be more fuel efficient. Therefore, frequent updates of MPG information may not be necessary.

Fuel Distribution

For each vehicle class, the user needs to specify the percentage of vehicles that use gasoline as their primary fuel type. The data is required to be entered in cells **C54:C73**. Once entered, the percentage of vehicles that use diesel as primary fuel type will be calculated automatically. Note that such information can be extracted from the Vehicle Inventory and Use Survey and the default values are based on VIUS 2002.

Average Annual Distance

For each vehicle class, the user needs to enter the average annual travel distance per vehicle. The data is required to be entered in cells **F54:F73**. Average annual distance per vehicle can be obtained either from Highway Statistics (Table VM-1) or from VIUS. The default data included with MHCAT is based on VIUS 2002.

Values of Vehicle Power Unit and Trailers

For each vehicle class, the average value for vehicle power units is assumed to be linear in vehicle's registered gross weight (RGW) and is calculated based on

$$Price = A + B \cdot (RGW). \tag{4.1}$$

The user needs to enter the values of coefficients A and B for each vehicle class in cells **C87:D106**. Also, the average value of a trailer for each vehicle class needs to be entered in cells **F87:F106**. The default values provided with the MHCAT are based on 2002 national averages provided in HCAT.

Number of Vehicles [Three input options are available]

The user needs to provide the number of vehicles for each vehicle class. There are three input options which can be entered in cell **Q59**, and option 2 is the default option. When option 1 is selected, the user can provide the number of vehicles for each vehicle class directly in cells **L58:L77**. When option 2 is selected, the number of vehicles for each class is estimated based on VMT and annual distance per vehicle. When option 3 is selected, the estimated number of vehicles in option 2 will be re-adjusted based on the number of vehicles reported to Highway Statistics. Note that when option 3 is selected, the user needs to enter the number of vehicles in the following categories: passenger cars, trucks, and buses, in cells **Q61:Q63**. These statistics can be found in Highway Statistics (Table VM-1).

4.2.4 INPUT-OGW-AXLE DISTRIBUTION

In this tab, the user needs to enter the operating gross weight distribution for each vehicle class in cells **B4:U34**. In addition, the axle distribution is also needed for each non-zero entry in **B4:U34**. The default values are calculated based on WIM from 2006. Because the program reads axle distribution line by line, the data for axle weight distribution needs to follow a specific format. We use an example below to explain this format.

Table 4.5: Example of Axle Weight Distribution Data Format

1	Auto	1	2
		3	6
1	1	0.4	0.2
1	2	1.4	0.8
1	3	0.2	0.6
1	4	0	0.4

Table 4.5 shows the axle weight distribution for passenger vehicles identified by the acronym Auto. The first two rows are header information. In the first row, the first and the second cells contain information about the vehicle classification (e.g.,[1, AUTO], [3, SU2], $\cdots$ [12, BUS]). The third and fourth cells are the indices of the first and the last non-zero entry in OGW distribution. In this example, [1 2] means that the first non-zero entry for AUTO is 1 and the last non-zero entry is 2. In the second row, the third and fourth cells include OGW for each non-zero entry, expressed in units of thousands of pounds. In Table 4.5, the numbers 3 and 4 in the third and fourth cells of the second row mean that the two non-zero entries for axle weight distribution are 3,000 lbs and 6,000 lbs, respectively.

Starting from the third row, the first cell is the axle type for an axle set and the second cell is the axle weight for an axle set. The third and fourth cells are the weight distributions for OGW categories identified in rows 1 and 2 (i.e. all weight categories with non-zero entries). In this example, because the passenger cars either have OGW up to 3,000 lbs or between 3,000 and 6,000 lbs, the table has two distribution columns: one for 3,000 lbs and one for 6,000 lbs.

We next show how axle weight distributions are calculated from OGW data. In Table 4.6, suppose that for passenger vehicles with OGW = 3,000 lbs, 40% of vehicles' first axle is a single axle with weight 1,000 lbs and 60% of vehicles' first axle is a single axle with weight 2,000 lbs. In addition, 80% of vehicles' second axle is a single axle with weight 2,000 lbs and 20% of vehicles' second axle is a single axle with weight 3,000 lbs. Then, the inputs for axle weight distribution can be calculated by aggregating numbers in each row. In Table 4.6, we show how to obtain the input values for passenger cars with OGW = 3,000 lbs shown in Table 4.5 (i.e. calculations shown below illustrate how to obtain the third column of Table 4.5). A

Table 4.6: Example of Axle Weight Distribution for AUTO with OGW equal to 3,000 lbs

Type	Axle Weight	Axle Set 1	Axle Set 2	Inputs for Axle Weight Distribution
1	1	0.4	0	0.4
1	2	0.6	0.8	$0.6 + 0.8 = 1.4$
1	3	0	0.2	0.2
1	4	0	0	0

similar set of calculations are performed for passenger cars with OGW = 6,000 to obtain the fourth column of Table 4.5. These calculations are not shown here. However, we provide a roadmap that can be used in the future to update OGW axle weight distribution from weight-in-motion data in Appendix B.

4.2.5 INPUT-TAX

This tab requires the user to enter all revenue information and corresponding tax rates. For the federal revenue, required information includes fuel taxes, heavy vehicle use tax, vehicle sales taxes, and tire taxes. For the state revenue, required information includes fuel taxes, weight fees (this applies to trucks only), registration fees (passenger vehicle and light trucks), vehicle sales taxes (including title fees), and permit fees. The default values in this section are provided by MnDOT's Lynn Poirier based on the annual averages between 07/01/2003 and 06/30/2007 (Tables 4.7 and 4.8). Note that input cells for weight-mileage tax information are also included for research purposes. The use of weight-mileage fee data is explained in Section 3.1.

Table 4.7: Minnesota State Revenues

(in thousands)	2004	2005	2006	2007	Average
Gasoline Tax	508,465	618,151	517,458	513,965	514,510
Diesel Tax	135,161	137,736	137,552	136,624	136,768
Registration Fees	404,452	399,873	383,200	382,547	392,518
Weight Fees	101,113	99,968	95,800	95,637	98,129
Sales Tax	184,087	165,235	165,060	153,750	167,033
Permit Fee	2,601	2,854	3,216	3,438	3,027
Total	1,335,879	1,323,817	1,302,286	1,285,961	1,311,986

Table 4.8: Federal Revenues Attributed to Minnesota

(in thousands)	2004	2005	2006	2007	Average
Gasoline Tax	360,754	371,111	383,805	390,315	376,496
Diesel Tax	132,715	140,060	137,654	151,909	140,584
Heavy Vehicle Use Tax	17,206	19,490	23,882	17,537	19,528
Vehicle Sales Tax	33,637	53,517	61,579	64,742	53,368
Tire Tax	8,121	8,353	8,307	7,834	8,153
Total	552,433	592,531	615,227	632,337	598,129

4.2.6 INPUT-Expenditures

Expenditures related inputs are provided in six parts: state level construction and maintenance (**B10:M36**), state level administration (**B48:M74**), state-aid construction and maintenance (**B84:M110**), state-aid administration (**B112:M148**), federal-aid construction and maintenance (**S10:AD36**), and federal-aid administration (**S48:AD74**). For each part, the user needs to provide expenditure disaggregated by highway functional class for each item listed below:

New Flexible Pavement Costs of asphalt pavement widening or pavements on new locations, not replacing worn out existing pavements.

New Rigid Pavement Costs of concrete or composite pavement widening or pavements on new locations, not replacing worn out existing pavements.

Flexible Pavement Repair Costs of repairing or replacing asphalt pavements, regardless of the type of pavement overlays or replacements for formerly-asphalt pavements.

Rigid Pavement Repair Costs of repairing or replacing concrete or composite pavements, regardless of the type of pavement overlays or replacements for formerly-concrete pavements.

New Bridge Costs of new bridges, not replacing old bridges.

Replacement Bridge Costs of bridges that replace structurally or functionally obsolete bridges.

Bridge Repair Costs of deck replacement, girder upgrading, and any other bridge repair.

Special Bridge Costs of any other bridge programs.

Grading and Drainage Culverts and box culverts, ditch excavation, roadway grade preparation, and other such items. (This should not include removal of old pavement and incidental grading associated with pavement repair.)

General Construction (Residual) Miscellaneous costs that do not differentially derive from highway usage by any particular class of vehicles. For example, roadway signs.

Transit and Rail Amounts spent from highway funds on mass transit.

Truck VMT Construction Weight stations, escape ramps, and any other costs identified in the highway program that apply only to trucks.

Travel-Related Maintenance Items such as bridge painting and sign replacement.

Wear-Related Flexible Pavement Maintenance Most flexible pavement maintenance related to vehicle usage.

Wear-Related rigid Pavement Maintenance Most rigid pavement maintenance related to vehicle usage.

Axle-Related Maintenance Pavement markings.

Truck-Mile Maintenance Weight station maintenance and other maintenance cost accounting system identified as exclusively truck responsibilities.

Light-Vehicle Maintenance Maintenance activities on facilities used only by light vehicles.

Rest Area Maintenance Costs related to rest areas.

In addition, expenditures that cannot be disaggregated by highway functional class are listed below:

Multi-System Travel-Related Any general construction, maintenance, operations, or administrative costs that cannot be categorized by highway functional class.

State Police Traffic Management The portion of state police costs that come from highway funds or that represent traffic management and operation costs.

Truck Related Any truck related costs that cannot break down by highway functional class.

Large Truck Related Any large truck related costs that cannot break down by highway functional class.

Fuel Consumption costs of collecting user fees on fuel (This cost is assumed to be zero by many states).

Vehicle Registration costs of administering vehicle registrations.

The default values included in MHCAT were provided by MnDOT's Lynn Poirier based on the annual averages between 07/01/2003 and 06/30/2007. For sake of brevity, we show only the total expenditures in Table 4.9. The MHCAT contains default values for each input.

Table 4.9: State and Federal Expenditures

(in thousands)	2004	2005	2006	2007	Average
State Revenue	956,719	1,046,181	1,061,811	1,054,140	1,029,713
Federal-Aid Revenue	358,170	392,630	397,393	383,306	382,875

4.2.7 INPUT-Allocation Factor

In this tab, the user needs to specify how each non-load-related expenditure is allocated. Default inputs in this tab are based on HCAT. We explain each next.

Grading

In cell **B3:M6**, the user can specify the percentage of grading costs responsibility for vehicles with different weights. We explain the calculations with the help of an example below. In this example (see Table 4.10),

Table 4.10: Example of Grading Shares

OGW Lower Bound (1,000 lbs)	Shares
0	0.875
25	0.035
55	0.035
70	0.055

all vehicle are responsible for 87.5% of the total grading cost. Vehicles above 25,000 lbs are responsible for an additional 3.5% of the total cost. Vehicles above 55,000 lbs (resp. 70,000 lbs) are assigned responsibility for an additional 3.5% (resp. 5.5%) of grading costs.

Residual Allocators

In cells **B9:M13**, the user specifies how costs are allocated for each category. The user can enter either "VMT", or "PCE", or a fraction between 0 and 1. When "VMT" is entered, it means that the cost is allocated based on VMT. When "PCE" is entered, it means that the cost is allocated based on PCE weighted VMT (PCE-VMT). PCE-VMT means that VMT is multiplied by its corresponding PCE value. When a fraction between 0 and 1 is entered, it means that the allocation is based on a weighted average between VMT and PCE-VMT. For example, an input "0.3" means that 30% of the cost is allocated based on VMT and 70% is allocated based on PCE-VMT.

