ABSTRACT

Title of Thesis: **SENSIBILITY OF A VMT-BASED INCREMENTAL ANALYSIS FOR BRIDGE COST ALLOCATION**

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Many methods for highway cost allocation procedures have been adopted previously by all levels of government; local, state, and federal. However, they rarely address the issue of long span bridge allocation properly, simply treating these unique structures as the typical short span bridge. This methodology can lead to grossly inaccurate results. Consequently, this thesis seeks to identify a method to be supplemented in conjunction with the commonly accepted approaches in order to address this problem and provide a thorough highway cost allocation analysis. In addition to discussion regarding the recommended procedures, alternative approaches, along with their pros and cons will be presented. Finally, results of the sensibility studies will be examined as supplemental information to ensure the accuracy of the recommended approach.

SENSIBILITY OF A VMT-BASED INCREMENTAL ANALYSIS FOR BRIDGE COST ALLOCATION

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ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average daily traffic
ENR	Engineering News Record
ESAL	Equivalent single-axle load
FHWA	Federal Highway Administration
GVW	Gross Vehicle Weight
HCA	Highway Cost Allocation
HCAS	Highway Cost Allocation Study
HUR	Highway User Revenues
LTPP	Long Term Pavement Performance
MdTA	Maryland Transportation Authority
NBI	National Bridge Inventory
NCHRP	National Cooperative Highway Research Program
PCE-VMT	Passenger-car-equivalent vehicle-miles of travel
VMT	Vehicle-miles of travel
WIM	Weigh-in-motion
3R	Pavement Reconstruction, Rehabilitation, Resurfacing

CHAPTER 1.0: INTRODUCTION

1.1 General Background

Equality means being equal or fair to all parties. This is the general concept behind any Highway Cost Allocation Study (HCAS); the goal is equitable cost responsibility for each vehicle class using a transportation facility. In other words, each category of highway users should ideally contribute to highway revenues an amount in proportion to the costs they impose on the highway system. Highway cost responsibility is a concept that has become increasingly significant during the past few decades, leading to increased frequency of HCAS at both the federal and state levels.

In 1997 the U.S. Federal Highway Administration (FHWA) released the results from its latest Federal Highway Cost Allocation study (FHWA, 1997). This cost allocation study attempted to allocate Federal costs of maintenance and preservation of highway infrastructure in proportion to the share of the costs attributable to each class of user vehicles. The results from the 1997 Federal highway cost allocation study provide a good background to the key results typical of these analyses.

As shown in Table 1, passenger vehicles accounted for about 93 percent of the estimated total vehicle miles of travel (VMT) in the United States for the year 2000, while single unit and combination trucks accounted for 3 and 4 percent of total VMT, respectively. Over two-thirds of single unit truck travel is by vehicles registered below 25,000 pounds while, among combination vehicles, 75 percent of travel is by vehicles registered between 75,000 and 80,000 pounds.

Table 2 shows the estimated cost responsibility of different vehicle classes and registered weight groups for Federal highway-related program costs funded from the Highway Trust Fund in 2000. Automobiles and combination trucks are responsible for the greatest shares of Federal highway costs, followed by pickups and vans, single unit trucks, and buses. There are large differences in cost responsibilities among single unit and combination trucks at different weights. The Federal cost responsibility per mile for single unit trucks registered at 25,000 pounds or less is only 13 percent of that for single unit trucks registered over 50,000 pounds. Combination trucks registered at 50,000 pounds have only 40 percent of the cost responsibility per mile as compared to combinations registered at 80,000 pounds, and less than 20 percent of the cost responsibility per mile as compared to combinations registered over 100,000 pounds. While combination vehicles of over 80,000 pounds registered weight account for only 3 percent of total truck travel, they are responsible for almost 8 percent of total truck cost responsibility. Single unit trucks registered at over 50,000 pounds account for 4 percent of total truck travel but 11 percent of total truck costs. The heaviest single units and combination trucks combined account for only 7 percent of truck travel but almost one-fifth of total truck costs.

In summary, while passenger vehicles account for 93% of total VMT in the United States and trucks account for 7%, the 1997 Federal Highway Cost Allocation Study apportioned only 60% of the cost responsibilities to passenger vehicles and the remaining 40% to trucks. Broadly similar trends can also be expected for the long span bridge facilities owned by the Maryland Transportation Authority.

Table 1. Total 2000 Travel and Number of Vehicles by Class and Registered Weights (FHWA, 1997)

Vehicle Class/ Registered Weight	**Vehicle Miles of Travel (millions)**		**Number of Vehicles**	
Passenger vehicles	**Total**	**Percent**	**Total**	**Percent**
Autos	1,818,461	67.5%	167,697,897	70.0%
Pickups/Vans	669,198	24.8%	63,259,330	26.4%
Buses	7,397	0.2%	754,509	0.3%
Total	2,459,056	92.6%	231,711,736	96.7%
Single Unit Trucks				
≤25,000 pounds	56,451	2.1%	4,126,241	1.7%
25,001 - 50,000 pounds	18,631	0.7%	1,352,441	0.6%
>50,000 pounds	8,018	0.3%	491,745	0.2%
Total	83,100	3.1%	5,970,431	2.5%
Combination Trucks				
≤50,000 pounds	6,744	0.3%	253,022	0.1%
50,001 - 70,000 pounds	16,685	0.4%	225,347	0.1%
70,001 - 75,000 pounds	5,926	0.2%	94,509	0.0%
75,001 - 80,000 pounds	86,176	3.2%	1,295,973	0.5%
80,00 - 100,000 pounds	3,879	0.1%	64,365	0.0%
>100,000 pounds	2,279	0.1%	37,788	0.0%
Total	115,689	4.3%	1,971,435	0.8%
Total Trucks	198,789	7.4%	7,941,435	3.3%
Total All Vehicles	2,693,845	100%	239,653,170	100%

Table 2. 2000 Federal Highway Cost Responsibilities by Vehicle Class and Weight Group ($ Millions; FHWA, 1997)

Vehicle Class/ Registered Weight	Total Cost Responsibilities	Cents per Mile	Shares of Total
Autos	$11,898	0.65	43.8%
Pickups/Vans	$4,198	0.65	15.4%
Buses	$190	2.57	0.7%
All passenger vehicles	$16,287	0.66	59.9%
Single Unit Trucks			
≤25,000 pounds	$985	1.75	3.6%
25,001 - 50,000 pounds	$842	4.38	3.1%
>50,000 pounds	$1,083	14.60	4.0%
All single units	$2,910	3.51	10.7%
Combination Trucks			
≤50,000 pounds	$187	2.78	0.7%
50,001 - 70,000 pounds	$454	4.25	1.7%
70,001 - 75,000 pounds	$370	6.25	1.4%
75,001 - 80,000 pounds	$6,103	7.08	22.5%
80,001 - 100,000 pounds	$484	12.50	1.8%
>100,000 pounds	$378	16.60	1.4%
All combinations	$7,978	6.90	29.4%
All trucks	$10,888	5.48	40.1%
Total	$27,175		

1.2 Bridge Specific Background

The general premise behind bridge design and construction is that bridges must be strong enough to safely accommodate all vehicular traffic. Typically, heavy truck loads are the critical element of consideration in the design of highway bridges. However, as the span length of a bridge increases, the critical design element transitions from the live loads acting on the structure to the dead load of the structure itself, consequently resulting in drastically different allocation percentages. In the 1997 Federal Highway Cost Allocation Study state guidelines, specific cost allocation percentages for various weight classifications for short span bridges were provided along with the claim that state-to-state variations were negligible and thus individual bridge investigations would be an added, unjustified, expense. These allocations are shown below in Table 3 for bridges with a maximum span length of 55 feet or less designed to withstand HS20 design loads. Bridges with maximum span lengths exceeding 55 feet are classified as long span structures by the FHWA and should not be allocated by the same percentages.

Table 3. New Bridge Allocation Percentages for HS20 Structures Spanning less than 55 Feet (FHWA, 1997)

Increment	Percent Allocation	Design Load (kips)
All Vehicles	83.19	N/A
H2.5+	4.19	5
H5+	2.41	10
H10+	3.04	20
H15+	2.44	30
HS15+	4.73	54
HS20+	0.00	72
Total	100.00	

Unfortunately, the allocation values above are not applicable to the majority of bridges in the nation and are not consistent with the HS-20 design increments, which will be discussed in Section 4.5. As can be seen in Figure 1 only 21% of bridges can be allocated as short span structure. This fact exacerbates the need for an accurate and efficient methodology by which larger span bridges can be allocated. Such is the case with the Millard E. Tydings Memorial Bridge, the focus of this study. Table 4 below displays the results of the 2005 FHWA National Bridge Inventory (NBI) in relative maximum span length categories. Tydings Memorial Bridge falls in the 450' – 500' category.

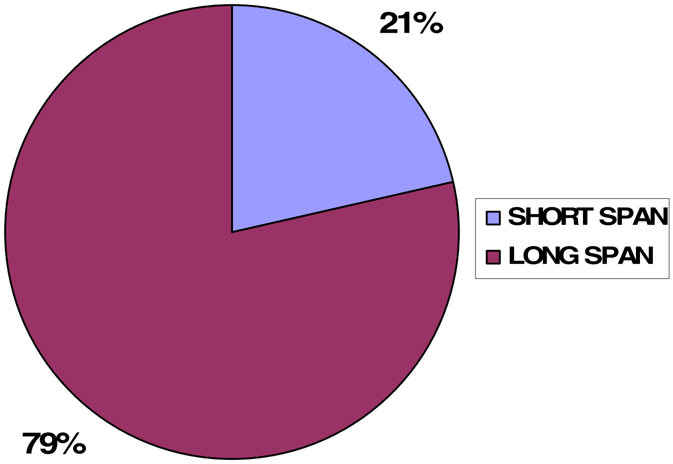

Figure 1. Short Span VS Long Span Structures

Table 4. Number of U.S. Bridges by Span Length

UNITED STATES BRIDGE INVENTORY AS OF DECEMBER 2005											
Max. Bridge Span Length (ft)	< 50'	50'-100'	100'-150'	150'-200'	200'-250'	250'-300'	300'-350'	350'-400'	400'-450'	450'-500'	> 500'
Number of Bridges	140575	162099	112366	84414	68875	42609	32656	22624	12369	7246	16385
Percentage of Total	**20.02%**	**23.08%**	**16.00%**	**12.02%**	**9.81%**	**6.07%**	**4.65%**	**3.22%**	**1.76%**	**1.03%**	**2.33%**

1.3 Purpose of Study

The study described in this report is a portion of the work utilized in the pilot implementation of a HCAS submitted to the Maryland Transportation Authority. The afore-mentioned facility studied in this report is the John F. Kennedy Memorial Highway, in particular, the Millard E. Tydings Memorial Bridge. The specific goals of this study are to:

1. Develop/refine the HCA methodology for specific application to long span bridges operated by the MdTA;
2. Illustrate the implications, if any, of the HCAS results for the existing toll structure on the John F. Kennedy Memorial Highway;
3. Confirm the methodology employed is accurate through multiple statistical analysis models; and
4. Provide the basis for application of the bridge cost allocation methodology to the other facilities owned and operated by the MdTA.

1.4 Organization of Thesis

This thesis consists of six chapters and provides a generalized methodology, analysis results, and recommendations that can be used as the basis for extension of the bridge cost allocation to other MdTA facilities. The thesis is organized as follows:

- **Chapter 1** provides a brief overview of HCAS issues and the goals of the thesis.
- **Chapter 2** summarizes existing methodologies used for HCA and describes the specific quantities used to allocate costs. There is also a summary of previous cost allocation studies at both the federal and state levels, as well as selected studies from abroad.
- **Chapter 3** provides background information about the Millard E. Tydings Memorial Bridge, in addition to an outline of the details for the analysis procedure adopted for allocating bridge costs.
- **Chapter 4** provides a discussion of the allocators used in the study, as well as an explanation of the statistical methods utilized in the analysis.
- **Chapter 5** presents the results of the study.
- **Chapter 6** summarizes the conclusions from the study through a means of comparison of the statistical results with those of the JFK pilot study.
- **Appendices** provide the following supplementary information:
    - A Glossary of Terms
    - Miscellaneous Data used for the Analysis
    - Sensitivity Analysis results from the JFK pilot study
    - Bibliography

CHAPTER 2.0: REVIEW OF HCAS STUDIES, METHODS & GENERALIZED METHODOLOGY

2.1 Introduction

State and federal agencies have long attempted to quantify highway agency costs associated with each vehicle class. Various highway cost allocation (HCA) methodologies have been proposed to accomplish this, each with its own respective advantages and disadvantages. Ultimately, each of these methods strives to achieve either equity or efficiency. Equity refers to fairness of the highway user tax structure, while efficiency is concerned with minimizing the overall costs generated through roadway usage. In either case, the approach for achieving the goal varies by methodology. The following section summarizes the capabilities, shortcomings, and applications of the most common HCAS methodologies, including those currently used in practice as well as alternative proposed approaches. These methodologies are organized based on whether their focus is equity or efficiency. A review of previous HCAS is summarized in Sections 2.4 through 2.6.

2.2 Equity Based Approaches

Benefits-Based Method

Benefits-based methods attempt to assign cost responsibility to highway users as well as non-users that receive benefits from the highway. The basic premise of this method is that the greater the benefit received by a particular user or non-user, the greater the share of fees that should be paid by that user or non-user. Examples of non-user benefits include increases of property values accruing to property owners when local roads are improved to increase the accessibility of others to the area. Although the property owner may not directly use the roadway (e.g., an absentee landlord), one can nonetheless argue that benefits are indirectly received in the form of increased property rents or sale prices. Thus, some share of the highway costs should be imposed to those particular property owners regardless of their utilization of the roadway. This method was developed during the 1950s and received increased support in the 1960s. Although the first major Federal cost allocation study sent to Congress in 1961 used a cost occasioning basis for allocation, an entire section, Part VI, was dedicated to the analysis of benefits. However, quantifying benefits, whether direct or indirect, obviously presents great difficulties and can rarely be accomplished thoroughly. Even if one is able to partially quantify certain benefits received by a particular user or non-user, there is a valid question as to whether this incomplete consideration of benefits will inadvertently produce biased—i.e., inequitable—results. The uncertainty and subjectivity in quantifying benefits, coupled with the fact that detailed information on actual highway costs are generally much more readily available, has ultimately led to the abandonment of the benefits-based approach. Nevertheless, it is still considered as a feasible alternative to the other widely accepted methodologies.

Cost-Occasioned Methods

The cost-occasioned methods allocate highway costs based on the relative roadway damage caused by a particular vehicle class. The two most common cost-occasioned HCA approaches are the Incremental and Federal approaches.

Incremental Approach

The premise behind this approach is that the majority of highway costs can be analyzed in an incremental fashion. Basically, this means that the costs are examined on an "as needed" basis. For instance, a small passenger vehicle requires a minimal pavement structure, while a fully loaded commercial freight truck requires a greater pavement thickness. The cost-occasioned approach allocates the costs associated with increased pavement thickness, changes in roadway dimensions, etc. to the vehicle class necessitating these design changes—i.e., the commercial truck. This approach can also be easily applied to the analysis of both short and long span bridges.

Complications arise because certain costs are not easily allocated, such as a climbing lane along steep inclines on interstate roadways. One can easily argue that if there were no trucks then there would be no need for the extra lane. One can alternatively argue that if there were no passenger vehicles then there also would be no need for the extra lane. Thus, which vehicle class actually occasions such costs is not always obvious. This presents just one example that exposes the inherent flaws with this methodology. Another criticism of the incremental approach is the claim that heavy vehicle classes experience unfair “economies of scale.” The argument for this is that initial costs for a minimum pavement thickness are high, while the incremental costs for increases in pavement thickness are comparatively low since pavement strength increases exponentially with thickness. Thus, the marginal costs associated with an additional heavy axle load are underestimated. This unfair allocation is eliminated in the Federal approach (described in the next section), thereby mitigating this criticism.

Despite these complications, the incremental approach is generally considered to be fundamentally sound. It is widely accepted and has been employed by most state agencies and the Federal Highway Administration. It also has the advantage of consistency in application to both bridges and pavements with relatively few exceptions.

Federal Approach

This approach, which was developed during the 1979-82 Federal HCAS and subsequently refined in the 1997 Federal HCAS, is a compilation of various approaches. Common costs, which are those costs that cannot be assigned to any one vehicle class, are distributed evenly among all vehicle classes based on VMT; this is similar to how common costs are treated in the incremental approach. Examples of common costs include right-of-way costs and maintenance and rehabilitation for weather related damage, among others. Load-related pavement costs are allocated based on the relative contribution of each vehicle class to the load-induced damage to the pavement. Load-related bridge costs are allocated using the incremental methodology.

The Federal approach is sometimes called a “consumption” approach, since it attempts to allocate costs of roadway elements based on the deterioration caused by each vehicle class. Generally, the Federal and Incremental approaches are the only two methodologies that have been widely adopted by the HCAS community. Although the Federal approach received criticism from the trucking industry because it generally assigns more costs to heavy vehicles, the unfair and incorrect assignment of costs in the Incremental approach (due to the “economies of scale” issue) has caused it to fall into disfavor to the point where the Incremental approach is no longer supported even by most trucking advocates when allocating pavement expenditures. However, the Incremental approach is valid for bridge allocation procedures.

2.3 Efficiency Based Approaches

Many variations of efficiency-based cost allocation approaches exist. However, all can be generalized into one method, marginal cost pricing. The other methods, which all share the same basic efficiency premise as the Marginal Cost approach, include the Efficient Pricing and the Production-Function approach. Since the variations of the principles in each of these studies are small, only the Marginal Cost method is summarized here.

Marginal Cost Method

The marginal cost method considers three basic roadway usage costs incurred by each vehicle class: operational costs, congestion costs, and social or external costs. Data limitations are usually the main obstacle to allocating many of these costs. Operational costs—i.e., the costs for pavement and bridge construction, maintenance, and rehabilitation—are the easiest to quantify. Operational costs are the only costs considered in the incremental and Federal approaches. Calculation of user delay and other costs due to congestion is far more difficult and contentious. Costs of environmental and social impacts from roadway usage are arguably the most difficult to quantify. Despite these data issues, the major appeal of the marginal cost method is that it is most closely related to economic principles. The principles of economic efficiency imply that if highway users are charged for each trip according to the total costs they incur (whether to themselves or others), they will not make trips in which the costs outweigh the benefits received. The end result will be maximized benefits to the society as a whole. However, as appealing as this concept is from a theoretical viewpoint, its severe data requirements limit its practical usefulness and implementation.

Table 5 provides a summary of the applicability of the various HCAS approaches to different cost categories. This summary is a combination of information taken from the 1997 FHWA HCAS and the 1990 Trucking Research Institute Study.

Table 5. Applicability of Methods by Category of Cost Responsibility

	HIGHWAY COST ALLOCATION METHOD			
CATEGORY OF COST RESPONSIBILITY	**FEDERAL**	**INCREMENTAL**	**BENEFITS-BASED**	**MARGINAL COST**
Total	▨	▨	▨	▨
All Capital	▨	▨	Most	
New Pavement	▨	▨	▨	
Pavement Rehabilitation	▨	▨	▨	▨
New Bridges	▨	▨		
Replacement Bridges	▨	▨		
Major Bridge Rehabilitation	▨	▨		
Bridge Repair	▨	▨		
Grading	▨	▨	▨	
Other Capital	▨	▨		
Maintenance				Part
Administration				
Congestion				▨
Environment				▨

Sources:
Trucking Research Institute – Rationalization of Procedures for Highway Cost Allocation Studies (October 1990)
Federal Highway Administration HCAS (1997)

2.4 Summary of Previous HCAS

Approaches used in prior State and Federal HCAS are summarized in this section. Table 6 lists those states that have completed a HCAS within the past 25 years (approximately), as well as other key information.

Table 6. Summary of Previous HCAS

STATE	HCAS YEARS COMPLETED	METHOD	KEY ALLOCATORS
Arizona	1993 Not Available, 1999 Update	Federal	VMT, Axle-Load, Gross Weight
Arkansas	1978	Incremental	
California	1987, 1995 Planned, but not conducted	Federal/Incremental	VMT
Colorado	1981, 1988	Federal	VMT, Truck-VMT, ESAL's, Ton-Miles
Delaware	1992, 1993	Federal/Incremental	VMT, PCE-Miles, ESAL, Axle Miles, Registrations
Florida	1979	Incremental	VMT, ESAL's, Axle Miles
Georgia	1979, 1982	Incremental	VMT, GVW, ESAL, Axle Miles Traveled
Idaho	1987, 1994, 2002	Prospective Cost-Occasioned	VMT
Indiana	1984, 1988 Update, 1989, 2000	Incremental	ESAL
Iowa	1983, 1984	Federal	ESAL, Ton-Miles, AMT, PCE, VMT
Kansas	1978 or 1980, 1985	Hybrid	
Kentucky	Early 1980s, 1992, 1994, 1999	Federal	VMT, ESAL-VMT, PCE-VMT, Axle Miles
Maine	1982, 1989	Hybrid	VMT, ESAL's, PCE, Delphi, TMT, Standard Vehicle Equivalent
Maryland	1989		
Minnesota	1990	Federal/Incremental	VMT, Truck-VMT
Mississippi	1980	Incremental	VMT, Truck-VMT
Missouri	1984, 1987, 1990	Federal	Vehicle Size, Weight, VMT
Montana	1992, 1999, One being worked on now	Federal	VMT, ESAL-MT, AMT
Nevada	1984, 1985, 1988, 1990, 1992, 1994, 1999	Incremental	ESAL's, VMT, Axle Miles, Ton-Miles
North Carolina	1983	Federal	PCE, ESAL's, VMT, Weighted Axle Miles
Ohio	1982	Federal/Incremental	VMT
Oregon	1937, 1947, 1963, 1974, 1980, 1984, 1986, 1990, 1992, 1994, 1999, 2001, 2003, 2005	Federal/Incremental	VMT
Pennsylvania	1989, 1990	Federal	ESAL, PCE, VMT, GVW
Texas	1984, 1985, 2000		
Vermont	1990, 1993 Supplementary Report	Federal	VMT, ESAL's
Virginia	1992	Federal	ESAL's, VMT, ADT
Wisconsin	1982, 1992	Federal	ESAL, VMT, PCE, Ton-Miles
Wyoming	1981, 1999	FHWA software	VMT, Vehicle Size, Horsepower Weight

States Not Listed: Alabama, Alaska, Connecticut, Hawaii, Illinois, Louisiana, Massachusetts, Michigan, Nebraska, New Hampshire, New Jersey, New Mexico, New York, North Dakota, Oklahoma, Rhode Island, South Carolina, South Dakota, Tennessee, Utah, Washington, West Virginia

Source:

2005 Oregon HCAS

A quick scan of Table 6 shows that the most utilized methods are those based on "cost-occasioning," i.e., the Federal and Incremental Approaches. This does not imply any lack of validity of the Benefits-Based and Marginal Cost methods, but rather it highlights the inherent difficulties associated with the implementation of these methods. As a consequence, no study has implemented either of these methods in recent years.

