A Framework for Multi-Dimensional Assessment of the Impacts of Overweight Vehicle Operations and a Corridor-Level Case Study

by

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An Independent Study

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To God,

for his grace and putting such great people in my path.

To my husband Oscar, for his unconditional love, support, and patience throughout the entire length of my Graduate program.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHO	American Association of State Highway Officials
AASHTO	America Association Highway Transportation Officials
ADT	Average Daily Traffic
APDC	Average Pavement Damage Cost
ARTBA	American Road and Transportation Builders Association
ATRI	American Transportation Research Institute
CPI	Consumer Price Index
DOT	Department of Transportation
ESAL	Equivalent Single Axle Loads
EUAC	Equivalent Uniform Annual Cost
FAF	Freight Analysis Framework
FHWA	Federal Highway Administration
GDP	Gross Domestic Product
GSP	Gross State Product
GVW	Gross Vehicle Weight
HCV	Heavy Commercial Vehicle
HMA	Hot-Mix Asphalt
HMA/PCC	Hot-Mix Asphalt/Portland Cement Concrete
IDOT	Illinois Department of Transportation
INDOR	Indiana Department of Revenues
INDOT	Indiana Department of Transportation
IoT	Internet of Things
IS	Interstates
ISTEA	Intermodal Surface Transportation Efficiency Act
ITIC	Intermodal Transportation and Inventory Cost
LCV	Longer Combination trucks
MCDA	Multi-Criteria Decision Analysis

MDOT	Michigan Department of Transportation
MPDC	Marginal Pavement Damage Cost
MR	Minor Roads
MR&R	Maintenance, Rehabilitation, and Reconstruction
NHS	National Highway System
NIS-NHS	Non-Interstates National Highway System
Non-NHS	Non-National Highway System
ODOT	Ohio Department of Transportation
OS	Oversize
OSOW	Oversize/Overweight
OW	Overweight
PA	Principal Arterials
PCE	Passenger Car Equivalent
PDC	Pavement Damage Cost
PDO	Property Damage Only
SPF	Safety Performance Function
STAA	Surface Transportation Assistance Act
TCDS	Traffic Count Database System
TIE	Traffic Impairment Effect
TRB	Transportation Research Board
TRE	Trips Reduction Effect
TS&W	Truck Size and Weight
USDOT	United States Department of Transportation
VMT	Vehicle Miles Traveled
VOC	Vehicle Operational Costs
WIM	Weight-In-Motion
WisDOT	Wisconsin Department of Transportation

LIST OF TERMS

Average Pavement Damage Cost (APDC):	are total maintenance, rehabilitation, and reconstruction cost divided by the total usage (e.g., number of Equivalent Single Axle Loads).
Equivalent Single Axle Loads (ESAL):	a concept developed by the AASHO Road Test to represent the pavement damage relationship that compares the impact of axles transporting different loads, using a reference axle load of 18,000 lbs. single axle, dual tires (TxDOT 2005).
Equivalent Uniform Annual Cost (EUAC):	The annual cost of owning, operating, and maintaining an asset over its entire lifespan.
Gross Domestic Product (GDP):	is a monetary indicator of the market value of all final products and services produced by a country over a certain period of time.
Gross State Product (GSP):	is a metric used to represent the sum of the outputs of all industries in a state.
Internet of Things (IoT)	Refer to the network of physical items, or "things," that are implanted with sensors, software, and other technologies for the purpose of communicating and exchanging data with other devices and systems through the internet.
Longer Combination Vehicle (LCV)	Any combination of a truck tractor pulling two or more trailers or semitrailers with a gross vehicle weight of more than 80,000 pounds operating on the Interstate Highway System.
Marginal Pavement Damage Cost (MPDC)	is the increase in MR&R cost due to the movement of an additional truck on a given highway segment (Ahmed 2012).
Oversize/Overweight Permits	Permits issued by States that allow vehicles of certain configurations and sizes to exceed the federal size and weight limitations.
Passenger Car Equivalent (PCE):	a metric used for representing the impact of a large vehicle on a highway by expressing it as the number of equivalent passenger vehicles.

ABSTRACT

Ground freight transportation is essential for the economy of any region. The efficient movement of goods from one location to another connects businesses with suppliers and customers, that enhances commerce and ultimately boosts the economy. The high volume of freight that has been transported on the nation's highway network has allowed the trucking industry to provide enormous socio-economic benefits. Unfortunately, these benefits come with some costs associated with the operation of overweight (OW) trucks, such as accelerated deterioration of highway pavement and bridge assets, and passenger and freight traffic safety degradation. Thus, to manage safety risk, traffic mobility, and infrastructure deterioration on the highway network, state agencies have established weight restrictions and permit policies to regulate the operation of OW trucks in their jurisdictions.

However, the task of finding a balance between an adequate recovery of highway asset repair expenditures and reasonable OW permitting policies that do not impair the propitious economic environment of trucking operations in the state is challenging. Consequently, to make informed decisions, highway agencies are in need of knowledge regarding the potential effects of changes in these policies in terms of infrastructure damage, revenues collection, traffic operation, and road user costs.

To address the various costs and benefits associated with the operation of OW truck operations, this study proposed a multi-criteria decision analysis (MCDA) framework to enable prioritization of the wide range of criteria involved in changes in policies related to trucking operations. A major feature of this framework is its ability to allow the simultaneous consideration of different standpoints such as economic, public, and private sector that can assist agencies achieve more balance, rational, and defensible decisions. The proposed MCDA framework incorporates some of the most relevant performance criteria used in the evaluation of OW permitting policies including infrastructure damage, safety, traffic mobility, OW permitting revenues, vehicle operation costs for trucks and shipping inventory cost. Lastly, the proposed framework was applied to I-70, a highway corridor with some of the highest OW truck traffic in the state of Indiana, to demonstrate its implementation.

1. INTRODUCTION

The movement of freight is of great importance for the economy of any region. The efficient and reliable movement of raw materials, intermediate goods, and finished products from one location to another connects businesses with suppliers and customers, enhancing commerce and promoting economic growth that ultimately boosts the economic competitiveness of a region. The United States Department of Transportation (USDOT) estimated that about 51 million tons of goods worth $51.8 billion (chained in 2018 dollars) were moved each day in 2018, which accounted for 9.4 percent of the nation's GDP in that year (U.S. Department of Transportation; Bureau of Transportation Statistics 2020).

Among all freight transportation modes, trucks are the most predominant mode for shipping goods under 1,000 miles and have been carrying the largest percentage of goods by weight and value in the United States for the last decades (U.S. Department of Transportation; Bureau of Transportation Statistics 2020). In 2018, for instance, trucks transported about 11.3 billion tons of the weight (60.8 percent) and $11.5 trillion of the value of freight (60.9 percent) (U.S. Department of Transportation; Bureau of Transportation Statistics 2020).

The high volume of freight that has been transported on the nation's highway network has allowed the trucking industry to provide enormous socio-economic benefits. Unfortunately, these benefits come with some costs associated with the operation of oversize (OS) and overweight (OW) trucks, such as accelerated deterioration of highway pavement and bridge assets, and passenger and freight traffic safety degradation (Ahmed et al. 2012).

To manage safety risk, traffic mobility, and infrastructure deterioration on the highway network, state transportation agencies have established size and weight restrictions to regulate trucking operations to protect public safety, improve traffic mobility, and prevent infrastructure damage without impairing the trucking industry's operations that can hinder the economic development and productivity of the region (Everett et al. 2014). Thus, highway agencies strive to strike a balance between an adequate and fair recovery of highway asset repair/replacement expenditures from its users' consumption and reasonable overweight permitting policies that do not impair the propitious economic environment associated with trucking operations in the state (Everett et al. 2014).

However, this task is challenging and dynamic, for the unit cost of infrastructure consumption changes over time due to the constant innovation of new technologies such as pavement and bridge materials, design, construction, and maintenance leading to changes in the repair cost and service life of these infrastructures (Everett et al. 2014). To keep up with these dynamic trends, highway agencies are required to review and update their OW permitting policies and fee structure periodically; and to do so knowledge regarding the potential effects of changes in these policies in terms of infrastructure damage, OW permitting revenues, safety degradation, mobility impairment, road user costs, and environmental impacts are needed to make informed decisions.

This study focuses on addressing the various costs and benefits associated with the operation of OW truck operations. For that purpose, the authors propose a multi-criteria analysis framework to enable prioritization of the wide range of criteria involved in changes in policies related to OW truck operations when considering the standpoints of different stakeholders simultaneously. The proposed multi-criteria analysis framework considers the following performance criteria for evaluation: 1) infrastructure damage, 2) safety degradation, 3) mobility impairment, 4) OW permitting revenues, 5) vehicle operation cost for trucks, and 6) shipping inventory cost. The methodology uses a combination of published research and documented experiences as well as some quantitative data analysis. In this study, the proposed framework will be evaluated in two scenarios, 1) without OW trucks (base case scenario) and 2) with OW trucks (alternative scenario) in a highway corridor. Then, the resulted framework will be applied to I-70, a highway corridor with some of the highest OW truck traffic in the state of Indiana. Ultimately, this framework aims to assist highway agencies in the decision-making process for evaluating the potential effects of changes on OW truck operation policies.

1.1 Background

1.1.1 Federal Legislations on Overweight Traffic Operations

The first federal regulations on truck size and weight were established in the Federal-Aid Highway Act of 1956 (Public Law 84-627) to protect the investment in the Interstate Highway system, and restricted combination trucks to an overall gross vehicle weight of 73,280 lb., single-axle weight to 18,000 lb., and tandem-axle weight to 32,000 lb. Federal truck size were only restricted to a width of 96 inches, leaving the height and length of trucks subjected to State law (FHWA 2015). Exceptions to the federal restrictions established in 1956 (Public Law 84-627) allowed the operation of trucks exceeding its axle load or gross vehicle weight (GVW) limits on Interstates is known as the "grandfather clause."

In 1974, Congress increased federal weight limits on the Federal-Aid Highway Act of 1956 to a maximum GVW of 80,000 lb., a single-axle load limit of 20,000 lb., and a tandem-axle load limit of 34,000 lb. (FHWA 2015). However, the increase was not mandated for all states which created institutional barriers to efficient cross-country trucking operations when some states kept lower weight limits in their territories (U.S. Department of Transportation 1997).

In 1982, the Surface Transportation Assistance Act (STAA) rectified the situation by establishing a "National Network" that included the Interstate system and other federal-aid highways critical to the trucking industry, for which the federal weight limits served as the minimum weight limits. STAA also increase the maximum truck width to 102 inches (FHWA 2015).

In 1991, the Intermodal Surface Transportation Efficiency Act (ISTEA) imposed weight and routes restrictions on longer combination trucks (LCTs) only. The ISTEA defined an LCV as, "any combination of truck-tractor or two or more trailers or semitrailers which operate on the National System of Interstate and Defense Highways with a GVW greater than 80,000 lb." (FHWA 2015). Currently, 17 States allow the operation of LCVs in their interstate system (see Figure 1.1).