Other Costs That are Distributed based on Highway Functional Class

In cells **B24:M27**, the user can enter either "VMT", or "PCE", or a fraction between 0 and 1 as explained in the previous section. In cells **M30:M30**, the user can enter either "'Axles", or 'Tires", or "Weight". When "Axles" is entered, the cost is allocated based on axle weight. When "Tires" is entered, the cost is allocated based on axle weight and the number of tires. When "Weight" is entered, the cost is allocated based on total vehicle weight. In cells **B31:M32**, the user can enter either "VMT", or "PCE", or a fraction between 0 and 1. However, "VMT" is recommended because these are travel-related costs.

Note that in cells **P24:AI33**, the user can exclude any vehicle class from the cost allocation for each expenditure type by setting the corresponding cell to zero. However, this is recommended only for advanced users.

Systemwide Costs and Department of Motor Vehicles (DMV) Administration Costs

For other travel-related cost, the user can specify the percentage of costs to be allocated based on PCE-VMT and VMT (cells **B37:B38**). For state police traffic management, the user can specify the percentage of costs to be allocated based on PCE-VM, VMT, and fatality involvement. For DMV administration costs, the user can specify the percentage of costs to be allocated based on VMT, taxes collected, and number of vehicles.

Note that in cells **C38:N47**, the user can exclude data for any functional class by setting the corresponding cell to zero. Similarly, in cells Q38:AJ47, any vehicle class can be excluded by entering zero. However, it is recommended that such changes be made only by advanced users.

4.2.8 INPUT-BridgeData

In this tab, the user is required to enter several bridge parameters for the state of Minnesota. We explain each entry in what follows. Note that the default values in MHCAT are imported from HCAT. However, these values can be changed to better reflect reality with state engineer's input.

Allocation of New Bridge Costs to Increments

The user enters allocation of new bridge costs to bridge increments for each bridge type in cells **B14:G20**. Each column in the array must sum to 100%. The default allocation provided with MHCAT is imported from HCAT. This allocation was based on an analysis of the increase in costs that occur when live loads used in bridge design are increased.

New and Replacement Bridges by Type of Bridge

The user enters the distribution of new and replacement bridge types for each highway functional class in cells **B26:M31**. These information can be updated using Minnesota's bridge inventory dataset if available.

Cost Responsibility for Bridge Replacement Decisions

In cells **B39:M40**, the user enters the percentage of bridge replacements due to structural deficiencies in existing bridges for each highway functional class.

Inventory Ratings of Structurally Deficient Bridges

In cells **B46:M52**, the user enters the percentages of structurally deficient bridges falling into each of the seven inventory rating ranges for each highway functional class.

Cost Responsibility for Bridge Repair Expenditures (percent)

In cells **B58:M59**, the user can specify the percentage of bridge repair costs that are load-related for each highway functional class.

Cost Responsibility for Special Bridge Expenditures (percent)

In cells **B65:M66**, the user can specify the percentage of special bridge program costs that are load-related for each highway functional class.

4.2.9 INPUT-MomentDist

In this tab, the user enters the fraction of vehicles falling into each bridge design increment, as a function of vehicle configuration and operating weight in cells **B5:P1000**. This information is provided for short and long span bridges. Vehicles are assigned to bridge increments based on a comparison of their live load moments and the live load moments used in bridge design. The default values provided in MHCAT are imported from HCAT. They can be calculated based on an analysis of axle weight distributions and spacings from weight-in-motion data. In calculating live load moments, a span length of 40 feet was assumed for short-span bridges and 110 feet for long-span bridges.

4.2.10 OUTPUT

In the output tab, the user can click the button "RUN" to an instance of the cost allocation problem. The results including state equity ratios and total (state and federal) equity ratios are displayed in the same tab. The cost allocations in MHCAT are based on methodologies provided in the FHWA's HCAT. Details of these calculation methods are provided in Appendices C and D.

4.3 Results of Highway Cost Allocation Study

In this section, we present results of Minnesota highway cost allocation based on MHCAT. The revenue expenditure allocations among different vehicle classes are presented in Table 4.11. We observe that most revenues and expenditures come from passenger vehicles and light trucks. In addition, among all trucks (except for light trucks), CB5 has the highest allocated revenues and expenditures.

These results are driven largely by weight distribution and VMT of each vehicle class. Similar to results shown in Chapter 2, the allocated expenditures may not match the attributed revenues for some vehicle classes. For example, AUTO generates 47.49% of total revenues and is responsible for 40.25% of total expenditures. In contrast, CB5 is responsible for 17.48% of total expenditures but contributes 12.17% of total revenue. To better explain these results, we next present equity ratios for each vehicle class.

Two type of equity ratios are included in a typical highway cost allocation study — revenue-to-expenditure ratio and adjusted revenue-to-expenditure ratio. Revenue-to-expenditure ratio is defined as follows.

$$\text{R-C ratio (for a particular vehicle class)} = \frac{\text{revenue from a particular vehicle class}}{\text{cost allocated to a particular vehicle class}}.$$

When revenues match expenditures, the ideal revenue-to-expenditure ratio is 1. That is, the revenue collected should equal the cost responsibility. If the ratio is greater than 1 for a particular vehicle class, then it means that the vehicle class pays more than its cost responsibility. Similarly, if the ratio is less than 1, then the vehicle class pays too little. However, expenditures in a particular period may not equal the cost of damage to roadways. Therefore, adjusted revenue-to-expenditure is also calculated. This ratio is defined as follows

$$\text{Adjusted R-C ratio} = \frac{\text{revenue from a particular vehicle class / total revenue}}{\text{cost allocated to a particular vehicle class / total cost}}.$$

If the adjusted ratio is greater than 1, then it means that the vehicle class pays more than a fair share as compared to other vehicle classes. Similarly, if the adjusted ratio is less than 1, then the vehicle class pays less than a fair share. In highway cost allocation study, we focus more on adjusted ratios because they can be compared across states and across time for the same state.

In Table 4.12, we compare equity ratios obtained from HCAT and MHCAT. The differences between the adjusted ratios and the traget ratios (one) are provided in Figure 4.1. Although the results obtained from MHCAT are not significantly different from those obtained from HCAT, we see that the equity ratios are generally less extreme with the new Minnesota-centric tool. As before, AUTO, LT4, SU2, and SU3 generate

Table 4.11: Revenue Attributions and Expenditure Allocations Using MHCAT (in thousands)

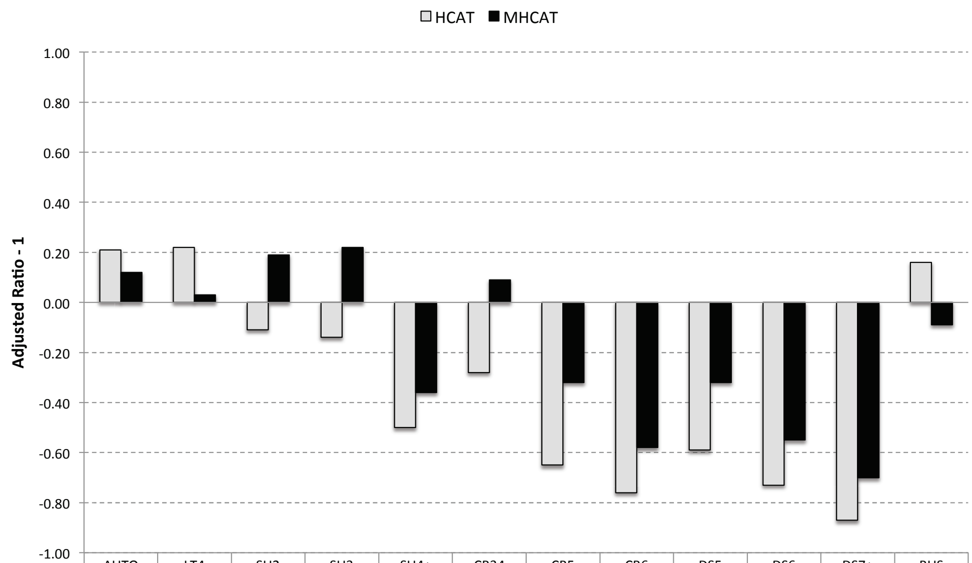
	State Only		Federal and State	
Class	**Revenues**	**Expenditures**	**Revenues**	**Expenditures**
AUTO	690,773 (52.65%)	483,514 (46.96%)	928,543 (47.49%)	56,8620 (40.25%)
LT4	358,814 (27.35%)	272,875 (26.50%)	506,903 (25.92%)	346,693 (24.54%)
SU2	53,535 (4.08%)	35,390 (3.44%)	104,585 (5.35%)	52,647 (3.73%)
SU3	29,817 (2.27%)	19123 (1.86%)	51,974 (2.66%)	31,630 (2.24%)
SU4+	7,783 (0.59%)	9,489 (0.92%)	15,211 (0.78%)	17,449 (1.24%)
CB34	18,144 (1.38%)	13,117 (1.27%)	35,209 (1.80%)	23,413 (1.66%)
CB5	114,467 (8.72%)	132,661 (12.88%)	237,978 (12.17%)	246,915 (17.48%)
CB6	28,227 (2.15%)	52,550 (5.10%)	56,348 (2.88%)	106,846 (7.56%)
DS5	1,770 (0.13%)	2,048 (0.20%)	3,868 (0.20%)	3,567 (0.25%)
DS6	439 (0.03%)	763 (0.07%)	939 (0.05%)	1,225 (0.09%)
DS7+	643 (0.05%)	1,668 (0.16%)	1,342 (0.07%)	2,991 (0.21%)
BUS	7,573 (0.58%)	6,515 (0.63%)	12431 (0.64%)	10,593 (0.75%)
Total	1,311,986 (100.00%)	1,029,713 (100.00%)	1,955,330 (100.00%)	1,412,588 (100.00%)

Table 4.12: Equity Ratios Obtained from MHCAT and HCAT

	Adjusted Ratios (State Only)		Adjusted Ratios (Federal and State)	
Class	**HCAT**	**MHCAT**	**HCAT**	**MHCAT**
AUTO	1.21	1.12	1.35	1.18
LT4	1.22	1.03	1.20	1.06
SU2	0.89	1.19	1.10	1.44
SU3	0.86	1.22	1.02	1.19
SU4+	0.50	0.64	0.51	0.63
CB34	0.72	1.09	0.87	1.09
CB5	0.35	0.68	0.36	0.70
CB6+	0.24	0.42	0.36	0.38
DS5	0.41	0.68	0.52	0.78
DS6	0.27	0.45	0.51	0.55
DS7	0.13	0.30	0.51	0.32
BUS	1.16	0.91	0.97	0.85

more revenues compared to their cost responsibilities. There are some significant differences as well. Note that CB34 and CB5 have greater ratios in MHCAT relative to HCAT. CB34 now pays more than its fair share, but CB5 still pays too little. In addition, the state only adjusted ratios for SU2, SU3, SU4, and CB34 are greater than one when using MHCAT but are less than one with HCAT. These differences are caused primarily by the fact that RGW, OGW, and axel distributions used in MHCAT are based on Minnesota's data instead of national averages in HCAT. We believe these calculations are therefore more accurate. The results are also different because we used more precise calculations of fuel consumption and annual distance per vehicle in MHCAT.