The following section has been taken directly from the 2005 Oregon HCAS to provide a brief insight into the methodologies used by previous State and Federal HCAS as a means for comparison.

2.5 State HCAS

Arizona 1999 HCAS Update

Arizona attempted to use the federal approach for its HCAS. However, data inputs that the federal model requires were not readily available for the state. As an alternative, Arizona developed a simplified model intended to provide reasonable estimates of cost responsibility ratios. The simplified model uses readily available data and can be implemented by state DOTs without the assistance of external consultants.

The Simplified Model uses revenue data obtained from the ADOT Finance Department. In essence, the Model uses an average of annual revenues for the forecast period to make the allocation to vehicles and weight classes. Fuel revenues were allocated based on VMT and relative fuel efficiency of vehicle and weight classes. The motor carrier tax was assigned to commercial vehicles based on the proportion of registrations in each category weighted by the differential in motor carrier fees assessed by weight. The vehicle license taxes, registration fees, and other miscellaneous taxes and fees required the addition of external data sets and a more detailed breakdown of the latter two categories in order to make an accurate allocation. This model allocated the greatest portion of highway user revenues to autos and pick-ups followed by a combination of trucks, single unit trucks, and buses. Revenues generated by the latter two categories reflect a higher incidence of reduced fee tax status among registered vehicles. In most cases, the results of the Simplified Model revenue allocation by vehicle class were close to the results produced by the Cost Allocation Model.

Arkansas 1978 Financial Program with Cost Allocation

In the 1978 Arkansas Report, costs were allocated using incremental and cost function methodologies. The cost-function method for distributing highway user responsibility among various vehicle classes was based on an assessment of highway use benefits; in other words, every cost item related to the highway facility is classified by the purpose it serves. The cost function method ultimately assigned responsibilities per vehicle that were generally higher than incremental responsibilities for all but the higher gross registered weight classes.

California 1987 HCAS

California used multiple approaches to allocate costs for ten vehicle classes. For capital outlay and project support, the State applied the cost-occasioned and incremental methods. Maintenance costs were allocated using a hybrid of two pavement allocation alternatives: a survey of Caltrans maintenance experts and an analysis of actual pavement maintenance experience. Operations, program development, administration, and miscellaneous Caltrans expenditures were considered common costs and were allocated based on VMT; highway-related expenditures by other state agencies were also considered common costs and allocated similarly. California Highway Patrol costs were allocated based on VMT for vehicles covered by different programs, and Department of Motor Vehicles' costs were allocated based on vehicle registrations and drivers' licenses.

Colorado 1988 HCAS and Tax Alternatives Study

Colorado's HCAS utilized a traditional cost-occasioned approach and based its analysis on established relationships between vehicle characteristics and cost items:

- Road pavement design and damage criteria were based on vehicle axle load.
- Bridge design was largely based on vehicle gross weight.
- Grading and drainage costs were affected by the steepness of grades, which, in turn, were affected by vehicle power-to-weight ratios.
- Some maintenance costs were not affected by traffic, some items vary with traffic, and some vary with vehicle weight.
- Most residual costs (such as right-of-way, roadside improvements, and administration, CDOH) were not related to distinct vehicle characteristics.

Construction and reconstruction activities were analyzed in an identical manner. Twelve-foot lanes and shoulders of various widths were viewed as necessities regardless of the percentage of trucks using a road facility.

Delaware 1992 HCAS

The Delaware approach combined the attributes of the marginal cost-marginal benefit and cost-occasioned methods with the two methods of allocating roadway pavement costs: the incremental and the minimum thickness method. The Delaware study employed only nine classifications of vehicles; the basic cost allocators are presented below along with the specific combinations of cost allocators used for various categories of highway system costs discussed in the study.

Allocators of common costs:

- Percentage distribution of registrations by vehicle class
- Daily vehicle miles traveled by vehicle class and major type of road

Cost-Occasioned Allocators:

- PCE Miles traveled (VMT for each vehicle class multiplied by the PCE per vehicle in each class)
- ESAL Miles Traveled (VMT for each vehicle class multiplied by the respective ESAL values in highway design and construction for each vehicle class)
- New Bridges. Use of the incremental method in the structural analysis of bridges as found in the Pennsylvania Transportation Institute's study, "A Preliminary Pennsylvania Highway Cost Allocation Study"
- Bridge Replacement. Based upon ten DelDOT bridge replacement projects over a three-year period. Costs allocated to vehicle classes by all components of the bridge sufficiency rating.

Florida 1979 HCAS

Florida's Department of Transportation conducted a HCAS in 1979 and utilized a distribution based upon vehicle classification and VMT for the highway system.

Georgia 1979 HCAS

Based on the Iowa 1973 HCAS and the 1964 Federal HCAS, Georgia's 1979 HCAS used the traditional cost-occasioned approach and applied the incremental approach for pavement cost allocation. The annual construction costs were developed based on the lifespan of various highway components; administrative, engineering, and supervision costs were also included and allocated to vehicle types. For the most part, the system used for allocating costs followed the Federal method.

Idaho 2002 HCAS

Idaho's HCAS methodology used the cost-occasioned approach. Construction, maintenance, and other projected expenditures were allocated among detailed vehicle categories based on various vehicle characteristics—including VMT, axle weights and travel patterns—broken down by vehicle class.

Indiana 1988 HCAS

Similar to its 1983-84 study, Indiana's 1988 HCAS used the incremental or consumption method for allocating costs to highway construction, bridge construction, rehabilitation, and maintenance cost allocation. The Indiana HCAS followed the 1986 AASHTO Guide and required extensive data on highway traffic, highway expenditures, and user revenues.

To allocate costs, each expenditure item was examined to determine the proportions of attributable and non-attributable costs. Next, appropriate cost-allocators were used to distribute those costs among vehicle classes. Finally, the study examined the sources of revenues paid by Indiana highway users and then apportioned the revenue amounts by vehicle class.

Iowa Guidelines for Allocating Highway System Costs 1983

Iowa's HCAS followed the federal approach to allocate the cost burden among seven vehicle classes. Iowa used the cost-occasioned approach to allocate Highway Transportation Plan alternatives and program expenditures or needs. Additionally, the State used the efficiency-based approach to allocate the full social costs of highways in a way that promoted supply-demand equilibrium.

For pavement cost allocation, Iowa replaced the incremental method with a "uniform traffic removal" technique that distributes the benefits of scale economies among all vehicle classes.

Kentucky 2000 HCAS Update

The Kentucky HCAS used a traditional cost-occasioned approach to allocate fixed and variable costs among each vehicle class. The Kentucky HCAS utilized ESAL-VMT and PCE-VMT to allocate costs. As in the 1982 Federal HCAS, the study allocated grading and draining costs to support all vehicle classes according to VMT. Additionally, the study used ESAL rather than the National Pavement Cost Model (NAPCOM) to allocate pavement-resurfacing costs among vehicle classes. Finally, the Kentucky HCAS method allocated costs for new construction or improvements to relieve traffic congestion using VMT on existing vehicles.

Maine 1989 HCAS

Maine’s HCAS was based on an expenditure allocation approach that examined expenditure shares from state and federal dedicated highway funds. This particular study analyzed user revenues and expenditures for the base period (1986-1987) and a future period (1990-1991) but did not examine the true costs of all highway consumption. Expenditures included administrative costs of vehicle registration, fuel taxation, purchase of equipment and facilities for weight enforcement, and a portion of state police outlays. Expenditure shares were determined for five major expenditure areas: maintenance, highway construction, bridge construction, local assistance, and other outlays. These expenditures, in turn, were allocated using VMT, ESALs, PCEs, TMT, Standard Vehicle Equivalent, the Delphi method (Research technique that collects expert opinions and uses the consensus to quantify or otherwise delineate a subject area which cannot be reliably quantified in any other way), overhead, and other miscellaneous allocators. Maine’s study involved intensive analysis of the relationship between vehicle classes and expenditures and relied on review of recent studies and discussions with key professionals.

Due to its time constraints, this study emphasized individual vehicles and average miles driven for each vehicle class when making intra-class equity comparisons. Pavement, structure, geometric cost responsibility, and administrative program expenditures were treated the same way as in the federal method.

Minnesota 1990 HCAS

While the Minnesota HCAS mostly used the traditional cost-occasioned approach, it also applied the federal method in pavement and bridge cost analysis because it was more widely accepted and used in recent studies and better reflected current highway research and design practice. The federal method for pavement cost allocation was based on the minimum pavement thickness method and the pavement consumption method while bridge repair costs were allocated to vehicle classes in proportion to VMT.

Mississippi Cost Allocation Based on Vehicle Size 1980

The Mississippi HCAS used the incremental approach to allocate costs. The study assumes that allocations for Mississippi would be the same as those made for California (27.3% for construction and engineering and 4.6% for right of way), and study results were compared with Georgia's 1979 HCAS.

Missouri 1990 HCAS

Missouri's HCAS used the traditional cost-occasioned approach with an incremental pavement cost analysis. This study considered the factors of vehicle size, vehicle weight, and miles traveled by the various vehicle registration classes and the relationship between the costs and the factors associated with each class.

Montana 1999 HCAS Update

The Montana HCAS used a cost-occasioned approach and performed analysis using algorithms developed specifically for the study and cost allocation software developed by the FHWA. The FHWA software generated higher equity ratios for personal vehicles relative to trucks than were calculated using the study-specific algorithms; this difference was attributed to the differences in the pavement cost allocation. Specifically, the Montana algorithm allocates part of the pavement cost using VMT while the remainder was allocated using ESAL-M.

Nevada 1999 HCAS

Nevada's HCAS used a modified incremental method to allocate expenditures. This method assumes that a certain level of expenditure is required to achieve a minimum facility for a minimum design vehicle and allocates that minimum level of expenditure to all vehicles in the traffic stream. Additional expenditures required to elevate the facility to a level that met actual design requirements were allocated to vehicle classes that made increased requirements necessary. This allocation method was consistent with the federal approach and was recommended by a steering committee that represented various transportation interests.

Each vehicle class's cost responsibility was calculated by apportioning expenditures based on the allocators for a particular highway system. The responsibilities calculated for each work category and system was accumulated to obtain each vehicle class's total responsibility.

Nevada divided their vehicles into two gross vehicle classifications: basic and for vehicles more than 10,000 pounds heavy.

North Carolina 1983 HCAS

The North Carolina HCAS used the federal method to allocate highway costs. Vehicle classes were consolidated into three weight/size categories, and VMT, Axle-Miles, PCE, and ESALs were used to allocate costs.

Ohio Cost Allocation Study 1982

Ohio selected the federal (cost occasioning) approach for its HCAS. The study examined a five-year time frame and limited costs to include only government expenditures on the highway system; the allocation process did not account for external or indirect costs such as noise and air pollution. Ultimately, the study concluded that a majority of costs were pavement-related: only one out of every five dollars of attributed costs was related to the expansion of the present highway system. Common costs (75 percent) were not related to vehicle characteristics or to highway usage.

Oregon 2005 HCAS

This study is just one of many that Oregon has conducted over the past 60 years. The State now requires that a HCAS be conducted biennially to adjust the highway user tax rates appropriately. This study, like many conducted before for it, utilized the Cost-

Occasioned, Incremental Approach for allocating bridge costs and the National Pavement Cost Model (NAPCOM) for the pavement costs.

Pennsylvania Preliminary HCAS 1990

The Pennsylvania HCAS methodology uses a federal, or cost-occasioned approach, to assess the equity of highway user charges. The Pennsylvania Transportation Institute (PTI) under the direction of the Highway Cost Allocation Task Force, conducted this study to determine whether the suggested methodology warranted further development and application.

A panel of experts developed Pennsylvania's cost allocation methodology; the procedure ultimately allocated new highway construction costs based on a 50 percent common-cost share of PCE miles and ESAL miles. Residual cost assignment techniques for drainage and grading, shoulder and lane width, and new structure costs were allocated by VMT.

Engineering and administration program costs were allocated based on VMT. For maintenance costs, 30 percent of non-load-related expenditures were allocated by VMT, and 70 percent of load-related expenditures were allocated based on ESAL miles. Finally, bridge costs were allocated based on GVW, overhead expenditures were allocated by VMT, and debt service costs were based on PCE equivalents.

Texas 2000 HCAS

This study was conducted in order to refine the methods of cost allocation developed by the previous Texas HCAS, most notably for highway system costs. Unlike most HCAS, this study chose just one year, 1998, as its basis for analysis. However, like the majority of state HCAS, this study was conducted using the Cost-Occasioning methodology.

Vermont 1990 HCAS

Vermont's HCAS utilized different computer models to identify the appropriate allocation for various highway components. While the state used both the federal and the incremental method to analyze data, the study ultimately based its conclusions and recommendations on the federal method alone. Among these conclusions, the study found that Vermont's highway user taxes and fees were reasonably fair compared to most other states and the federal government. The study also concluded that motorcycles, pickups, and light trucks paid more than their cost share while buses and heavy single unit trucks underpaid, four axle combination trucks moderately overpaid, and five or more axle combinations moderately underpaid. Finally, the study concluded that if the current fee structure remained unchanged, equity ratios for automobiles would increase to greater than one while ratios for heavy trucks would decrease.

Virginia Cost Responsibility Study 1991 SJR 121

The Virginia Cost Responsibility Study, using the federal or cost-occasioned approach, first grouped vehicles into nine classes and then further combined them into five classes to compare revenues and costs. The study allocated costs using ESALs for pavements and live load moments for bridges; construction expenditures were also divided for roads and bridges. Common costs for administration, planning, research, and general maintenance were allocated by VMT.

For pavement cost allocation, ESAL-occasioned costs were allocated to each vehicle class in proportion to its ESAL contribution. Minimum pavement costs were allocated in proportion to each class's ADT contribution, and costs of widening beyond minimum required width were assigned to wider vehicles based on their representation in the traffic stream and their ESAL contributions. The study allocated bridge costs using the design-based incremental approach developed for the 1982 FHWA HCAS and expanded in the 1988 Heavy Vehicle Cost Responsibility Study.

Wisconsin 1982 HCAS

Wisconsin used the traditional cost occasioned approach by establishing relationships between specific vehicle characteristics and particular cost categories. Highway expenditures were distributed among eight highway categories, and the general allocation procedure was quite uniform among expenditure items. First, each cost item was examined and, if applicable, divided into three portions: basic, service, and fixed. Specifically, basic reflected expenditure items themselves, service costs reflected the item’s size, and fixed costs reflected repair and restoration expenses associated with natural phenomena. Fixed costs were assigned to each vehicle class in proportion to the class variable (service plus basic) costs.

The cost responsibility for each vehicle class was determined by adding its per-mile responsibility for basic costs to its per-mile responsibility for service costs and applying an 11 percent markup to cover fixed costs. In terms of cost responsibility, motorcycles, small automobiles, and heavy tractor-trailers significantly underpaid while heavy single unit trucks, light-tractor-trailers, farm trucks, and motor homes significantly overpaid. Large automobiles, light single unit trucks, and commercial buses paid close to their full share of costs.

Wyoming 1999 HCAS for 1995-1997

The Wyoming HCAS utilized FHWA software (released in June of 1999) that was developed by Oregon’s HCAS consultant team. A WYDOT committee selected methods for allocating costs to vehicle classes based on their ability to explain each vehicle class’s contribution to particular costs. Ultimately, the study allocated highway costs based on vehicle miles, handling characteristics (i.e., vehicle size and horsepower), weights, or combinations of these factors, and new bridge costs were allocated using an incremental approach similar to the one used in the 1997 FHWA study. WYDOT chose not to include external costs, congestion, crashes, air pollution, and noise costs, in this analysis.

2.6 Miscellaneous HCAS

1985 Korean HCAS

The objective of this study was to develop the analytical methodologies for the various approaches available by which a HCAS can be undertaken. Particularly, the study developed alternative analytical procedures for three items:

- Cost Allocation
    - Two methods were developed and analyzed by the study:
        - Equity-Based approach (Cost-Occasioning)
        - Modified Equity-Based approach, which considers some of the effects of efficiency as well as equity.
- Pricing Approach
    - Based on VMT and is highly sensitive to changes in user charge structures.
- Design of User Charge Structure
    - Three steps were created for this procedure:
        - Utilizes a specific cost allocation method in order to estimate the cost responsibility of each vehicle class.
        - Application of the cost responsibility estimates for the determination of the appropriate user charge for each class
        - User charges are finalized through an equilibrium analysis of all vehicle classes and their respective user charges.

1990 Trucking Research Institute HCAS Procedure Rationalization

The purpose of this study was to evaluate the current acceptable HCAS methodologies, develop guidelines for the conduct of studies, and suggest improvements that can be made. The report analyzed the four main HCA methods, Benefits-Based, Incremental, Federal, and Marginal Cost. Ultimately, the study developed a variety of ways in which a HCAS should be conducted as well as which methodology is the most appropriate in any given situation.

1997 Federal Highway Administration HCAS

This was the first study performed by the FHWA since 1982, in which the Federal Method had been developed. The purpose of this study was to analyze the highway costs incurred by the various highway users in order to evaluate the current equity and efficiency of the user charges. Also, this study examined how changes created by the 1982 study had affected the various user classes. Cost occasioning was the principle methodology behind this study, with slight variations being incorporated from the 1982 approach. Costs were allocated in the study through the use of ESALs and PCEs. The study concluded that six changes in user fees be implemented. Among those are the elimination of the cap on the heavy-vehicle user tax, a weight distance tax, and an axle weight distance tax. This study also produced a software package to facilitate more consistent and frequent individual state highway cost allocation studies.

CHAPTER 3.0: PROPOSED HCAS METHODOLOGY FOR BRIDGE ANALYSIS

3.1 Introduction

The Millard E. Tydings Memorial Bridge is a deck truss structure that spans the Susquehanna River just north of Baltimore, Maryland. The bridge has been owned and operated by the Maryland Transportation Authority (MdTA) since its opening in 1961. This six-lane toll facility is one of seven governed by the MdTA due to the fact that at the time in the late 1950's, Route 40 was the only thoroughfare across the Susquehanna and had Federal funds been used, completion would have taken an additional seven years.

The design of this bridge met or exceeded all of the mandated bridge design requirements that existed at the time. Specifically, it was constructed for HS-20 truck loading in conjunction with the 1957 edition of the American Association of State Highway Officials (AASHTO) for highway bridges. Some other general design information is that the deck utilizes a lightweight concrete with a 115 pcf unit weight, the design temperature range is from -10° F - 120° F, and also it employs a combination of riveted as well as bolted connections.

The 13 span, 5,056 foot structure possesses a deck width of 87'-4", with 39'-0" of roadway width in each direction. The cross slope of the deck is approximately 1.56% and crowned at the center. The bridge utilizes two parallel truss structures, spaced at 45'-0" Center-to-Center and each consisting of three unique truss panel arrangements as shown in Figure 2 below. Refer to Figure 3, which was taken from the original construction plans, for a typical cross-section of the structure.

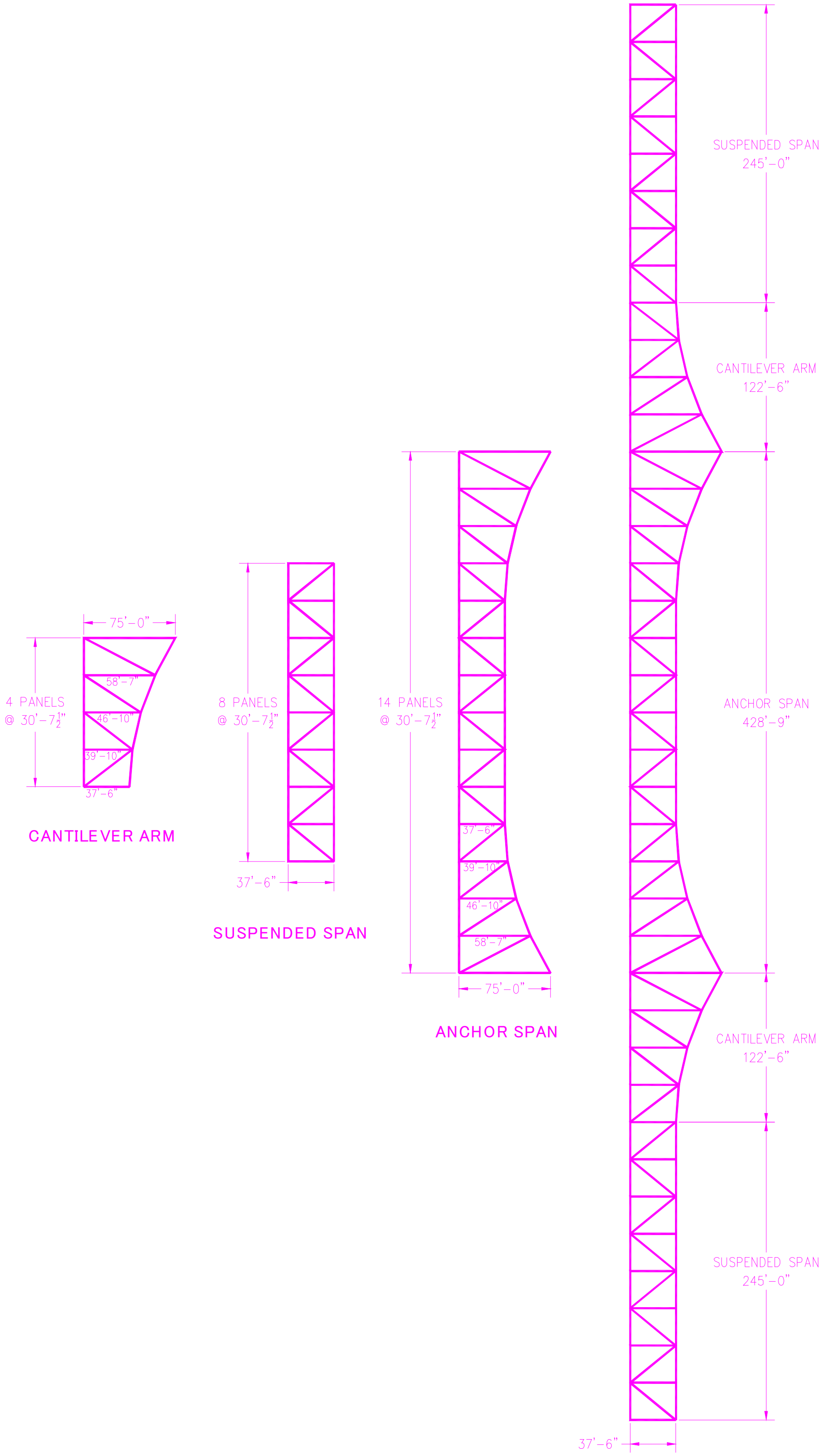

Figure 2. Truss Panel Arrangements of Tydings Memorial Bridge

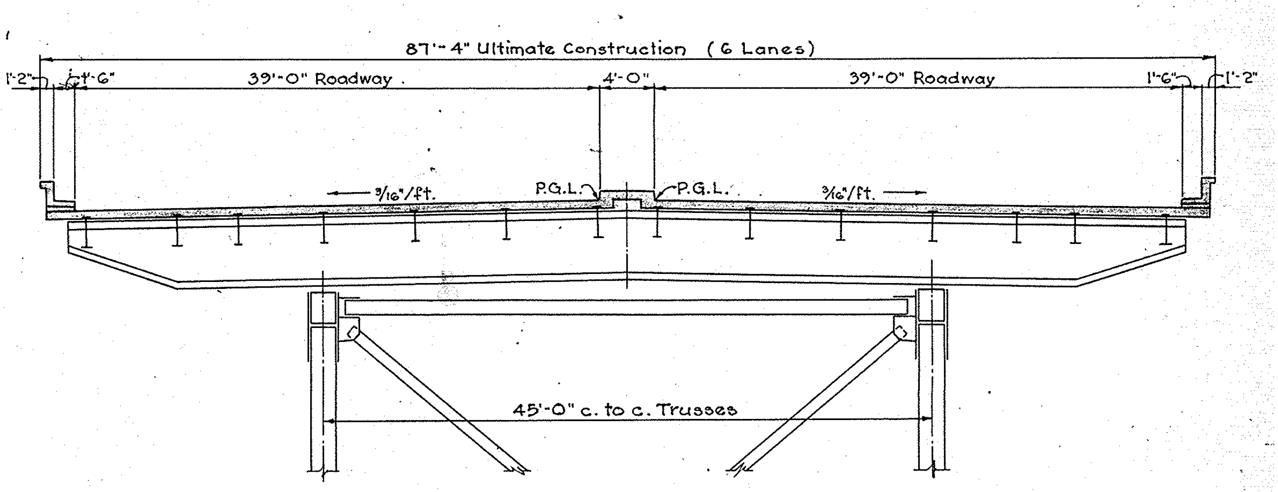

Figure 3. Cross Section of Tydings Memorial Bridge

The bridge utilizes the above configuration in a repetitive fashion and consists of a total of six suspended spans each consisting of eight truss panels spaced at 30'-7½", providing a total length of 245'. Also, ten cantilevered arms were used with 4 panels spaced at 30'-7½" make up the 122'-6" span. Finally, the bridge employs five anchored spans of seven panels at a spacing of 30'-7½" for a total length of 214'-4½". For the substructure, the bridge utilizes 13 piers, with piers 2 and 13 supporting the end of the truss suspension spans and thus carrying identical loads, while piers 3 through 12 support equal loads. The loadings used for the bridge design are as shown in Table 7 and Table 8 for the truss sections and piers, respectively. This data was also taken from the original construction documents for the bridge.