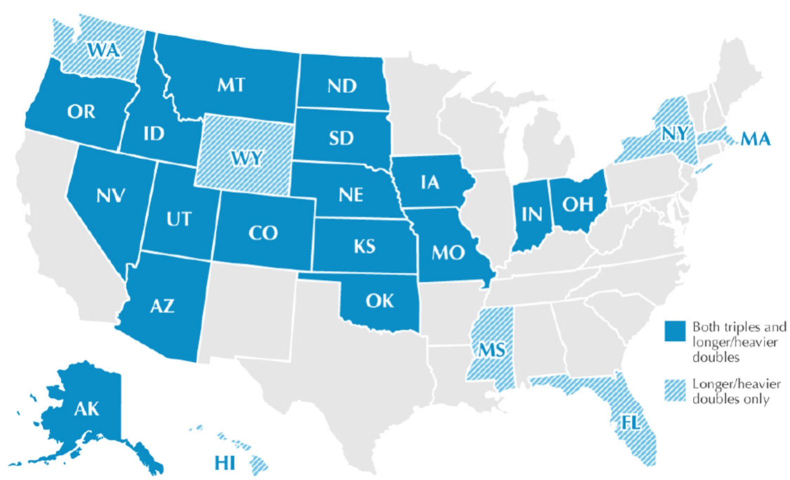


Figure 1.1. States Allowing the Operation of Longer Combination Vehicles (LCVs) on Some Portion of their Interstate System.
Source: USDOT (2015).

Table 1.1 presents a summary of the federal laws that affect State exemptions/grandfather rights and their established truck weight and size restrictions.

Table 1.1. Chronology of Federal Size and Weight Laws, 1956 – 2022.

Regulation	**Weight Limits**	**Size Limits**
Federal-Aid Highway Act, 1956	Interstate System: ▪ Single-axle limit: 18,000 lb. ▪ Tandem-axle limit: 32,000 lb. ▪ Gross vehicle weight: 73,280 lb.	Interstate System: ▪ Width limit: 96 in.
Federal-Aid Highway Act Amendments, 1974	Interstate System: ▪ Single-axle limit: 20,000 lb. ▪ Tandem-axle limit: 34,000 lb. ▪ Gross vehicle weight: 80,000 lb.	Interstate System: ▪ Width limit: 96 in.
Surface Transportation Assistance Act (STAA), 1982	Interstate System: ▪ Mandated states to allow the federal weight limits on Interstates	Interstate System: ▪ Width limit: 102 in.
Intermodal Surface Transportation Efficiency Act (ISTEA), 1991	Longer Combination Vehicle (LCV) freeze	Longer Combination Vehicle freeze imposed by Congress

Additionally, to protect bridges from overstressing, the Federal Highway Administration (FHWA) also developed a Federal Bridge Weight Formula to establish the weight-to-length ratio limits for trucks crossing a bridge (FHWA 2019). Since longer vehicles with wider axle spacings have less concentrated loads and therefore result in less stress on the bridge, the Federal Bridge Weight Formula (Equation 1.1) allows longer axle groups to carry heavier loads.

$$W = 500 \left[\frac{L\,N}{N-1} + 12N + 36\right. \qquad \text{(Equation 1.1)}$$

Where
W: overall gross weight on any group of two or more consecutive axles to the nearest 500 lbs.
L: distance in feet between the outer axles of any group of two or more consecutive axles
N: number of axles in the group under consideration.

1.1.2 Indiana State Legislations on Overweight Traffic Operations

The laws governing the truck size and weight in Indiana are detailed in the Indiana Code under Title 9: Motor Vehicles in Article 20: Size and Weight Regulations (Indiana General Assembly 2021).

Truck operations on the National Highway System (NHS) in Indiana are regulated by several provisions in the State law to permit trucks to exceed some elements of the Federal limits. These State provisions can be summarized in two main cases, in which the Indiana State allows: 1) several axles and GVW exemptions for various types of trucks and commodities and 2) two types of weight tolerances for axle and/or GVW (FHWA 2015).

In summary, to travel legally on any Indiana roads, vehicles must not exceed the following dimensions or weights:

Height:	13 feet 6 inches
Width:	8 feet 6 inches
Length:	40 feet for single vehicles
	60 feet for two-vehicle combination*
	*When the two-vehicle combination is connected by a fifth-wheel hook-up, there is not an overall length limit, but the trailer and load length must not exceed 53 feet
Weight:	80,000 lbs. GVW
	12,000 lbs. on the steering axle
	20,000 lbs. on a single axle
	34,000 lbs. on a tandem axle
	800 lbs. per inch of rim width and subject to the above axle weights

Moreover, grandfather provisions under the Federal law allow Indiana to permit the operations of heavy-duty and extra heavy-duty trucks on some segments of the Interstate system with a maximum weight limit of 22,400 lbs. on a single axle, 36,000 lbs. on a tandem axle, and 134,000 lbs. GVW depends on the type of highway (Heavy-Duty or Extra Heavy-Duty Highways). For these vehicles exceeding the legal state weight limits, a permit is required for transiting on the highway network of Indiana. A summary of the weight limits for truck operations in Indiana is presented in Table 1.2.

Furthermore, the State of Indiana has established and designated specific routes for heavy-duty and extra heavy-duty truck operations (Everett et al. 2014). Figure 1.2 and Figure 1.3 show the maps with the routes for extra-heavy-duty truck operations for North West Indiana and North East Indiana, respectively.

Table 1.2 Summary of Indiana Truck Weight Limits for Truck Operations.

Characteristic	State and Interstate Highways	Heavy-Duty Highways	Extra Heavy-Duty Highways
Single Axle	20,000 lbs.	22,400 lbs.	18,000 lbs.
Tandem Axle	34,000 lbs.	36,000 lbs. (18,000 lbs. for each axle)	32,000 lbs. (1)
Gross Vehicle Weight	80,000 lbs.	80,000 lbs.	134,000 lbs. (2) 90,000 lbs. (3)
Other	800 lbs. per inch width of tire 1.5 percent scale tolerance	800 lbs. per inch width of tire 1.5 percent scale tolerance	800 lbs. per inch width of tire 1.5 percent scale tolerance

(1) An axle in an axle combination may not exceed 13,000 lbs. per axle, or 26,000 lbs. total for a two-axle group, except for one tandem group, which may weigh 16,000 lbs. per axle, or 32,000 lbs. total.
(2) Routes (1 to 21) where trucks are allowed to operate with a maximum weight of 134,000 lbs. can be found in the State Form 944 (Form M-233ST) at https://www.in.gov/dor/tax-forms/motor-carrier-forms-and-applications/.
(3) Routes (22) where trucks are allowed to operate with a maximum weight of 90,000 lbs. can be found in the State Form 944 (Form M-233ST) at https://www.in.gov/dor/tax-forms/motor-carrier-forms-and-applications/.

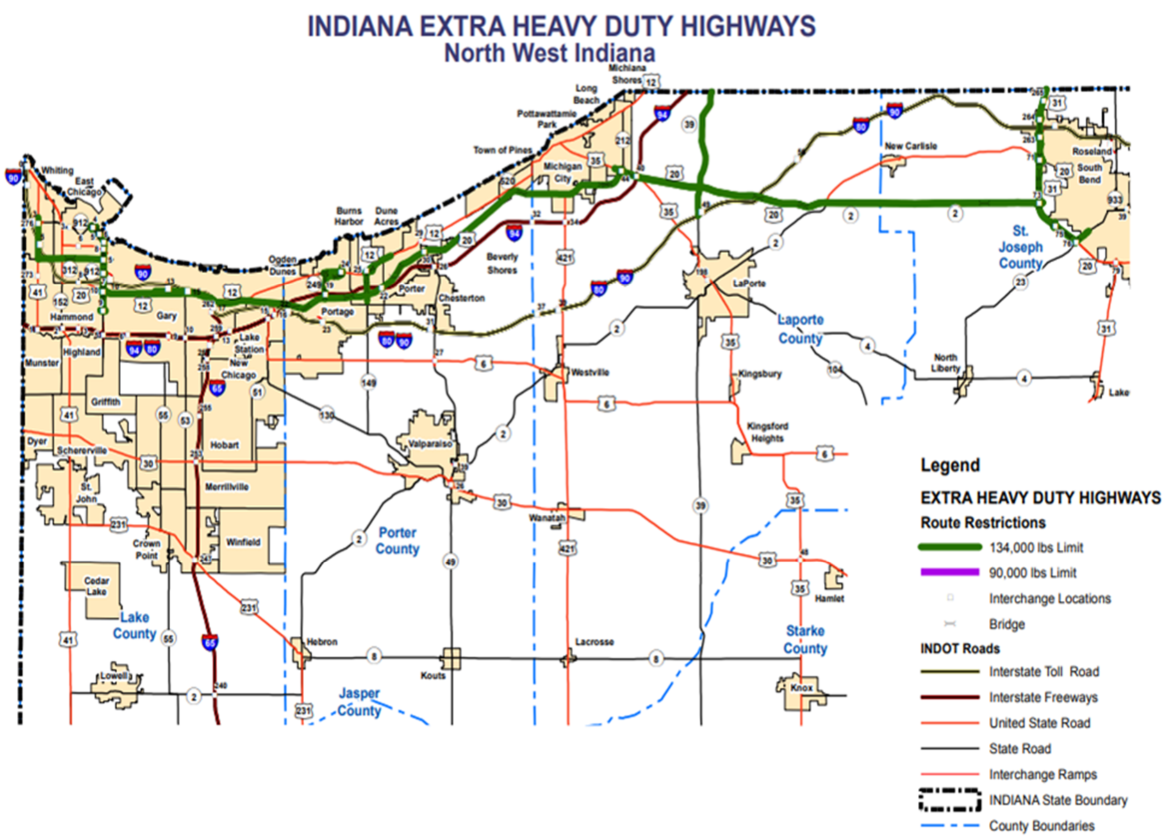


Figure 1.2. North West Indiana Extra Heavy-Duty Highways.
Source: (INDOT 2022).