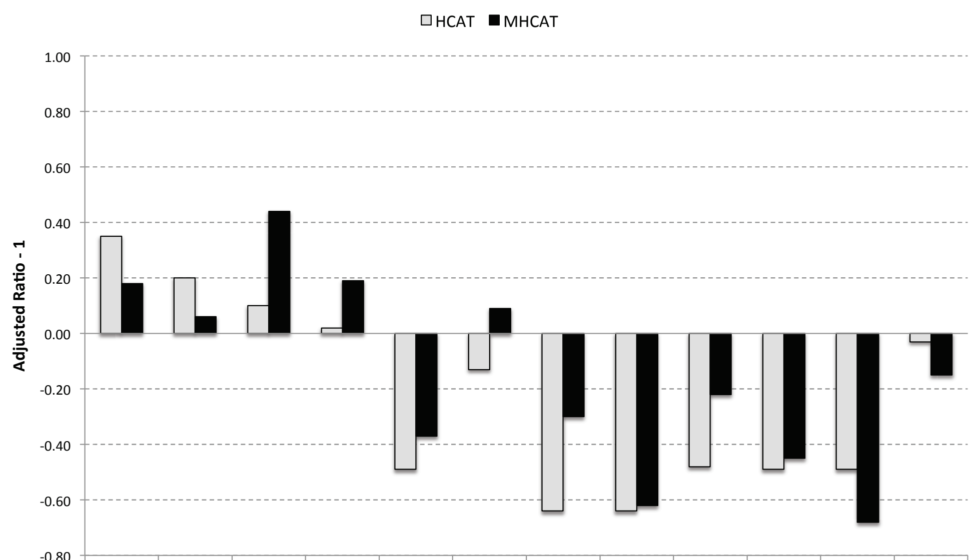
One reason why equity is not achieved for some vehicle classes is that taxes such as registration fees,



	AUTO	LT4	SU2	SU3	SU4+	CB34	CB5	CB6	DS5	DS6	DS7+	BUS
HCAT	0.21	0.22	-0.11	-0.14	-0.50	-0.28	-0.65	-0.76	-0.59	-0.73	-0.87	0.16
MHCAT	0.12	0.03	0.19	0.22	-0.36	0.09	-0.32	-0.58	-0.32	-0.55	-0.70	-0.09

Vehicle Class

(a) State Ratios



	AUTO	LT4	SU2	SU3	SU4+	CB34	CB5	CB6	DS5	DS6	DS7+	BUS
HCAT	0.35	0.20	0.10	0.02	-0.49	-0.13	-0.64	-0.64	-0.48	-0.49	-0.49	-0.03
MHCAT	0.18	0.06	0.44	0.19	-0.37	0.09	-0.30	-0.62	-0.22	-0.45	-0.68	-0.15

Vehicle Class

(b) Federal and State Ratios

Figure 4.1: (Adjusted Ratios - Target Ratios) for HCAT and MHCAT

weight fees, and sales taxes are not collected based on actual usage. However, expenditure allocations are affected a great deal by VMT of each vehicle class. Although fuel taxes and VMT are correlated, their effect on equity ratios is limited because a vehicle causing twice the damage may consume less than twice the amount of fuel (MPG does not change proportional to damage allocation). In addition, fuel tax rates are identical for all vehicle classes. Therefore, in order to achieve tax equity, adopting a tax structure that is based on actual usage, such as weight-mileage fee may be more equitable. We reached a similar conclusion in Chapter 2 as well. In Chapter 3, a stylized mathematical model was presented to demonstrate the effect of different tax structures.

4.3.1 The Effect of Weight-Mileage Fee

In this section, we investigate the effect of weight-mileage fee using MHCAT. When weight-mileage fee is included, the road user pays the usage fee based on his/her miles of travel and the tax rate per mile is determined by the registered gross weight of the vehicle. To demonstrate how weight-mileage fee affects equity ratios, we include two scenarios in this section. In the first scenario, we assume that the total revenues from trucks remain unchanged. Put differently, we assume that the state collects $98 million through weight-mileage fee. In the second scenario, we assume that the state collects $160 million through weight-mileage fee, which is approximately the load-related expenditures (pavement and bridge) allocated to trucks.

For each vehicle class, we first estimate cost per mile for each vehicle-RGW class. Then, we set the tax rate for each vehicle-RGW class to be proportional to the corresponding cost per mile information. This way, we only need to set one value for each vehicle class instead of providing tax rates for all weight groups within a vehicle class. Using this method, the weight-mileage tax rates shown in Table 4.13 are applied to scenario 2. Note that the tax rates for scenario 1 are approximately 60% of the tax rates for scenario 2. Hence, we omit table for scenario 1 in the interest of brevity.

The equivalent average tax rates per mile for each vehicle category for both weight fee system and weight-mileage fee system are summarized in Table 4.14. The tax rate per mile for single unit trucks is lower when weight-mileage fee is applied as compared to that when weight fee is applied.

Suppose that VMT's do not change as a result of charging weight-mileage fees, then the adjusted ratios are shown in Table 4.15. We observe that the adjusted ratios for most vehicle classes are closer to one when weight-mileage fees are applied. This is because weight-mileage fees can better match revenues and expenditures based on vehicles' actual usage. Also, the equity ratios under scenario 2 are better than that under scenario 1. This is because the revenues from trucks are simply not enough to cover a fair share of expenditure. Therefore, the improvements are limited. However, under scenario 2, because the revenues from trucks are higher, fair equity ratios are easier to achieve. Moreover, because weight-mileage fees do not apply to BUS, AUTO, and LT4, the adjusted ratios for those classes become slightly worse.

Note that the tax rates and results in this section are based on several assumptions. For instance, we assume that road-use patterns, fleet composition and their use do not change as a result of a different tax structure. In reality, freight companies are likely to react to changes in tax structure and this may change VMT patterns for each vehicle class. That is, our calculations may not represent what may happen in reality if Minnesota implements a weight-mileage fee system. The cost of implementation of such a system is also not included in our analysis. The purpose of the example presented in this section is simply to demonstrate how MHCAT can be used as a tool in studying different tax policies, provided certain types of data are available. Further investigation into estimates of various inputs needed to quantify the effect of a different tax structure is beyond the scope of the current project.

4.3.2 Adding a Customized Vehicle Class

MHCAT also has the ability to handle new vehicle classes in addition to the standard 12 vehicle classes. In this section, we present results when a new vehicle class VC1 is added to the system. Suppose that all vehicles in class VC1 are 100,000 lbs (RGW) and have the same axle configuration as CB6 and 50% of VMT from CB6 are transferred from CB6 to VC1. When VC1 carries approximately 10,000 lbs of additional goods as compared to vehicle class CB6, the equity ratios are presented in Table 4.16.

Because VC1 carries more weight than that for CB6, the equity ratio for VC1 is much smaller than the ratio for CB6. This is due to the fact that heavier VC1 causes more damage to the roads and bridges as compared to CB6. In fact, if we want VC1 to achieve the same state (resp. federal+state) equity ratio as CB6, each vehicle in class VC1 needs to pay $800 (resp. $1600) additional fee.

4.4 Conclusions and Recommendations

This chapter provides documentation needed to use Minnesota highway cost allocation tool (MHCAT) in future highway cost allocation studies and for research purposes. It contains details about data requirement and allocation methods and options. Results from carrying out a cost allocation study using MHCAT are also presented. These results are expected to be more accurate than those obtained in Chapter 2 from using the FHWA's HCAT. The MHCAT is designed for Minnesota's data format and fixes several bugs in FHWA's HCAT.

The researchers found that automobiles, light trucks, and single unit trucks with three or less axles have adjusted equity ratios greater than one, which means that the revenues from those vehicles are relatively higher than their cost responsibility. In addition, except for single trailer with four or less axles, all combination trucks or trailer trucks have adjusted ratios less than one. These results are similar to observations in Chapter 2, which was based on FHWA's HCAT. Researchers also found that weight-distance fees can effectively improve equity ratios (bring them closer to 1) for most vehicle classes.

Table 4.13: Weight-Mileage Tax Rates for Scenario 1

RGW UB (000)	**SU2**	**SU3**	**SU4+**	**CB34**	**CB5**	**CB6**	**DS5**	**DS6**	**DS7+**
1.5	0.41	19.08	11.38	2.61	12.39	19.17	8.90	6.36	51.96
3.0	0.43	18.58	12.15	2.61	12.91	19.17	10.05	6.36	51.96
4.5	0.46	18.09	12.92	2.61	13.42	19.17	11.20	6.36	51.96
6.0	0.48	17.59	13.69	2.61	13.94	19.17	12.35	6.36	51.96
10.0	0.51	17.10	14.46	2.61	14.46	19.17	13.50	6.36	51.96
12.0	0.54	16.61	15.23	2.61	14.98	19.17	14.65	6.36	51.96
15.0	0.59	16.11	16.00	2.61	15.50	19.17	15.80	6.36	51.96
18.0	0.66	15.62	16.77	5.38	16.01	19.17	16.95	6.36	51.96
21.0	0.73	15.38	17.54	8.15	16.53	19.17	18.09	6.36	51.96
26.0	0.90	16.04	18.31	10.92	17.05	19.17	19.24	6.36	51.96
33.0	1.10	20.52	19.08	13.69	17.57	19.17	20.39	6.36	51.96
39.0	1.19	22.35	19.85	16.46	18.09	19.17	21.54	12.94	51.96
45.0	1.35	24.81	21.25	19.24	18.61	19.17	22.69	19.53	51.96
51.0	1.50	28.01	23.72	22.57	19.12	23.44	23.84	26.11	51.96
57.0	1.66	55.38	39.66	27.81	19.64	27.70	24.99	32.70	51.96
63.0	1.81	82.76	79.91	35.28	20.35	31.96	27.92	39.28	51.96
69.0	1.97	110.13	108.89	43.94	21.22	38.49	31.36	45.87	51.96
73.0	2.12	137.50	137.88	50.69	22.11	45.46	34.88	52.46	51.96
78.0	2.28	164.88	166.86	58.40	23.78	54.75	37.02	54.38	72.96
80.0	2.44	192.25	195.85	66.11	44.20	59.37	37.56	55.83	83.56
82.0	2.59	219.63	224.84	73.81	48.34	65.76	37.92	57.96	86.69
84.0	2.75	247.00	253.82	81.52	53.83	76.15	38.43	60.40	89.35
86.0	2.90	274.37	282.81	89.23	59.32	83.13	39.09	62.55	91.80
88.0	3.06	301.75	311.79	96.94	64.82	91.63	40.13	66.25	90.45
90.0	3.21	329.12	340.78	104.64	70.31	108.74	41.17	69.94	89.70
92.0	3.37	356.50	369.76	112.35	75.80	134.96	42.21	73.63	90.06
94.0	3.52	383.87	398.75	120.06	81.29	258.81	43.26	79.82	90.47
96.0	3.68	411.24	427.74	127.77	86.79	312.56	44.30	84.85	91.82
98.0	3.83	438.62	456.72	135.47	92.28	366.31	45.34	89.85	94.92
100.0	3.99	465.99	485.71	143.18	97.77	420.06	46.38	97.96	97.99
102.0	4.14	493.37	514.69	150.89	103.27	473.81	47.42	106.06	104.00
104.0	4.30	520.74	543.68	158.59	108.76	527.55	48.46	114.16	112.37
106.0	4.45	548.11	572.66	166.30	114.25	581.30	49.51	122.26	127.41
108.0	4.61	575.49	601.65	174.01	119.75	635.05	50.55	130.37	145.23
110.0	4.76	602.86	630.64	181.72	125.24	688.80	51.59	138.47	178.11
112.0	4.92	630.24	659.62	189.42	130.73	742.55	52.63	146.57	178.11
114.0	5.08	657.61	688.61	197.13	136.22	796.29	53.67	154.67	178.11
116.0	5.23	684.98	717.59	204.84	141.72	850.04	54.71	162.78	178.11
118.0	5.39	712.36	746.58	212.55	147.21	903.79	55.76	170.88	178.11
120.0	5.54	739.73	775.57	220.25	152.70	957.54	56.80	178.98	178.11
122.0	5.70	767.11	804.55	227.96	158.20	1011.29	57.84	187.08	178.11
124.0	5.85	794.48	833.54	235.67	163.69	1065.04	58.88	195.19	178.11
126.0	6.01	821.85	862.52	243.38	169.18	1118.78	59.92	203.29	178.11
128.0	6.16	849.23	891.51	251.08	174.67	1172.53	60.96	211.39	178.11