Table 7. Truss Loadings

AVERAGE DEAD LOADS - LBS. PER FOOT PER TRUSS			
ITEM	245'-0" SUSPENDED SPAN	122'-6" CANTILEVER ARM	428'-9" ANCHOR SPAN
Rdwy. Slab & Wear. Surface	4072	4072	4072
Railing & Curb	313	313	313
Floor Beam & Stringers	1016	1016	1016
Truss	1042	1964	1819
Bracing	298	402	340
Total	6741	7767	7560
Average Panel Load - Kips	**206.4**	**237.9**	**231.5**

Table 8. Pier Reactions

MAX & MIN VERTICAL REACTIONS - KIPS/TRUSS						
	PIERS 2 & 13		PIERS 3,5,7,9 & 11		PIERS 4,6,8,10 & 12	
	MAX	MIN	MAX	MIN	MAX	MIN
Dead Load	843	760	3433	3030	3433	3090
Live Load	288	-33	986	-112	986	-112
Impact	39	-4	94	-11	94	-11
Lateral 75# Wind	94	-94	951	-951	951	-951
Lateral 22.5# Wind & W.L.L.	43	-43	391	-391	391	-391
Dead Load + Live Load + Impact	1170	723	4513	2967	4513	2967
D.L. + L.L. + Imp. + 22.5# W. + W.L.L.	1213	680	4904	2576	4904	2576
D.L. + 75# Lat. Wind	957	666	4384	2139	4384	2139

Each of the afore mentioned spans consists of a variety of truss members, some in compression, others in tension, and even a few redundant members with negligible loadings. However, all members are built-up plate sections constructed with one of two possible materials, high-strength low alloy structural steel, or the typical structural carbon steel. For analysis purposes, specific section properties such as member area, yield stress, and radius of gyration are of vital importance to ensure accuracy throughout the analysis; refer to Appendix B at the end of this report for detailed truss member data.

Supported by the trusses, the bridge is comprised of just over 300 floorbeams, of three unique types. The beams are designated F1, F2, and F3. Beams F1 and F3 are plate girders with (1) 60”x5/16” web, (2) 14”x3/4”x56’ cover plates, and (4) 8”x6”x3/4” angles. F2 beams are composed of (1) 60”x5/16” web, (2) 13”x1/2”x56’-10½” cover plates, and (4) 6”x6”x9/16” angles. F3 beams can be seen at all floorbreaks, while F2’s are located at each expansion joint, and F1 beams are at all the remaining panel point locations. Carried by the floorbeams, seven different stringers were used. Designated A through G, each stringer spans the voids between the floorbeams, stiffening the entire structure. The sections utilized in the design are as shown in Table 9, while the spacing is shown in Table 10 below.

Table 9. Stringer Designations and Their Respective Sections

STRINGER	END SPANS	INTERMEDIATE SPANS
A	W24 X 76	W24 X 76
B	W24 X 76	W24 X 76
C	W24 X 76	W24 X 76
D	W24 X 76	W24 X 76
E	W24 X 84	W24 X 76
F	W24 X 76	W24 X 76
G	W24 X 84	W24 X 76

Table 10. Stringer Spacing

SPACING	DISTANCE
A - B	6' - 9"
B - C	6' - 9"
C - D	6' - 9"
D - E	6' - 3/16"
E - F	4' - 4"
F - G	6' - 9"

The preceding information is typical of that required to perform a thorough analysis for bridge allocation. Although each state has tailored its own approach in performing a bridge cost allocation study, the basic underlying principles are shared by all for new bridge construction or bridge replacement. Major and minor bridge rehabilitation costs are allocated differently still, which are primarily based on VMT values in the 1982 and 1997 FHWA studies. However, this is beyond the scope of this study, which focuses on new bridge and bridge replacement construction allocation. With this type of analysis or any other allocation study, data constraints are the biggest obstacle to development of a single universally accepted HCAS methodology. As described in the preceding chapter, the two most commonly employed methods are the Federal and Incremental approaches. The approach utilized in this study is the Incremental method as described below.

3.2 Bridge Cost Allocation Analysis Method

Unlike pavement strength design, bridge strength design is almost totally a function of the GVW acting on the structure. Possible deterioration of the bridge structure members is implicitly considered to some extent in the design process but only the heaviest vehicles have measurable effect on the fatigue life of the bridge. Furthermore, any incremental increase in the size of the heaviest vehicle will require an incremental increase in the size/strength of the bridge. Thus, the Incremental Method of cost allocation is an obvious and ideally suitable choice for analysis.

The Incremental procedure relates the increments of cost necessary to make the bridge incrementally stronger to the set of vehicles that occasion these increased costs. As previously discussed, it would be computationally impractical to allocate the cost of every single bridge in a cost allocation study. Consequently, only large span structures should be subjected to a rigorous analysis. The model works by comparing the live load moment of each vehicle class/weight group on the representative bridge (the representative bridge is described by the mean primary span length) of a specific functional class, with the moment (or force in case of truss bridges) produced by the design vehicles. This comparison allows each vehicle class/weight group to be categorized in a specific design increment, based upon whether or not its live load moment is less than or equal to the moment (or force) of the design vehicle associated with that specific design increment for that functional class.

For example, given identical vehicles on bridges of equal spans, the only distinguishing bridge characteristic data in the National Bridge Inventory (NBI) that can affect the moment produced by the vehicles is support type. Two support types, simple and continuously-supported, are considered. The representative vehicle axle loads and axle spacing are required to determine live load moments accurately; GVWs acting as point loads do not provide a realistic picture of the moments generated under trucks with different axle arrangements and weights.

Secondly, all vehicles in any specific design increment are allocated the costs associated with that increment based on their relative PCE-weighted VMT compared to the other vehicles in the design increment. PCE-VMT is considered the most equitable factor upon which to allocate incremental bridge design costs among vehicles in each increment.

The incremental design of highway bridge structures is based upon the difference in design costs which result when various classes of vehicles are applied as loadings. The total cost C_i of any structural element i is given by the expression:

$$C_i = \sum_{j=1}^{n} Q_{ij} U_j \qquad i = 1 \ldots m \tag{1}$$

in which m is the number of elements comprising the structure (e.g., deck, stringer, pier, etc.), n is the number of materials used to construct the elements, Q_{ij}, is the quantity of each j^{th} material for the i^{th} structural element, and U_j is the unit cost for that material. The quantity of material, for example the volume of steel in a bridge girder, will be a function of the classes of vehicles applying loadings to the structure. Multiplying this quantity by the unit cost gives the total cost of the element. When the vehicular classes are applied incrementally, the resulting cost differences are the incremental costs attributable to the respective vehicular classes, which caused the cost difference. Thus,

Q_{ij} represents a quantity function which is dependent upon the classes of loadings which are applied to a structural element.

Every vehicle class shares the cost of the first structural increment, which is not attributable to any vehicle loading. All vehicle classes except the lightest one pay the cost of the second increment, and so on. Each incremental cost is assigned to the responsible vehicle classes according to their respective PCE-VMT values.

Let the index *i* denote the vehicle class in increasing order of the GVW. Then the bridge costs assigned to vehicle class *i* are estimated by using the following equation:

$$U_i = \sum_{j=1}^{i} \frac{\Delta C_j}{Z_j} P_i X_i \tag{2}$$

$$\text{and} \qquad Z_j = \sum_{i=j}^{l} P_i X_i \tag{3}$$

where

U_i : cost assigned to vehicle class *i*

ΔC_j : the ^{jt}h incremental cost

P_i : the PCE of vehicle class *i*

X_i : the number of vehicle (or VMT) of class *i* per period

l : number of vehicle classes analyzed

To emphasize the general procedure described above, the following example which was produced by the 2000 Texas HCAS is provided below. In this example, three vehicles are considered, with the accompanying hypothetical VMT matrix shown in

Table 11. Suppose that the initial bridge cost is 100 units, while the second and third increments cost 10 and 15 units, respectively. Allocation of the initial bridge cost is attributed to all vehicles, since all vehicles require that base design increment, see Figure 4. Following the initial allocation, all subsequent allocations for increased increments in design strength occur. Since only two vehicles require the second design increment, only those two vehicles are responsible for the increased cost of 10 units for that increment. The same holds true for the third increment, in which only the 5-Axle vehicle requires that added strength of the bridge, thus only that vehicle should be responsible for the increased cost to produce the necessary strength. The final cost allocation values for the example, as well as a step-by-step calculation process, is shown in Figure 7. A specific description of the analysis procedure used for the evaluation of the Millard E Tydings Memorial Bridge is described in Section 3.3.

Table 11. Hypothetical VMT Matrix

	0-10 kips	11-20 kips	21-30 kips
Auto	65	0	0
2-Axle Truck	20	5	0
5-Axle Truck	0	5	5

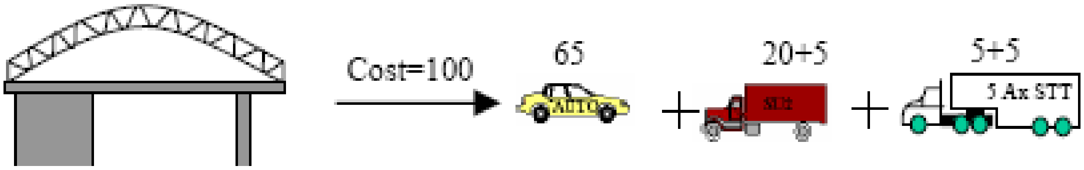

Figure 4. Example Allocation - Step 1

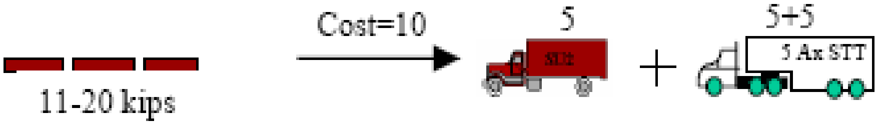

Figure 5. Example Allocation – Step 2

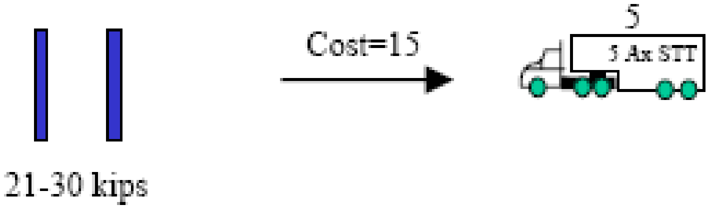

Figure 6. Example Allocation – Step 3

$$\text{Auto :}\quad 100\times\frac{65}{65+20+5+5+5}=65.0$$

$$\text{SU2 :}\quad 100\times\frac{20+5}{65+20+5+5+5}+(110-100)\times\frac{5}{5+5+5}=28.3$$

$$\text{5 Ax STT :}\quad 100\times\frac{5+5}{65+20+5+5+5}+(110-100)\times\frac{5+5}{5+5+5}+(125-110)\times\frac{5}{5}=31.7$$

Figure 7. Final Allocation Values

3.3 Bridge Specific Incremental Analysis Procedures

In general, the allocation of the Millard E. Tydings Memorial Bridge follows the procedures described in Section 3.2. The purpose of the following is to present a few of the critical evaluation steps as they pertain to this unique structure.

First, initial construction costs were obtained from old contract data, while miscellaneous rehabilitation contract expenditures were evaluated in a fashion similar to pavements and therefore neglected in the incremental analysis. Once adequate contract data had been collected, the specific contract items (i.e., Aluminum Railing, Structural Steel, etc.) were placed into one of three categories, VMT, PCE-VMT, and Incremental. All costs allocated by VMT and PCE-VMT were analyzed in exactly the same manner as the remainder of the JFK pilot study. However, those costs directly dependent upon the GVW of the traffic crossing the structure were placed into the Incremental category; these include items such as structural steel and concrete decking costs among others. In order to properly allocate these expenditures, a theoretical model of the entire structure had to be created and evaluated.

Utilizing the UMD BEST Center Truss Rating and Analysis Program (TRAP) as well as information obtained from the actual construction documents of the initial construction of Tydings, a detailed model and subsequent evaluation of the entire bridge structure was completed. Through the analysis, critical information was obtained such as the relative percentages of the live load versus the dead load as well as requirements in volume of each individual structural steel member. Refer to Table 12 for a sample of the volume requirements.

Table 12. Volume of Bridge Structural Elements as Function of Truck Loading

Diagonal Members				Volume HS-20 (in^3 or mm^3)	Volume HS-17.5 (in^3 or mm^3)	Volume HS-15 (in^3 or mm^3)	Volume HS-12.5 (in^3 or mm^3)	Volume HS-10 (in^3 or mm^3)	Volume HS-7.5 (in^3 or mm^3)	Volume HS-5 (in^3 or mm^3)	Volume HS-2.5 (in^3 or mm^3)
L	1	U	2	46122.96	44818.81	43514.67	42210.53	40906.38	39602.24	38298.10	36993.95
U	2	L	3	20808.55	20182.81	19557.06	18931.31	18305.57	17679.82	17054.07	16428.32
L	3	U	4	31376.16	30269.65	29163.14	28056.64	26950.13	25843.62	24737.11	23630.60
U	4	L	5	11839.15	11166.15	10493.16	9820.16	9147.17	8474.17	7801.17	7128.18
L	5	U	6	11841.60	11169.24	10496.88	9824.52	9152.17	8479.81	7807.45	7135.10
U	6	L	7	31369.68	30264.11	29158.53	28052.96	26947.38	25841.81	24736.23	23630.66
L	7	U	8	20812.85	20187.28	19561.71	18936.14	18310.57	17685.00	17059.43	16433.86
U	8	L	9	46113.43	44809.00	43504.57	42200.14	40895.71	39591.28	38286.85	36982.41

Using the data obtained, percentages of material requirements were found utilizing HS-20 as the baseline. Once those increments had been calculated, the actual allocation of the material expenditures could be done. In the case of the volume requirements of structural members, the percentages of each increment were used for the allocation. Substructure expenditures such as concrete footings and steel reinforcement were incrementally allocated based on the percentages of the live load versus dead load reactions at each pier. Finally, the only remaining incrementally based allocation is the concrete decking. To properly allocate these costs a minimum thickness of decking had to be assumed as a base. Once this was done, a linear based allocation from HS-2.5 up to HS-20 was done and the subsequent percentages obtained were utilized in allocating the costs. After the incremental analysis was performed using the vehicle classifications from HS-2.5 through HS-20, the relative shares of each of these classes were combined using the appropriate VMT percentages to be described in Section 4.2. Following the bridge evaluation portion of the allocation, the procedures described in Section 3.2 were followed in conjunction with those set forth for the VMT and PCE-VMT items in order to arrive at a thorough analysis and relative toll responsibility for each vehicle class, the results are presented in Chapter 5.

CHAPTER 4.0: HCAS INPUT DATA, ALLOCATORS, AND STATISTICAL METHODS USED FOR BRIDGE ANALYSIS

4.1 Introduction

As with many studies before, this study utilizes the cost-occasioned approach, meaning an incremental design and allocation procedure was used for bridge analysis and a deterioration approach was employed for pavement. As no previous HCAS have been performed on the MdTA facilities, the analysis period for the present study dates back to the beginning of accurate known facility data, 1960, with modifications made to certain variables for proper evaluation.

Proper implementation of a highway cost allocation study requires extensive and detailed information in the following categories:

- Traffic Data: Data such as vehicle weight and classification as well as vehicle miles of travel (VMT), passenger car equivalent (PCE) values by vehicle class, and vehicle/axle weight distributions.
- Expenditure Data: Costs for past construction projects, highway maintenance, and administrative overhead.

This information is described in the following subsections.

4.2 Traffic Data

The data used for this study was obtained from the MdTA toll collection records for the JFK Memorial Highway between the years of 2001-2004. This data was then used to generate approximations for VMT.

Information regarding vehicle classification and weight distributions was also gathered during the same time frame from toll facilities. Additional data on typical axle weight distributions were obtained from the analysis of FHWA Long Term Pavement Performance (LTPP) data conducted as part of NCHRP Project 1-37A. One traffic variable that has been neglected for analysis simplicity is traffic growth during the study period.

Vehicle Classifications

The Authority provided toll revenue sheets that document the traffic and revenue by vehicle class and payment method for its seven toll facilities. The current Authority classification system is axle-based with 6 categories: 2-Axle, 3-Axle, 4-Axle, 5-Axle, 6-Axle, and "Unusual" classes.

Because highway cost responsibility is so strongly influenced by vehicle axle configurations and axle weights, it is beneficial to base highway revenue and cost analyses on a wider range of vehicle configurations. Table 13 and Figure 8 describe the 20 vehicle classes used in the Federal HCAS. The Federal HCAS analysis method allows travel, Highway User Revenues (HURs), and highway cost responsibility to be estimated for up to thirty 5,000-pound weight intervals (ranging from 5,000 lbs or less to over

145,000 lbs) for each vehicle class. Frequency distributions for axle loads within each vehicle class are estimated using Maryland weigh station data and/or regional or national default distributions, e.g., as derived from the Long Term Pavement Performance database in NCHRP Project 1-37A (NCHRP, 2004).

In the end, however, cost allocations based on these more detailed vehicle and axle load distributions must be collapsed into a simpler vehicle classification for implementation at the Authority's toll facilities. The mapping between the FHWA and MdTA vehicle classification is shown in Table 14.