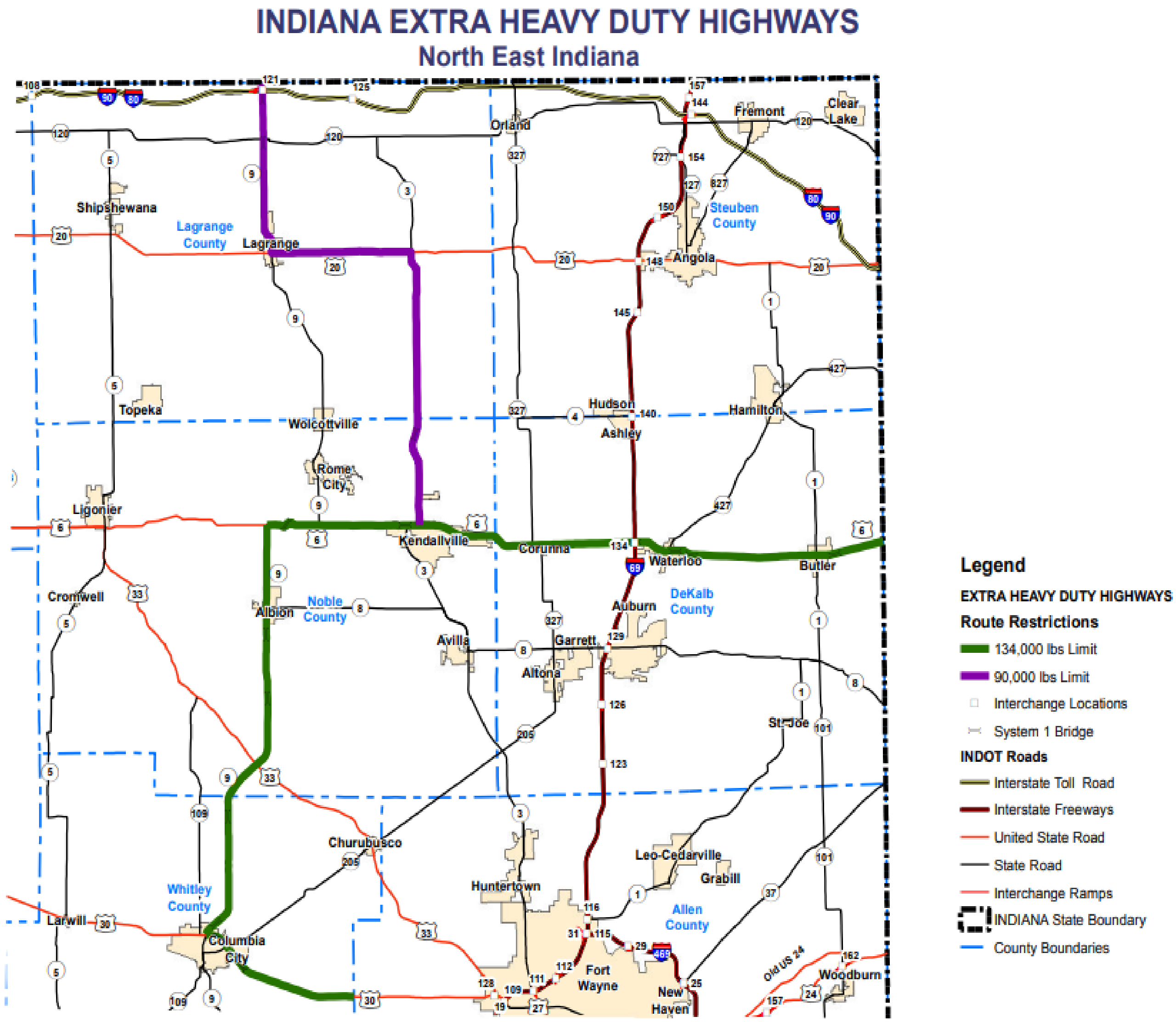


Figure 1.3. North East Indiana Extra Heavy-Duty Highways.
Source: (INDOT 2022).

1.2 Chapter Summary

Freight operations are important for the economy of any region. The efficient and reliable movement of raw materials, intermediate goods, and finished products from one location to another connects businesses with suppliers and customers, enhancing commerce and promoting economic growth that ultimately boosts the economic competitiveness of the region. Unfortunately, the economic benefits associated with truck operations also come with some costs from its adverse impacts on highway infrastructure, road safety, and traffic mobility.

To manage safety risk, traffic mobility, and infrastructure deterioration on the highway network, the Federal Government has established federal truck size and weight limits to regulate truck operations on the Interstate system. Exceptions to the federal truck size and weight regulations are granted to individual states through grandfather provisions (FHWA 2015). Oversize/Overweight permit fees are issued by most states with the primary purpose of collecting funding from commercial oversize and overweight vehicles to lessen their burden in terms of infrastructure asset maintenance and replacement.

Because changes in policies associated with the regulation of oversize/overweight truck operations have a great impact on the economic development and productivity of the state, highway agencies are faced with the challenging task of finding a balance between an adequate and fair recovery of highway asset repair/replacement expenditures from its users' consumption and a reasonable overweight permitting policies that do not impair the propitious economic environment associated with trucking operations in the state (Everett et al. 2014).

2. IMPACTS OF OVERWEIGHT VEHICLE OPERATIONS

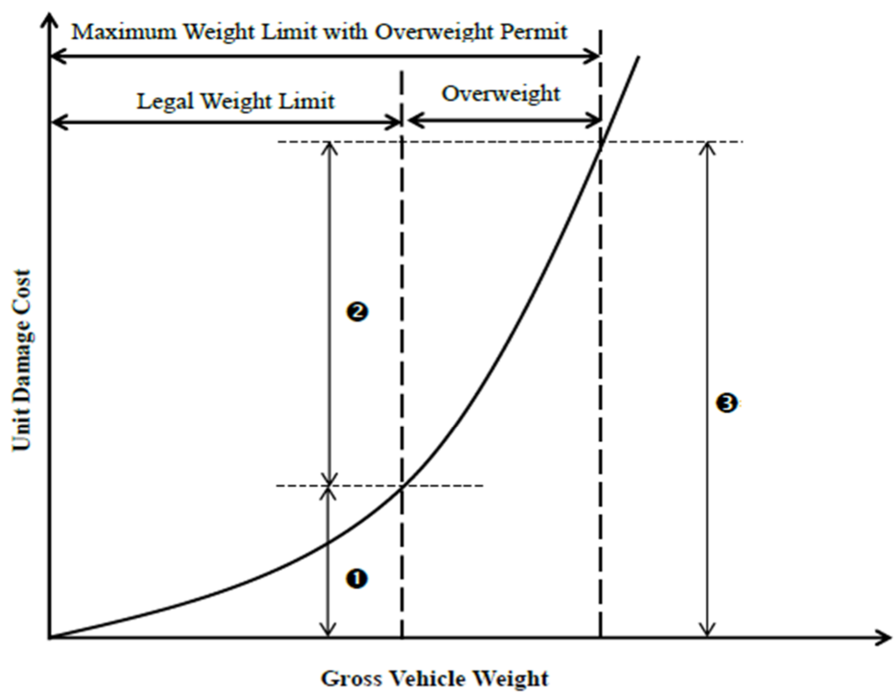
2.1 Infrastructure Damage

The amount of ground transportation freight on the U.S. highway system is continuously increasing in size and weight. Overweight truck operations cause significant damage to highway infrastructure that consequently reduces the service life of pavement and bridges. Overweight trucks cause much greater damage to pavement surfaces than the damage expected from legal weight trucks (Straus et al. 2006). A study in Texas estimated that the damage caused by overweight truck traffic associated with natural gas development is approximately 20.6 percent greater than the damage caused by the design traffic (Banerjee et al. 2012). Findings from the same study also showed that the additional damage caused by overweight trucks reduces pavement service life by 50 percent (Banerjee et al. 2012). Another study conducted by Salen (2008) in Egypt showed that an excess of 6,000 lbs. above the legal axle load limit (20,000 lbs.) decreases the pavement design life by 40 – 65 percent depending on the elastic modulus of the asphalt concrete layer. The accelerated deterioration caused by the "additional" traffic loading from overweight vehicles increases the frequency/intensity of infrastructure routine maintenance and rehabilitation activities, and hence the costs associated with them, which ultimately imposes a great burden on transportation agencies whose financial funds are continuously being cut off. Thus, an adequate quantification of the infrastructure damage occasioned by overweight vehicles is of great importance for state transportation agencies to ensure the safety of the highway system, develop effective infrastructure management and rehabilitation strategies, establish an adequate permit fee structure that allows the collection of sufficient funds for maintaining those infrastructures, and update policies for regulating OSOW truck operations.

2.1.1 Overweight Truck Impacts on Pavement Damage

In the past, several studies have been conducted to estimate the impacts and costs associated with pavement damage due to overweight truck operations. These studies sought to estimate either the average pavement damage cost (APDC) or the marginal pavement damage cost (MPDC). The APDC is the total maintenance, rehabilitation, and reconstruction (MR&R) cost divided by the total usage [e.g., number of Equivalent Single Axle Loads (ESAL)]; while the MPDC is the increase in MR&R cost due to the movement of an additional truck on a given highway segment (Ahmed et al. 2012).

Several factors such as traffic loading, pavement material (asphalt or concrete pavement), pavement layer thickness, environmental conditions, and underlying soil characteristics influence pavement deterioration (Everett et al. 2014). However, vehicle type and weight are the most significant factors in pavement deterioration. Heavy truck loads can develop excessive stress and strain on the different structural layers of the pavement causing different forms of distress and ultimately pavement fatigue failure (Chowdhury et al. 2013). Studies have shown that increments in trucks' number of axles and load magnitude provoke an exponential increase in pavement damage (David Luskin 2001). Moreover, the damage contribution of trucks at different gross vehicle weights on highway infrastructure can be depicted in Figure 2.2. Studies on Pavement Damage Costs by Highway Functional Class. As shown, the unit damage cost can be divided into two parts, the damage cost due to the legal weight (1) and the damage cost due to the additional weight allowed by an overweight permit beyond the legal weight limit (2) (Chowdhury et al. 2013).



Note:
❶ Unit damage cost for a truck loaded at the legal weight limit.
❷ Additional unit damage cost due to additional weights above the legal weight limit to the maximum weight limit with overweight permits.
❸ Unit damage cost for a truck loaded at the maximum weight limit with an overweight permit.

Figure 2.1 Damage Contribution of Trucks at Different Gross Vehicle Weights. Modified from Chowdhury et al. (2013).

Based on the literature, there are two main approaches to estimating pavement damage cost (PDC), Empirical and Engineering approaches (Ali et al. 2020). The Empirical approach seeks the statistical correlation between pavement cost (e.g., maintenance, rehabilitation, and reconstruction) and pavement usage (or road-use variables such as climate, pavement condition, traffic, and pavement structural characteristics) to generate the pavement damage cost (Ahmed et al. 2012). The Engineering approach seeks the theoretical relationship between the total pavement cost over its life cycle and pavement usage (e.g., traffic loading) for a unit road segment that is further generalized for the entire road network (Ahmed et al. 2012).

Several efforts have been made by different states to estimate the impact and cost associated with overweight traffic on pavement service life. Straus et al. (2006) estimated that overweight truck operations in Arizona inflict an annual uncompensated damage cost of $12 to $53 million on the state's highway system.

Ahmed et al. (2012) estimated the load-related overall marginal pavement damage cost of overweight traffic for Interstates (IS), non-Interstates National Highway System (NIS-NHS), and non-National Highway System (Non-NHS) in Indiana as $0.006, $0.055, and $0.218 per ESAL-mile, respectively. These marginal pavement damage costs were estimated using a life-cycle cost analysis that considered pavement maintenance, rehabilitation, and reconstruction costs.

Chowdhury et al. (2013) conducted a study to estimate the cost of pavement deterioration (chained in 2012 dollars) due to different overweight truck types in South Carolina and found that the additional per mile damage for an overweight truck with 5 axles (80 – 90 kips) with its ESAL between the legal weight limit and the maximum overweight limit was $0.3801. The study also evaluated the adequacy of standards permitting practices in state agencies.

Nassif et al. (2015) performed Life-cycle Cost Analysis to obtain the unit pavement damage costs incurred by overweight trucks on Interstate highways (IS) and state roads (SR) in New Jersey. To evaluate the change in cost due to economic analysis parameters, the study considered two different discount rates and analysis periods in the computation of the unit pavement damage costs. For an analysis period of 30 years, the unit pavement damage costs for IS and SR were found to be $0.038 and $0.250 per ESAL mile, respectively. Whereas the unit pavement damage costs in the 60 years analysis period for IS and SR were $0.027 and $0.161 per ESAL-mile.

Al-Qadi et al. (2017) also conducted a life-cycle cost analysis to estimate the average pavement damage cost for full-depth hot-mix asphalt (HMA) pavement and hot-mix asphalt/Portland cement concrete (HMA/PCC) pavement on Interstates (IS) and non-Interstates (NIS) highways in Illinois. For Interstates highways, the average pavement damage cost of HMA and HMA/PCC pavement was found to be $0.0493 and $0.027 per ESAL-mile, respectively. For non-Interstate highways, the average pavement damage cost of HMA and HMA/PCC pavement was found to be $1.328 and $0.5483 per ESAL-mile, respectively.

Ali et al. (2020) conducted a pavement damage cost estimation for Interstates (IS), principal arterials (PA), and minor roads (MR) in Florida, and found that the average pavement damage cost for IS, PA, and MR, was $0.018, $0.049, and $0.147 per ESAL-mile, respectively. Table 2.1 summarizes pavement damage cost studies.