Table 4.14: Average Fees (Cents per Mile): Weight Fees versus W-M Fees

VC	$0.01/Mile - Weight Fees	$0.01/Mile - W-M Fees	$0.01/Mile - W-M Fees
		Scenario 1	Scenario 2
SU2	1.17	0.06	0.08
SU3	4.02	2.93	4.34
SU4+	3.08	5.00	7.41
CB34	3.20	3.42	5.06
CB5	2.27	4.43	6.55
CB6+	3.37	8.95	13.24
DS5	1.52	3.79	5.61
DS6	1.94	6.41	9.48
DS7	2.70	11.48	16.99

Table 4.15: State Adjusted Ratios for Weight Fees and W-M Fees

VC	Weight Fees	W-M Fees (Scenario 1)	W-M Fees (Scenario 2)
AUTO	1.12	1.12	1.08
LT4	1.03	1.03	1.00
SU2	1.19	0.89	0.86
SU3	1.22	0.89	1.00
SU4+	0.64	0.67	0.80
CB34	1.09	0.95	1.07
CB5	0.68	0.75	0.88
CB6+	0.42	0.57	0.71
DS5	0.68	0.81	0.93
DS6	0.45	0.63	0.77
DS7	0.30	0.52	0.67
BUS	0.91	0.91	0.88

Table 4.16: Equity Ratios with Customized Vehicle Class

VC	State Adjusted Ratios	Federal and State Adjusted Ratios
AUTO	1.14	1.20
LT4	1.05	1.08
SU2	1.19	1.48
SU3	1.24	1.25
SU4+	0.70	0.76
CB34	1.14	1.20
CB5	0.71	0.76
CB6+	0.49	0.46
DS5	0.73	0.87
DS6	0.51	0.66
DS7	0.37	0.41
BUS	0.98	0.93
VC1	0.39	0.36

Chapter 5

Auction-Based Permit System (ABPS)

5.1 Introduction

This part of the project focused on the development and testing of an auction based permit system by which a state transportation agency such as MnDOT could learn the demand for permits and freight companies' willingness to pay. Because multiple permits are expected to be on sale at each auction date, researchers studied the literature on multi-item auctions and picked three mechanisms that have been shown to work well in such settings. The criteria used to select these mechanism were as follows:

1. Price paid by a winning bid should depend only on the opposing participants' bids – as in the sealed-bid, second-price auction, or Vickrey auction – so that each participant has full incentive to truthfully reveal his or her valuation for the item on sale. (Two common sealed-bid auction mechanisms are first-price and second-price auctions. The highest bid wins in both cases. The difference is that in the former, the bidder pays the amount bid, whereas in the latter, the bidder pays the amount bid by the highest losing bid. Second price or Vickrey auctions have been shown to have the desirable property that rational buyers' equilibrium bidding strategy is to bid their true valuations.)

2. Bidders should not gain from under- or over-bidding their true demand. That is, each buyer should place bids for as many items as it needs and for which its valuation exceeds the minimum price.

3. The auction mechanism should maximize MnDOT's revenue per permit sold. This is deemed more important than maximizing total revenue because the agency also incurs a damage cost, which may not be recovered in its entirety from the sale of each permit sold.

The three mechanisms selected were (1) Vickrey auction with reserve price, (2) Ascending clock auction, and (3) Clinched ascending clock auction. We describe each of these mechanisms in a separate section next. In practical implementation of all three mechanisms, buyers will be asked to deposit a sum of money up front to be allowed to participate in bidding. Winners will be required to honor their bids at the end of the auction when sales are finalized.

5.1.1 Vickrey Auction with Reserve Price

The Vickrey auction is a sealed-bid second-price auction in which winners are determined in a single round. Based on its demand and valuation for each item desired, each buyer can place multiple bids, each with a different price. However, only bids higher than the reserve price are considered valid. Reserve price is the amount at which the seller is indifferent between selling the item or keeping it for its own use. The seller prefers to sell if the offered price exceeds reserve price and not to sell if offered price is less than the reserve price. For MnDOT, reserve prices could be calculated from the HCAST developed in Chapter 4. If there are n items for sale, then the highest up-to-n bids win. Winning bids for the i-th item pay either the price offered by the i-th highest losing bid among other buyers or the reserve price, whichever is higher. This can be explained with the help of the following example.

Suppose there are 3 permits for sale, there are 3 buyers, the seller's reserve price is $100, and the three buyers place bid as shown in the second column in Table 5.1. Then, buyer A will win two permits and buyer B will win one permit because A and B have the highest three bids. In addition, buyer A will pay $110 for the first permit because $150 is the highest bid and $110 is the highest losing bid. Bidder B will pay $100 for its first permit because $90 is the highest losing bid, which is smaller than the reserve price of $100. Finally, buyer A will pay $100 for the second permit for which it places a bid because the corresponding losing bid ($90) is lower than the reserve price ($100).

Table 5.1: Example of Vickrey Auction with $100 Reserve Price

Bidder	Bid	Price Paid
A	150	110
B	130	100
A	120	100
B	110	Does Not Win
C	90	Does Not Win

5.1.2 Ascending Clock Auction

The ascending clock auction is a multi-round sealed-bid auction. Unlike Vickrey auction, buyers who participate in a ascending clock auction bid on the number of items they wish to purchase, and not their prices. Price is determined by the clock (or round number) with prices increasing according to a pre-announced schedule at each round. The initial price in ascending clock auctions is the reserve price. In each round, which lasts a predetermined time known to all buyers, each buyer submits its bid for the number of permits it intends to buy. If the total number of requested permits is greater than the number of available permits, then price goes up according to a pre-announced increment schedule and the auction moves to the next round. Otherwise, the buyers that remain in the game win the quantity they bid and pay the current price. Note that at the conclusion of each round, bidders will know whether the total demand exceeded number of available permits, but not the quantities bid by other freight companies. It is possible that MnDOT would sell less than the number of permits available for sale in an ascending clock auction. We illustrate how this mechanism works with the help of a simple example next.

Suppose there are 3 permits for sale, there are 3 buyers, and the seller's reserve price is $100. This auction goes through three rounds with bids shown in Table 5.2. The total demand in the first round is 6, which is greater than the number of permits available. Therefore, the auction moves to the second round and the price increases to $110. The buyers are informed of the size of the increment in each round before the start of bidding. The total demand in the second round is 4, which is still higher than the number of permits for sale. Therefore, the auction moves to the third round. In round 3, the total demand equals 3, which can be satisfied by available permits. The auction ends in round 3 and all buyers who placed a bid in round 3 win the number of permits they bid. Bidders pay $130 for each permit they purchase.

Table 5.2: Example of Ascending Clock Auction

Round 1 $100		Round 2 $110		Round 3 $120	
Bidder	Quantity	Bidder	Quantity	Bidder	Quantity
A	3	A	2	A	2
B	1	B	1	B	1
C	2	C	1	C	0
Total	6	Total	4	Total	3

5.1.3 Clinched Ascending Clock Auction

The clinched ascending clock auction is similar to the ascending clock auction in many respects. Key differences lie in the determination of the winners and the amounts they pay. In clinched ascending clock auction mechanism, a buyer can win one or more permits in each round if the total number of bids placed by other buyers is less than the total number of permits. The price for each permit is determined when the winner of that particular permit is decided. Note that in each round, the buyer is required to bid at least the quantity that it clinched in previous rounds.

In Table 5.3, we use an example to demonstrate how clinched ascending clock auction works. Similar to ascending clock auction example in Table 5.2, the auction ends after round 3 when the total demand becomes less than or equal to the number of available permits. However, in round 2, because the total demand from buyers B and C is less than the total number of permits for sale, buyer A clinches 1 permit out of the 2 permits that it requested. Therefore, buyer A pays $110 for the first permit and $120 for the second permit. Because buyer B does not win any permit prior to round 3, it pays $120 for the permit it purchases.

Table 5.3: Example of Clinched Ascending Clock Auction

Round 1 $100			Round 2 $110			Round 3 $120		
Bidder	Quantity	Clinched	Bidder	Quantity	Clinched	Bidder	Quantity	Clinched
A	3	0	A	2	1	A	2	NA
B	1	0	B	1	0	B	1	NA
C	2	0	C	1	0	C	0	NA

5.2 Equilibrium Bidding Strategy

In this section, we explore how expected utility maximizing freight companies would bid under equilibrium – i.e. under a competitive Nash equilibrium. The equilibrium strategies are worked out for each mechanism in a separate section. We assume that there are n identical permits for sale in a particular auction and that there are m bidders. Also, we use the letter b, with additional subscripts and superscripts, to denote amounts bid and the letter v to denote valuations (utilities).

5.2.1 Vickrey Auction with Reserve Price

Let b_i^j be the bid placed by buyer-i for the j-th item. We index bids such that $b_i^1 \geq b_i^2 \geq \cdots \geq b_i^n$. Also, let c_{-i}^j denote the maximum between j-th highest bid placed by buyers other than the buyer-i and the reserve price r. We have $c_{-i}^1 \geq c_{-i}^2 \geq \cdots \geq c_{-i}^n \geq r$.

Based on the rules for selecting winners in a Vickrey auction, it is easy to see that if the buyer-i were to win $\hat{n}_i \leq n$ items, then the bid price for j-th item ($j \in [1, \hat{n}_i]$) must satisfy $b_i^j \geq c_{-i}^{n-j+1}$ and the corresponding payment is $c_{-i}^{n-\hat{n}_i+j}$. That is, suppose v_i^j is the valuation for the j-th item for the buyer-i. The total gain for buyer i is

$$\sum_{j=1}^{\hat{n}_i}(v_i^j - c_{-i}^{n-\hat{n}_i+j}). \tag{5.1}$$

We present arguments next to show that in equilibrium, a freight company maximizes its gain by bidding its true valuations for each permit that it places a bid for. The proof argues that both over- and under-bidding are dominated by truthful bidding, given that other players bid truthfully. Thus, truthful bidding must be an equilibrium strategy as no player can unilaterally increase its gain by bidding differently if others bid according to this strategy. Below, we present arguments against overbidding. Similar arguments apply in the case of underbidding. Those are omitted in the interest of brevity.

Suppose buyer-i wins $\hat{n}_i$ permits when it bids truthfully. Given that other buyers bid truthfully and do not change their strategies, two scenarios could happen when buyer-i decides to overbid. In the first scenario, buyer-i wins exactly $\hat{n}_i$ items. From (5.1), we know that the total gain is not affected by buyer-i's bid so long as $b_i^j \geq c_{-i}^{n-\hat{n}_i+j}$ for $1 \leq j \leq \hat{n}_i$. Hence, buyer-i's total gain remains unchanged regardless of whether it overbids or bids truthfully. In the second scenario, buyer-i wins $\tilde{n}_i$ items by over bidding, where $\tilde{n}_i > \hat{n}_i$, and gains

$$\sum_{j=1}^{\tilde{n}_i}(v_i^j - c_{-i}^{n-\tilde{n}_i+j}). \tag{5.2}$$

$$= \sum_{j=1}^{\hat{n}_i}(v_i^j - c_{-i}^{n-\tilde{n}_i+j}) + \sum_{j>\hat{n}_i}^{\tilde{n}_i}(v_i^j - c_{-i}^{n-\tilde{n}_i+j}) \tag{5.3}$$

$$= \sum_{j=1}^{\hat{n}_i}(v_i^j - c_{-i}^{n-\hat{n}_i+j}) + \sum_{j>\hat{n}_i}^{\tilde{n}_i}(v_i^j - c_{-i}^{n-j+1}) \tag{5.4}$$

$$\leq \sum_{j=1}^{\hat{n}_i}(v_i^j - c_{-i}^{n-\hat{n}_i+j}). \tag{5.5}$$

The right hand side of inequality (5.5) is the buyer's gain when it bids truthfully. It comes from the fact that $v_i^j - c_{-i}^{n-j+1} < 0$ when $\hat{n}_i < j \leq \tilde{n}_i$. Hence, overbidding is dominated by bidding truthfully. We can use similar arguments to show that underbidding is dominated by truthful bidding. Because these arguments hold for all possible outcomes (all possible $\hat{n}_i$), this completes the assertion that an equilibrium strategy is to bid true valuations.