Table 13. Federal HCAS Vehicle Classification Categories

VEHICLE CLASS	ACRONYM	DESCRIPTION
1	AUTO	Automobiles and Motorcycles
2	LT4	Light trucks with 2-axles and 4 tires (Pickup Trucks, Vans, Minivans, etc.)
3	SU2	Single unit, 2-axle, 6 tire trucks (includes SU2 pulling a utility trailer)
4	SU3	Single unit, 3-axle trucks (includes SU3 pulling a utility trailer)
5	SU4+	Single unit trucks with 4- or more axles (includes SU4+ pulling a utility trailer)
6	CS3	Tractor-semitrailer combinations with 3-axles
7	CS4	Tractor-semitrailer combinations with 4-axles
8	CS5T	Tractor-semitrailer combinations with 5-axles, two rear tandem axles
9	CS5S	Tractor-semitrailer combinations with 5-axles, two split (>8 feet) rear axles
10	CS6	Tractor-semitrailer combinations with 6-axles
11	CS7+	Tractor-semitrailer combinations with 7- or more axles
12	CT34	Truck-trailers combinations with 3- or 4-axles
13	CT5	Truck-trailers combinations with 5-axles
14	CT6+	Truck-trailers combinations with 6- or more axles
15	DS5	Tractor-double semitrailer combinations with 5-axles
16	DS6	Tractor-double semitrailer combinations with 6-axles
17	DS7	Tractor-double semitrailer combinations with 7-axles
18	DS8+	Tractor-double semitrailer combinations with 8- or more axles
19	TRPL	Tractor-triple semitrailer or truck-double semitrailer combinations
20	BUS	Buses (all types)

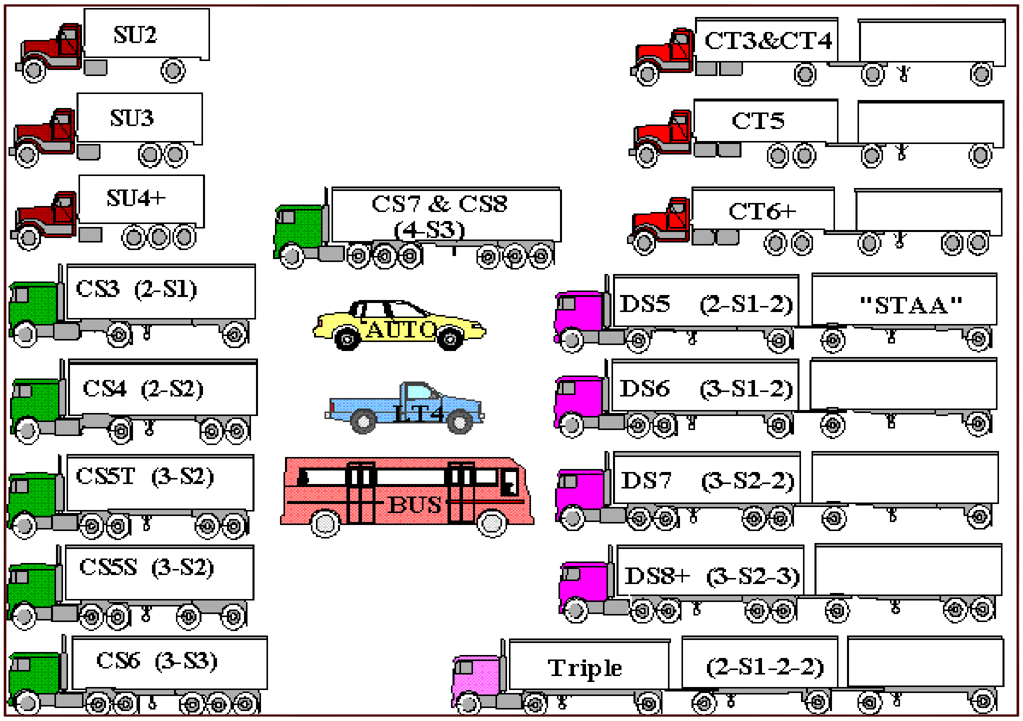

Figure 8. Federal HCAS Vehicle Classes

Table 14. Mapping of Federal Vehicle Classes to MdTA Axle Categories

PROPOSED VEHICLE CLASSIFICATION		
GROUPED CLASSES	CLASSIFICATION	VEHICLE CLASSES TO BE INCLUDED
1	2-Axle	AUTO, LT4, SU2, BUSES
2	3-Axle	SU3, CS3
3	4-Axle	CS4, SU4+, CT34
4	5-Axle	CS5T, CS5S, CT5, DS5
5	6-Axle	CS6, CT6+, DS6
6	Unusual	CS7+, DS7, DS8+, TRPL

VMT Generation Procedure

The steps followed to generate VMT data for the JFK study are as follows, please note that the entire initial VMT matrix production was done by Dr. James Saklas, who was a member of the 1997 FHWA research team:

1. Measured vehicle count data were available from toll records for the six MdTA vehicle classes (2, 3, 4, 5, 6, and 7-Axles). Estimated distributions of vehicle classes from year 2000 data specific to rural interstates in Maryland were then used to "expand" the measured vehicle count data for the 6 MdTA vehicle classes to the 24 Federal vehicle classes.
2. The 24 FHWA vehicle classes were then collapsed to the 20 classes for which we had a weight distribution matrix.
3. The weight distribution matrices were used to distribute the total number of vehicles in each of the 20 vehicle classes according to gross vehicle weight (GVW) in 5 kip increments from 0-5 kips to 145+ kips. The results after this step are the computed VMT for each of the 30 weight groups for each of the 20 vehicle classes.
4. The actual cost allocator for the HCA is VMT in percentage. This was determined by dividing the results from Step 3 by the total VMT.
5. In order to reflect the traffic numbers in the most current "Balanced Network" data, the original numbers came from the toll booth counts that were then adjusted and distributed based on Maryland rural interstate data from the year 2000. The actual VMT from the ADT data in the "Balanced Network" data was computed and then the vehicle class percentages were then adjusted accordingly.

The results from these calculations are summarized in Table 15

Table 15. VMT Data for Pilot Study Area: John F. Kennedy Memorial Highway

Maximum Weight (in kips)	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150
Auto & MCs																	
LT4																	
SU2																	
SU3	0.005%	0.003%	0.000%														
SU4+	0.003%	0.002%	0.002%	0.001%	0.001%	0.000%	0.000%	0.000%									
CS3																	
CS4	0.015%	0.009%	0.005%	0.004%	0.003%												
3S2	0.487%	0.534%	0.485%	0.378%	0.249%	0.136%	0.058%	0.032%	0.014%								
Other CS5	0.040%	0.042%	0.041%	0.039%	0.025%	0.017%	0.009%	0.004%	0.001%	0.001%							
CS6	0.001%	0.002%	0.001%	0.001%	0.001%	0.001%	0.001%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%				
CS7																	
CT4	0.000%	0.000%															
CT5																	
CT6	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%					
DS5	0.055%	0.048%	0.035%	0.019%	0.010%	0.006%	0.002%										
DS6	0.008%	0.008%	0.006%	0.005%	0.003%	0.002%	0.001%	0.001%	0.001%	0.000%	0.000%						
DS7																	
DS8																	
TS7																	
Bus																	

Legend	
2-Axle	🟦
3-Axle	🟨
4-Axle	🟩
5-Axle	🟪
6-Axle	🟥

Maximum Weight (in kips)	5	10	15	20	25	30	35	40	45	50	55	60	65
Auto & MCs	57.192%	5.116%											
LT4	9.339%	14.288%	0.329%										
SU2	0.021%	0.860%	0.777%	0.585%	0.304%	0.123%	0.043%	0.013%	0.004%	0.001%	0.000%		
SU3			0.033%	0.120%	0.122%	0.101%	0.080%	0.077%	0.060%	0.030%	0.016%	0.012%	0.008%
SU4+				0.001%	0.005%	0.006%	0.005%	0.004%	0.002%	0.002%	0.002%	0.003%	0.004%
CS3		0.001%	0.004%	0.027%	0.048%	0.044%	0.028%	0.017%	0.011%	0.004%	0.002%	0.000%	0.000%
CS4			0.011%	0.027%	0.087%	0.184%	0.209%	0.158%	0.128%	0.088%	0.048%	0.030%	0.020%
3S2				0.050%	0.139%	0.368%	0.714%	0.801%	0.602%	0.530%	0.460%	0.400%	0.443%
Other CS5				0.007%	0.013%	0.044%	0.057%	0.042%	0.033%	0.029%	0.026%	0.030%	0.032%
CS6				0.000%	0.000%	0.001%	0.002%	0.002%	0.002%	0.002%	0.001%	0.001%	0.001%
CS7													
CT4		0.002%	0.010%	0.008%	0.008%	0.008%	0.006%	0.004%	0.002%	0.001%	0.001%	0.001%	0.000%
CT5													
CT6				0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
DS5				0.002%	0.009%	0.024%	0.033%	0.033%	0.034%	0.045%	0.051%	0.063%	0.062%
DS6				0.000%	0.000%	0.002%	0.005%	0.006%	0.009%	0.008%	0.008%	0.008%	0.007%
DS7													
DS8													
TS7													
Bus			0.070%	0.159%	0.156%	0.178%	0.204%	0.134%	0.052%	0.018%	0.011%		

PCE Factors

Since trucks and other heavy duty vehicles are larger than cars, typically have less acceleration and require more room for maneuvering, lane changing, and braking, they consume more of the highway's capacity. Traffic engineers account for the impact of these vehicles on highway capacity by assigning each class of vehicle a passenger car equivalent (PCE) value. This PCE represents the number of passenger cars that would consume the same percentage of the highway's capacity as the vehicles under consideration under prevailing roadway and traffic conditions.

The PCE value of a truck depends on its weight, length, engine, and other characteristics. The PCE value also depends on roadway characteristics such as the number of lanes and length and steepness of grades. The PCE values adopted for usage in the MdTA HCAS were obtained from a Battelle working paper prepared as part of a FHWA Truck Speed and Weight Study (Battelle, 1995). The PCE values reported in the Battelle working paper for conditions typical of those along the JFK Memorial Highway are summarized in Table 16. The "average" values listed in the last column, which are the approximate averages of the urban, rural—flat, and rural—rolling PCE values, are considered the best estimates of appropriate PCE values for this study.

Table 16. Passenger Car Equivalents for Different Truck Types on Typical Freeway Sections (Battelle, 1995)

	Urban	Rural—Flat	Rural—Rolling	**Average**
Single Unit Truck	1.887	1.189	1.402	**1.5**
Tractor-Trailer with Medium Load	3.349	2.516	2.760	**3.0**
Tractor-Trailer with Full Load	4.844	3.146	3.803	**4.0**
Double Bottom	6.881	5.130	6.346	**6.0**

4.3 Expenditure Data

Under normal circumstances, one must include all federal, local, and state expenditure data in order to obtain reasonably accurate results for an HCAS. However, given that the MdTA is an independent agency, this hierarchic breakdown of expenditures simply does not exist. Rather, MdTA funds all construction projects through toll revenues. This simplifies the analysis because there is only one source of expenditure data, as opposed to the multiple sources required in other studies. Expenditure data collected for this study includes the initial estimated construction costs for both the superstructure and substructure of the bridge.

Given that the data project expenditure data was from 1961, inflation factors must be applied to convert all expenditures to constant dollars. In this study, all costs were adjusted to 2005 dollar amounts. After assessing inflation factors from several sources, the most complete and appropriate set of data was judged to be the series from the *Engineering News Record* (ENR). Their database consists of actual material and labor construction costs since 1918.

4.4 Allocator Selection Methodology

The process by which costs are assigned to different vehicle classes is the most subjective and consequently the most criticized step in the cost allocation practice. As a starting point, all costs can be divided into two categories: wear-related and non wear-related.

Wear-related expenditures are the easiest to allocate as the amount of damage imposed by a specific vehicle is usually quantifiable, either through model predictions or obvious damaging characteristics. For instance, damage imposed on striping of a highway is directly proportional to the number of axle passes; hence axle-miles are the ideal allocator.

On the other hand, non wear-related expenditures prove to be much more difficult to allocate appropriately. An example is an overhead sign above a highway; clearly, the cost of the sign is independent of the number of vehicles that pass beneath it. However, the initial cost for the sign may be influenced by the clearance heights required by different classes of vehicles, providing a justification for allocating more cost to larger vehicles.

There are also other less tangible expenditures that must be recovered, such as overhead and other common cost items. Overhead costs include but are not limited to administrative, planning, management, and enforcement costs. The state HCAS guidelines developed by the FHWA recommend that overhead costs be allocated in proportion to the allocations for the projects and programs covered by each overhead cost element. Common costs such as mowing, reforestation, and snow plowing are similar to overhead costs in that they are not load related. However, common costs cannot be allocated similar to overhead because they are not associated to any individual project.

Therefore, it is recommended that these costs be allocated according to VMT (or sometimes PCE weighted VMT), as this penalizes each vehicle an identical amount. Table 17 is a comprehensive list of all the allocators used in the JFK pilot study, some of which may not have been utilized in the allocation of Tydings Memorial Bridge. Therefore, they are listed for reference only.

Table 17. Summary of Cost Allocators for Pilot Study

Activitiy Description	Allocator 1	Share 1 (%)	Allocator 2	Share 2 (%)
Preliminary and Construction Engineering (etc.)	VMT	100.0	-	0.0
Right of Way (and Utilities)	VMT	100.0	-	0.0
Grading and Drainage	VMT	100.0	-	0.0
New Pavements - Rigid	VMT	25.0	ESAL's	75.0
New Pavements - Flexible	VMT	25.0	ESAL's	75.0
New Shoulders - Rigid	VMT	25.0	ESAL's	75.0
New Shoulders - Flexible	VMT	25.0	ESAL's	75.0
Pavement and Shoulder Reconstruction - Rigid	VMT	25.0	ESAL's	75.0
Pavement and Shoulder Reconstruction - Flexible	VMT	25.0	ESAL's	75.0
Pavement and Shoulder Rehab - Rigid	VMT	25.0	ESAL's	75.0
Pavement and Shoulder Rehab - Flexible	VMT	25.0	ESAL's	75.0
Pavement and Shoulder Rehab - Other	VMT	25.0	ESAL's	75.0
Truck Weight/Inspection Stations	VMT_{Trucks}	100.0	-	0.0
Truck Escape Ramps	VMT_{Trucks}	100.0	-	0.0
Toll Collection Equipment	VMT	100.0	-	0.0
Interchanges	VMT	25.0	ESAL's	75.0
Roadside Improvements	VMT	100.0	-	0.0
Safety Improvements	VMT	100.0	-	0.0
Traffic Service Improvements	VMT	100.0	-	0.0
Other Construction (modernization)	VMT	100.0	-	0.0
Other Construction (preservation)	VMT	100.0	-	0.0
Surface and Shoulder Maintenance - Rigid	VMT	25.0	ESAL's	75.0
Surface and Shoulder Maintenance - Flexible	VMT	25.0	ESAL's	75.0
Surface and Shoulder Maintenance - Other	VMT	25.0	ESAL's	75.0
Roadside Items Maintenance	VMT	100.0	-	0.0
Safety Items Maintenance	VMT	100.0	-	0.0
Traffic Service Items Maintenance	VMT	100.0	-	0.0
Pavement Striping and Marking (maintenance)	PCE-VMT	100.0	-	0.0
Sanding and Snow and Ice Removal (maintenance)	VMT	100.0	-	0.0
Extraordinary Maintenance	VMT	100.0	-	0.0
Miscellaneous Maintenance	VMT	100.0	-	0.0
Highway Planning	VMT	100.0	-	0.0
Other Common Costs	VMT	100.0	-	0.0
Other Administration	VMT	100.0	-	0.0
Bridge Maintenance	PCE-VMT	100.0	-	0.0
Bridge Safety Improvements	PCE-VMT	100.0	-	0.0
Miscellaneous Bridge Structural Improvements	Moments	50.0	PCE-VMT	50.0
Bridge Deck Resurfacing	Moments	100.0	-	0.0
Small Span Bridges - Construction	-	-	-	-
Large Span Bridges - Substructure Construction	Moments	100.0	-	0.0
Large Span Bridges - Superstructure Construction	Varies	-	Varies	-

Note: General administrative and overhead costs are allocated in proportion to the composite allocations from all other costs.

4.5 Statistical Methods Employed for VMT Verification

The previous sections have discussed the approach that was used in the analysis. However, regardless of how theoretically sound an approach may be, if inaccurate VMT percentages are used the results will be completely irrelevant. Thus, a critical piece of information that must be found in a cost allocation study is accurate VMT values. The difficulty in estimating VMT values for the Tydings Memorial bridge analysis originates from the manner by which traffic data at the MdTA toll booths have been collected. As discussed previously in Section 4.2, the MdTA separates traffic data into 6 classes, based on the number of axles. However, data organized in this manner cannot be used for the bridge analysis, as the increments for bridge design are currently based on the AASHTO HS design vehicles. Tydings Memorial Bridge was initially designed to the 1957 AASHTO standards, which was adequate at the time of construction, however, more commonly used today is the HS20 design vehicle, which is what this analysis was based upon. The HS20 design increments are shown in Table 18 below.

Ideally, the bridge allocation procedure generally follows the way in which bridges are designed (where HS-20 is the standard design truck for most of the major highway bridges). In simple terms, bridges are designed so that the bridge can withstand the application of the dead load (the weight of the bridge itself) and the live load of the heaviest truck, plus a safety factor. Furthermore, any incremental increase in the size of the heaviest vehicle will require an incremental increase in the size/strength of the bridge. Thus, rather than utilize the initial VMT matrix weight increments which are not consistent with the HS20 design increments, it has become desirable to perform a further analysis on the data in order to approximate the VMT values that will follow the appropriate bridge design increments.

Table 18. HS20 Design Increments

Increment	Weight Range (kips)
HS2.5+	0-9
HS5+	9-18
HS7.5+	18-27
HS10+	27-36
HS12.5+	36-45
HS15+	45-54
HS17.5+	54-63
HS20+	63+

Table 19. VMT Matrix for Tydings Memorial Bridge Structural Analysis

Weight (kips)	Auto & MCs	LT4	SU2	SU3	SU4	CS3	CS4	3S2	OCS5	CS6	CT4-	CT6	DS5	DS6	Bus
0-10	60.96%	23.12%	1.00%			0.00%					0.00%				
10-20		0.32%	1.55%	0.17%	0.00%	0.04%	0.04%	0.06%	0.01%	0.00%	0.02%	0.00%	0.00%	0.00%	0.26%
20-30			0.48%	0.25%	0.01%	0.11%	0.31%	0.58%	0.06%	0.00%	0.02%	0.00%	0.04%	0.00%	0.38%
30-40			0.06%	0.18%	0.01%	0.05%	0.42%	1.72%	0.11%	0.00%	0.01%	0.00%	0.07%	0.01%	0.38%
40-50			0.01%	0.10%	0.01%	0.02%	0.24%	1.28%	0.07%	0.00%	0.00%	0.00%	0.09%	0.02%	0.08%
50-60			0.00%	0.03%	0.01%	0.00%	0.09%	0.98%	0.06%	0.00%	0.00%	0.00%	0.13%	0.02%	0.01%
60-70				0.01%	0.01%	0.00%	0.04%	1.06%	0.08%	0.00%	0.00%	0.00%	0.13%	0.02%	
70-150				0.00%	0.01%		0.03%	2.14%	0.20%	0.01%	0.00%	0.00%	0.14%	0.03%	

The initial analysis, which was used in the JFK pilot study, utilized the VMT matrix shown in Table 15. This, however, is not entirely accurate, as the percentages were lumped into the weight groups shown in Table 19 from the overall VMT matrix comprised of 24 vehicle classifications. This is not consistent with the HS design increments of Table 18. Generally, however, this regrouping of the original VMT matrix follows the HS incremental design loadings and was therefore assumed to be a good approximation of the actual VMT values for the HS loading. Nevertheless, this study took the analysis one additional step to verify that appropriate VMT percentages were used. In order to confirm the accuracy of the VMT percentages, four statistical methods were employed to approximate the mean and standard deviation of each vehicle class. Additional methods would have been suitable for this analysis, such as the log-normal distribution, Gamma, and Beta distributions. Subsequently, a check of the data was performed to see how consistently the data follows the traditional bell curve. Once each vehicle class had successfully passed the normality check, each underwent an identical set of procedures in order to approximate the VMT percentages for the HS design vehicle loading increments. To accomplish this, z-values were calculated for each vehicle class in each of the 30 weight classifications. Finally, this value was converted to a percentage, which would ultimately contribute to the overall VMT matrix for its respective statistical method. A step-by-step example of this process is discussed later in this section.

Approach 1 – Basic Sample Mean and Standard Deviation

The mean used in this approach was simply the arithmetic average of a set of values, found by the following equation

$$\overline{X} = \frac{\sum (\Pr ob(x,a)}{\sum (x * \Pr ob(x,a))} \tag{4}$$

where

x : vehicle weight

E : x*(Prob(x,a))

a : vehicle classification (i.e. Auto & MCs, etc)

Accordingly, the basic sample standard deviation was also used to measure how spread out the values in each data set are. The standard deviation was found by:

$$\sigma = \sqrt{\frac{(x-E)^2 (\Pr ob(x,a))}{\sum (\Pr ob(x,a))}} \tag{5}$$

Table 20. Approach 1 Example

Maximum Weight (kips)	Auto & MCs		
x	Prob(x,a)	E = x*Prob(x,a)	(x-E)^2*Prob(x,a)
5	55.96%	2.7978	0.0943
10	5.01%	0.5005	1.0542
15		0.0000	0.0000
20		0.0000	0.0000
25		0.0000	0.0000
30		0.0000	0.0000
35		0.0000	0.0000
40		0.0000	0.0000
45		0.0000	0.0000
50		0.0000	0.0000
55		0.0000	0.0000
60		0.0000	0.0000
65		0.0000	0.0000
70		0.0000	0.0000
75		0.0000	0.0000
80		0.0000	0.0000
85		0.0000	0.0000
90		0.0000	0.0000
95		0.0000	0.0000
100		0.0000	0.0000
105		0.0000	0.0000
110		0.0000	0.0000
115		0.0000	0.0000
120		0.0000	0.0000
125		0.0000	0.0000
130		0.0000	0.0000
135		0.0000	0.0000
140		0.0000	0.0000
145		0.0000	0.0000
150		0.0000	0.0000
TOTALS	60.96%	3.2983	1.1485
	Mean	**Variance**	**Standard Deviation**
	5.4105	1.8840	1.3726

Approach 2 – Discrete Distribution Analysis (Poisson and Binomial)

A discrete probability distribution that is useful when *n* (the number of trials) is large and *p* (the probability of success) is small and when the independent variables occur over a period of time is called the Poisson distribution. The mean and standard deviation are calculated from equations 6 and 7, respectively. The results of one Poisson distribution analysis is shown in Table 21, which utilized Microsoft's Excel solver program to approximate the Poisson value.

$$f(x) = \frac{e^{-a}a^{x}}{x!}, \qquad \sqrt{a} \qquad (6), (7)$$

where

a : mean

e : the base of the natural logarithm (e = 2.71828….)

x : vehicle weight (kips)

x! : the factorial of x

Table 21. Approach 2 Example (Poisson)

Max. Weight (kips)	Auto & MCs									
x	Prob(x,a)	E = x*Prob(x,a)	Prob(xla)						P(x-5,x)	((P(x-,x))-Prob(xla))^2
5	55.96%	2.80	0.92	0.00	0.00	0.01	0.03	0.05	0.10	0.67
10	5.01%	0.50	0.08	0.08	0.11	0.13	0.13	0.12	0.57	0.24
15		0.00	0.00	0.10	0.08	0.06	0.04	0.02	0.30	0.09
20		0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.03	0.00
25		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
35		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
45		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
55		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
65		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
75		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
85		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
90		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
95		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
105		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
110		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
115		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
120		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
125		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
130		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
135		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
140		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
145		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
150		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Prob(a)			9.27	3.04				1.00	1.00
TOTALS	60.96%	3.30	1.00	Poisson Mean	Standard Deviation				Constraint	Target

A second discrete distribution analysis utilized was the binomial distribution. Although, this type of distribution is inherently flawed for data of this nature since the outcome cannot be reduced to two possibilities, and also has a variance larger than the mean value in many cases, it was nonetheless attempted for completeness. The mean and standard deviation of this type of distribution are as follows, respectively. Again, the Excel solver program was used to achieve the results shown for the probability "p."

$$f(x) = \frac{n!\,p^x(1-p)^{n-x}}{x!(n-x)!}, \qquad \sqrt{np(1-p)} \qquad (8), (9)$$

where

n : the total number of vehicle weight groups

n! : the factorial of n

p : the numerical probability of success

x : vehicle weight (kips)

x! : the factorial of x

Table 22. Approach 2 Example (Binomial)

Auto & MCs								
n	**p**						**P(x-5,x)**	**((P(x-5,x))-Prob(x|a))^2**
150	0.06123541	0.00	0.00	0.00	0.00	0.00	0.00	0.84
Mean	**Variance**	0.08	0.08	0.08	0.08	0.08	0.42	0.11
9.19	8.62	0.10	0.10	0.10	0.10	0.10	0.52	0.27
St Deviation		0.01	0.01	0.01	0.01	0.01	0.06	0.00
2.94		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00	0.00	0.00
							1.00	1.22
							Constraint	**Target**

Approach 3 – Normal Distribution Analysis

The normal distribution was the final approach attempted for this analysis. The normal distribution or Gaussian distribution is one in which the data set when plotted resembles a bell curve. No variable fits the normal distribution perfectly, since the normal distribution is a theoretical distribution. However, the normal distribution can be used to describe many variables, because the deviations from the normal distribution are very small. The following equation was used to determine the mean and standard deviation of the normal distribution, with the aid of Excel's solver function once again.

$$f(x;\mu;\sigma) = \frac{1}{\sigma\sqrt{2\Pi}} e^{(-\frac{(x-\mu)^2}{2\sigma^2})} \tag{10}$$

where

μ : the population mean

σ : the population standard deviation

Π : 3.14

x : vehicle weight (kips)

Table 23. Approach 3 Example

Maximum Weight (kips)	Auto & MCs				
x	Prob(x,a)	E = x*Prob(x,a)	P(x-5,x)	P(X<=x)	((P(x-5,x))- Prob(x|a))^2
5	55.96%	0.92	0.92	0.92	0.00
10	5.01%	0.08	0.08	1.00	0.00
15		0.00	0.00	1.00	0.00
20		0.00	0.00	1.00	0.00
25		0.00	0.00	1.00	0.00
30		0.00	0.00	1.00	0.00
35		0.00	0.00	1.00	0.00
40		0.00	0.00	1.00	0.00
45		0.00	0.00	1.00	0.00
50		0.00	0.00	1.00	0.00
55		0.00	0.00	1.00	0.00
60		0.00	0.00	1.00	0.00
65		0.00	0.00	1.00	0.00
70		0.00	0.00	1.00	0.00
75		0.00	0.00	1.00	0.00
80		0.00	0.00	1.00	0.00
85		0.00	0.00	1.00	0.00
90		0.00	0.00	1.00	0.00
95		0.00	0.00	1.00	0.00
100		0.00	0.00	1.00	0.00
105		0.00	0.00	1.00	0.00
110		0.00	0.00	1.00	0.00
115		0.00	0.00	1.00	0.00
120		0.00	0.00	1.00	0.00
125		0.00	0.00	1.00	0.00
130		0.00	0.00	1.00	0.00
135		0.00	0.00	1.00	0.00
140		0.00	0.00	1.00	0.00
145		0.00	0.00	1.00	0.00
150		0.00	0.00	1.00	0.00
TOTALS	60.96%	1.57	2.47	6.08	0.00
		Mean	St Deviation	Variance	Target

Normalcy Check and Z-value Data Evaluation

Once the mean and standard deviation values have been calculated for each of the three approaches, the next step is to verify that the data is normally distributed. Obviously, Approaches 2-1 and 2-2 will not follow the normal distribution patterns because as will be discussed in Section 5.2 the results from these approaches fail to meet the ideal experiment conditions. However, the results were nevertheless subjected to the same tests for completeness. Equation (11) was used to accomplish this, in which a "Q" value is found for each measurement and ultimately multiplied by the total number of observations expected for that particular measurement which then contributes to a plot against the cumulative observed frequency.

$$Q = \frac{1}{\sigma\sqrt{2\Pi}} e^{-\frac{1}{2}(\frac{Y-\mu}{\sigma})^2} \tag{11}$$

where

σ : standard deviation

e : the base of the natural logarithm (e = 2.71828….)