Table 2.1. Summary of Pavement Damage Costs Studies.

Study	**State**	**Analysis Approach**	**Traffic Variable & Performance Index**	**MR&R Cost Data**	**Pavement Damage Cost**
Ahmed et al. (2012)	IN	Empirical	ESAL	Life-cycle cost with maintenance, rehabilitation, and reconstruction costs	Flexible Pavement $0.0066/ESAL-mi for IS $0.0599/ESAL-mi for NIS-NHS $0.2349/ESAL-mi for Non-NHS Rigid Pavement $0.0083/ESAL-mi for IS $0.0756/ESAL-mi for NIS-NHS $0.2967/ESAL-mi for Non-NHS
Chowdhury et al. (2013)	SC	Theoretical	GVW excess 80 kips ESAL	Pavement replacement costs	Additional damage to an OW truck: $0.3801/ESAL-mi for 5-axle, 80-90 kips $0.4160/ESAL-mi for 6-axle, 90-100 kips $0.6773/ESAL-mi for 7-axle, 110-120 kips $0.7565/ESAL-mi for 8-axle, 120-130 kips
Nassif et al. (2015)	NJ	Empirical	ESAL	Life-cycle cost with maintenance and rehabilitation costs (milling and resurfacing)	30 Years Analysis Period $0.038/ESAL-mi for IS $0.250/ESAL-mi for state roads 60 Years Analysis Period $0.027/ESAL-mi for IS $0.161/ESAL-mi for state roads
Al-Qadi et al. (2017)	IL	Theoretical	ESAL	Life-cycle cost with maintenance, rehabilitation, and initial construction costs	Full-depth HMA Pavement $0.0493/ESAL-mi for IS $1.328/ESAL-mi for NIS HMA/PCC Pavement $0.0270/ESAL-mi for IS $0.5483/ESAL-mi for NIS

Study	State	Analysis Approach	Traffic Variable & Performance Index	MR&R Cost Data	Pavement Damage Cost
Ali et al. (2020)	FL	Theoretical	ESAL	Life-cycle cost with maintenance costs (milling and resurfacing)	$0.018/ESAL-mi for IS $0.049/ESAL-mi for PA $0.147/ESAL-mi for MR

For a practical comparison of the pavement damage costs among the previously mentioned studies in Table 2.1, all costs were updated to 2022 dollars by using the Civil Construction Cost Index obtained from the US Army Corps of Engineers website.

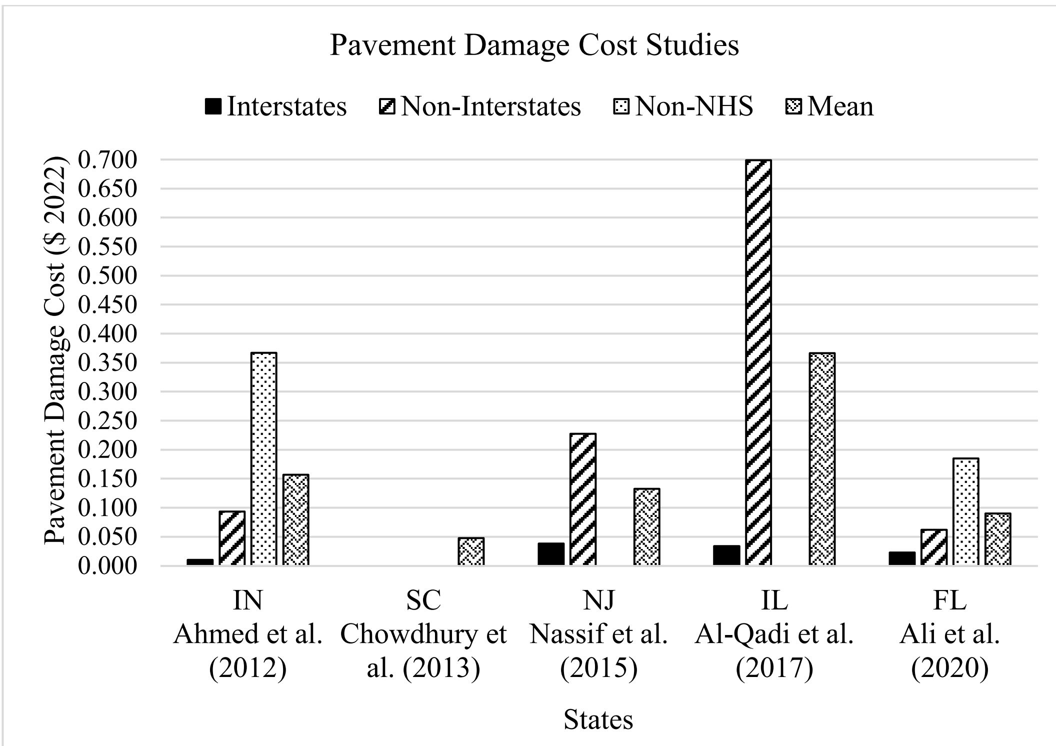


Figure 2.2. Studies on Pavement Damage Costs by Highway Functional Class.

As seen in Figure 2.2, all studies found that pavement damage costs for Non-Interstates and Non-NHS are significantly greater than the pavement damage cost for an interstate highway. Since the pavement damage costs are generally estimated by distributing the life-cycle costs (e.g., maintenance, rehabilitation, and reconstruction costs) among the traffic (e.g., number of total ESALs), the higher pavement damage costs of Non-Interstates and Non-NHS highways are explicable. Moreover, it is important to mention that the significant difference in pavement damage costs among states results from the different pavement life-cycle lengths, interest rates, and agency costs considered in the analysis. For instance, South Carolina has the lowest pavement damage cost mainly because the analysis only considered pavement replacement costs, while Indiana and Illinois present higher pavement damage costs resulting from the consideration of additional agency costs such as maintenance, rehabilitation, and reconstruction. These results are consistent with a study conducted by Ahmed et al. (2012), which demonstrated that non-consideration of reconstruction or maintenance costs can lead to a 79 percent and 83 percent underestimation of the actual pavement damage, respectively.

2.1.2 Overweight Truck Impacts on Bridge Damage

Unlike pavement, bridge damage costs are more complex and difficult to estimate due to the different moments that vehicles with similar axle configurations impose across a bridge span. When a truck crosses a bridge, it induces stresses that can cause fatigue and/or overload damage to the structural components of the bridge. Increased number of loading cycles and magnitude of the stress induced by overload trucks over the bridge's lifecycle contribute to accelerated fatigue damage (Ali et al. 2020; Dey et al. 2015). Consequently, bridge maintenance becomes more difficult and more costly, for maintenance, rehabilitation, and/or replacement activities become more frequent (Everett et al. 2014). For this reason, bridge consumption estimation due to overweight truck operations is of great importance for state transportation agencies (Babu 2019).

Several factors such as traffic loads, structure's age and materials, natural hazards, and extreme events can affect the service life of a bridge. When estimating bridge damage consumption due to overweight vehicles (GVW > 80,000 lbs.), gross weight, axle weight, and axle configuration need to be considered in the analysis, since they have a direct impact on the service life of highway bridge superstructure. The weight of each group of axles and the distance between axle groups have a significant impact on how trucks affect bridges. The impact increases as the axle group weight increases and decreases as the distance between axle groups increases (USDOT 2000a; b).

To date, a number of states have conducted studies to quantify the damage caused by overweight vehicles to monetarily assess bridge consumption. Cambridge Systematics and SRF Consulting Group (2006) estimated that the bridge fatigue cost for a loaded (80,000 lbs.) tractor-semitrailer on non-Interstate highways in Minnesota is $0.0014 per mile.

Zhao and Tabatabai (2009) studied the impact of permit loads on bridges in Wisconsin. The study suggested that the current State vehicle-weight-dependent permit fee schedule did not reflect the impact of overweight vehicles (vehicles that do not comply with the federal bridge gross weight formula) on bridges. Findings from another study in South Carolina revealed that revenues collected from the current state permit system are not sufficient to offset the damage to pavement and bridges inflicted by overweight trucks (Chowdhury et al. 2013).

Prozzi et al. (2012) estimated the bridge consumption cost per mile for overweight vehicles based on the fatigue concept. The aggregated consumption per mile was estimated using a moment analysis approach on the structure (i.e., bridge) and permit records, which were divided into routed (historical data) and non-routed (Monte Carlo simulation). For the routed loads in Texas, the bridge consumption per mile for all GVW categories is as follows: $0.23 for GVW from 80 to 120 kips, $0.38 for GVW from 120 to 160 kips, $0.49 for GVW from 160 to 200 kips, and $0.90 for GVW from 200 kips to 254 kips.

Ahmed et al. (2012) proposed a disaggregated model to estimate the marginal bridge consumption cost for the state of Indiana using an incremental cost analysis, a method that is based on the cost-occasioned approach and is widely used by most states in bridge damage estimation by vehicle class. Their model takes into consideration bridge (e.g., bridge reconstruction, deck rehabilitation, superstructure replacement, and the bridge age) and vehicle characteristics. The authors performed a life-cycle cost analysis to estimate the agency costs by calculating and distributing the equivalent uniform annual cost (EUAC) for each vehicle. The EUAC was then converted into unit costs per foot-pass.

Dey et al. (2014) estimated the total bridge damage cost in South Carolina using a fatigue analysis of four archetype bridges that were further extrapolated to represent the total fatigue damage of all bridges in the State. The study established unit bridge damage costs per mile for each axle group ranging from 2-axles to 8-axles.

Nassif et al. (2015) used bridge deterioration models to assess the effects of overweight trucks on the service life of bridges in New Jersey. In that study, the authors estimated that the state-wide average bridge damage cost of moving one ton of overweight load on one mile is about $0.132 (chained in 2011 dollars).

Gungor et al. (2019) developed a framework that considered vehicles' load and bridge's structural capacity to quantify the impact of OW trucks on bridges in Illinois. The authors developed prediction models to estimate bridge conditions and use them for computing bridge service life and then bridge life reduction per damaging load (load greater than the load level that can safely use an existing bridge for an indefinite period of time) by simulating different loading scenarios. Ultimately, the study conducted a bridge life-cycle costs analysis to convert calculated life service into a fee. Findings from the study showed that the average per-mile cost of bridge damage is \$0.0182/mi *Δkip, where Δkip is the difference between the gross weight of an overweight vehicle and the average inventory rating of the state-owned bridges.

Ali et al. (2020) developed a damage assessment technique to calculate the monetary consumption of overweight trucks on bridges in Florida. The study computed bridge consumption for a representative bridge in the state by using the existing permit vehicles operating on its roads and bridges. Then, the monetary consumption caused by permitted overweight vehicles was calculated based on the current State's permit fee structure. Findings from the consumption cost analysis found that the current permit fee schedule was insufficient for offsetting the pavement and bridge damage caused by overweight trucks. Thus, the authors proposed a new permit fee schedule that reflects the actual infrastructure cost and compared it with the permit fees imposed by other states.

2.2 Safety Degradation

Due to their size and weight, OSOW trucks have been considered major contributors to road traffic fatalities and injuries (Dong et al. 2017). Since crashes involving OSOW trucks can have substantial economic losses and serious consequences for all road users, the operation of OSOW vehicles has been a major safety concern to highway transportation agencies.