5.2.2 Ascending Clock Auction

Let $q_i(p)$ denote the number of permits for which bidder i places a bid at price p. Hereafter, we refer to this term as the quantity chosen by bidder i. Based on the rules of ascending clock auctions, the auction ends when price reaches the clearing price $p^* = \min\{p : \sum_{i=1}^{m} q_i(p) \leq n\}$ and buyer-i pays $(q_i(p^*) \cdot p^*)$ for its permits. Clearly, a rational buyer would choose $q_i(p) = \max\{j : v_i^j \geq p\}$. (Recall that denotes v_i^j buyer-i's valuation of the j-th item.) This is because if the auction ends when price is p, the buyer-i's total gain is

$$\sum_{j=1}^{q_i(p)} (v_i^j - p), \tag{5.6}$$

which is higher than $\sum_{j=1}^{q'} (v_i^j - p)$ for any $q' \neq q_i(p)$.

One concern that has been raised in the literature about ascending clock auctions is that they may lead to lower demand from some buyers in earlier rounds. We explain this phenomenon next. Suppose that after several repeated auctions, a buyer learns the total demand curve. That is, it can estimate p^*. When this happens, it is possible that a buyer would choose a $q < q_i(p)$ during a round in which $p < p^*$ to make the auction end sooner, i.e. at some $p < p^*$. This is because buyer-i's total gain by under bidding $(\sum_{j=1}^{q} (v_i^j - p))$ can possibly be higher than the total gain by bidding truthfully $(\sum_{j=1}^{q_i(p^*)} (v_i^j - p^*))$. We discuss several remedies that have been suggested in the literature to overcome such bidding behavior in Section 5.3. Our experiments did not reveal underbidding by those that participated in experimental auctions (see Section 5.5 for details).

5.2.3 Clinched Ascending Clock Auction

In clinched ascending clock auctions, a rational buyer would also bid truthfully by choosing $q_i(p) = \arg\max_q \sum_{j=1}^{q} (v_i^j - p) = \max\{j : v_i^j \geq p\}$. This can be briefly explained as follow. We define the cumulative clinches for the buyer-i when the price reaches p as

$$C_i(p) \quad = \quad \max\left(0, n - \sum_{j \neq i} q_j\right), \tag{5.7}$$

which is not affected by the buyer-i's own strategy. Hence, when every buyer bids truthfully, no player can unilaterally increase its gain by bidding untruthfully, and the auction will always yield the final price p^*.

5.3 Literature Review

Next, we briefly present a review of literature that focuses on auctions for selling multiple identical items. Auction design is driven by multiple desirable performance metrics associated with auction outcomes. The first of these metrics is *efficiency*. When each item is sold to the buyer with the highest valuation for that item, then the auction outcome is said to be efficient. Clearly, such an allocation maximizes the overall benefit from trade. Usually, an efficient allocation can be achieved if buyers bid truthfully, i.e. they bid their true valuations. Truthful bids occur when the price that a buyer pays upon winning is independent of its bid price and depends entirely on opposing players' bids (see Vickrey 1961).

It has been shown in theoretical models that Vickrey auction with private valuation can achieve efficiency. However, from a practical viewpoint, bidders may find it difficult to calculate the dominant bidding strategy and may not bid their true valuations. We observe this phenomenon in our experiments in Section 5.5. A similar result was observed by Kagel et al. (1987), who showed that in experiments ascending auctions actually perform better than Vickrey auctions in terms of efficiency. This is because buyers can more easily figure out the dominant strategy in ascending auctions.

One of many auction mechanisms that deal with multiple identical units is the ascending clock auction mechanism. Usually, some rules are specified in ascending auctions to prevent buyers from holding back their initial bids in order to observe other buyer's demand information. For example, Wilson (1997) proposed that a bidder in each round cannot choose a bid (quantity) that is higher than the bid (quantity) placed in the previous round. However, in ascending clock auctions, bidders may reduce their bids (i.e. bid less than their true demand) to keep the price down (Ausubel and Cramton 1998). This makes more sense for buyers with higher demand. Underbidding can lead to inefficiency — buyers with large demand would win too little as compared to buyers with small demand. Ausubel (2004) proposes an improved ascending clock auction that resolves such issues. This improved auction mechanism is what we called clinched ascending clock auction in this chapter. In clinched ascending clock auction, some items are clinched by a bidder when they are not claimed in other bidders' bids, providing greater incentives to bid truthfully.

Another important metric is revenue. Auction design and choice of auction mechanism is greatly influenced by the need to maximize revenue. Although it has be shown that Vickrey auction can achieve efficiency, the total revenue for seller can be low in such auctions, especially when competition among bidders is low. For example, during the auction of spectrum licenses in New Zealand in 1990, a winner bid $100,000 but paid only $6 (McMillan 1994). This happened because the highest losing bid was low, either because there was too much on sale or there were too few participating buyers.

A simple approach to avoid low revenue is to utilize reserve prices. A reserve price can be set directly by the seller prior the auction. For example, the first mechanism in this chapter utilizes a Vickrey auction mechanism with reserve price. In this case, the selling price cannot be lower than the reserve price even when there are too few bidders, or the total quantity bid is small relative to available amount. Alternatively, price can be maintained by limiting the number of items to sell at the end of the auction. For example, in Ausubel and Cramton (2004), the quantity on sale is determined after bids are received. Because the seller can decide the number of items for sell based on bids received, fewer items are sold and the price is maintained high when demand is low. Ausubel and Cramton (2004) also showed that in such settings, essential features of Vickrey auctions are preserved and truthful bidding is still a dominant strategy for bidders.

Some papers suggest that reserve prices may reduce the seller's revenue by making the auction less attractive to some buyers, particularly those with low valuations (though still higher than reserve price). This happens because buyers with low valuations may consider their chances of winning to be low. However, having fewer participants lowers competition, which in turn, may lead to lower total revenue (Harstad 1990). In our setting, the important metric for MnDOT would be revenue per permit sold, rather than the total revenue. Such concerns do not arise when the focus is on maximizing per-unit revenue.

Kagel and Levin (2001) is also related to the models reported here. In one of the experiment reported in Kagel and Levin (2001), the authors compared the bidding behavior and the revenue for uniform price ascending clock auction (Mechanism 2 in our report) and clinched ascending clock auction (Mechanism 3 in our report). Kagel and Levin (2001) found that demand reduction happened in Mechanism 2 but not in Mechanism 3. This confirmed the arguments presented in the theoretical paper by Ausubel (2004). Kagel and Levin (2001) also found that the total revenue for seller was higher in clinched ascending clock auction. We also found that the total MnDOT revenue was higher when using Mechanism 3 in some auctions, but not in all auctions. On the important metric of revenue per unit sold, the ascending clock mechanism (Mechanism 2) performed better than the clinched ascending clock mechanism (Mechanism 3). We observed that some buyers bid less than their demand in our experiments as well. However, we did not find evidence that demand reduction could be eliminated in clinched ascending clock auction. That is, bidders who bid less than their demand in Mechanism 2 continued to bid less than their demand in Mechanism 3. Complete details are presented in Section 5.5.

5.4 Experimental Design

We created eight independent experiments on the web. The subjects in the first three trials were five University of Minnesota graduate students. The subjects in the remaining five experiments were 12 MnDOT staff members. Participant were explained the rules of all three auctions and allowed to participate in a test run. Then, participants created their unique accounts on the web based auction system. In each iteration, buyers were told the number of permits for sale, reserve price, current price (if applicable), and their own private demands and valuations. The buyers were told that their valuations reflected their best estimates of the value of each permit to them. Valuations were ordered from highest to lowest when presented to buyers.

In each trial, participants were randomly assigned their demand (the number of permits) and the corresponding private valuations. The demand and valuation were generated based on distributions listed in Table 5.4. Participants were told that their objective was to maximize the differences between the valuation and price paid for each winning permit. In each trial, we recorded participants' responses within each of the three auction mechanisms. Each participant's demand and valuations remained constant in all rounds of the same experiment. The purpose of this design was to record the participants' decision patterns and to compare performance in terms of the total number of permits sold and the selling prices.

Table 5.4: Demand and Valuation Distributions

Experiment Set	Demand	Valuation
Student 1	Discrete Uniform (1, 10)	Uniform (100, 200)
Student 2	Discrete Uniform (2, 7)	Uniform (100, 200)
Student 3	Discrete Uniform (2, 7)	Uniform (100, 200)
MnDOT 1	Discrete Uniform (1, 5)	Uniform (100, 250)
MnDOT 2	Discrete Uniform (1, 5)	Uniform (100, 250)
MnDOT 3	Discrete Uniform (1, 5)	Uniform (100, 250)
MnDOT 4	Discrete Uniform (1, 5)	Uniform (100, 250)
MnDOT 5	Discrete Uniform (1, 5)	Uniform (100, 250)

The parameters for each experiment are provided in Table 5.5. For the student experiments, there were eight permits available for sale and the reserve price was \$120. For the MnDOT experiments, there were 20 permits for sale and the reserve price was \$130. The "Maximum Revenue per Unit" column calculates the average revenue per permit by assuming that all available permits (n) were sold to participants with the highest n private valuations. In other words, "Maximum Revenue per permit" can be considered as the maximum average price per permit when all buyers act rationally. The last two columns calculate the average demand per participant and average valuation per permit for each trial based on their randomly assigned demands and valuations in each trial.

Table 5.5: Experiment Parameters

Experiment Set	Permits for Auctions	Reserve Price	Maximum Revenue per Unit	Number of Participants	Avg. Demand per person	Avg. Valuation per Item
Student 1	8	120	185.5	5	7.0	146.4
Student 2	8	120	182.5	5	4.2	147.6
Student 3	8	120	175.9	5	3.8	145.1
MnDOT 1	20	130	214.6	12	3.2	182.4
MnDOT 2	20	130	211.6	12	3.0	174.6
MnDOT 3	20	130	201.1	12	3.2	165.2
MnDOT 4	20	130	213.6	12	3.0	184.8
MnDOT 5	20	130	212.6	12	2.9	182.8

5.5 Data Analysis and Results

In this section, we summarize the results of the auction experiments and test a variety of hypotheses about buyer behavior. We begin by tabulating the total and average revenue per permit sold. Table 5.6 summarizes these results and shows that the average selling price for the second mechanism (ascending clock auction) is usually the highest among the three mechanisms except for one case in which the clinched ascending clock mechanism has the highest average selling price. This suggests that if MnDOT were to select a mechanism based on average price per permit sold, it should pick the ascending clock mechanism. Additional tests reported in the next section further support this recommendation.

In order to test how buyers placed bids relative to theoretical predictions, we tested a variety of hypotheses inspired by theoretical underpinnings of the three auction mechanisms. We next present the results of these tests, starting with the Vickrey auctions first.

5.5.1 Vickrey Auctions

Let μ_d^i be the mean difference in the buyer-is bids and the corresponding valuations. Then, our first test considers whether buyers offer their valuations in bids.

H1: Bidder would bid their valuation in Vickrey Auction, i.e. $\mu_d^i = 0$.

A t-test for the above hypothesis showed that there was a statistically significant difference between a buyer's offered prices and the corresponding valuations for most buyers (p-value$<$0.05, see Table A.1). In particular, more than 50% of the buyers' offer prices that are lower than their valuations. When combining all bidding records of all buyers and treating all these experimental outcomes as a single sample, we also found that the mean difference between bids and valuations are statistically less than 0 (p-value ≈ 0).