Y : observational measurement used (1, 2, 3…)

μ : mean

Π : 3.14159….

Following the creation of the normality plots for each vehicle class, the graphs must be compared to Figure 9 shown below, which displays three non-normality plots, which indicate that the data cannot be evaluated accurately by the assumption of a bell curve distribution. Plot (a) indicates that the population distribution is skewed; (b) indicates that the population distribution has heavier tails than a normal curve; and (c) displays the presence of an outlier. If the plot resembles that shown in Figure 10 more closely than any in Figure 9, than one can assume the data to be consistent with the properties of the traditional bell curve.

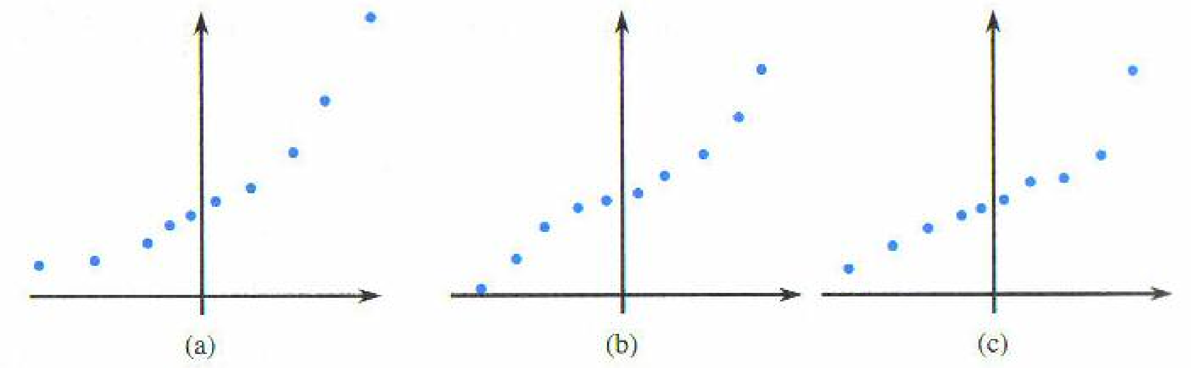

Figure 9. Plots Suggesting Non-normality

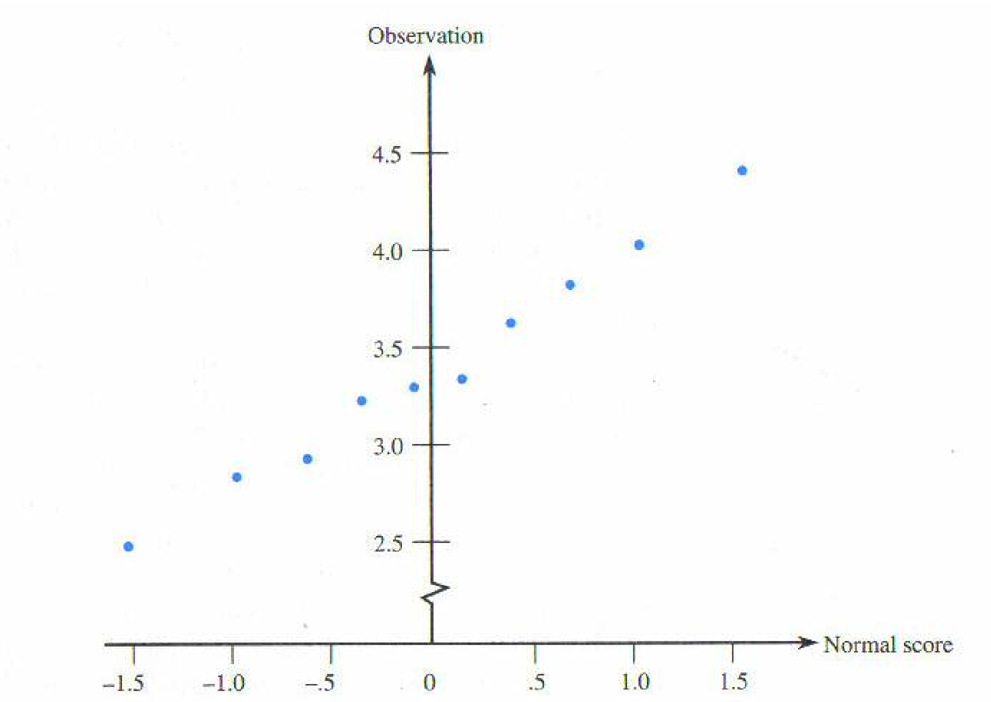

Figure 10. Typical Normality Plot of Bell Curve Representative Data

After careful evaluation of the normality plots for each of the vehicle classes in this study, all except for one strongly suggest that the data generally follows the normal distribution pattern. The only unique group appears to be the Autos and Motorcycles class, which suggests that the population distribution is skewed, as shown in Figure 11. More often than not, this would be of significant concern, however, given that the weight range of this particular class of vehicles only spreads from 0-10 kips and the HS-2.5 loading nearly encompasses that entire range, including weights up to 9.0 kips, this is not a concern. Thus, evaluation of this vehicle class by means of Z-values is permitted since virtually the entire range of VMT values will fall within the first design increment regardless of the approach pursued.

The final step prior to the assignment of VMT percentages of each vehicle class to the appropriate design increment is the calculation of the Z-value for each class in the respective design increment. Since each normally distributed variable has its own mean and standard deviation, the shape and location of these curves will vary. Thus, the use of the standard normal distribution, shown in Figure 12, with a mean of "0" and a standard deviation of 1 was utilized in the Z-value approximation process. All normally distributed variables, such as those assumed to be such in this study, can be transformed into the normally distributed variable by using the following formula:

$$Z = \frac{\text{Value} - \text{Mean}}{\text{St. Dev.}} \qquad (12)$$

This value can ultimately be used to approximate the area under the normal distribution curve through the use of statistical tables and finally converted to a VMT percentage. The results of this process are shown below in Table 24 and will ultimately contribute to the overall VMT matrix for that particular approach.

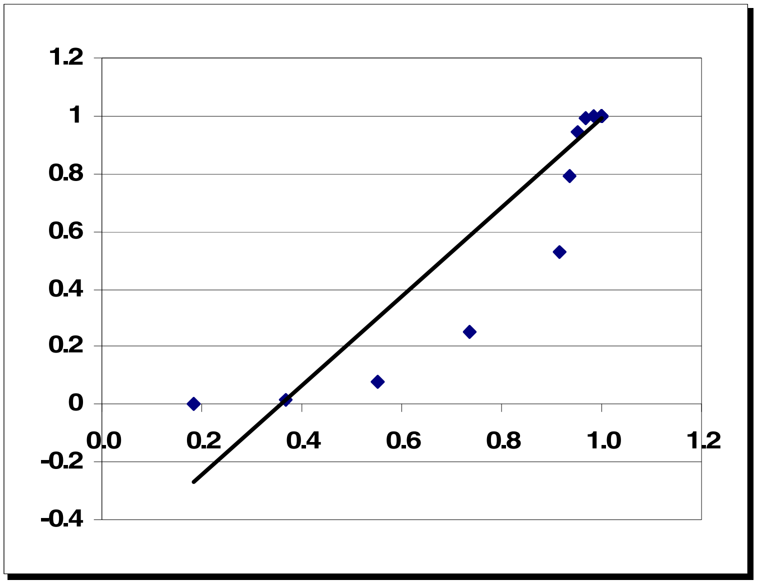

Figure 11. Autos and Motorcycles Normality Plot

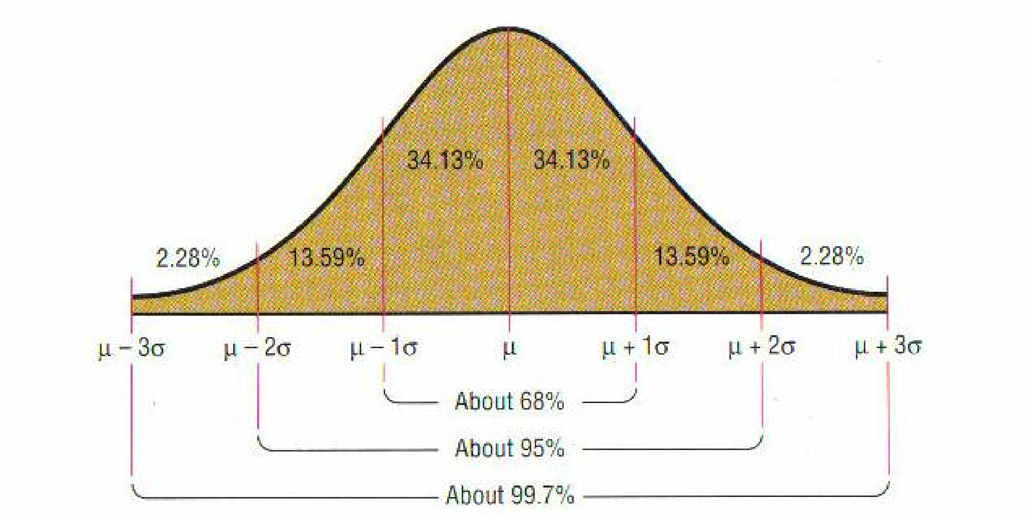

Figure 12. Normal Distribution Curve

Table 24. Z-Value Calculation Example

Auto & MCs	Maximum Weight (in kips)	% VMT	Z-VALUE	AREA	% TOTAL	Design Increment VMT
Mean (Approach 1)	9	60.96%	2.62	0.50	99.55%	60.69%
5.41	18		9.17	0.50	0.45%	0.27%
St. Dev.(Approach 1)	27		15.73	0.50	0.00%	0.00%
1.37	36		22.29	0.50	0.00%	0.00%
	45		28.84	0.50	0.00%	0.00%
	54		35.40	0.50	0.00%	0.00%
	63		41.96	0.50	0.00%	0.00%
	150		8.95	0.50	0.00%	0.00%

CHAPTER 5.0: STUDY RESULTS

5.1 Baseline Scenario

The proposed HCAS methodology described in the preceding chapters was applied to Millard E. Tydings Memorial Bridge. A baseline scenario was defined based on:

- Initial project construction costs as summarized in Appendix B;
- Conversion of all costs to constant 2005 dollars using the *Engineering News Record* construction cost index;
- Cost allocators as summarized in Table 17;
- VMT data as summarized in Table 15;
- PCE factors as summarized in Table 16;

Some of the above items have some inherent variability. For example, see PCE factors as in the range of values reported in the literature. The baseline scenario is based upon the best estimate of each of these variables as determined by Dr. Charles W. Schwartz, Dr. Chung C. Fu, and myself, the team compiled to perform the JFK pilot study. The impact of these assumptions on the HCA results was evaluated via sensitivity analyses performed in the JFK pilot study; refer to Appendix C for more information on this study.

A key output from any HCAS is the assignment of highway and bridge costs to each vehicle class. The study results for the baseline bridge allocation scenario are summarized in Table 25 and Figure 13. For the baseline conditions, the cost allocation study finds that 2-Axle vehicles are responsible for approximately 63% of the bridge costs while trucks (3-Axle vehicles and above) are responsible for the remaining 37% of costs. When combined with the pilot study results, this can be compared against toll revenue shares currently paid by each vehicle class. Based on annual traffic levels over the 2000-2004 time period and the existing gross toll structure[1] on the JFK Memorial Highway, 2-Axle vehicles currently pay 65% of total toll revenue and trucks (3-Axle vehicles and above) pay the remaining 35%. The results of the pavement and bridge analysis from the pilot HCAS found that approximately 58% of the cost responsibility attributed to 2-Axle vehicles, while 42% being allocated to the remainder of the vehicles, as shown in Table 26 and Figure 13, respectively. This suggests that trucks are undercharged in the current toll structure in comparison to the costs they incur for the pavement and bridge infrastructure. For supplemental information regarding the JFK pilot report, refer to Appendix C.

Table 25. Baseline Scenario: Bridge Costs Only

Vehicle Class	Cost Share	
2-Axle	$58,542,008	62.6%
3-Axle	$3,899,009	4.2%
4-Axle	$2,910,366	3.1%
5-Axle	$27,740,159	29.7%
6-Axle	$400,347	0.4%
Total	$93,491,889	100.0%

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[1] Gross toll revenue does not include any commuter, EZ Pass, or other discounts. Most recent actual toll data available from MdTA shows total revenues of $87.3M for the JFK Memorial Highway.

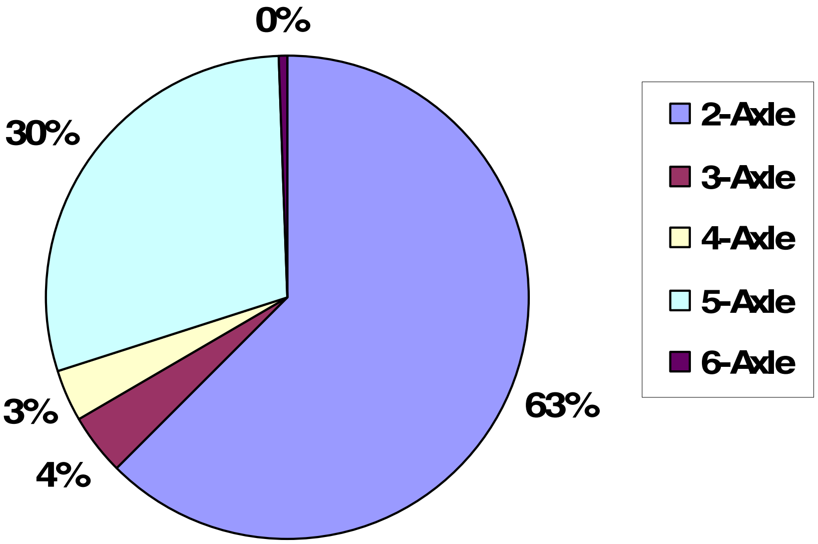

Figure 13. Allocation of Bridge Costs to MdTA Vehicle Classes for Baseline Scenario

Table 26. Baseline Scenario: Bridge and Entire JFK Pavement Costs

Vehicle Class	Cost Share	
2-Axle	$1,055,331,816	57.6%
3-Axle	$38,714,407	2.1%
4-Axle	$26,967,568	1.5%
5-Axle	$708,874,876	38.7%
6-Axle	$3,085,199	0.2%
Total	$1,832,973,866	100.0%

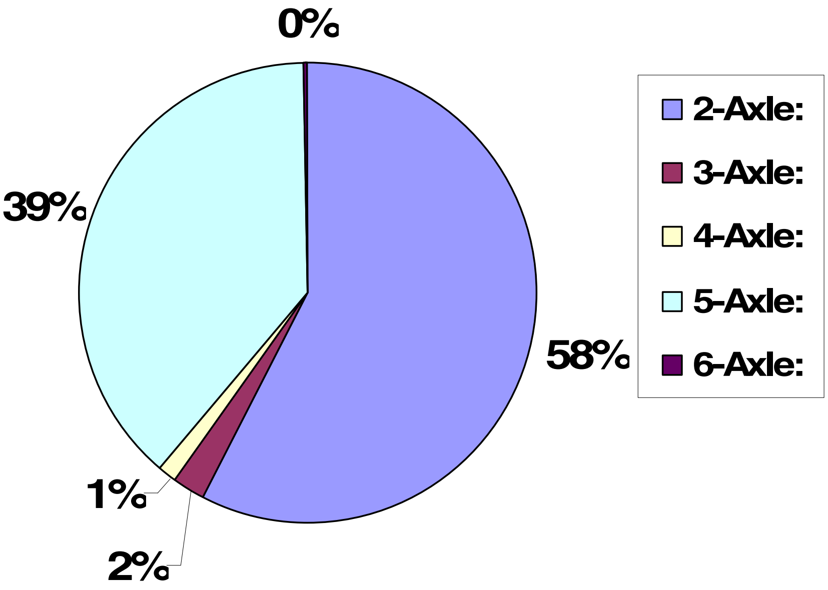

Figure 14. Allocation of Bridge and Pavement Costs to MdTA Vehicle Classes for Baseline Scenario

5.2 Statistical Analyses

All engineering analyses require varying numbers of assumptions, and HCAS are no exceptions. In addition to the assumption that the compiled costs data are complete and accurate, there are several other detailed assumptions embedded in the analyses:

- The PCE factors for each vehicle class. Although the values assumed for the PCE factors in Table 16 are believed to be reasonable, the PCE factors reported in the literature vary over a considerable range.
- Accuracy of the VMT values used for the JFK Highway
- Inflation factors were used to convert to 2005 dollars.

The impact of these assumptions (and others) on the results from the HCAS can be evaluated via sensitivity studies. Appendix C summarizes these studies and proves without a doubt that minor variability of the subjective assumptions will not result in significant variations of the final result. In addition to the sensitivity analysis which was performed via the pilot study and has already proved that minor variations in VMT values are negligible, this thesis conducted a secondary statistical analysis of those values. These analyses were described in the Section 4.5 and the final VMT values for each approach are shown in Table 27, which displays the weight ranges used for the initial analysis (refer to Table 19 for the overall VMT chart) next to those used for the statistical analyses of Approaches 1 through 3 (refer to Table 18 for the HS truck design increments). Utilizing the VMT matrix for each method, an analysis identical to the initial one was performed with these new VMT percentages, which resulted in the cost share percentages and relative tolls shown in Table 28 and Table 29, respectively.