As the volume of ground freight transportation increases and the highway infrastructure system is almost reaching its capacity, funding for highway improvement/expansions is constantly tightening up. As a result, some state transportation agencies have opted for increasing their truck maximum size and weight limits to decrease the number of vehicles on their roads while supporting the trucking industry and promoting the economic development of the region. However, truck size and weight limits increase are a controversial issue (Neff and Bai 2012). Some argue that an increase in truck size and weight would reduce the number of trucks on the roads, for fewer trips would be needed to move the same amount of freight, resulting in less traffic volume and thus less exposure to crash situations that ultimately can improve the overall road safety (TRB 1990). Others argue that the increase in truck size and weight limits would increase the frequency and severity of crashes that can result in more fatal crashes, for overweight trucks have reduced maneuverability and stability (David Luskin 2001; Neff and Bai 2012). However, information in existing truck crash data set is not sufficient to scientifically demonstrate the contribution of size and weight of overweight trucks to the frequency and severity of crashes, therefore, more studies are needed (AASHTO 2009).

Despite this controversy, in general, overweight trucks pose a threat to all road users. Past studies found that crash frequency tends to increase as GVW increases (TRB 1990; USDOT 2015). Also, the probability of a truck being involved in an accident with severe consequences is higher for an overweight truck than for a legally loaded truck (Pigman and Agent 1999; Jacob and La 2010). The heavier a truck is, the higher its kinetic energy is, and therefore the greater the impact and damage are in the event of a collision.

There are several reasons why overweight trucks are more likely to be involved in an accident (Jacob and La 2010). First, overloaded trucks are less stable because of the increased mass and inertia, which increase the risk of rollover and lane departure. Second, the capacity of a truck to break is also reduced with any weight exceeding the maximum allowable weight. Third, the ability of overloaded trucks to maneuver in up-hill, down-hill, and overtaking operations is diminished. Fourth, the internal temperature of the tires of a truck is elevated due to the overloads, which can raise the risk of tire blow-outs. Fifth, the risk and severity in the event of a fire are greater when flammable goods are being transported in excess of the legally permitted weight limit.

In the past, only a few studies have been conducted to evaluate the impacts of OSOW trucks on road safety. Most available studies in the literature discuss the safety impacts of large or heavy trucks, which do not necessarily mean they are exceeding the legal size and weight limits.

Pigman and Agent (1999) conducted a truck crash study in Kentucky using a database of crashes and 383 police crash reports from 1994 to 1997 in which truck weight data from WIM stations were collected to evaluate the distribution of overweight trucks (average truck weight was 158,000 lbs.) transporting coal on the US 23 (an Extended-Weight Coal Haul Road). In the study, the speed differential between vehicles was identified as the main contributing factor for rear-end crashes involving heavy trucks on long upgrades in hilly areas of the State.

Gao et al. (2004) identified overloading as the primary contributing factor for crashes involving heavy trucks in China, with oversized and overloaded trucks representing 70 – 90 percent of truck crashes in China.

Prozzi et al. (2012) analyzed the 1,137 crashes reported on Texas highways during the Fiscal Year 2010-2013 and found that the common contributing factor for those crashes was the over-dimension or/and overloading of the trucks. From the 1,137 crashes, 4 fatalities and 35 injuries were reported. The analysis estimated that approximately a total of $27,490,200 were attributed to the reported 1,137 crashes.

Everett et al. (2014) proposed a methodology that was used to determine the net effect on traffic safety due to the operation of overweight trucks. Real data for various roadway functional classes, including urban arterials, rural highways, urban and rural freeways, was collected and used in the analysis. For the analysis of the net effects of overweight operations on safety, a set of regression equations was developed that takes into consideration factors such as the percentages of OW trucks in relation to the total number of trucks (i.e., 3%, 6%, and 9%) and the percentages of weight above the legal limit (i.e., 5%, 10%, 15%, and 20%), and the PCE of OW trucks (i.e., 2, 3, or 4). The authors of that report found that when an average percentage extra weight (APEW) of 33.4 percent is reached (considered as the critical APEW), the average net crash frequency would no change compared to the scenario of having only legal-weight trucks (base case). Beyond that critical APEW, the net percentage change in crash frequency becomes negative, meaning a lower crash frequency compared to the base case.

Dong et al. (2017) conducted an empirical and methodological analysis to estimate the frequency and severity of crashes involving large trucks (commercial vehicles weighing more than 10,000 lbs.). The authors proposed a negative binomial model to analyze the crash frequency and a multinominal logit model to analyze the crash severity of large trucks-involved crashes. The study identified truck percentage, annual average daily traffic (AADT), driver characteristics, operational conditions, and weather conditions as significant contributing factors to the frequency and severity of crashes involving large trucks. Findings of the study include 1) the presence of large trucks significantly increases the frequency and severity of crashes; 2) AADT has a significant and opposing impact on the frequency and severity of crashes involving large trucks. As the AADT increases, the frequency of crashes involving large truck increases, while the severity of crashes decreases; 3) driver characteristics such as truck operator age, was found to be correlated with the frequency of large trucks-involved crashes. Young and aged drivers have increased crash risk because young drivers lack experience and are more willing to take risks, while aged drivers have a relatively weak ability to detect and react to emergency situations. The study found that young truck drivers (<30) are significantly associated with higher crash frequency, with a relatively crash risk of 1.14; 4) operational conditions such as speed limit influence the frequency of crashes involving a large truck. For instance, the speed limit of 80 km/h and higher was associated with a lower crash frequency compared with a speed limit of 72 km/h or less. Moreover, the study found that the risk of crashes is 1.55 higher at intersections than in roadway segments; 5) harsh weather conditions such as fog, rain, and snow can have an impact on the frequency and severity of large truck-involved crashes. Moreover, daylight condition was related to lower severity of crashes as compared to other types of conditions.

2.3 Mobility Impairment

Overweight truck operations also have significant impacts on road traffic conditions. Compared with legally loaded trucks (GVW ≤ 80,000 lbs.), overloaded trucks have reduced maneuverability and inferior acceleration/deceleration capabilities that caused them to have lower running speeds that ultimately impose more significant impacts on the traffic (Wang et al. 2018). A study conducted in Nanjing, China, estimated that overweight trucks experience an average travel speed reduction of 16 percent compared with legally loaded trucks with the same configuration (Zhou et al. 2012).

Moreover, overweight trucks require larger space and time headways and longer time reactions than regular trucks (Aghabayk et al. 2012). Due to their heavy loads and reduced running and breaking performance, overweight trucks require longer reaction times to safely stop which ultimately creates the necessity for larger space and time headways. Furthermore, heavy trucks influence the behavior of other drivers disrupting the stability of the traffic stream (Aghabayk et al. 2012). Several studies have found that passenger cars slightly kept larger headway and spacing when traveling behind a heavy truck than when traveling behind another passenger car (Krammes and Crowley 1986; McDonald et al. 1997; Yoo and Green 1999; Wang et al. 2018).

The presence of OSOW trucks in the traffic stream may cause disruptions in the traffic flow that can impede the efficient mobility of road users causing delays that in turn translates into a loss in productivity for businesses and people in general (Aghabayk et al. 2012). Thus, the assessment of the impacts of OSOW truck operations on traffic conditions is of great importance to highway transportation agencies.

However, the impacts of OSOW trucks on traffic conditions have not been properly quantified in the literature (Everett et al. 2014; Wang et al. 2018). The effect of overweight truck operations on traffic conditions in terms of congestion can be captured by the Passenger Car Equivalent (PCE) factor. Campbell et al. (2009) estimated that PCE values of heavy vehicles range from 1.5 to 15. Ahmed et al. (2013) found that the PCE factor increased with the presence of trucks in the traffic stream. Results from that study estimated the PCE factor of heavy trucks as 1.76 under congested conditions with more than 9 percent of heavy trucks present in the traffic stream under congested conditions.

Gao et al. (2004) conducted a study to evaluate the impacts of OSOW trucks on a freeway in China and found that the increase in size and weight of heavy trucks causes variations in operating speeds between different vehicle classes, decreases traffic mobility, and reduces highway capacity.

Everett et al. (2014) developed a set of regression equations to determine the net effect of the operation of overweight trucks on traffic mobility. Factors such as the percentages of OW trucks in the traffic stream, percentages of weight above the legal weight limit (APEW), and passenger car equivalent of OW trucks (PCE) were used to analyze the effects of OW operations on traffic mobility for different urban arterials, rural highways, and urban and rural freeways. Findings suggested that high PCE values of OW trucks, for instance PCE values of 3 and 4, lead to an improvement on the average net travel time of 1.14 percent and 1.98 percent, respectively. However, this positive effect on average net travel time continues only to a certain extent, that is, up to an APEW critical value of 34 percent. Beyond that point, any excess load of OW trucks operations, would have a negative effect on traffic mobility as the impairment effect of OW truck operations offset the congestion reduction effect caused by the reduction in the number of trips (Everett et al. 2014).

In Jiangsu, China, Wang et al. (2018) analyzed the impacts of overloaded trucks on free-flow traffic conditions and found that increases in the overloading proportion result in greater speed reductions and longer congestion durations. Similarly, increases in the truck size result in greater speed reduction. The study also found that overloaded truck operations do not only cause infrastructure damage but also result in low travel speeds and inferior level of service, especially in circumstances where road capacity is reduced such as work zones.

2.4 Overweight Trucks Permitting Revenues

As the demand for ground freight transportation increases, the maintenance expenditures that come along with it have also increased. Unfortunately, the funding sources needed to cover these expenditures have been dramatically tightening up, consequently creating a backlog of overdue infrastructure maintenance work (Dehghan-Niri et al. 2020).

Oversize/Overweight permit fees are one of the main funding sources for maintaining and recovering existing highway infrastructure associated with truck operations. State transportation agencies exercise Oversize/Overweight permit fees not only for collecting funding from commercial oversize and overweight vehicles to lessen their burden in terms of infrastructure asset maintenance and replacement, but also to enforce required safety procedures to ensure a safe and conducive environment for all users of the road network (INDOR 2017).

2.4.1 Oversize/Overweight Permit Fees Structures in the East North Central Division of the Midwest Region

Oversize/Overweight permit types and fees vary greatly from state to state. The variations in fees among States reflect the different priorities that highway agencies have regarding truck operations in their jurisdictions. A simplified summary of oversize and overweight permit types and fees for all states in the East North Central Division of the Midwest Region (Indiana, Michigan, Ohio, Wisconsin, and Illinois) is presented in Table 2.2 and Table 2.3, respectively.

Table 2.2. Summary of OS Permit Fee Structure for the East North Central Division of the Midwest Region.