Next, we divided valuations into two groups: (1) those below 120% of reservation price and (2) others. We tested whether these two groups have statistically significant differences in the paired difference between bid prices and valuations as indicated in the hypothesis below.

H2: Bidder with low valuations bid higher than their valuations in Vickrey auctions.

The independent-samples t-test suggested that the two groups are significantly different at the 0.05 level. In fact, we observe that a buyer is more likely to place a bid that is greater than or equal to the corresponding valuation when the valuation is less than or equal to 120% of the reserve price; see Tables 5.8 and 5.9. Note that we assume the two groups have equal variances, which was supported by the Levene's Test for Equality of Variances, $p = 0.468$.

Table 5.6: Summary of the Results

Experiment Set	Auction Mechanism	Number of Rounds	Total Revenue	Total Permit Sold	Average Price (% Up or Down Relative to Reserve Price)
Student 1	1		1174	8	146.75 (+22.0%)
	2	6	1190	7	170.00 (+41.7%)
	3	5	1120	7	160.00 (+33.3%)
Student 2	1		1099	8	137.37 (+14.4%)
	2	4	900	6	150.00 (+25.0%)
	3	7	1050	7	150.00 (+25.0%)
Student 3	1		1080	8	135.00 (+12.5%)
	2	4	1050	7	150.00 (+25.0%)
	3	7	940	6	156.67 (+30.5%)
MnDOT 1	1		2851	20	142.55 (+6.7%)
	2	8	3420	18	190.00 (+46.2%)
	3	7	3680	20	184.00 (+41.5%)
MnDOT 2	1		2700	20	135.00 (3.8%)
	2	9	3420	19	180.00 (+38.4%)
	3	4	2710	17	159.41 (+22.6%)
MnDOT 3	1		2660	20	133.00 (+2.3%)
	2	6	3200	20	160.00 (+23.0%)
	3	3	3000	20	150.00 (+15.3%)
MnDOT 4	1		2924	20	146.20 (+12..5%)
	2	4	3230	17	190.00 (+46.2%)
	3	6	3570	20	178.50 (+37.3%)
MnDOT 5	1		2977	20	148.85 (+14.5%)
	2	7	3230	17	190.00 (+46.2%)
	3	7	3020	16	188.75 (+45.2%)

Our next hypothesis concerned whether prices paid and valuations were correlated. Recall from our earlier discussion that we want these two parameters to be uncorrelated.

H3: Prices paid are positively correlated with winners' valuations.

There is no evidence that the prices paid are positively correlated with corresponding valuations. In fact, there is only one experiment (out of eight) that shows positive correlation between prices paid and valuations (see Table 5.10). The test is not applicable for auctions #31 and #32 because all buyers paid the same price.

H4: Bids are positively correlated with corresponding valuations.

In six out of eight experiments, there was a positive correlation between the bid prices and their corresponding valuations. (see Table 5.11). This is consistent with theory.

H5: Prices paid are positively correlated with corresponding bids.

In five out of eight experiments, there was a positive correlation between the prices paid and their corresponding bids (see Table 5.12). This is also consistent with theory.

In conclusion, we find that by and large, participants in the auction placed their bids as predicted by theory. The only significant departure was that the participants did not consistently bid their valuations. We conjecture that in an actual implementation of a Vickrey type auction, participants will learn to bid

Table 5.7: One-Sample t-Test (Test Value = 0)

					95% Confidence Interval	
Bidder ID	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
22	2.069	5	0.093	5.33333	-1.2928	11.9595
23	-0.927	17	0.367	-6	-19.654	7.654
24	-14.683	8	0	-7.11111	-8.228	-5.9943
26	-9.974	12	0	-70.23077	-85.5723	-54.8893
27	-12.201	9	0	-39.8	-47.1789	-32.4211
28	-3.032	16	0.008	-26.52941	-45.0782	-7.9806
30	-2.073	12	0.06	-13.84615	-28.4012	0.7089
32	-3.327	11	0.007	-14.83333	-24.6459	-5.0207
33	-3.058	19	0.006	-24.95	-42.0265	-7.8735
34	-1.759	7	0.122	-26.5	-62.1182	9.1182
35	-3.609	16	0.002	-26.47059	-42.018	-10.9232
36	1.98	11	0.073	59.83333	-6.6685	126.3352
37	1.631	14	0.125	8.66667	-2.7319	20.0652
38	-5.941	10	0	-59.54545	-81.8782	-37.2127
39	-0.278	18	0.784	-4.84211	-41.3986	31.7144
All Bidders	-4.655	214	0	-15.44186	-21.981	-8.9027

Table 5.8: One-Sample t-Test (Test Value = 0)

					95% Confidence Interval	
t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
3.993	213	0.000	27.43498	6.89053	13.79204	40.97793

their valuations over time. Because the participants' bids were positively correlated with their valuations, MnDOT will be able to learn freight companies' willingness to pay by collecting data on the bids tendered.

5.5.2 Clock Ascending and Clinched Clock Ascending Auctions

In ascending clock auctions, buyers can drive prices down by bidding less than their true demand. Therefore, we tested if data suggest that buyers either more or less than their demand.

H6: Bidders bid less than their true demand in using ascending clock auctions.

A t-test was performed to evaluate the difference between the mean value of the paired differences (bid quantity - demand). For most buyers, there was no evidence that he or she bid lower or higher than his or her corresponding demand. Only a few buyers (#26, #28, #34) bid less than their demand. Also, #36 actually bid higher than its demand (see Table 5.13).

However, except for buyer #26, we do not find evidence that buyers use different bidding strategy for

Table 5.9: Independent Samples Test (t-test for Equality of Means between the two Groups)

					95% C. I.	
Bidder	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Low Valuation	.491	68	.093	3.1884	-9.7673	16.1441
High Valuation	+6.748	145	.000	-24.2466	-31.3484	-17.1447

Table 5.10: Pearson Correlation (Prices Paid vs. Valuations)

Auction ID	Pearson Correlation	Sig. (2-tailed)
16	.982	.000
17	.492	.216
18	.311	.497
30	.467	.290
31	.325	.285
33	.383	.264
34	.039	.916
35	.152	.676

Mechanisms 2 and 3 among the fours buyers mentioned above. Particularly, buyers #28 and #34 consistently bid less than their demand under both Mechanisms 2 and 3. Bidder #36 bid consistently higher than its demand under both Mechanisms 2 and 3. Only buyer #26 bid lower than demand for Mechanism 2 and bid according to demand for Mechanism 3 (see Tables 5.13 and 5.14).

H7: Prices paid are positively correlated with corresponding valuations (Clinched Clock Ascending Only)

There is no evidence showing that prices paid by winners are positively correlated with their corresponding valuations (see Table 5.15).

5.6 Recommendations

In this chapter, researchers identified three auction mechanisms for use by MnDOT in an auction based system for selling special permits. The three mechanisms were implemented in a web-based test site. The researchers tested the performance of the three mechanisms in experiments involving graduate students at the University of Minnesota and MnDOT staff. Although theory suggests that all three mechanisms induce truthful revelation of demand and valuation by bidders, the experimental results were quite different. In most cases, bidders bid lower than their valuations in Vickrey auction. In ascending clock auctions, bidders typically did not underbid their demand, as found in some earlier studies. However, a subset of bidders either consistently bid lower than their demand or higher than their demand. We found that the ascending clock auction produced the maximum revenue per permit sold for the MnDOT. This mechanism is also straightforward to implement and the results of auctions can help MnDOT develop a price demand curve because the total number of permits demanded would be known at each list price. Recall that the list price is

Table 5.11: Pearson Correlation (Bid Prices vs. Valuations)

Auction ID	Pearson Correlation	Sig. (2-tailed)
16	.975	.000
17	.997	.000
18	.997	.000
30	-.047	.788
31	.295	.144
33	.571	.001
34	.738	.000
35	.720	.000

Table 5.12: Pearson Correlation (Prices Paid vs. Bids)

Auction ID	Pearson Correlation	Sig. (2-tailed)
16	.965	.000
17	.491	.000
18	.264	.613
30	.788	.012
31	.610	.033
33	.659	.041
34	.720	.029
35	.362	.304

known at the start of each round. Thus, the auction based permit system achieves both efficiency – permits are allocated to those buyers whose valuations are the highest – and allows the seller to recover important demand information.

Table 5.13: One-Sample t-Test (Test Value = 0) for Clock Ascending Auction

					95% Confidence Interval	
Bidder ID	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
22	1.710	13	.111	.42857	-.1128	.9699
23	-1.749	13	.104	-.28571	-.6386	.0672
25	-1.803	13	.095	-1.00000	-2.1984	.1984
26	-2.726	26	.011	-.22222	-.3898	-.0546
27	1.000	28	.326	.03448	-.0362	.1051
28	-3.822	28	.001	-.44828	-.6886	-.2080
33	.239	28	.813	.03448	-.2616	.3306
34	-3.266	28	.003	-.27586	-.4489	-.1028
35	.441	28	.663	.03448	-.1257	.1947
36	4.929	28	.000	1.10345	.6449	1.5620
37	-1.000	28	.326	-.03448	-.1051	.0362
38	-.610	26	.547	-.14815	-.6474	.3511
39	-1.955	28	.061	-.58621	-1.2005	.0281

Table 5.14: One-Sample t-Test (Test Value = 0) for Clinched Clock Ascending Auction

					95% Confidence Interval	
Bidder ID	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
21	1.000	18	.331	.05263	-.0579	.1632
22	-1.897	12	.082	-.69231	-1.4873	.1027
23	1.289	16	.216	.23529	-.1516	.6222
25	-.669	18	.512	-.31579	-1.3069	.6753
26	.568	21	.576	.04545	-.1209	.2118
27	.000	22	1.000	.00000	-.1304	.1304
28	-5.100	22	.000	-.78261	-1.1008	-.4644
30	.994	20	.332	.90476	-.9935	2.8030
32	7.091	22	.000	.69565	.4922	.8991
33	3.148	22	.005	.43478	.1484	.7212
34	-1.738	22	.096	-.21739	-.4767	.0420
35	.327	22	.747	.04348	-.2324	.3194
36	3.275	22	.003	1.21739	.4465	1.9883
37	1.000	22	.328	.04348	-.0467	.1336
38	-.438	18	.667	-.10526	-.6106	.4001
39	-2.826	22	.010	-.60870	-1.0554	-.1620

Table 5.15: Pearson Correlation (Prices Paid vs. Valuations)

Auction ID	Pearson Correlation	Sig. (2-tailed)
26	NA	NA
27	.043	.936
28	.612	.388
43	.387	.304
44	.298	.403
45	.362	.480
47	.160	.639
48	NA	NA

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Appendix A

Summary of Inputs and Methodologies for MHCAT

A.1 Summary of Inputs for MHCAT

2.1 INPUT-VMT	**Cell Range**
◇ Total system miles	B5:M5
◇ VMT option	B2
◇ Avg VMT/day by functional class (when B2=1)	B6:M6
◇ # of vehicles per day (when B2=1)	B14:M34
◇ VMT by functional class (when B2=2)	B38::M57

2.2 INPUT-RGW	**Cell Range**
◇ weight distribution in 2000-lb increments	C3:V75

2.3 INPUT-MPG, Distance and Fuel	**Cell Range**
◇ MPG for gasoline by vehicle class and RGW	E8:BY27
◇ MPG for diesel by vehicle class and RGW	E33:BY52
◇ Avg MPG for gasoline by vehicle class (optional)	C8:C27
◇ Avg MPG for diesel by vehicle class (optional)	C33:C52
◇ Fuel distribution by vehicle class	C54:C73
◇ Avg annual distance by vehicle class	F54:F73
◇ Avg value for vehicle power unit by vehicle class	C87:D106
◇ Avg value of a trailer by vehicle class	F87:F106
◇ Option for number of vehicles	Q59
Q59=1, ◇ # of vehicles by class	L58:L77
Q59=2, ◇ # of vehicles is estimated by VMT and annual distance/vehicle	–
Q59=3, ◇ adjusted option 2's results by Highway Statistics	Q61:Q63