Table 27. VMT Percentages by Approach

Weight(kips)		2-Axle					3-Axle				
INITIAL ANALYSIS	APP. 1-3	INITIAL ANALYSIS	APP. 1	APP. 2-1	APP. 2-2	APP. 3	INITIAL ANALYSIS	APP. 1	APP. 2-1	APP. 2-2	APP. 3
0-10	0-9	100.00%	99.86%	100.00%	100.00%	99.63%	0.00%	0.04%	0.00%	0.00%	0.09%
10-20	9-18	75.68%	96.69%	99.84%	99.67%	81.04%	18.98%	1.55%	0.14%	0.31%	8.41%
20-30	18-27	21.63%	52.93%	85.68%	13.53%	26.08%	32.89%	24.06%	10.46%	57.86%	33.26%
30-40	27-36	2.06%	9.52%	0.76%	0.00%	0.94%	20.23%	38.97%	29.20%	17.25%	33.65%
40-50	36-45	0.29%	0.27%	0.00%	0.00%	0.00%	10.29%	23.79%	4.08%	1.94%	16.94%
50-60	45-54	0.00%	0.00%	0.00%	0.00%	0.00%	3.53%	7.86%	1.42%	0.00%	4.86%
60-70	54-63	0.00%	0.00%	0.00%	0.00%	0.00%	1.05%	1.68%	13.59%	0.00%	0.62%
70-150	63-150	0.00%	0.00%	0.00%	0.00%	0.00%	0.14%	0.12%	10.07%	0.00%	0.00%

Weight(kips)		4-Axle					5-Axle				
INITIAL ANALYSIS	APP. 1-3	INITIAL ANALYSIS	APP. 1	APP. 2-1	APP. 2-2	APP. 3	INITIAL ANALYSIS	APP. 1	APP. 2-1	APP. 2-2	APP. 3
0-10	0-9	0.00%	0.02%	0.00%	0.00%	0.02%	0.00%	0.08%	0.00%	0.00%	0.26%
10-20	9-18	2.61%	0.47%	0.01%	0.02%	2.05%	2.72%	1.29%	0.00%	0.00%	8.45%
20-30	18-27	15.09%	6.99%	2.27%	14.63%	12.15%	30.21%	15.90%	1.59%	13.98%	28.26%
30-40	27-36	14.41%	15.50%	19.87%	16.09%	20.50%	62.74%	35.68%	50.11%	66.57%	44.46%
40-50	36-45	13.18%	17.66%	8.79%	4.75%	18.51%	75.07%	57.68%	86.92%	93.05%	63.77%
50-60	45-54	7.22%	13.57%	2.04%	0.61%	9.59%	87.70%	77.63%	95.92%	98.59%	84.33%
60-70	54-63	3.58%	6.62%	3.18%	0.00%	2.13%	93.94%	90.54%	78.36%	92.15%	95.92%
70-150	63-150	1.25%	1.28%	2.50%	0.00%	0.39%	97.07%	96.97%	80.91%	71.72%	98.05%

Weight(kips)		6-Axle				
INITIAL ANALYSIS	APP. 1-3	INITIAL ANALYSIS	APP. 1	APP. 2-1	APP. 2-2	APP. 3
0-10	0-9	0.00%	0.00%	0.00%	0.00%	0.00%
10-20	9-18	0.01%	0.01%	0.00%	0.00%	0.06%
20-30	18-27	0.17%	0.13%	0.00%	0.01%	0.25%
30-40	27-36	0.56%	0.33%	0.07%	0.09%	0.46%
40-50	36-45	1.18%	0.59%	0.20%	0.26%	0.78%
50-60	45-54	1.55%	0.94%	0.62%	0.80%	1.23%
60-70	54-63	1.43%	1.15%	4.87%	7.85%	1.33%
70-150	63-150	1.54%	1.62%	6.52%	28.28%	1.56%

Table 28. Cost Share by Approach

CLASS	COST SHARE BY APPROACH				
	INITIAL ANALYSIS	APPROACH 1	APPROACH 2-1	APPROACH 2-2	APPROACH 3
2-Axle:	62.6%	62.1%	71.8%	71.7%	62.1%
3-Axle:	4.2%	4.5%	3.9%	3.8%	4.3%
4-Axle:	3.1%	3.2%	2.5%	2.6%	3.1%
5-Axle:	29.7%	29.8%	21.4%	21.5%	30.1%
6-Axle:	0.4%	0.4%	0.4%	0.4%	0.4%
	100.0%	100.0%	100.0%	100.0%	100.0%

Table 29. Relative Toll by Approach

CLASS	RELATIVE TOLL BY APPROACH				
	INITIAL ANALYSIS	APPROACH 1	APPROACH 2-1	APPROACH 2-2	APPROACH 3
2-Axle	$5.00	$5.00	$5.00	$5.00	$5.00
3-Axle	$13.98	$15.06	$11.44	$11.09	$14.57
4-Axle	$17.08	$17.79	$12.19	$12.57	$17.12
5-Axle	$22.99	$23.23	$14.47	$14.57	$23.48
6-Axle	$24.27	$23.92	$18.64	$20.80	$24.31

The results shown through Approaches 1 and 3 confirm the validity of the initial analysis performed on the bridge. However, approaches 2-1 and 2-2 differ considerably. Upon further investigation of the statistical methodology chosen for these approaches, it was discovered that the variance in most cases exceeded the mean value, which ultimately led to inaccurate results. A requirement of the Poisson distribution is that the mean and variance be equal, while the Binomial distribution necessitates a mean greater than the variance, which renders Approaches 2-1 and 2-2, respectively, incorrect. In addition to that, the binomial distribution must meet the following requirements in order to be successful.

1. The experiment consists of a fixed number of observations or trials
2. There exist only two outcomes of each trial, success and failure
3. The outcomes of all the trials are statistically independent
4. All the trials have the same probability of success

Once one understands the requirements for a successful binomial experiment, the basis for the distinct variation in the results suddenly becomes obvious. This approach is simply not well suited for the subject data and thus should not be considered as a feasible option for this particular analysis.

Accordingly, the other discrete distribution analysis performed, the Poisson distribution, seems to be questionable as well. Justification for this discrepancy is not as apparent as that for the binomial distribution, other than the failure of a general characteristic for a successful Poisson analysis where the mean equals the variance. However, in addition to that, it can be shown that under certain circumstances the binomial and Poisson distributions will converge. This can occur as the number of trials goes to infinity, while the product of "**np**" (number of trials*probability) remains fixed. A general rule of thumb for this convergence is if $\mathbf{n} \geq 20$ and $\mathbf{p} \leq 0.05$, also if $\mathbf{n} \geq 100$ and $\mathbf{np} \leq 10$. After a review of the results, this scenario occurs with many of the vehicle classes, thus providing some insight as to the obvious similarities displayed between both of the discrete distribution approaches as shown in Table 27. Conclusively, it is suggested that Approach 2-1 be omitted as a viable option for VMT approximation.

Now that Approaches 2-1 and 2-2 have been removed from consideration, Approaches 1 and 3 must also be evaluated. Upon first glance of the results in Table 28, one instantly notices the strong correlation between the initial analysis with Approaches 1 and 3. However, this alone does not provide conclusive evidence to the validity of the initial analysis. As discussed earlier, the normal distribution can be used to evaluate many types of data. Also, as a general rule, the larger the sample size, the less variability can be seen from the traditional bell curve. Such is the case with the JFK traffic count data. With an original VMT matrix compiled from nearly 8 million vehicles, the presence of outliers (vehicle weights significantly greater or less than normal) in certain vehicle classifications will obviously have a negligible influence. Additionally, the data was subjected to the normality tests as described in Section 4.5, which provides further support that the data may be idealized as a bell curve. Ultimately, there is limited evidence to disprove Approaches 1 and 3 as reasonably accurate estimators of the VMT matrix. Provided that the sample data is as robust as that used for the JFK pilot study, the methodology chosen for Approach 1 can be generalized by the normal distribution. This is due to the fact that deviations from mean will progressively become smaller as the sample size grows, producing a nearly identical mean and median value and thus provides concrete evidence as to the validity of the results found in the initial analysis.

In closing, following a thorough evaluation, it has been determined that VMT matrix formulation for large data samples can be described accurately by two methods. The normal distribution analysis has proven to be sufficient, as well as the basic mean and standard deviation. Although these methods are clearly the ideal choice for this study, one should not overlook additional possibilities that may better suit variable traffic count data under different circumstances.

CHAPTER 6.0: CONCLUSIONS

Recall that the specific goals of this bridge cost allocation thesis were to:

1. Develop/refine the HCA methodology for specific application to long span bridges operated by the MdTA;
2. Illustrate the implications, if any, of the HCAS results for the existing toll structure on the John F. Kennedy Memorial Highway;
3. Confirm that the methodology employed is accurate through multiple statistical analysis models; and
4. Provide the basis for application of the bridge cost allocation methodology to the other facilities owned and operated by the MdTA.

These goals have been achieved, as documented in this report. An incremental methodology has been developed and applied to the Millard E. Tydings Memorial Bridge, which can readily be applied to additional MdTA facilities. The methodology adapted for this study is based upon well-accepted cost allocation principles and the best estimates available for the various categories of required input data. The results from this implementation are reasonable in practical engineering terms and are acceptably insensitive to variations in the assumptions that are inevitable in any engineering analysis.

Specific findings and conclusions from the study of relevance to the application of Tydings Memorial Bridge and to the implementation of the HCAS methodology to the other MdTA facilities are as follows:

- The combined results from the pilot HCAS at the JFK Memorial Highway and those found through this study are broadly consistent with Federal HCAS findings in terms of percentages of costs attributable to passenger cars vs. trucks.
- The results from the pilot HCAS were remarkably robust in terms of sensitivity to analysis assumptions. A systematic examination of the influence of key analysis assumptions on the cost allocations by vehicle class found surprisingly little sensitivity, as shown in Appendix C.
- Initial construction cost data is assumed to be sufficiently accurate in terms of completeness as well as through the conversion to 2005 dollar values.
- Traffic volume and vehicle classification distributions, two key inputs to the HCAS, were relatively easy to compile, at least as derived from toll records for the MdTA vehicle classifications. High quality vehicle and axle weight distributions specific to the MdTA facilities are generally unavailable, and therefore representative values from prior studies and/or national databases (e.g., the FHWA LTPP database) must be adapted.
- VMT matrix formulation has been shown to be accurate through multiple statistical analyses, most notably by the normal distribution and the basic sample mean and standard deviation.
- Table 30 below shows how significantly variable the percentages are for short span bridges versus a bridge such as Tydings Memorial. The allocation percentages for short span bridges are those listed in Table 3 of Chapter 1 from

the FHWA state guidelines, in addition to the results of the bridge allocation percentages from the 2000 Texas HCAS. Also, the percentages for Tydings are the results of the most effective statistical approaches, 1 and 3. Even though the design load increments are not equal between the FHWA and those utilized in this study, one can nevertheless identify the incredible variation amongst the approaches and subsequent dire need for an effective individual bridge allocation analysis on long span structures. The tremendous variation is allocation percentages can be attributed to many factors. The most obvious is the length of the structure. As discussed throughout this paper, the greater the span of the bridge, the less significant the role large vehicles, such as the HS20 truck, play on the design criteria and thus a dramatic increase in costs shared by all vehicles can be seen as the allocation percentages begin to approach those that would be expected from a pavement allocation analysis.

Table 30. FHWA/Texas Allocation VS. Study Results

FHWA Increment	FHWA Percent Allocation	FHWA Design Load (kips)	Texas Increment	Texas Percent Allocation	Texas Design Load (kips)	Study Increment	Study Percent Allocation (APP. 1)	Study Percent Allocation (APP. 3)	Study Design Load (kips)
All Vehicles	83.19	N/A	H2.5	80.78	5	HS2.5	93.78	95.77	9
H2.5+	87.38	5	H5	82.61	10	HS5	95.84	96.43	18
H5+	89.79	10	H10	86.52	20	HS7.5	96.39	96.91	27
H10+	92.83	20	H15	90.43	30	HS10	96.95	97.48	36
H15+	95.27	30	H20	95.80	40	HS12.5	97.57	98.04	45
HS15+	100.00	54	HS15	94.59	54	HS15	98.20	98.52	54
HS20+	100.00	72	HS20	100.00	72	HS17.5	98.79	99.03	63
						HS20	100.00	100.00	72

In closing, the methodology developed for this study and documented in this report is judged to be a rational, well-founded, and robust procedure for evaluating bridge costs attributable to different vehicle classes. Given the varying specific characteristics of each of the MdTA facilities, the methodology will inevitably need to be “tweaked” for each implementation. Nevertheless, the conclusions from this study are that the methodology is suitable for application to the remaining MdTA bridge facilities.

APPENDICES

A. GLOSSARY OF TERMS (From 2005 Oregon HCAS)

AADT: Average annual daily traffic.

AASHO Road Test: American Association of State Highway Officials (later the American Association of State Highway Transportation Officials) road test conducted at Ottawa, Illinois from 1958-1960. The results were used in developing the incremental cost assignment approach.

Access Charge: A fee charged for the right to use all or a selected portion of the highway system for a period of time. Fee provides the user with access to the road system but does not vary with the amount of usage.

Activity Measures: Measures which reflect different aspects of the intensity and extent of highway use by user groups. Examples are vehicle registrations, vehicle miles of travel, gallons of fuel consumed, ESAL miles of travel, and PCE miles of travel. Critical to revenue estimates and assignment of cost responsibility.

ADT: Average daily traffic; the average number of vehicles passing a given point or using a given highway per day.

Allocation Method: Any of several available means to assign responsibility for a particular expenditure/cost item (e.g., the incremental method or the federal recommended method).

Allocator: Measures of the vehicle stream activity level used to assign occasioned cost responsibility for highway program expenditures to user groups. Typically a relative use measure such as vehicle miles or axle miles of travel.

Arterial Road: A road used primarily for through traffic.

Attributable Costs: Those expenditures/costs that are a function of vehicle size, weight, or other operating characteristics (e.g., increased pavement and bridge strength for heavy vehicles.) Costs can be attributed to the responsible classes of vehicles.

Axle Equivalency: The impact—in terms of road damage—of a single or tandem axle compared to a standard 18,000-pound axle. As axle weight increases, equivalencies increase at an exponential rate.

Axle Miles of Travel (AMT): Vehicle miles of travel multiplied by number of axles. Since trucks, on average, have roughly twice as many axles as cars (i.e., four versus two), their share of the total axle miles of travel on any given highway system will be about double their share of the vehicle miles of travel on that system.

Axle Weight/ Axle Load: The gross load carried by an axle.

Basic (or Light) Vehicles: The smallest vehicle, usually a passenger car, that is used to determine the minimum geometric and structural components of the roadways and bridges.

Basic Increment: A theoretical concept which refers to the road needed to accommodate basic vehicle traffic (passenger cars and light trucks.) The cost of the basic increment is considered common and is shared by all vehicles using the road.

Benefits: Anything of value is a benefit and anything of negative value is a cost.

BUS: Vehicles manufactured as traditional passenger-carrying buses. Vehicles in this user group may have two axles and six tires or three or more axles.

Collector: A road that connects local roads with arterial roads.

Common Costs: Expenditures that are independent of vehicle size, weight, or other operating characteristics and so cannot be attributed to any specific class of vehicles. These expenditures must therefore be treated as a common responsibility of all vehicle classes and are most typically assigned to all classes on the basis of a relative use measure such as vehicle miles of travel.

Common-Cost Programs: Program expenditures which cannot be directly associated with specific classes of highways.

Cost Allocation: The analytical process of determining the cost responsibility of highway system users.

Cost Assignment: The level or proportion of costs attributable to particular, or all, users.

Cost Occasioned Approach: An approach which determines responsibility for highway expenditures/costs based on the costs occasioned or caused by each vehicle class. Such an approach is not based solely on relative use, nor does it attempt to quantify the benefits received by different classes of road users.

Cost Responsibility: The principle that those who use the public roads should pay for them and, more specifically, that payments from road users should be in proportion to the road costs for which they are responsible. The proportionate share of highway costs legitimately assignable to a given vehicle type user group.

Cost Responsibility (Allocation) Study: A study that determines the equitable share that each class of road users should pay for the maintenance, operation, and improvement of highways or other transportation modes.

Cost Share: See Cost Responsibility.

Cost-Based Approach: An approach in which the dollars allocated to the vehicle classes are costs rather than actual expenditures. Conceptually, the dollars allocated in a cost-based study should include the total costs - both direct and indirect - resulting from use of the system.

Dead Weight: The weight of a structure, such as a bridge, without traffic loadings.

Debt Service: Funds used for the repayment of previously incurred debt (both principal and interest.)

Deck: The roadway or surface of a bridge.

Declared Weights, Operating Weights, and Registered Weights: Declared weights are the base for the weight-mile tax and the maximum weights allowed; operating weights are the actual weights during operation; registered weights are the base for the registration fee.

Delphi: A research technique that collects expert opinions and uses the consensus to quantify or otherwise delineate a subject area which cannot be reliably quantified in any other way.

Design Section: A section of pavement with specific attributes.

Distress: A specific physical manifestation of pavement deterioration.

DMV: Department of Motor Vehicles.

Earnings Credit: A method for dividing highway cost responsibility between users and the general public.

Economic Cost: The measure of what must be given up in order to obtain a good or service. The forgone consumption of resources, both present and future, needed to acquire a good or service.

Efficiency: The measure of the success with which resources available to society are employed to generate satisfaction.

Elasticity: The percentage change in the quantity of demand for a good or service relative to a percentage change in the price of that good or service. Also called price elasticity.

Environmental Factor: The portion of pavement deterioration and associated maintenance expenditures/costs attributable to weather and other non-traffic-related causes such as natural aging and utility cuts.

Equity: Generally interpreted as the state of being just, impartial, or fair. Horizontal equity refers to the fair treatment of individual units with similar circumstances. Vertical equity refers to the fair treatment of units in different circumstances. Distributional equity refers to the equal distribution of costs or wealth among units.

Equity Ratio: The ratio of revenue contribution shares for a highway user group to a proportionate share of cost responsibility for the group.

Equivalent Single Axle Load Miles of Travel (ESAL-Miles): Axle miles of travel weighted by the ESAL's of each axle. Because of the exponential relationship between axle weight and ESAL's, trucks and other heavy vehicles account for a very large majority of the ESAL-miles on most road systems.

Equivalent Single Axle Loadings (ESAL's): The relative pavement stress applied by a given axle weight compared to the stress applied by an 18,000-lb single axle. ESAL-Miles: A travel function allocator estimated from annual miles of travel for a highway user group multiplied or weighted by equivalent single axle loadings for the group. Pavements are designed to withstand the application of a certain number of ESAL's over their design life. Most research has concluded that the relationship between axle weight and ESAL's an approximate third or fourth-power exponential relationship;, ESAL's therefore rise rapidly with increases in axle weight.

Excise Tax: A tax levied on the production or sale of a specific item such as gasoline, diesel fuel, or vehicles.

Exempt Vehicles: Vehicle classes that are exempt—either partially or entirely—from payment of one or more taxes or fees. Examples include publicly owned vehicles, public transit vehicles, and some types of farm equipment.

Expenditure: The amount of money spent in Pennsylvania for highway-related items and activities. Expenditures may or may not be the same as cost.

Expenditure-Based Approach: An approach in which dollars allocated to the various vehicle classes are the actual expenditures for some historical period and/or the expenditures anticipated for a future period.

Federal Recommended Allocation Method: Based on the design for a basic facility where cost is assigned to all vehicles as common, usually by vehicle miles of travel. All vehicles also share in the cost of additional thickness required to bring the design up to the full facility thickness, usually by equivalent single axle loadings (ESAL's).

Fee: A price paid for a service. In the context of highways, a fee or a user fee is the same as a user charge.

Financial Management Information System (FMIS): An accounting system used to record highway program expenditures under Motor License Fund.

First-Structure Revenues: A fixed, lump sum payment that does not vary with vehicle use. (Ex: Vehicle registration fees, operator license fees, and vehicle tag sales.)

Four-R (4R): Reconstruction, rehabilitation, restoration, and resurfacing.

Fourth-Power Rule: Common term used for the AASHO axle pavement damage relationship. Although the exact value varies by pavement type, the ESAL value varies approximately as the fourth power of axle weight. For example, if the axle load is doubled, the impact, or pavement damage, increases by 16 times.

Functional Classification: The classification of roads according to their general use, character, or relative importance. Definitions may vary from state to state and for the federal government. In this report, roads are classified as Interstate, Principal Arterial, Minor Arterial, Major and Minor Collector, and Functionally Local. In addition, roads may be classified under different jurisdictions such as State, County, Municipal, and local.

Gross Vehicle Weight (GVW): The actual maximum loaded weight allowed for a vehicle (based on registration or legal limits) or the total weight of a vehicle (includes both the weight of the vehicle itself and its load.) The latter is sometimes referred to as operating weight.

HCAS: Highway Cost Allocation Study.

Heavy Vehicle: Vehicles larger (usually meaning heavier) than the basic vehicle (see *basic vehicle*). Includes trucks, buses, and other vehicles weighing 8,001 pounds or more.

Highway (or Road) System: A grouping of highways, roads, or streets that have similar characteristics, serve a similar function, or fall under the same jurisdictional ownership.

Highway Cost: See expenditure.

Highway User Groups: Vehicles that use the highway system as defined by vehicle type and axle configuration.

Highway User: The owner of a motor vehicle in use on highways, roads, and streets. Often cited as "user," "motor vehicle user," or even "motor vehicle."

HPMS: Federal Highway Performance Monitoring System.

Incremental Cost: The additional portion of cost which is occasioned or caused by a particular type of use.

Incremental Method: A method of assigning responsibility for highway expenditures/costs by comparing the costs of constructing and maintaining roads for basic (light) vehicles only with the costs of constructing and maintaining roads for different traffic mixes containing larger and heavier vehicles. The increased costs resulting from the presence of larger and heavier vehicles are referred to as incremental costs. Under this method, all vehicles share in the cost of a facility designed for basic vehicle traffic only. Each group of successively larger and heavier vehicles also shares in the incremental costs it occasions.

International Registration Plan (IRP): A registration reciprocity agreement among States and Canadian provinces developed in 1973 by the American Association of Motor Vehicle Administrators.

Iterative Proportional Fitting: A mathematical technique which forces cell values to sum to row and column controls. Since there are an infinite number of possible combinations of cell values that could add up properly, the process must start with a “seed” distribution. The more closely the seed distribution reflects the true distribution, the more accurate will be the results of the iterative proportional fitting.

Jointly Occasioned Cost: The portion of highway expenditure cost which can be disproportionately assigned to specific user groups based on vehicle characteristics reflected in equivalent standard volume level activity statistics.

Jurisdictional Classification: A highway classification scheme based on the level of government (federal, state, county, local) financially responsible for the particular road system.

Kip: A one thousand lb unit of weight.

Lane-Miles: The number of lanes in a section of street or highway multiplied by the length of the section in miles.

Load-Related Costs/Expenditures: Those costs/expenditures that are a function of traffic loading, particularly heavy truck axle loads.

Marginal Cost: The increase in total cost that results from producing one additional unit of output. With respect to highway use, the marginal cost is the increase in total highway costs that results from one additional vehicle trip. In economic theory, economic efficiency is achieved when the price of an additional unit of output is equal to its marginal cost.

MC: Motorcycles including two and three-wheeled motorized vehicles. Typically these vehicles have saddle-type seats and are steered by handlebars rather than a wheel. This includes motor scooters, mopeds, motor-powered bicycles, and three-wheeled motorcycles.

MPG: Miles-per-gallon.

NAPCOM: National Pavement Cost Model

Non-Divisible Load Vehicles: One of the overweight truck shipments categories for application of special permits. Non-divisible loads are typically large pieces of equipment or materials which cannot be easily divided into smaller individual shipments. All states issue special permits for nondivisible loads which would violate state and federal gross vehicle weight, axle weight, and bridge formula limits if hauled without a special permit.

Non-Load-Related Costs/Expenditures: Those costs/expenditures judged to be independent of traffic loading (e.g., the portion of pavement deterioration and therefore pavement maintenance expenditures due to weather and other “environmental” influences).

Net State Expenditures: The amount of money spent on highway programs by PennDOT and funded directly by the State. Net expenditures consist of current year cash expenditures, plus prior year authorizations paid in the current period, plus inter-account transfers of funds not counted elsewhere, less federal and other reimbursements received in the current period.

Non-User: A member of the general public.

Occasioned Costs: Costs incurred by—or determined to be caused by—one or more classes of vehicles over and above the costs of the basic facility.

OHCAS: Oregon Highway Cost Allocation Study

Overhead: Costs that are not related to specific activities.

PaHCAS: Pennsylvania Highway Cost Allocation Study.

Passenger Car Equivalent (PCE): A measure of road space effectively occupied by a vehicle of a given type under given terrain, vehicle mix, road type, and congestion conditions. The reference unit is the standard passenger car operating under the conditions on the road category in question.

Passenger Car Equivalents (PCE's): A measure of the effective roadway space occupied or consumed by any vehicle relative to the space consumed by a standard passenger car. The standard passenger car is assigned a factor of 1.0. Larger and heavier vehicles have PCE factors greater than 1.0. The PCE factor for any vehicle will vary depending on the type of highway (e.g., number of lanes) and terrain (e.g., flat or mountainous) under consideration.