State	Permit Type	Permit Dimension Limit	Permit Fee
Indiana (INDOR 2021a)	Single Trip Permit	Height < 13' 6" 8' 6" < Width < 12' 4" Length ≤ 95'	$20
		13' 6" < Height < 15' 12' 4" < Width < 16' 95' < Length < 110'	$30
	90 Day Permit	Height ≤ 15' Width ≤ 16' Length ≤ 110'	$100
	Annual Permit		$405
	Superload Permit	Height: 15' Width: 16' Length: 110'	$40 + $10 (Executive fee)
Michigan (MDOT 2019)	Single Trip Permit	Height ≤ 15' Width ≤ 16' Length ≤ 150'	$15
	Extended Permit (Annual Permit)		$30
Ohio (ODOT 2019, 2020)	Single Trip Permit	13' 6" < Height ≤ 14' 6" 8' 6" < Width ≤ 14'	$75 (One Way), $110 (One Way & Return)
		Height > 14' 6" Width > 14'	$145 + TM* (One Way), $110 + TM* (One Way & Return) * TM - ton Mile = [(GVW - 120,000)/2,000] times $0.04 per mile traveled
		Multi-State 13' 6" < Height ≤ 14' 6" 8' 6" < Width ≤ 14'	$65 (One Way)
	Continuing (90 Day) Permit	13' 6" < Height ≤ 14' 6" 8' 6" < Width ≤ 14 ft	$260 (One Way), $385 (One Way & Return)
Wisconsin (WisDOT 2021a; b)	Single Trip Permit (Valid for 5 days)	Single Vehicle and Load: Length > 45' Combination of Two Vehicles: Length > 70 ' Truck/Tractor and Semi-Trailer: Length > 75' Width > 8' 6" or Height > 13' 6" Width > 8' 6" and Height > 13' 6"	$15 $15 $15 $20 $25
	Multiple Trip	Dimension limits same as for Single Trip Permits Overlength 3 Month 4 Month 5 Month 6 Month 7 Month 8 Month 9 to 12 Month Over width and/or Over height and/or Overlength 3 Month 4 Month 5 Month 6 Month 7 Month 8 Month 9 Month 10 to 12 Month	$30 $35 $40 $45 $50 $55 $60 $37.50 $45 $52.50 $60 $67.50 $75 $82.50 $90

State	Permit Type	Permit Dimension Limit	Permit Fee
Illinois (IDOT 2022)	Single Trip/Round Trip Permit	Category A: Width ≤ 10' Height ≤ 14' 6" Length ≤ 70'	$12 (0 - 90 mi), $15 (91 - 180 mi), $18 (181 - 270 mi), $21 (> 270 mi)
		Category B: Width ≤ 12' Height ≤ 14' 6" Length ≤ 85'	$15 (0 - 90 mi), $20 (91 - 180 mi), $25 (181 - 270 mi), $30 (> 270 mi)
		Category C: Width ≤ 14' Height ≤ 15' Length ≤ 100' Mobile home combinations Length ≤ 85'	$25 (0 - 90 mi), $30 (91 - 180 mi), $35 (181 - 270 mi), $40 (> 270 mi)
		Category D: Width ≤ 18' Height ≤ 16' Length ≤ 120'	$30 (0 - 90 mi), $40 (91 - 180 mi), $50 (181 - 270 mi), $60 (> 270 mi)
		Category E: Width > 18' Height > 16' Length ≤ 120'	$50 (0 - 90 mi), $75 (91 - 180 mi), $100 (181 - 270 mi), $125 (> 270 mi)
	Limited Continuous Operation Permit (OS-OW)	Width ≤ 12' Height ≤ 13' 6" Length ≤ 115'	$250 (3 Month Permit) $1000 (Annual Permit)

Table 2.3. Summary of OW Permit Fee Structure for the East North Central Division of the Midwest Region.

State	Permit Type	Permit Weight Limit	Permit Fee
Indiana (INDOR 2021a)	Single Trip Permit	Non-Divisible Loads 80,000 lbs. < GVW ≤ 108,000 lbs. 108,000 lbs. < GVW ≤ 134,000 lbs. 134,000 lbs. < GVW ≤ 150,000 lbs. 150,000 lbs. < GVW ≤ 200,000 lbs. GVW > 200,000 lbs.	$20 + $0.35 per mile + $35 (bridge review fee if required) $20 + $0.60 per mile + $35 (bridge review fee if required) $20 + $0.60 per mile + $35 + $10 per bridge crossed on permitted route* $20 + $1 per mile + $10 per bridge crossed on permitted route* $20 + $1 per mile + $35 (required bridge review fee) + $10 per bridge crossed* * Bridge fee cannot exceed $200 for one-way-trip and $400 for round-trip
		Divisible Loads (All commodities) ESAL > 2.4	$20 + $0.25 per mile per ESAL in excess of 2.4
	Annual Permit	Divisible Loads ESAL ≤ 2.4	$20
	Special Weight Permit	GVW: 90,000 lbs. on Heavy-Duty Highways GVW: 134,000 lbs. on Extra Heavy-Duty Highways	$42.50 per day + $25 annual registration fee
	Superload Permit	120,000 lbs. <GVW ≤ 150,000 lbs. 150,000 lbs. < GVW ≤ 200,000 lbs. GVW > 200,000 lbs.	$20 (Base fee) + $10 (Executive fee) + $0.60 per mile $20 (Base fee) + $10 (Executive fee) + $1 per mile $20 (Base fee) + $10 (Executive fee) + $25 (Design review fee) + $1 per mile
Michigan (MDOT 2019)	Single Trip Permit (May include OS)	Non-Divisible Loads GVW: > 80,000 lbs. Single Axle: > 20,000 lbs. Tandem Axle: > 34,000 lbs.	$50
	Extended Permit/Annual Permit (May include OS)	Non-Divisible Loads GVW: > 80,000 lbs. Single Axle: > 20,000 lbs. Tandem Axle: > 34,000 lbs.	$100
Ohio (ODOT 2019, 2020)	Single Trip Permit	Routine Load (OS/OW) 80,000 lbs. < GVW < 120,000 lbs.	$145 (One Way), $210 (One Way & Return)
		Superload (OS/OW) (width > 14' or height > 14' 6") GVW > 120,000 lbs.	$145 (One Way), $210 (One Way & Return)
		Steel/Aluminum Coil 80,000 lbs. < GVW < 120,000 lbs.	$75 (One Way)
		Multi-State (OS/OW) 80,000 lbs. < GVW < 120,000 lbs.	$145 (One Way)
		Emergency 80,000 lbs. < GVW < 120,000 lbs.	$260 (One Way), $375 (One Way & Return)

State	Permit Type	Permit Weight Limit	Permit Fee
	Continuing (45-Day) Permit	International Sealed Container 80,000 lbs. < GVW < 120,000 lbs.	$260 (One Way)
	Continuing (90-Day) Permit	Routine Load (OS/OW) 80,000 lbs. < GVW < 120,000 lbs.	$510 (One Way), $760 (One Way & Return)
		Steel/Aluminum Coil 80,000 lbs. < GVW < 120,000 lbs.	$135 (One Way)
		Michigan Legal Routine Load 80,000 lbs. < GVW < 120,000 lbs. Superload GVW > 120,000 lbs.	$125 (One Way & Return) $165 (One Way & Return)
		International Sealed Container 80,000 lbs. < GVW < 120,000 lbs.	$510 (One Way)
	Continuing Annual Permit	Routine Load (OS/OW) 80,000 lbs. < GVW < 120,000 lbs.	$1,980 (One Way), $2,980 (One Way & Return)
		Steel/Aluminum Coil 80,000 lbs. < GVW < 120,000 lbs.	$480 (One Way)
		Michigan Legal Routine Load 80,000 lbs. < GVW < 120,000 lbs. Superload GVW > 120,000 lbs.	$470 (One Way & Return) $630 (One Way & Return)
	Blanket Permit (365 Day)	Routine Load 80,000 lbs. < GVW < 120,000 lbs.	$100 (One Way)
Wisconsin (WisDOT 2021a; b)	Single Trip Permit (May include OS)	Non-Divisible Load 80,000 lbs. < GVW ≤ 170,000 lbs. 170,001 lbs. < GVW ≤ 180,000 lbs. 180,001 lbs. < GVW ≤ 190,000 lbs. 190,001 lbs. < GVW ≤ 200,000 lbs. 200,001 lbs. < GVW ≤ 210,000 lbs. 210,001 lbs. < GVW ≤ 220,000 lbs. 220,001 lbs. < GVW ≤ 230,000 lbs. GVW > 230,000 lbs.	 $20 $35 $45 $55 $65 $75 $85 $85 + $10 per 10,000 lbs. or fraction thereof
	Annual Multiple Trip Permit (May include OS) Note: Permits are available for shorter periods	Non-Divisible Load 80,000 lbs. < GVW ≤ 170,000 lbs. 170,001 lbs. < GVW ≤ 180,000 lbs. 180,001 lbs. < GVW ≤ 190,000 lbs. 190,001 lbs. < GVW ≤ 200,000 lbs. 200,001 lbs. < GVW ≤ 210,000 lbs. 210,001 lbs. < GVW ≤ 220,000 lbs. 220,001 lbs. < GVW ≤ 230,000 lbs. GVW > 230,000 lbs.	 $200 $350 $450 $550 $650 $750 $850 $850 + $10 per 10,000 lbs. or fraction thereof
		Agricultural Products to and From a Farm and Sealed Load in International Trade	$300
Illinois (IDOT 2022)	Single Trip/Round Trip Permit	Category F: ≥ 6 Axles GVW ≤ 88,000 lbs. Front Tandem/Axle ≤ 34,000/2 Rear Tandem/Axle ≤ 48,000/3 Category G: ≥ 6 Axles GVW ≤ 100,000 lbs. Front Tandem/Axle ≤ 44,000/2 Rear Tandem/Axle ≤ 54,000/3 Category H: ≥ 6 Axles GVW ≤ 110,000 lbs. Front Tandem/Axle ≤ 44,000/2 Rear Tandem/Axle ≤ 54,000/3 Category I:	$10 (0 - 45 mi), $12.50 (46 - 90 mi), $15 (91 - 135 mi), $17.50 (136 - 180 mi), $20 (181 - 225 mi), $22.50 (226 - 270 mi), $25 (271 - 315 mi), $27.50 (316 - 360 mi), $30 (361 - 405 mi), $32.50 (406 - 450 mi), $35 (451 - 495 mi) $15 (0 - 45 mi), $25 (46 - 90 mi), $35 (91 - 135 mi), $45 (136 - 180 mi), $55 (181 - 225 mi), $65 (226 - 270 mi), $75 (271 - 315 mi), $85 (316 - 360 mi), $95 (361 - 405 mi), $105 (406 - 450 mi), $115 (451 - 495 mi) $20 (0 - 45 mi), $32.50 (46 - 90 mi), $45 (91 - 135 mi), $57.50 (136 - 180 mi), $70 (181 - 225 mi), $82.50 (226 - 270 mi), $95 (271 - 315 mi), $107.50 (316 - 360 mi), $120 (361 - 405 mi), $132.50 (406 - 450 mi), $145 (451 - 495 mi)