2.4 INPUT-OGW-AXLE DISTRIBUTION	**Cell Range**
◇ Operating gross weight distribution by vehicle class	B4:U34

2.5 INPUT-TAX	**Cell Range**
◇ Federal revenue	B6:F11
◇ State revenue	I6:M13
◇ State weight fee	R4:R59
◇ Federal heavy vehicle use tax	T4:T59
◇ Weight-mileage fee	V4:AO59

2.6 INPUT-Expenditures	**Cell Range**
◇ State level construction and maintenance	B10:M36
◇ State level administration	B48:M74
◇ State-aid construction and maintenance	B84:M110
◇ State-aid administration	B112:M148
◇ Federal-aid construction and maintenance	S10:AD36
◇ Federal-aid administration	S48:AD74

2.7 INPUT-Allocation Factor	**Cell Range**
◇ Grading	B3:M6
◇ Residual Allocators	B9:M13
◇ Other Costs	
◇ Miscellaneous costs	B24:M27
(see section 2.7 and MHCAT for details)	B31:M32
	P24:AI33
◇ Systemwide costs allocation rule	B37:B38
◇ Vehicle exclusion rule	C38:N47

2.8 INPUT-BridgeData	Cell Range
◇ Allocation of new bridge costs to increments	B14:G20
◇ New and replacement bridges by type of bridge	B26:M31
◇ Cost responsibility for bridge replacement decisions	B39:M40
◇ Inventory ratings of structurally deficient bridges (%)	B46:M52
◇ Cost responsibility for bridge repair expenditures (%)	B58:M59

2.9 INPUT-MomentDist	Cell Range
◇ Fraction of vehicles by bridge design increment	B5:P1000

A.2 Procedures for Calculating Axle Weight Distributions

The axle weight distribution for each vehicle class and weight class can be calculated based on weight-in-motion (WIM) data. We briefly describe the procedure for extracting axle weight information from WIM. This procedure can help calculate inputs described in Section 2.4.

The WIM raw data in Minnesota contain 47 to 67 fields (details can be found in Appendix A of iANALYZE Software Operator's Manual). Among these fields, the information we need are as follows:

class FHWA vehicle class

GVW The operating gross vehicle weight

weight axle 1 The axle weight of the first axle

axle spacing 1:2 The distance between the first and the second axle

weight axle 2 The axle weight of the second axle

. . .

weight axle k The axle weight of kth axle

axle spacing k:k+1 The distance between the first and the second axle

weight axle k+1 The axle weight of $(k+1)$th axle

Using information above, the user can calculate axle weight for each data entry based on the following procedure:

1. **Identify vehicle type and weight class:** Using [class] and [GVW], the user can categorize each data entry into the right vehicle type and weight class.

2. **Group axles into axle set:** Using [axle spacing], the user can group adjacent axles into an axle set based on their distance. If the distance between any two adjacent axles is between 40 and 96 inches, then the two axles should be categorized into the same group. An axle set with only one axle is labeled as "single axle". An axle set with two axles is labeled as "tandem axle". Similarly, a three-axle set is labeled as "tridem axle".

3. **Calculate the average weight per axle for each axle set:** For each axle set above, the user needs to calculate the average weight per axle. For example, the average weight per axle for a tandem axle set with one 10,000 lbs axle and another 8,000 lbs axle is 9,000 lbs.

A.3 Revenue Attribution Methods

We introduce the revenue attribution methods used in MHCAT in this appendix.

A.3.1 Federal/State Gasoline/Diesel Tax

All fuel taxes are attributed to road users based on estimated fuel consumption using the same method. The data requirements for fuel tax attribution include [1] the average miles per gallon (MPG) for each vehicle class and registered gross weight, [2] the vehicle mile travelled (VMT) for each vehicle class, [3] the registered gross weight distribution for each vehicle class, [4] the revenue from fuel tax, and [5] the tax rate.

The algorithm for calculating fuel tax attribution is as follows. Let μ_v is the VMT for vehicle class v and $m_{v,g}$ be the MPG for class v vehicles that have RGW g. Suppose that $\alpha_{v,g}$ is the fraction of vehicles v that have RGW g. The estimate fuel consumption f_v for vehicle v is

$$f_v = \mu_v \sum_{g \in G} \frac{\alpha_{v,g}}{m_{v,g}}. \tag{A.1}$$

Suppose that r_v is the fuel tax rate for vehicle class v, the fuel tax attribution ratio for vehicle class v is

$$\text{\% of fuel tax for } v = \frac{r_v f_v}{\sum_{i \in V} r_i f_i}, \tag{A.2}$$

where the numerator is the revenue for vehicle v and the denominator is the total revenue for all vehicle classes.

A.3.2 Permit Fees / State Weight Fees / Federal Heavy Vehicle Use Tax

State permit fees, weight fees and Federal heavy vehicle use tax are attributed to road users based on a weighted average tax rate and an estimated number of vehicles. These taxes are applied to trucks only. The data requirements for either weight fee or heavy vehicle use tax are: [1] vehicle mile travelled (VMT) for each vehicle class, [2] average annual mile travelled per vehicle for each vehicle class, [3] registered gross weight distribution for each vehicle class, [4] revenue from weight fee/heavy vehicle use tax, and [5] tax rate.

Let μ_v be the VMT for vehicle class v and $\alpha_{v,g}$ be the fraction of vehicle v with RGW g. Suppose that r_g is the tax rate for vehicle with RGW g. The average tax rate for vehicle class v is

$$r'_v = \sum_{g \in G} \alpha_{v,g} r_g. \tag{A.3}$$

Let d_v be the average annual miles travelled per vehicle for vehicle class v. The weight fee/heavy vehicle use tax attribution ratio for vehicle v is

$$\text{\% of weight fee for } v = \frac{n_v r'_v}{\sum_{i \in V} n_i r'_i} \tag{A.4}$$

where $n_v = \mu_v / d_v$ is the estimated number of vehicles v.

A.3.3 Registration Fees

Registration Fees are attributed to passenger vehicles and light trucks based on the average tax rate and the estimated number of vehicles in these two vehicle classes. The data requirements for registration fees are: [1] the vehicle mile travelled (VMT) for each vehicle class, [2] the average annual mile travelled per vehicle for each vehicle class, [3] the revenue from registration fee, and [4] the tax rate.

The calculation is similar to weight fee and heavy vehicle use tax. Let μ_v be the VMT and r'_v be the average tax rate for vehicle class v. Suppose that d_v is the average annual mile travelled per vehicle for vehicle class v. The registration fee attribution ratio for vehicle v is

$$\text{\% of registration fee for Vehicle Class } v = \frac{n_v r'_v}{\sum\limits_{i \in V} n_i r'_i} \tag{A.5}$$

where $n_v = \mu_v / d_v$ is the estimated number of vehicles v.

A.3.4 Federal / State Sales Taxes

Sales taxes are attributed to road users based on estimated vehicle values and estimated number of vehicles in each vehicle classes. We assume that the number of vehicle sales is proportional to the number of vehicles. Note that federal sales taxes are applied to trucks only. The data requirements for sales tax are: [1] the vehicle mile travelled (VMT) for each vehicle class, [2] the average annual mile travelled per vehicle for each vehicle class, [3] the average vehicle value in each vehicle class, [4] the revenue from sales tax, and [5] tax rate.

Let μ_v be the VMT and r'_v be the average tax rate for vehicle class v. Suppose that d_v is the average annual mile travelled per vehicle and u_v is the average value per vehicle for vehicle class v. The sales tax attribution ratio for vehicle v is

$$\text{\% of sales tax for Vehicle Class } v = \frac{n_v u_v r'_v}{\sum\limits_{i \in V} n_i u_i r'_i} \tag{A.6}$$

where $n_v = \mu_v / d_v$ is the estimated number of vehicles v.

A.3.5 Federal Tire Excise Taxes

Tire taxes are attributed to truck users based on VMT and the average load on tire for each truck class. The data requirements are: [1] the vehicle mile travelled (VMT) for each vehicle class, [2] the registered gross weight distribution for each vehicle class, [3] the revenue from tire tax, [4] the estimated tax rate per mile for each vehicle class and weight class.

Let $\alpha_{v,g}$ be the fraction of vehicle v with RGW g and $r_{v,g}$ is the estimated tax rate per mile for vehicle class v with weight g. Note that $r_{v,g}$ are obtained from default data in HCAT. For single unit trucks and buses, we have $r_{v,g} = 6$ for $g \leq 26000$ lbs, $r_{v,g} = 10$ for $26,000$ lbs $< g \leq 51,000$ lbs, and $r_{v,g} = 14$ when $g > 51,000$ lbs. For other truck classes, we have $r_{v,g} = 10$ for $g \leq 39,000$ lbs, $r_{v,g} = 14$ for $39,000$ lbs $< g \leq 57,000$ lbs, and $r_{v,g} = 18$ when $g > 57,000$ lbs.

Suppose that μ_v is the VMT for vehicle class v. The tire excise tax attribution ratio for vehicle v is

$$\text{\% of tire excise tax for Vehicle Class } v = \frac{\sum_{g} \alpha_{v,g} r_{v,g} \mu_v}{\sum_{i \in V} \sum_{g} \alpha_{i,g} r_{i,g} \mu_i}. \tag{A.7}$$

A.3.6 Weight-Mileage Fees

Weight-mileage fees are allocated based on VMT for each truck class and each RGW range. The data requirements are: [1] the vehicle mile travelled (VMT) for each vehicle class, [2] the registered gross weight distribution for each vehicle class, [3] the tax rate for each RGW range, and [4] the tax collected.

Let $\alpha_{v,g}$ be the fraction of vehicle v with RGW g and r_g is the tax rate per mile for vehicle with RGW g. Suppose that μ_v is the VMT for vehicle class v. The weight-mileage fee attribution ratio for vehicle v is

$$\text{\% of Weight-mileage fees for Vehicle Class } v = \frac{\sum_{g} \alpha_{v,g} r_g \mu_v}{\sum_{i \in V} \sum_{g \in G} \alpha_{i,g} r_g \mu_i}. \tag{A.8}$$

A.4 Expenditure Allocation Methods

In this section, we present the allocation methods used in MHCAT for each expenditure category. Note that all allocation methods are adopted from the HCAT.

A.4.1 Gradings

The Expenditure on Gradings is allocated based on VMT for each vehicle and its operating gross weight. The data requirements for expenditure on gradings are: [1] the vehicle mile travelled (VMT) for each vehicle class and OGW class, [2] the user specified grading sharing parameter, and [3] the amount of expenditure.

Let $\gamma_G(o)$ be the grading cost sharing for vehicle weight o. Note that $\gamma_G(o)$ is increasing in o. Also, $\gamma_G(0) > 0$ and $\gamma_G(o') = 1$ for $o' \geq 70,000$ lbs. Suppose that $\mu_{v,o}$ denotes the VMT for vehicle class v with operating gross weight o. The gradings share ratio for vehicle class v is calculated as

$$\text{\% of Expenditure on Gradings for Vehicle Class } v = \frac{\sum_{o \in O} \gamma_G(o) \mu_{v,o}}{\sum_{i \in V} \sum_{o \in O} \gamma_G(o) \mu_{i,o}}. \tag{A.9}$$

A.4.2 Expenditures that are allocated based on VMT and/or PCE weighted VMT

Expenditures listed in Table A.1 are allocated based on either VMT, or PCE weighted VMT, or the weighted average of both. The data requirements for these expenditures are [1] the vehicle mile travelled (VMT) for each vehicle class and OGW class, [2] the PCE for each OGW class, [3] the amount of expenditure.