Pax: Passenger cars including sedans, coupes, and station wagons manufactured for the primary purpose of carrying passengers and pulling recreational and light trailers.

Residual Costs: The portion of total cost that is not recovered through prices or other charges to users.

Revenue Attribution: The process of determining the revenue contributions made by highway user groups.

Right of Way: The strip of land, property, or interest therein, over which a highway or roadway is built.

Road Functional Class/Road Characteristic: The rural classifications are: Interstate, Other Principal Arterial, Minor Arterial, Major Collector, Minor Collector, or Local. The urban classifications are: Interstate, Other Freeways and Expressways, Other Principal Arterial, Minor Arterial, Collector, or Local.

Road-Specific Programs: Program expenditures which can be associated with particular classes of roads as a result of accounting techniques.

Second-Structure Revenues: User charges which vary directly with amount of use of the road system. Various gasoline and diesel fuel taxes are considered second-structure revenue sources.

Sensitivity Analysis: A type of model testing where a single variable of interest is varied over a range of values to determine the effect on model results.

Social (or Indirect) Costs: Those costs which highway users impose on other users or on nonusers (e.g., adjacent property owners). Costs typically included in this category are those associated with noise, air, and water pollution, the time loss due to traffic congestion, and personal and property losses due to traffic accidents. Note, however, that the dividing line between direct and indirect costs is sometimes imprecise. The pollution associated with highway use, for example, imposes a cost on individuals (both users and non-users) but can also damage physical highway facilities and therefore involve a direct cost.

SRT: OHCAS Study Review Team formed by OEA.

STIP: Statewide Transportation Improvement Program.

Tax: A levy imposed by government on the resources of citizens and enterprises for the purpose of raising revenues to support government and its purposes.

TIUS: U.S. Bureau of the Census, Truck Inventory and Use Survey.

Ton Miles of Travel: Vehicle miles of travel weighted by vehicle weight in tons.

Truck Combinations: A truck tractor and a semitrailer, either with or without a full trailer, or a truck with one or more full trailers.

Truck: A general term denoting a motor vehicle designed for transportation of property. The term includes single-unit trucks and truck combinations.

Uniquely Occasioned Costs: Expenditures/costs that apply only to a particular class of vehicles and are therefore a unique responsibility of that class. For example, expenditures made to repair the damage caused by studded tires are assigned exclusively to cars and other light vehicles since, with very rare exceptions, trucks do not use these devices. Similarly, the cost of registering basic vehicles is assigned only to these vehicles, while the cost of maintaining and operating the state’s truck weigh stations is assigned only to trucks.

Unladen Weight: The weight of a truck, railroad car, or the like, not including its load.

User Charge: A fee, tax, or charge that is imposed on facility users as a condition of usage. An excise tax on gasoline or tires is a user charge because only highway users pay it, but a general sales tax on the same items is not a user charge.

User Charge Structure: A fee structure that is imposed upon users to repay the costs they induced. A package of instruments and rates that constitutes financing for the anticipated highway expenditures. Non-user charge instruments may be included in the complete package.

User Cost: The value of resources consumed by the traveler in using the highway system, (includes pavement wear, time in transit, and space requirements.) These are analogous to but do not necessarily equal direct highway expenditures.

User Revenues: Highway revenues raised through the imposition of user charges or fees.

Variable Cost: Costs that vary with the level of output or use. Short-run variable costs are those that could be avoided if certain or all current travel were to be eliminated. In the long run, all costs are variable.

Vehicle Class: Any grouping of vehicles having similar characteristics for cost allocation, taxation, or other purposes. The number of vehicle classes used in a cost responsibility (allocation) study will depend on the needs, purpose, and resources of the study.

Vehicle Miles of Travel (VMT): The miles of travel by an individual vehicle or class of vehicles on public highways, roads, and streets in the state during a specified period of time (usually a year).

Vehicle Type: One of the numerous subdivisions of the vehicle fleet, established on the basis of particular tire, axle, or body characteristics.

Weight-Distance Tax: A tax based on vehicle weight and miles traveled. The weight base may be gross registered vehicle weight, tare weight, or actual weight.

Width-Related Costs: Expenditures/costs that are a function of or influenced by vehicle widths. Many highway professionals, for example, believe that the greater width of trucks and other heavy (wider) vehicles requires somewhat wider travel lanes and shoulders, so that a portion of pavement expenditures is width-related.

B. MISCELLANEOUS DATA

In addition to the information provided in previous sections regarding specific data about the bridge, the following was also used. Table 31 provides a summary of the quantities used for initial construction, while Table 32 and Table 33 summarize the individual contract expenditures for the construction of the Millard E. Tydings Memorial Bridge and also show the conversion of the 1961 expenditure to 2005 dollars. Table 34 – Table 36 provide supplemental information pertaining to individual truss member characteristics for each of the three unique truss arrangements, while Figure 15 distinguishes the panel point designations utilized.

Table 31. Construction Quantity Estimates

NO.	DESCRIPTION	UNIT	TOTALS	PROPOSAL
1	Preparation of Bearing Areas	L.S.		
2	Structural Carbon Steel - Beam Spans	Lbs	636600	455000
3	Structural Carbon Steel - Truss Spans	Lbs	18784600	1598500
4	Structural Low Alloy Steel - Truss Spans	Lbs	12685300	12685000
5	Lightweight Concrete Deck	C.Y.	9748	7150
6	Reinforcing Steel Bars	Lbs	2484420	1820000
7	Dampproofing	L.S.		
8	Epoxy Waterproof	L.S.		
9	Precast Concrete Parapet	L.F.	10059	10060
10	Aluminum Railing	L.F.	10265	10265
11	Bit. Conc. Spec. "B" - Binder Course	Tons	3022	2125
12	Silica Sand Asphalt - Surface Course	Tons	1824	1275
13	Inspection Facilities	L.S.		
14	Navigation Lighting	L.S.		
15	Field Office Maintenance	Mo.		12
16	Motor Boat Operation	Mo.		12
17	Access Roads	L.S.		

Table 32. Contract NE101 Expenditures

CONTRACT NE101 - SUBSTRUCTURE		
DESCRIPTION	**UNIT PRICE**	**2005 UNIT PRICE**
Clearing and Grubbing	$ 4,500.00	$ 39,559.62
Cubic Yards of Roadway Excavation Unclassified	$ 3.00	$ 26.37
Cofferdams	$ 450,000.00	$ 3,955,962.22
Cubic Yards of Subbase	$ 6.00	$ 52.75
Central Field Office	$ 15,600.00	$ 137,140.02
Months of Field Office Maintenance	$ 240.00	$ 2,109.85
Months of Motor Boat Operation	$ 1,760.00	$ 15,472.21
Access Roads	$ 78,000.00	$ 685,700.12
Incremental Analysis Items	**Price/lb**	
Structural Excavation Class 3	$ 0.002	$ 0.02
Structural Excavation Class 4	$ 0.001	$ 0.01
Underwater Rock Excavation	$ 0.026	$ 0.23
Class HES Tremie Concrete	$ 0.005	$ 0.04
Class A Concrete in Footings	$ 0.006	$ 0.05
Concrete above Footings	$ 0.013	$ 0.11
Reinforcing Steel Bars	$ 0.135	$ 1.19
Protection Plates	$ 0.250	$ 2.20

Table 33. Contract NE102 Expenditures

CONTRACT NE102 - SUPERSTRUCTURE		
DESCRIPTION	**UNIT PRICE**	**2005 UNIT PRICE**
For Preparation of Bearing Areas	$ 17,300.00	$ 152,084.77
For Dampproofing	$ 26,800.00	$ 235,599.53
For Epoxy Waterproofing	$ 17,300.00	$ 152,084.77
For Inspection Facilities	$ 158,000.00	$ 1,388,982.29
For Navigation Lighting	$ 21,000.00	$ 184,611.57
Months of Field Office Maintenance	$ 500.00	$ 4,395.51
Months of Motor Boat Operation	$ 1,000.00	$ 8,791.03
For Access Road	$ 25,000.00	$ 219,775.68
Linear Feet of Precast Concrete Parapet	$ 11.70	$ 102.86
Linear Feet of Aluminum Railing	$ 4.25	$ 37.36
Incremental Analysis Items	**Price/lb**	
Structural Carbon Steel Beam Spans	$ 0.16	$ 1.40
Structural Carbon Steel Truss Spans	$ 0.20	$ 1.76
Structural Low Alloy Steel Truss Spans	$ 0.24	$ 2.07
Lightweight Concrete Deck	$ 0.02	$ 0.18
Bituminous Concrete Specification B - Binder Course	$ 0.01	$ 0.06
Silica Sand Asphalt - Surface Course	$ 0.01	$ 0.07
Reinforcing Steel Bars	$ 0.18	$ 1.54

Table 34. Suspended Span Truss Data

		STRESSES IN KIPS									UNIT STRESS (K/IN^2)			AREA FURN. (IN^2)		
MEMBER		D	L	I	D + L + I	WIND	DESIGN STRESS	L (FT)	r (in)	L/r	ALLOW	ACTUAL	AREA REQ'D (IN^2)	GROSS	EFF. GROSS	NET
TOP CHORD	U0-U1	0	0	0	0	WIND DOES NOT GOVERN	0	30.737	9.76	37.7	14.7	0	0	44.44	39.94	31.03
	U157-U158							30.513								
	U30-U31	0	0	0	0		0	DUMMY MEMBER								
	U37-U38															
	U31-U33	-1012	-323	-44	-1379		-1379	30.625	9.68	38	21.19	21.1	65	72.94	65.44	
	U35-U37															
	U33-U35	-1351	-430	-58	-1839		-1839	30.625	9.02	40.8	21.08	21.08	87.2	94.74	87.34	
BOTTOM CHORD	L30-L32	590	188	25	803		803	30.625			18	18	44.6			45.6
	L36-L38															
	L32-L34	1265	404	55	1724		1724	30.625			27	26.7	63.85			64.63
	L34-L36															
DIAGONALS	L30-U31	-933	-322	-44	-1299		-1299	48.416	8.82	65.8	19.58	19.3	66.4	79.38	67.38	
	U37-L38															
	U31-L32	668	247	37	952		952	48.416			27	26.6	35.3			35.82
	L36-U37		-21	-6	574											
	L32-U33	-401	-181	-30	-612		-612	48.416	7.88	73.7	13.64	13.6	44.9	54	45	
	U35-L36		53	14	-294											
	U33-L34	136	125	24	285		285	37.5			18	14	15.8			20.38
	L34-U35		-85	-18	19											
VERTICALS	U31-L31	0	0	0	0		0	37.5	5.43	82.9	13.28	0	0	36.3	27.3	20.38
	U37-L37															
	U33-L33	0	0	0	0		0	37.5	5.43	82.9	13.28	0	0	36.3	27.3	20.38
	U35-L35															
	U32-L32	-210	-146	-39	-395		-395	37.5	6.06	74.2	13.62	12.8	29	39.9	30.9	
	U36-L36															
	U34-L34	-210	-146	-39	-395		-395	37.5	6.06	74.2	13.62	12.8	29	39.9	30.9	
	U30-L30	722	250	34	1006		1006	37.5			27	26.76	37.3			37.57
	U38-L38															
	U0-L0	-118	-137	-41	-296		-296	37.5	6.06	74.2	13.62	9.6	21.7	39.9	30.9	
	U158-L158															

Table 35. Cantilever Arm Truss Data

MEMBER		STRESSES IN KIPS									UNIT STRESS (K/IN^2)		AREA REQ'D (IN^2)	AREA FURN. (IN^2)		
		D	L	I	D + L + I	WIND	DESIGN STRESS	L (FT)	r (in)	L/r	ALLOW	ACTUAL		GROSS	EFF. GROSS	NET
TOP CHORD	U38-U40 U58-U60	725	225	28	976	WIND DOES NOT GOVERN	976	30.625			27	26.4	36.2			37.06
	U40-U41 U57-U58	1378	415	48	1841		1841	30.625			27	26.85	68.2			68.57
	U41-U42 U56-U57	1835	540	58	2433		2433	30.625			27	26.8	90.2			90.76
BOTTOM CHORD	L38-L39 L59-L60	0	0	0	0		DUMMY MEMBER									
	L39-L40 L58-L59	-1414	-426	-49	-1889		-1889	31.415	10.4	36.5	21.25	21.03	89	97.33	89.83	
	L40-L41 L57-L58	-1965	-578	-63	-2606		-2606	32.802	9.93	39.7	21.12	20.86	123.4	132.46	124.96	
	L41-L42 L56-L57	-2393	-687	-71	-3151		-3151	34.75	9.61	43.4	20.94	20.62	150.5	160.34	152.84	
DIAGONALS	U38-L39 L59-U60	-1190	-394	-49	-1633		-1633	50.245	8.63	69.9	19.26	19.14	84.8	95.82	85.32	
	L39-U40 U58-L59	1071	347	40	1458		1458	50.245			27	27	54			54.02
	L40-U41 U57-L58	835	272	29	1136		1136	55.957			27	27	42.1			42.11
	L41-U42 U56-L57	592	199	20	811		811	66.105			18	17.8	45.1			45.49
VERTICALS	U39-L39 U59-L59	-220	-147	-44	-411		-411	39.833	6.19	77.2	13.51	12.46	30.5	43.52	33.02	
	U40-L40 U58-L58	-1088	-340	-37	-1465		-1465	46.833	8.96	62.8	19.79	19.71	74	86.44	74.44	
	U41-L41 U57-L57	-951	-296	-30	-1277		-1277	58.583	9.12	77	18.68	18.68	68.4	80.44	68.44	
	U42-L42	-1152	-519	-47	-1718		-1718	75	13	69.3	19.31	19.1	89	105.57	89.82	
	U56-L56		240	24												

Table 36. Anchor Span Truss Data

		STRESSES IN KIPS									UNIT STRESS (K/IN^2)			AREA FURN. (IN^2)		
MEMBER		D	L	I	D + L + I	WIND	DESIGN STRESS	L (FT)	r (in)	L/r	ALLOW	ACTUAL	AREA REQ'D (IN^2)	GROSS	EFF. GROSS	NET
TOP CHORD	U42-U43	1925	775	80	2780		2780	30.625			27	26.6	103			104.5
	U55-U56		-206	-19												
	U43-U44	1604	971	100	2675		2675	30.625			27	26.9	99.1			99.31
	U54-U55		-476	-43												
	U44-U45	1126	1140	117	2383		2383	30.625			27	27	88.3			88.31
	U53-U54		-768	-69												
	U45-U47	581	1210	125	2194	138	2194	30.625	9.74	37.8	27	26.7	81.25	117.74	110.24	82.31
	U51-U53		-989	-89	-833	-12	-842				21.2	7.63	39.7			
	U47-U49	-116	-1187	-107	-2026		-2026	30.625	10.6	34.9	21.28	21.2	95.2	103.07	95.57	72.7
	U49-U51		1210	125	1847		1847				27	25.4	68.4			
BOTTOM CHORD	L42-L43	-2393	-687	-71	-3151		-3151	34.75	9.61	43.4	20.94	20.62	150.5	160.34	152.84	
	L55-L56															
	L43-L44	-2062	-830	-86	-2978		-2978	32.802	9.7	40.5	21.08	21	141.3	149.46	141.96	
	L54-L55		220	20												
	L44-L45	-1646	-995	-103	-2744		-2744	31.415	9.8	38.5	21.17	20.93	129.6	138.6	131.1	
	L53-L54		488	44												
	L45-L46	-1129	-1143	-118	-2390	1098	-2390	30.713	10.1	36.6	21.25	20.95	112.5	121.58	114.08	85.9
	L52-L53		771	69			66				27	0.77	2.45			
	L46-L48	-143	-1216	-125	-2027	-512	-2234	30.625	10.3	35.7	21.3	21.3	104.8	112.33	104.83	80.09
	L50-L52		1114	100	1628	504	1907				27	23.8	70.6			
	L48-L50	202	1213	109	2101	516	2302	30.625	10.3	35.7	27	26.93	85.26	119.59	112.09	85.48
			-1210	-125	-1730	-523	-2011				21.28	17.95	94.5			
DIAGONALS	U42-L43	397	468	42	943	146	943	66.105	8.75	90.6	18	17.85	52.4	73.45	62.95	52.91
	L55-U56		-388	-40	-107	-155	-271				12.95	4.32	21			
	U43-L44	586	523	47	1156		1156	55.957			27	26.95	42.8			42.91
	L54-U55		-376	-39												
	U44-L45	785	517	47	1349		1349	50.245			27	26.7	49.96			50.58
	L53-U54		-296	-31												
	U45-L46	862	446	48	1356		1356	48.416			27	26.8	50.2			50.58
	L52-U53		-185	-21												
	L46-U47	-692	-419	-47	-1158		-1158	48.416	8.95	64.9	19.64	19.6	58.9	69.5	59	

	U51-L52		214	28												
	U47-L48	409	368	44	821		821	48.416			18	17.75	45.6			46.36
	L50-U51		-244	-32												
	L48-U49	-137	-321	-40	-595		-595	58.583	8.67	67	13.8	13.7	42.9	52.47	43.47	34.53
	U49-L50		280	36	290		290				18	8.4	16.1			
VERTICALS	U43-L43	-744	-498	-45	-1287		-1287	46.833	9.17	76.7	18.7	18.5	68.9	83.06	69.56	
	U55-L55		315	32												
	U44-L44	-862	-487	-44	-1393		-1393	39.833	8.53	66	19.56	19.48	71.3	82.06	71.56	
	U54-L54		234	24												
	U45-L45	-903	-401	-41	-1345		-1345	37.5	7.8	61.3	19.9	19.75	67.6	78.58	68.08	
	U53-L53		138	15												
	U46-L46	-217	-146	-44	-407		-407	37.5	6.19	72.8	13.67	12.33	29.8	43.52	33.02	
	U52-L52															
	U48-L48	-211	-146	-44	-407		-407	37.5	6.19	72.8	13.67	12.17	29.4	43.52	33.02	
	U50-L50															
	U47-L47	0	0	0	0	14	14	37.5	6.37	70.6	13.75	0.48	1.02	39.92	29.42	
	U51-L51															
	U49-L49	0	0	0	0	14	14	37.5	6.37	70.6	13.75	0.48	1.02	39.92	29.42	

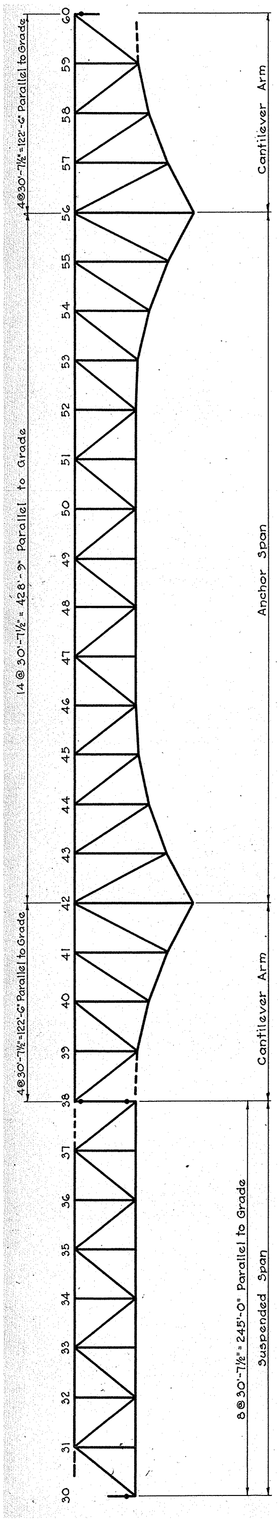

Figure 15. Truss Panel Point Designation

C. JFK PILOT SENSITIVITY ANALYSES RESULTS

Please note that Appendix C has been taken directly from the 2006 JFK Pilot report submitted by the University of Maryland to the Maryland Transportation Authority (MdTA).

All engineering analyses require varying numbers of assumptions, and HCAS are no exceptions. In addition to the assumptions that the compiled costs data are complete and accurate and that the VMT values are realistic for the JFK Highway, there are several other detailed assumptions embedded in the analyses:

- Contract cost data. A comprehensive search of the MdTA contract data was conducted and it is believed that all contract data for the study period have been identified. However, some contract data may still be missing.
- In-House maintenance costs. The average annual in-house maintenance expenditures available for FY 2002-2006 have been assumed representative and constant (in 2005 dollars) over the entire study period.
- The PCE factors for each vehicle class. Although the values assumed for the PCE factors in Table 16 are believed to be reasonable, the PCE factors reported in the literature vary over a considerable range.
- The split between load and non-load related costs for 3R projects (e.g., resurfacing/overlays). Other studies and the State HCAS Guidelines suggest that the load-related portion of 3R costs varies between 70 and 80%; the value of 75% assumed for the baseline scenario was simply taken as the middle of this range.

- The factors *a* and *b* in the axle load equivalency factor (LEF) Equation used to determine ESALs for each vehicle class. The values assumed for the pilot HCAS are based on the overall LEF relations in the State HCAS Guidelines and are assumed to be reasonable composite estimates. However, these values do vary as a function of distress type, pavement section, and other variables.

The impact of these assumptions (and others) on the results from the HCAS can be evaluated via sensitivity studies. Figure 18 summarizes some "limiting cases" for the pilot HCAS results as quantified in terms of relative tolls by vehicle class assuming a constant $5 base toll for 2-Axle vehicles. Allocating all pavement and bridge costs strictly by unweighted VMT divides costs equally among all vehicles and produces a constant toll of $5 for all vehicles, as would be expected. Allocating all pavement and bridge costs by PCE-weighted VMT produces a relative toll structure that is broadly consistent with the current MdTA rates. The baseline scenario, which allocates pavement and bridge costs based on the mix of cost allocators summarized in Table 17, has a higher percentage of combined pavement and bridge costs allocated to trucks and consequently generates the largest increase in the relative tolls for trucks. Recall that most truck traffic on the JFK Highway is in the 5-Axle category and that toll revenues from the 3, 4, and 6-Axle categories are insignificant even under the existing toll structure.

The historical MdTA facility maintenance and rehabilitation costs data are major inputs to the HCA. A very thorough search was conducted to compile all MdTA contract records for the pilot facility from 1960 to the present. It is nonetheless possible that some contracts may still have been overlooked. The sensitivity of the analysis results to missing contract data is evaluated by randomly deleting 20% of the compiled contracts from the HCA for three separate trials. As shown in Figure 16, deleting 20% of contracts slightly increased relative tolls for two-axle vehicles and slightly decreased relative tolls for 5-Axle vehicles. The converse is that adding any contracts that may be missing from the baseline condition would tend to decrease two-axle tolls and increase 5-Axle tolls.