State	Permit Type	Permit Weight Limit	Permit Fee
		≥ 6 Axles GVW ≤ 120,000 lbs. Front Tandem/Axle ≤ 48,000/2 Rear Tandem/Axle ≤ 60,000/3	$30 (0 - 45 mi), $55 (46 - 90 mi), $80 (91 - 135 mi), $105 (136 - 180 mi), $130 (181 - 225 mi), $155 (226 - 270 mi), $180 (271 - 315 mi), $205 (316 - 360 mi), $230 (361 - 405 mi), $255 (406 - 450 mi), $280 (451 - 495 mi)
		Category J: 5 Axles GVW ≤ 88,000 lbs. Front Tandem/Axle ≤ 44,000/2 Rear Tandem/Axle ≤ 44,000/2	$20 (0 - 45 mi), $32.50 (46 - 90 mi), $45 (91 - 135 mi), $57.50 (136 - 180 mi), $70 (181 - 225 mi), $82.50 (226 - 270 mi), $95 (271 - 315 mi), $107.50 (316 - 360 mi), $120 (361 - 405 mi), $132.50 (406 - 450 mi), $145 (451 - 495 mi)
		Category L: 5 Axles GVW ≤ 100,000 lbs. Front Tandem/Axle ≤ 48,000/2 Rear Tandem/Axle ≤ 48,000/2	$30 (0 - 45 mi), $55 (46 - 90 mi), $80 (91 - 135 mi), $105 (136 - 180 mi), $130 (181 - 225 mi), $155 (226 - 270 mi), $180 (271 - 315 mi), $205 (316 - 360 mi), $230 (361 - 405 mi), $255 (406 - 450 mi), $280 (451 - 495 mi)
		Category M: ≥ 4 Axles GVW ≤ 72,000 lbs. Front Tandem/Axle ≤ 34,000/2 Rear Tandem/Axle ≤ 40,000/2	$15 (0 - 45 mi), $25 (46 - 90 mi), $35 (91 - 135 mi), $45 (136 - 180 mi), $55 (181 - 225 mi), $65 (226 - 270 mi), $75 (271 - 315 mi), $85 (316 - 360 mi), $95 (361 - 405 mi), $105 (406 - 450 mi), $115 (451 - 495 mi)
		Category N: ≥ 4 Axles GVW ≤ 76,000 lbs. Front Tandem/Axle ≤ 44,000/2 Rear Tandem/Axle ≤ 44,000/2	$20 (0 - 45 mi), $32.50 (46 - 90 mi), $45 (91 - 135 mi), $57.50 (136 - 180 mi), $70 (181 - 225 mi), $82.50 (226 - 270 mi), $95 (271 - 315 mi), $107.50 (316 - 360 mi), $120 (361 - 405 mi), $132.50 (406 - 450 mi), $145 (451 - 495 mi)
		Category O: ≥ 3 Axles GVW ≤ 60,000 lbs. Front Tandem/Axle ≤ 21,000/1 Rear Tandem/Axle ≤ 40,000/2	$12.50 (0 - 45 mi), $21.50 (46 - 90 mi), $30.50 (91 - 135 mi), $39.50 (136 - 180 mi), $48.50 (181 - 225 mi), $57.50 (226 - 270 mi), $66.50 (271 - 315 mi), $75.50 (316 - 360 mi), $84.50 (361 - 405 mi), $93.50 (406 - 450 mi), $102.50 (451 - 495 mi)
		Category P: ≥ 3 Axles GVW ≤ 68,000 lbs. Front Tandem/Axle ≤ 21,000/1 Rear Tandem/Axle ≤ 48,000/2	$20 (0 - 45 mi), $32.50 (46 - 90 mi), $45 (91 - 135 mi), $57.50 (136 - 180 mi), $70 (181 - 225 mi), $82.50 (226 - 270 mi), $95 (271 - 315 mi), $107.50 (316 - 360 mi), $120 (361 - 405 mi), $132.50 (406 - 450 mi), $145 (451 - 495 mi)
		Category Q: 2 Axles GVW ≤ 48,000 lbs. Front Tandem/Axle ≤ 25,000/1 Rear Tandem/Axle ≤ 25,000/1	$15 (0 - 45 mi), $25 (46 - 90 mi), $35 (91 - 135 mi), $45 (136 - 180 mi), $55 (181 - 225 mi), $65 (226 - 270 mi), $75 (271 - 315 mi), $85 (316 - 360 mi), $95 (361 - 405 mi), $105 (406 - 450 mi), $115 (451 - 495 mi)
		Category R: 2 Axles GVW ≤ 54,000 lbs. Front Tandem/Axle ≤ 28,000/1 Rear Tandem/Axle ≤ 28,000/1	$20 (0 - 45 mi), $32.50 (46 - 90 mi), $45 (91 - 135 mi), $57.50 (136 - 180 mi), $70 (181 - 225 mi), $82.50 (226 - 270 mi), $95 (271 - 315 mi), $107.50 (316 - 360 mi), $120 (361 - 405 mi), $132.50 (406 - 450 mi), $145 (451 - 495 mi)
	Limited Continuous Operation Permit (OS-OW)	Non-Divisible Loads Weight limits same as the ones for Single Trip Permit	$250 (3 Month Permit) $1000 (Annual Permit)

As shown in Table 2.2. Summary of OS Permit Fee Structure for the East North Central Division of the Midwest Region.and Table 2.3. Summary of OW Permit Fee Structure for the East North Central Division of the Midwest Region.all states in the East North Central Division of the Midwest Region offer single-trip permits and multi-trip permits (annual permits); however, truck dimensions and gross weight limits for the same type of permit vary among them. These variations in truck dimensions and gross weight are determined by the characteristics of their existing infrastructure (road and bridges’ dimensions, age, structural capacity, etc.), the type of load, and its impact on the infrastructure.

Although most states in the region have established their permit structure based on two main types of loads, divisible load (any load that takes less than eight hours to disassemble) and non-divisible load (loads that exceed legal length or weight limits and cannot be broken into smaller parts or require more than eight hours to be disassembled), some states also have permits for specific loads (raw materials, final goods, etc.) that are considered significant to the state economy. For instance, to favor industrial and agricultural competitiveness in its jurisdiction and ultimately promote the state's economic development, Ohio issues specific permits for steel/aluminum coil commodities (ODOT 2019), Wisconsin has permits for agricultural products (WisDOT 2021a), whereas Indiana has recently made available Overweight Commodity Permits for all type of commodities (INDOR 2022a). In addition to divisible and non-divisible loads, few states also allow the movement of superloads. The definition for superload differs from state to state and can be based on the dimension, weight, or a combination of both. For instance, Indiana and Ohio have a superload permit with dimension and weight criteria where both states have a threshold of 120,000 lbs. gross weight, and a different threshold of dimension (Indiana's threshold are 15' high and 16' wide while Ohio's threshold are 14' 6" high and 14' wide). In contrast to the rest of the states in the East North Central Division of the Midwest Region whose established their permit fee structure based on the type of load (divisible load, non-divisible load, and Superload), Illinois uses a different criterion in its OSOW permit fee structure that is not based on the type of load, instead it is based on a categorical weight/dimension and distance matrix. Illinois OS permit fees have five distinct categories based on dimensions limits, traveled distance, vehicle type, and permit type, whereas the OW permit fee structure is composed of twelve different categories that are based on gross weight, the number of axles, axle weight, and traveled distance.

In the region, four types of permit fee structures can be seen, fixed fees, weight-based fees, distance-based fees, and a combination of weight-distance-based fees. Fee types among these states range from simple to complex in terms of administration and relevance to actual consumption, as shown in Figure 2.3. At one extreme, Michigan, with fixed fees, has the simplest permit fee structure that is the easiest to administer for it requires the least administrative resources but is least reflective of actual asset consumption. On the other extreme, Indiana and Illinois, with weight-distance-based fees, have the most reflective permit structure for actual consumption but the most complex to administer. Ohio and Wisconsin, with weight-based fees, fall in between the spectrum of administration complexity and relationship to actual consumption.

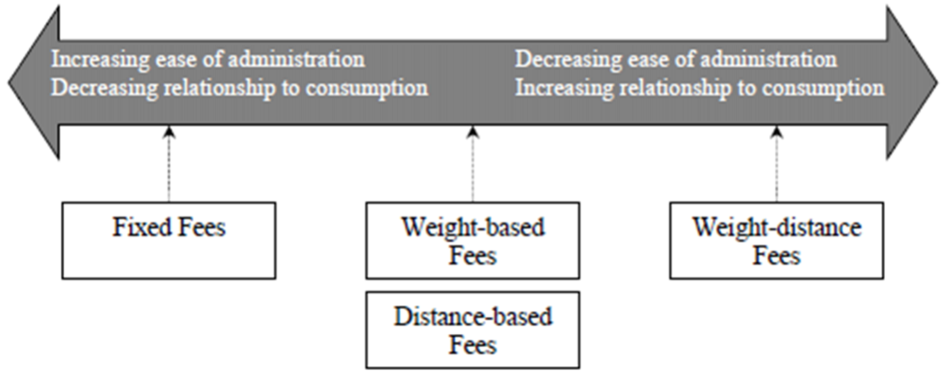


Figure 2.3. Classification of Permit Fee Structures.
Source: Everett (2015).

As states try to accommodate businesses and economic development goals, exceptions to size/weight limits are placed to allow the movement of specific loads (commodities) creating additional permits that add more complexity to the permitting structure. Hence, the complexity of the permitting structure in each state can be indicated by the number of types of permits in the system. On one side of the spectrum, Michigan has only two categories for all permit-required and eligible loads and imposes no additional add-on fees, while on the other side of the spectrum, Illinois has around 17 categories for regulating OSOW truck operations with several criteria-based and supplementary fees.

Ultimately, OSOW permit fees in the East North Central Division of the Midwest Region vary greatly in type and cost among states. These differences in permit types and fees reflect the type of load that is being transported across each state as well as the level of impact those OSOW loads are having in terms of infrastructure damage, operational costs, traffic, and safety (Dehghan-Niri et al. 2020).

2.4.2 Revenues from OSOW permit sales

One of the primary purposes of OSOW permitting and fee structures are to allow States to collect sufficient revenues to offset the additional pavement and bridge damage inflicted by the operations of heavy trucks. Unfortunately, past studies have shown that in most cases, the collected revenues from OSOW permit sales do not fully cover the additional highway asset expenditures associated with the consumption of overweight trucks, creating a significant gap between revenue and consumption (Crockford 1993; Luskin et al. 2000; Dey et al. 2015; Everett

2015; Nassif et al. 2015; Al-Qadi et al. 2017). In a highway cost allocation study conducted by the FHWA in 2000, overweight trucks (GVW > 80,000 lbs.) were found to be paying on average about 60 percent of their highway cost responsibility (FHWA 1997). Moreover, the study also found that the more axles a vehicle has, the farther it comes to pay its share of highway costs, even though its impact on the highway is greater, and therefore its cost responsibility at any given weight is also greater (FHWA 1997).

The Wisconsin Department of Transportation (WisDOT) conducted a study in which state DOTs were surveyed to collect data regarding their OSOW permit fee structures and their respective distribution and allocation of revenues from permit sales. In that study, the agency's operational costs such as permit processing labor, traffic engineering reviews, trip routing check, infrastructure (road and bridges) engineering reviews, etc., were evaluated and compared with permitting revenues for each state. The findings show that in cases where more in-depth evaluation is required, such as administrative and engineering review for trip routing, permit fees are even unlikely able to recover the issuance costs of OS/OW permits (Adams et al. 2013).

The Ohio Department of Transportation (ODOT) estimated that the annual gap between pavement and bridge damage costs due to the operation of overweight trucks ($144 million) and the revenues collected from various taxes and fees ($72 million), OSOW permits included ($27 million), paid by the trucking industry is about $45 million (Campbell et al. 2009).

Moreover, in 2014, a study conducted by Purdue University and the Indiana Department of Transportation (INDOT) in which the impacts of changes on the State's OSOW permit fee structure on asset degradation and revenues generation were studied reported that the gap between road infrastructure consumption ($44.15 million) and revenues ($12.46 million) was about $32 million for the period June 1, 2013 - December 31, 2013 (Everett et al. 2014).

To improve the overall equity in the highway user fees and minimize the gap between highway asset consumption and revenues, more and more states are investing further efforts in evaluating the impacts of OSOW truck operations on their highway system and economy to assist them in the challenging task of establishing a reasonable and fair OSOW permitting fee structure that can allow them to collect sufficient funding for covering highway asset expenditures (repair/replacement) without impairing the economic productivity of the trucking industry.

2.4.3 Revenues from Oversize/Overweight Permit Sales in Indiana

According to the Indiana Department of Revenues (INDOR), the State issued 419,278 oversize/overweight permits in 2021, which represents a total revenue of $24,176,800 (INDOR 2022b). Table 2.4 presents the number of OSOW permits issued in Indiana and the revenues collected from their sales (INDOR 2021b).