Let $\mu_{v,o}$ denote the VMT for vehicle class v with operating gross weight o and p_o denote the PCE for

Table A.1: Expenditures Allocated Based on VMT and/or PCE weighted VMT

General construction costs
Transit costs
Truck-related construction
Travel-related maintenance
Truck-mile related maintenance (VMT recommended)
Light-vehicle-related maintenance (VMT recommended)
Other-travel-related
Truck-related (VMT only)
Large truck-related (VMT only)

OGW class o. When the expenditure is allocated based on VMT, the expenditure allocation ratio is

$$\text{\% of VMT Based Expenditure for Vehicle Class } v = \frac{\sum_{o \in O} \mu_{v,o}}{\sum_{i \in V} \sum_{o \in O} \mu_{i,o}}. \tag{A.10}$$

When the expenditure is allocated based on PCE weighted VMT, the expenditure allocation ratio is

$$\text{\% of PCE weighted Expenditure for Vehicle Class } v = \frac{\sum_{o \in O} p_o \mu_{v,o}}{\sum_{i \in V} \sum_{o \in O} p_o \mu_{i,o}}. \tag{A.11}$$

Note that the heavier vehicles are responsible for more costs with PCE weighted allocation as compared to raw VMT allocation because PCE for heavier vehicles is greater than one.

A.4.3 Rest Area Maintenance Expenditure

Rest area maintenance expenditures are allocated based on weighted VMT. The weight for each vehicle class can be determined by the usage. For example, the VMT for each class of trucks is multiplied by a factor of 1.3 in the default setting. The data requirements for rest area expenditures are [1] the vehicle mile travelled (VMT) for each vehicle class and OGW class, [2] the user specified usage factor for each vehicle class, and [4] the amount of expenditure.

Let $\mu_{v,o}$ denote the VMT for vehicle class v with operating gross weight o and $f_u(v)$ denote the usage factor for vehicle v. The expenditure allocation ratio can be calculated based on

$$\text{\% of Rest Area Expenditure for Vehicle Class } v = \frac{f_u(v) \sum_{o \in O} \mu_{v,o}}{\sum_{i \in V} f_u(i) \sum_{o \in O} \mu_{v,o}}. \tag{A.12}$$

A.4.4 State Police Traffic Management Expenditures

Expenditures on state police traffic management are allocated based on VMT, PCE weighted VMT, and fatality involvement. The weights among the three factors can be specified by users. The data requirements include [1] the vehicle mile travelled (VMT) for each vehicle class and OGW class, [2] the PCE for each OGW class, [3] the number of fatality involvement for each vehicle class, and [4] the amount of expenditure.

Let $\mu_{v,o}$ denote the VMT for vehicle class v with operating gross weight o and p_o denote the PCE for OGW class o. The allocation ratios based on VMT or PCE weighted VMT can be calculated using formulation shown (A.10) or (A.11). Suppose the annual fatality involvement for vehicle class v is denoted as τ_v. The fatality-based allocation ratios can be calculated as follows.

$$\text{\% of Fatality-Based Traffic Management Expenditure for } v = \frac{\tau_v}{\sum\limits_{i \in V} \tau_i}. \tag{A.13}$$

The final allocation ratios can be calculated based on the weighted average of VMT, PCE weighted VMT, and fatality involvement ratios.

A.4.5 Axle-Related Maintenance Management Expenditures

Axle-related maintenance management expenditures are allocated based on either OGW weighted VMT, or Axle-Tire weighted VMT or axle weighted VMT. The data requirements include [1] VMT for each vehicle class and OGW class, [2] VMT for each vehicle class, axle type and axle weight, and [3] the amount of expenditure.

Let $\mu_{v,o}$ denote the VMT for vehicle class v with operating gross weight o and $\mu'_{x,z,v}$ denote the total VMT for vehicle class v associated with axle type $a_t \in \{1, 2, 3\}$ and unit axle weight a_w. When the allocation ratios are calculated based on OGW weighted VMT, they follow the formula below.

$$\text{\% of Axle-Related Maintenance Expenditures for } v = \frac{\sum\limits_{o \in O} \mu_{v,o} o}{\sum\limits_{i \in V} \sum\limits_{o \in O} \mu_{i,o} o}. \tag{A.14}$$

When the allocation ratios are calculated based on axle weighted VMT, they follow the formula below.

$$\text{\% of Axle-Related Maintenance Expenditures for } v = \frac{\sum\limits_{a_w} \sum\limits_{a_t} \mu'_{a_t,a_w,v} a_t \cdot a_w}{\sum\limits_{i \in V} \sum\limits_{a_w} \sum\limits_{a_t} \mu'_{a_t,a_w,i} a_t \cdot a_w}. \tag{A.15}$$

When the allocation ratios are calculated based on axle-tire weighted VMT, they follow the formula below.

$$\text{\% of Axle-Related Maintenance Expenditures for } v = \frac{\sum\limits_{a_w} \sum\limits_{a_t} \mu'_{a_t,a_w,v} a_t \cdot a_w \cdot t(a_w)}{\sum\limits_{i \in V} \sum\limits_{a_w} \sum\limits_{a_t} \mu'_{a_t,a_w,i} a_t \cdot a_w \cdot t(a_w)}, \tag{A.16}$$

where $t(z)$ denotes the number of tires per axle. Note that $t(z) = 2$ if $z < 6,000$ lbs and $t(z) = 4$ if $z \geq 6,000$ lbs because a heavier loaded axle has two tires on each side.

A.4.6 Flexible/Rigid Pavement Repair Expenditures

Based on the National Pavement Cost Model (NAPCOM), the flexible pavement distresses includes: [1] PSR loss, [2] fatigue cracking, [3] rutting, [4] loss of skid resistance, [5] expansive-clay-related PSR loss, and [6] thermal cracking, where [1] - [4] are load-related and [5] - [6] are non-load-related.

Similarly, the rigid pavement distresses includes: [1] PSR loss, [2] faulting, [3] loss of skid resistance, [4] fatigue cracking, [5] Spalling, and [6] Swelling, where [1] - [4] are load-related and [5] - [6] are non-load-related.

The cost allocation for pavement repair does not require running NAPCOM models. Instead, regression coefficients for cost allocation derived from NAPCOM for Minnesota are provided. These parameters include:

$shr(i)$: distress share for distress type $i \in [1, 6]$

$ashr$: load-related distress share, $ashr = 1 - shr(5) - shr(6)$

$cshr(i)$: conditional distress share for distress type $i \in [1, 4]$, cshr(i) = shr(i) / ashr

$m(i)$: regression coefficient for distress type $i \in [1, 4]$

$b(i)$: regression coefficient for distress type $i \in [1, 4]$

We are now ready to calculate allocated cost for each vehicle type. For each pavement type, let c denote the expenditure. First consider non-load-related cost. Because $shr(5) + shr(6)$ are non-load-related cost, $c \cdot (1 - ashr)$ is the total non-load-related cost. This portion of cost can be allocated based on either PCE-VMT, or VMT, or the combination of both using the method described earlier in this section.

For load-related portion of the cost ($c \cdot ashr$), it is allocated as follows. Let $Axshrs(a_w, a_t)$ be the distress share for an axle set weighted a_w with type $a_t \in \{1, 2, 3\}$. For each combination of (a_w, a_t), we calculate

$$Axshrs(a_w, a_t) = \sum_{i=1}^{4} 10^{(b(i)+m(i)\cdot log_{10}(a_w \cdot a_t))} AxVMT(a_w, a_t) \cdot cshr(i), \tag{A.17}$$

where $AxVMT(a_w, a_t)$ is the VMT for axle type a_t with weight a_w. Let

$$ESALs = \sum_{a_w} \sum_{a_t} Axshrs(a_w, a_t). \tag{A.18}$$

The load-related cost for vehicle type t is

$$LC(t) = \sum_{w} \sum_{a_w} \sum_{a_t} \frac{c \cdot ashr \cdot (\frac{Axshrs(a_w, a_t)}{ESALs})}{AxVMT(a_w, a_t)} \cdot AxVC(a_w, a_t, w, t), \tag{A.19}$$

where $c \cdot ashr \cdot (Axshrs(a_w, a_t)/ESALs)/AxVMT(a_w, a_t)$ is the cost per mile for axle type a_t with axle weight a_w.

A.4.7 New Pavement Expenditures Allocation

The new pavement cost is divided into two parts: load-related and non-load-related, where the fraction of load-related cost is

$$ashr = \frac{\text{required thickness of the pavement} - \text{minimum zero traffic thickness}}{\text{required thickness}}. \tag{A.20}$$

For non-load-related cost ($c \cdot (1 - ashr)$), the allocation is based on either PCE-VMT or VMT, or the combination of both. For load-related cost ($c \cdot ashr$), it is allocated using allocation rules for load-related pavement repair shown in the previous section.

A.4.8 Bridge Expenditures Allocation

The VMT for bridge cost allocation needs to be adjusted based on PCE and aggregates by bridge increments. Suppose that $VMT(o,v)$ is the VMT and PCE(o,v) is the PCE for vehicle v with OGW equal to o. Let $LiveDist(o,v,b)$ is the fraction of vehicle v with OGW equal to o that have live load within each designed bridge increment b. The adjusted VMT $A_V(o,v,b)$ for vehicle v with OGW o for bridge increment b is calculated based on

$$A_V(o,v,b) = VMT(o,v) \cdot PCE(o,v) \cdot LiveDist(o,v,b). \tag{A.21}$$

Suppose that $B_T(t)$ is the percentage of bridges that belong to bridge type t and $NBA(b,t)$ is the new bridge allocation share for bridge increment b or above for bridge type t. Then, the average new bridge allocation share $N_B(b)$ for bridge increment b is

$$N_B(b) = \sum_t NBA(b,t) \cdot B_T(t). \tag{A.22}$$

Let c be the expenditure on new bridge. Because all VMT with live load greater than or equal to bridge increment b are responsible for cost associated with bridges designed with bridge increment b. The new bridge cost for vehicle v is

$$\sum_b c \cdot N_B(b) \frac{\sum_{i \geq b} \sum_{o \in O} A_V(o,v,i)}{\sum_{i \geq b} \sum_{j \in V} \sum_{o \in O} A_V(o,j,i)}. \tag{A.23}$$

The special bridge cost is categorized into two parts, non-load-related and load-related, which the fraction is specified by the user. The non-load-related cost is allocated based on either PCE-VMT, or VMT, or the combination of both. The load-related cost is allocated based on rules for new bridge cost.

The bridge replacement cost is categorized into two parts: non-load-related and load-related with a user specified split of fraction. The non-load-related cost is allocated based on either PCE-VMT, or VMT, or the combination of both. the load-related cost is allocated based on new bridge cost allocation rules adjusted by the inventory rating distribution. Let $I_V(b)$ be the percentage of bridge replacements that belong to inventory rating b. The adjusted bridge replacement allocation share $N_R(b)$ for bridge increment b is

$$N_R(b) = \sum_i \frac{N_B(b)}{\sum_{j \geq i} N_B(j)} I_V(i). \tag{A.24}$$

Let c be the expenditure on new bridge. Because all VMT with live load greater than or equal to bridge increment b are responsible for cost associated with bridges designed with bridge increment b. The new bridge cost for vehicle v is

$$\sum_b c \cdot N_R(b) \frac{\sum_{i \geq b} \sum_{o} A_V(o,v,i)}{\sum_{i \geq b} \sum_{v} \sum_{o} A_V(o,v,i)}. \tag{A.25}$$

A.4.9 Wear-Related Pavement Maintenance Costs

These costs are allocated based on rules that are set for pavement repair expenditure. Hence omitted.