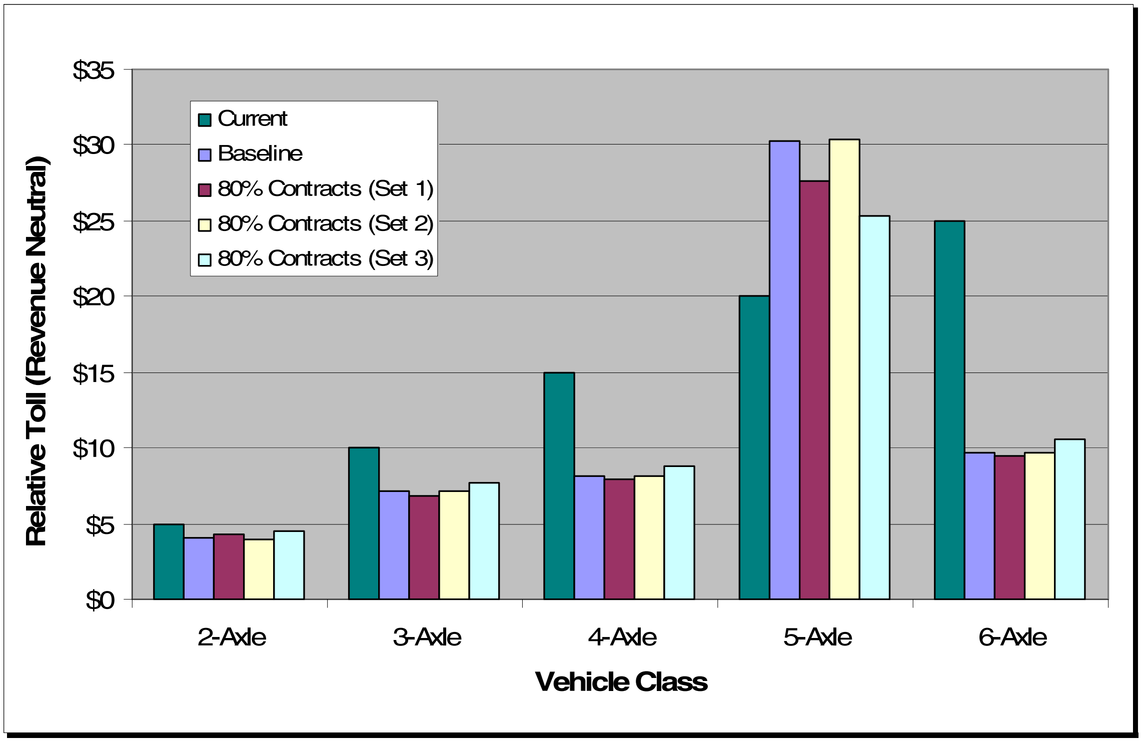

Figure 16. Sensitivity of Analysis Results to Contract Cost Data.

Annual in-house maintenance costs were assumed constant throughout the study period and equal to the average value (in 2005 dollars) over the 2002-2006 period for which good data exist. The sensitivity of the analysis results to in-house maintenance costs was evaluated by varying the annual in-house costs by ±25%. As summarized in Figure 17, the variations of in-house maintenance costs had only a slight effect on relative tolls. 2-Axle tolls are all in the range of $3.75 to $4.25, and 5-Axle tolls are all in the range of $28.50 to $32.50 (rounded to the nearest $0.25).

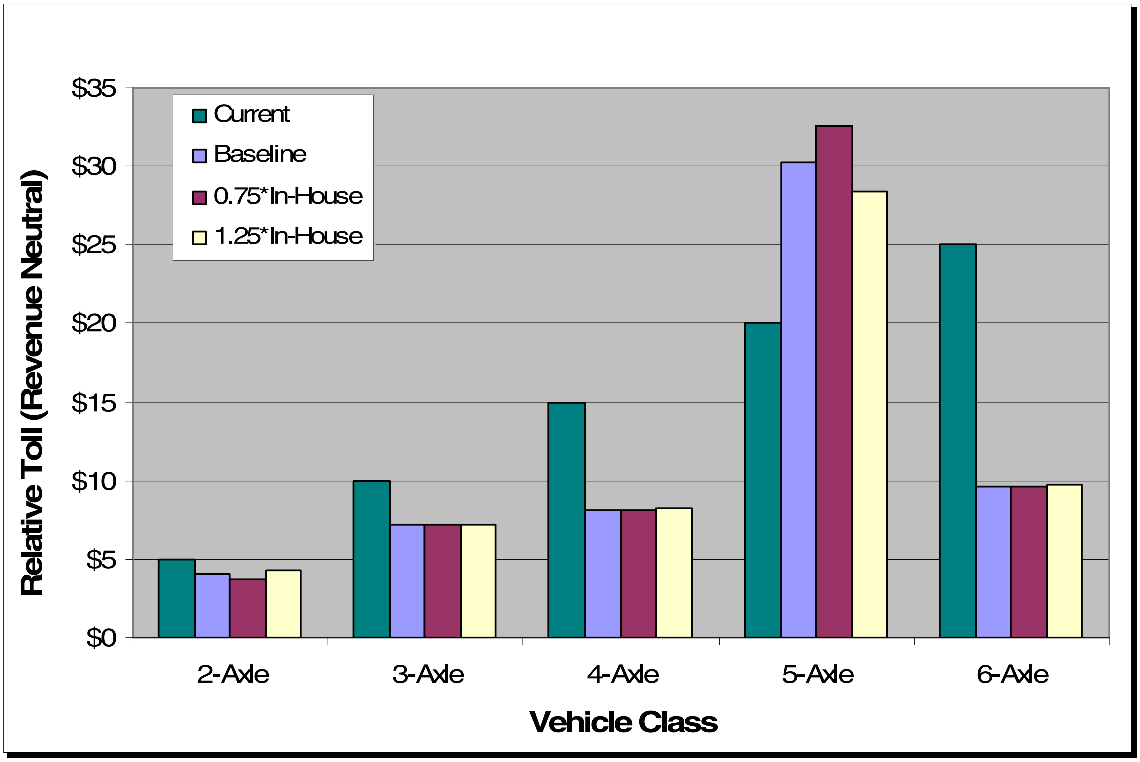

Figure 17. Sensitivity of Analysis Results to In-House Maintenance Cost Levels.

Figure 19 illustrates the sensitivity of the pilot HCAS results to variations in the values of the PCE factors. In this sensitivity study, the baseline PCE factors in Table 16 are varied upward and downward by 25%. All pavement and bridge costs are still allocated as in the baseline scenario using the cost allocators summarized in Table 17. It is clear from the results in Figure 19 that the ±25% variations in the PCE values have a negligible practical consequence on the HCAS results as expressed in terms of relative tolls for each vehicle class.

Figure 20 depicts the sensitivity of the pilot HCAS results to variations in the load vs. non-load share of pavement 3R costs. As detailed in Table 17, the load-related share of pavement 3R costs are allocated by ESALs and the non-load-related share is allocated by unweighted VMT. Four cases are considered in this sensitivity analysis: (a) the baseline scenario, which defines 75% of 3R costs as load-related; (b) 70% load-related, which is the lower limit of the commonly accepted range; (c) 80% load-related, which is the upper limit of the commonly accepted range; and (d) 100% load-related, which represents the physical upper limit. The results in Figure 20 show that the impact of load-related cost share is modest for the 5-Axle vehicles and negligible for the other vehicle classes. The largest impact for the 5-Axle vehicles corresponds to the 100% load-related cost share. However, although a 100% load-related share may represent the physical upper bound, it would be difficult to justify this high a value for HCAS purposes. The differences between the 75% baseline scenario and the more justifiable 70% and 80% load-related share alternatives on the relative toll assignments are considerably smaller.

Figure 21 summarizes the sensitivity of the pilot HCAS results to variations in the axle LEF values. In this sensitivity study, the baseline LEF factors coefficients *a* and *b* from Table 37 are varied upward and downward by 25%. All pavement and bridge costs are still allocated as in the baseline scenario using the cost allocators summarized in Table 17. It is clear from the results in Figure 21 that the ±25% variations in the LEF values have a negligible practical consequence on the HCAS results as expressed in terms of relative tolls for each vehicle class.

Figure 22 summarizes the results from all of the sensitivity studies performed during the pilot study. As clearly shown in the figure, cost allocation results in terms of relative tolls (revenue neutral) are remarkably insensitive to reasonable variations of major analysis inputs. Only the tolls for 5-Axle trucks show any significant effect of variations in analysis assumptions, and even here the variations are only about ±15% of the baseline values. If tolls are to be set in proportion to the costs incurred by each vehicle class, the preliminary results in Figure 22 for the <u>pilot implementation</u> suggest that, for revenue-neutral conditions:

- Tolls for 2-Axle vehicles should be modestly reduced by $0.75 to $1.00
- Tolls for 5-Axle trucks should be increased by $5 to $15.
- Tolls for 3, 4, and 6-Axle vehicles could be reduced. However, there are very few vehicles in these categories at the pilot facility.

Table 37. Overall LEF Factors Used in This Study (from State HCAS spreadsheets; FHWA, 2000)

Axle Type	Flexible		Rigid		Average	
	log *a*	*b*	log *a*	*b*	log *a*	*b*
Single	-3.2517	2.5904	-3.0983	2.4683	-3.175	2.529
Tandem	-4.6469	3.2430	-3.7011	2.5517	-4.174	2.897
Tridem	-4.5528	2.3065	-3.7864	2.4327	-4.170	2.370

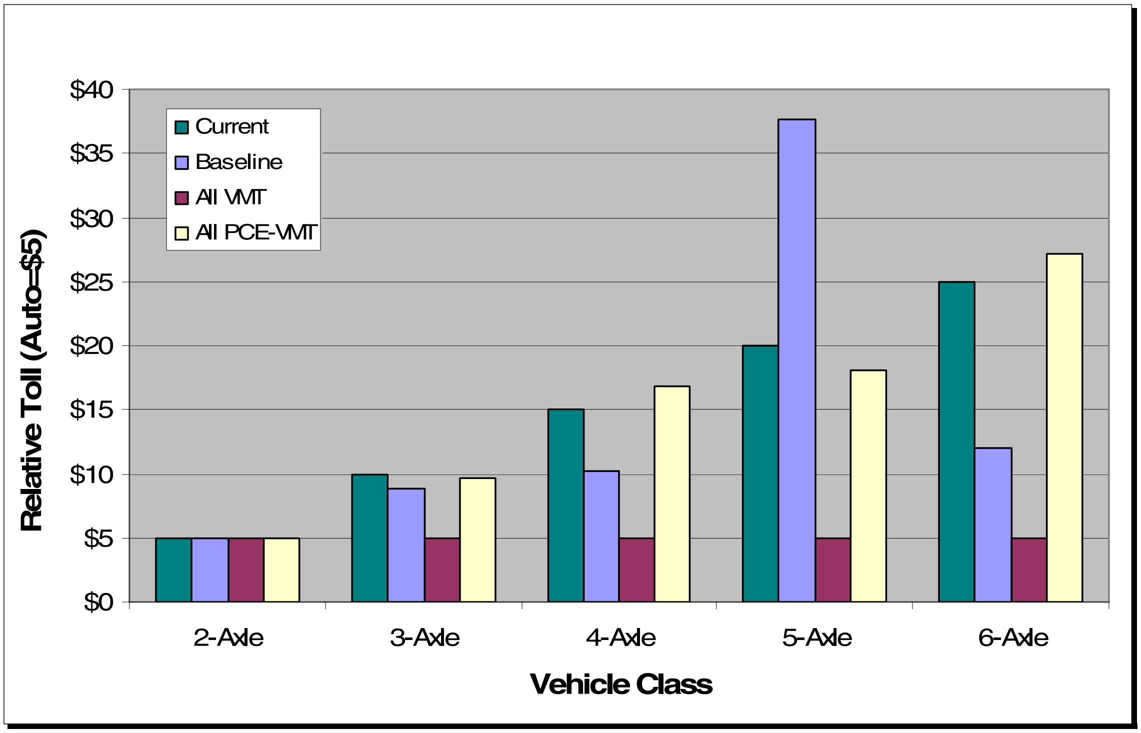

Figure 18. Limiting Cases for Impact of Analysis Assumptions on Pilot HCAS Results

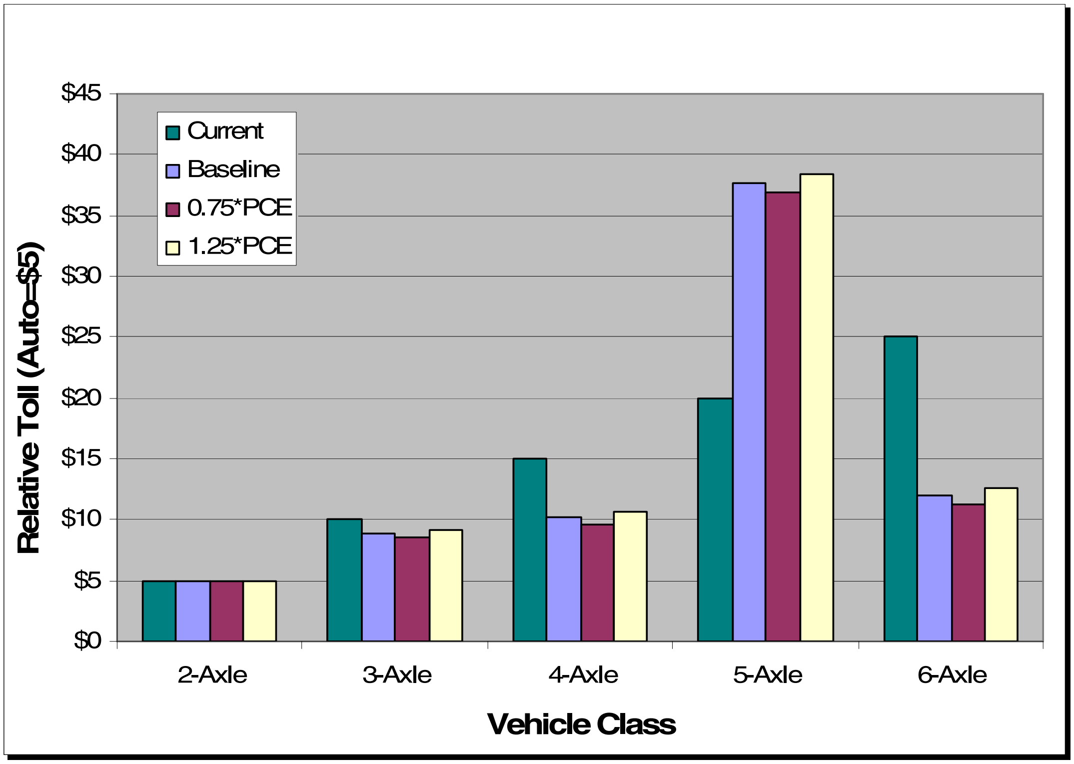

Figure 19. Sensitivity of Pilot HCAS Results to Variations in PCE Factor Values

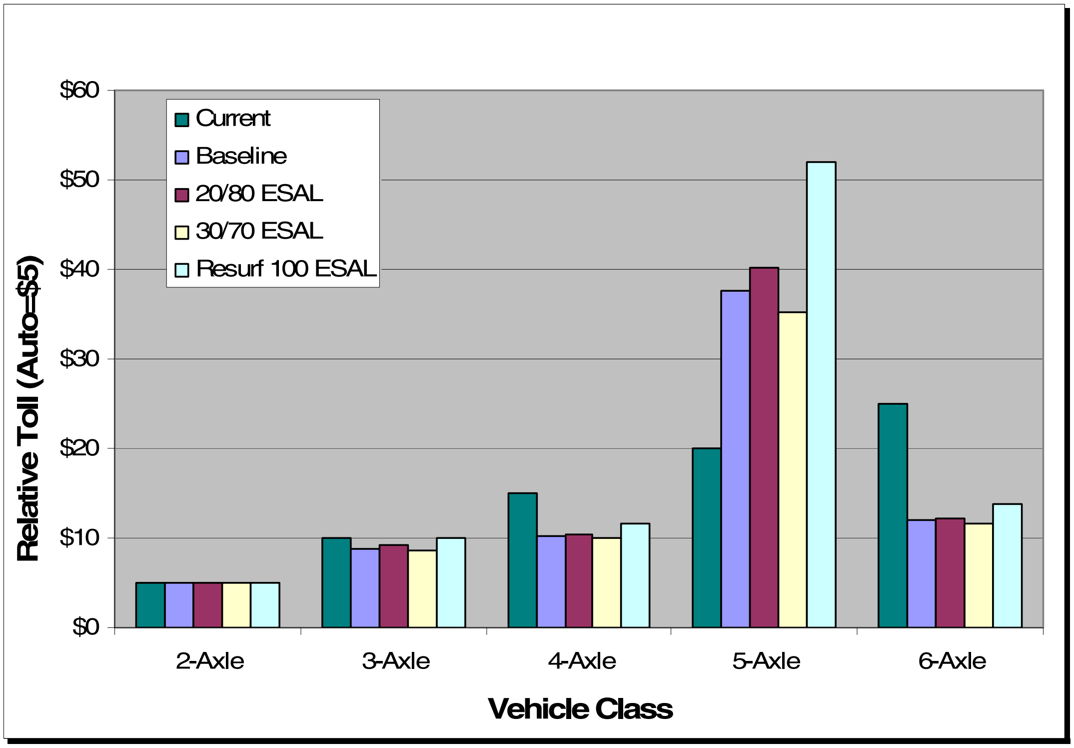

Figure 20. Sensitivity of Pilot HCAS Results to Variations in Load vs. Non-Load 3R Pavement Costs

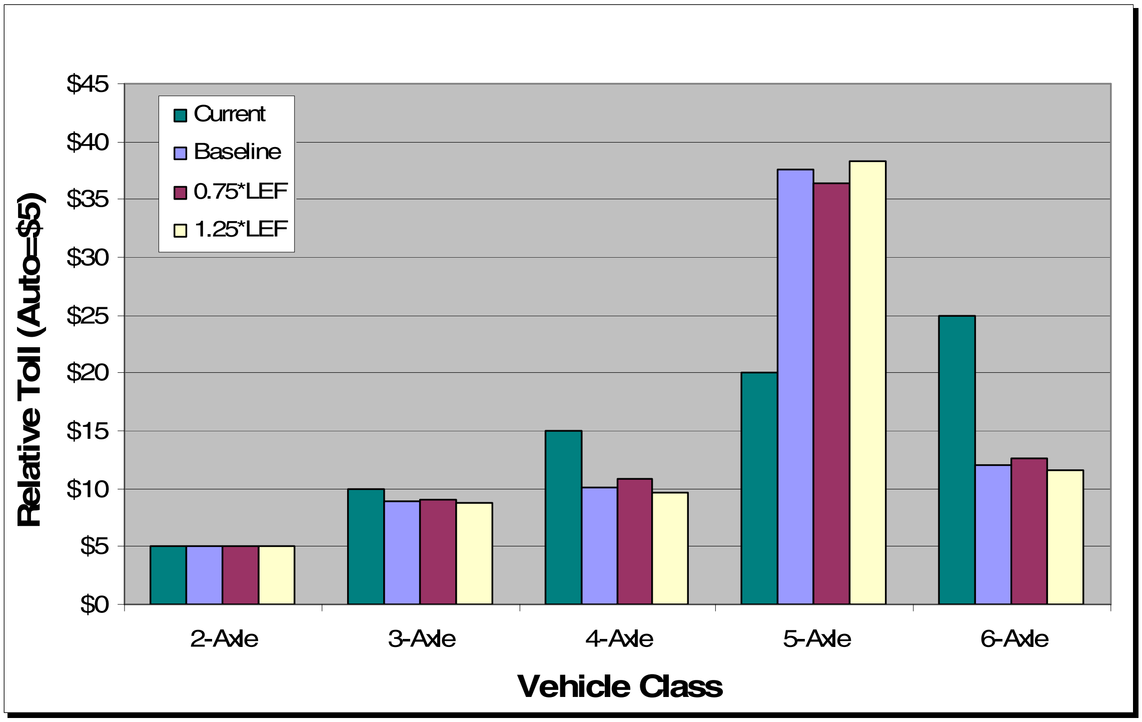

Figure 21. Sensitivity of Pilot HCAS Results to Variations in Axle LEF Values

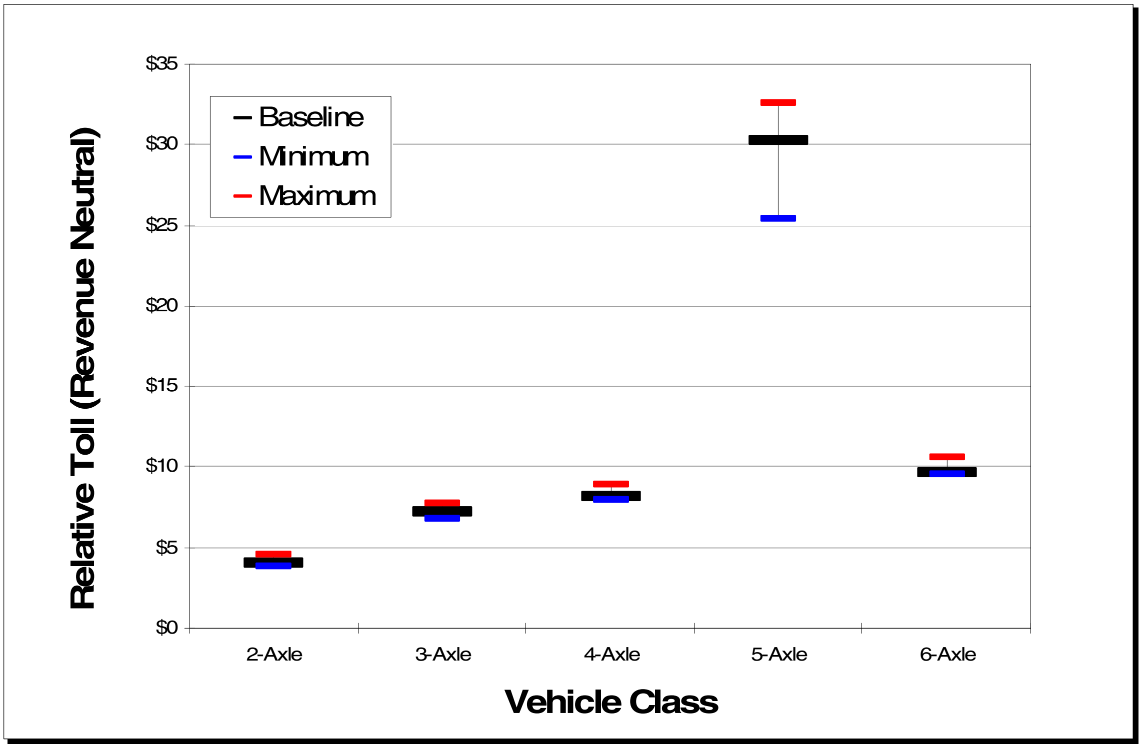

Figure 22. Summary of Sensitivity Study Results.

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