Table 2.4. OSOW Permits and Revenues in Indiana 2018 – 2021.

Year	Number of Permits Issued	OSOW Permit Fee Revenues
2018	400,000	$ 22,168,100
2019	359,059	$ 25,084,200
2020	379,523	$ 22,683,000
2021	419,278	$ 24,176,800

A compendium of the revenues collected from oversize/overweight vehicle permits in Indiana from 2014 to 2021 (INDOR 2022b) is presented in Figure 2.4.

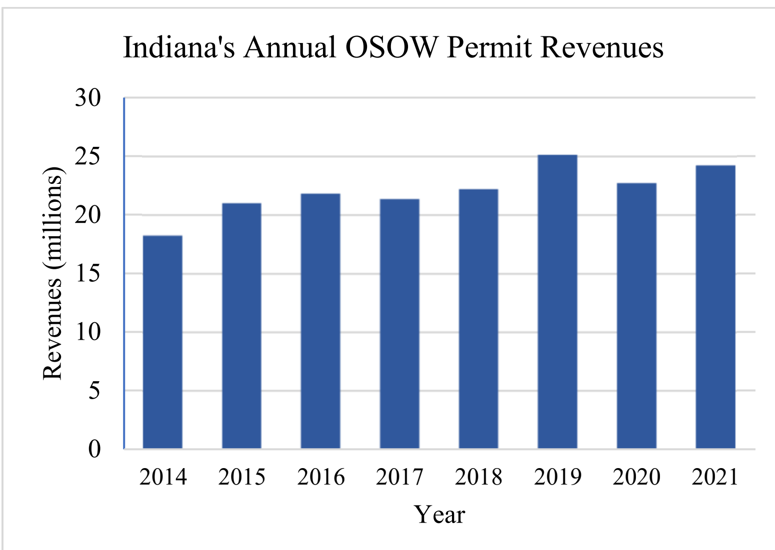


Figure 2.4. Historic data on revenues collected from OSOW vehicle permits in Indiana.

As shown in Figure 2.4, revenues collected from OSOW vehicle permit sales increased steadily from 2014 to 2019 with $18,200,300 and $25,084,200, respectively. The reduction in permitting revenues seen in 2020 is most likely linked to the Executive Emergency Declaration that granted regulatory relief for commercial motor vehicle operations that provided direct assistance in support of emergency relief efforts related to the COVID-19 outbreak (Federal Motor Carrier Safety Administration 2020; Specialized Carriers & Rigging Association 2020).

2.5 Economy Productivity

Overweight truck operations have an important impact on the economic productivity of the freight industry. In fact, surveys of county agencies and the trucking industry in Texas revealed that the issuance of permits for allowing the movement of loads greater than the legal weight was saving substantial costs to the trucking industries (Crockford 1993). By allowing the movement of heavier loads, the same amount of goods can be transported with fewer trips which in turn reduces labor costs, vehicle operational costs (vehicle wear and tear, repair, fuel, etc.), and overhead costs (Luskin et al. 2000; Adams et al. 2013). These savings in freight transportation costs result in increased productivity that benefits not only the trucking industry but also the entire economy of a region. For instance, carriers may pass cost savings on to shippers in the form of lower rates, and shippers may pass cost savings on to consumers in the form of lower prices for goods, and so on (Dey et al. 2015; Adams et al. 2013). Figure 2.5 shows a diagram with the series of effects that increases in truck size and weight (TS&W) limits on economic development found in the literature. Thus, truck shipping productivity is critical for the economic health of any state (Crockford 1993) and it must be considered when investigating truck size and weight issues (Hewitt et al. 1999).

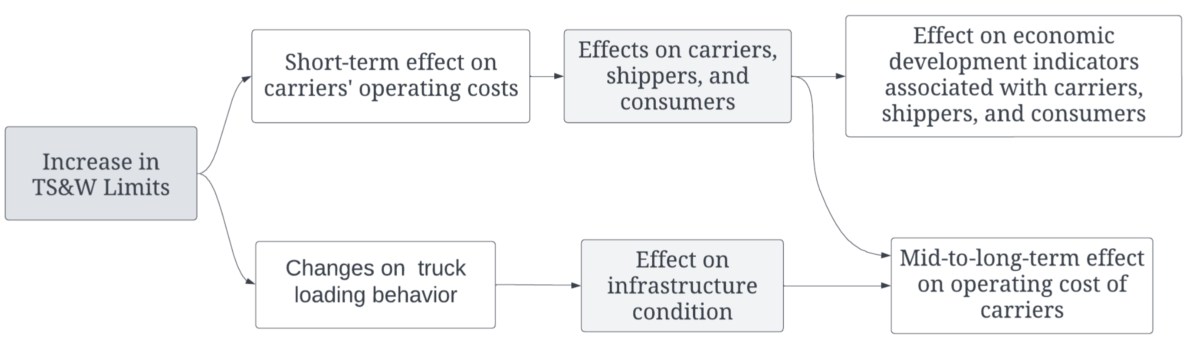


Figure 2.5. Expected concatenating effects of increased TS&W limits on economic development. Source: Everett et al. (2014).

Productivity, known as the ratio of total output produced per unit of input (Weisbrod 2016), is one of the most commonly used indicators to measure economic development (Everett et al. 2014). Freight operators, for example, measure fleet productivity in ton-miles moved per truck. For the trucking industry, an increase in productivity can occur when the ton-miles of commodity shipment (output) increase without increasing the logistics costs (input), or when the amount of freight is moved with reduced logistics costs. In her dissertation, Everett (2015) stated that overweight truck operations generate significant productivity gains for the trucking industry, for even small increases in the allowed GVW limit represent significant increases in the number of goods transported, which in the end will benefit the end-users of these goods through lower prices. A 5-axle combination truck, for instance, weighs 29,000 lbs. unloaded; thus, the payload for a lawfully loaded truck (GVW = 80,000 lbs.) is 51,000 lbs. Since there is no increase in the tare weight of the truck, a 5 percent increase in the GVW, which corresponds to an extra weight of 4,000 lbs., equates to a 7.8 percent increase in the payload.

Several states have invested efforts to assess the impacts of changes in the OSOW permit structures. While most of these efforts focused on infrastructure damage and permitting revenues, economic impacts, such as trucking productivity, have been briefly mentioned in only a few of them (Everett et al. 2014). The lack of needed input data has been the common denominator in all these past studies and the reason why the economic impacts of changes in overweight truck permitting have not been rigorously assessed before (Everett et al. 2014). In Texas, a study that investigated the infrastructure damage due to changes in the overweight permitting fee structure, acknowledged the importance of assessing the economic productivity impacts associated with overweight truck operations (Prozzi et al. 2012). Crockford (1993) stated that highway agencies must find a balance between vehicle weight management policies and infrastructure management policies in the maximization of productivity truck shipping productivity is critical for the economic health of any state. In a study sponsored by the Wisconsin Department of Transportation (WisDOT), interviews with several carriers and state highway transportation agencies were conducted to determine the sensitivity of OSOW permit fees to the heavy hauling industry. The results from these interviews showed that increases in permit fees tremendously influence the carrier’s decision-making processes, as most representatives of the trucking industry stated that the current OSOW permit fees are closely aligned with their actual operating costs (Adams et al. 2013). A study in Florida revealed that stricter overweight restrictions would increase the shipping costs which can result in higher production and retail costs. These adverse effects would offset the benefits from the saving in infrastructure damage preservation (Florida Transportation Commission 1993).

Some states that attempted to assess the economic development impacts of changes in truck weight policies include Montana and Indiana. In Montana, in the study conducted by Hewitt et al. (1999), infrastructure and economic impacts were evaluated based on changes in GVW limits. An Input-Output model was used to simulate the impacts of four GVW limits (80, 88, 105, and 128 kips) using trucking productivity as one of the inputs and the gross state product (GSP) as a parameter for measuring the economic impacts in the model. From the analysis, the authors found that increasing the maximum GVW limit has positive effects on the economy of the state and that the changes in the GSP are between 2 and 20 times greater than that of the infrastructure costs, and it continues to expand over time. In Indiana, a study conducted by Everett et al. (2014) evaluated the economic impacts of changes to the State OSOW permit fee structure. The research team conducted a qualitative and quantitative analysis to estimate the economic impacts of a new overweight commodity permit that allow the movement of greater loads for agricultural (97,000 lbs.) and metal (120,000 lbs.) commodities for divisible loads at or under 2.4 ESAL. Findings from the qualitative analysis (based on an industry stakeholder's questionnaire-survey and a literature review of past research) showed that the introduced commodity permit will lead to a direct reduction in carriers' operating costs because of the increased weights and thus the need for fewer trips; an indirect reduction in transportation costs due to lower permit fees; and reduction in vehicle operating costs due to reduced loading of infrastructure. Savings from these cost reductions will in turn reduce the overall operational costs and increase net profits of the trucking industry (carriers and shippers), subsequently benefiting consumers, and ultimately increasing the economic development of the state. Findings from the quantitative analysis (based on the elasticity concept and the FHWA's ITIC simulation model) suggested that the introduced overweight commodity permit is expected to lead to an increase in the productivity of the trucking industry that transports agricultural and metal commodities. The study predicted that the reduction in transportation costs (input) caused by the new commodity permit could lead to a 6% and 22% increase in the ton-miles of agricultural and metal commodities shipment (output), respectively.

2.6 Trucks Vehicle Operation Cost (VOC)

Changes in policies regulating truck weight limits can lead to important changes in the vehicle operations costs of shippers and carriers. By allowing the movement of heavier loads, the same amount of goods can be transported with fewer trips which in turn reduces labor costs, vehicle operational costs (vehicle wear and tear, repair, fuel, etc.), and overhead costs (Luskin et al. 2000; Adams et al. 2013).

To date, few research that has conducted studies for the estimation of the operational costs on trucking are publicly available. In 2003, a study sponsored by the Minnesota Department of Transportation reviewed different trucking cost sources to estimate the operational costs of large commercial trucks and reported that with a fuel price of $1.50 per gallon, the total operational cost for large commercial trucks on highways was $0.434/mile, composed of $0.214/mi for fuel consumption, $0.105/mi for maintenance and repair, $0.035/mi for tires, and $0.08/mi for truck depreciation (Barnes and Langworthy 2003). In 2008, a relevant study conducted by the American Transportation Research Institute (ATRI) quantified the operational costs of trucking (e.g., fuel consumption, maintenance and repair, tire, and driver's wages and fringes) using real-world data collected from commercial motor carriers, an effort that has been updated in an annual basis (Leslie and Murray 2021). Table 2.5 and Figure 2.6 show the ATRI's average marginal operational costs per mile of large commercial trucks from 2008 to 2020.

Table 2.5. Average Marginal Operational Costs per Mile of Large Commercial Trucks.

Carrier Costs ($/mile)	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Fuel	0.63	0.41	0.49	0.59	0.64	0.65	0.58	0.40	0.34	0.37	0.43	0.38	0.31
Repair & Maintenance	0.10	0.12	0.12	0.15	0.14	0.15	0.16	0.16	0.17	0.17	0.17	0.15	0.15
Tires	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Driver Wages	0.44	0.40	0.45	0.46	0.42	0.44	0.46	0.50	0.52	0.56	0.60	0.55	0.57
Driver Fringes	0.14	0.13	0.16	0.15	0.12	0.13	0.13	0.13	0.16	0.17	0.18	0.19	0.17

Data Source: An Analysis of the Operational Costs of Trucking: 2021 Update Report (Leslie and Murray 2021).

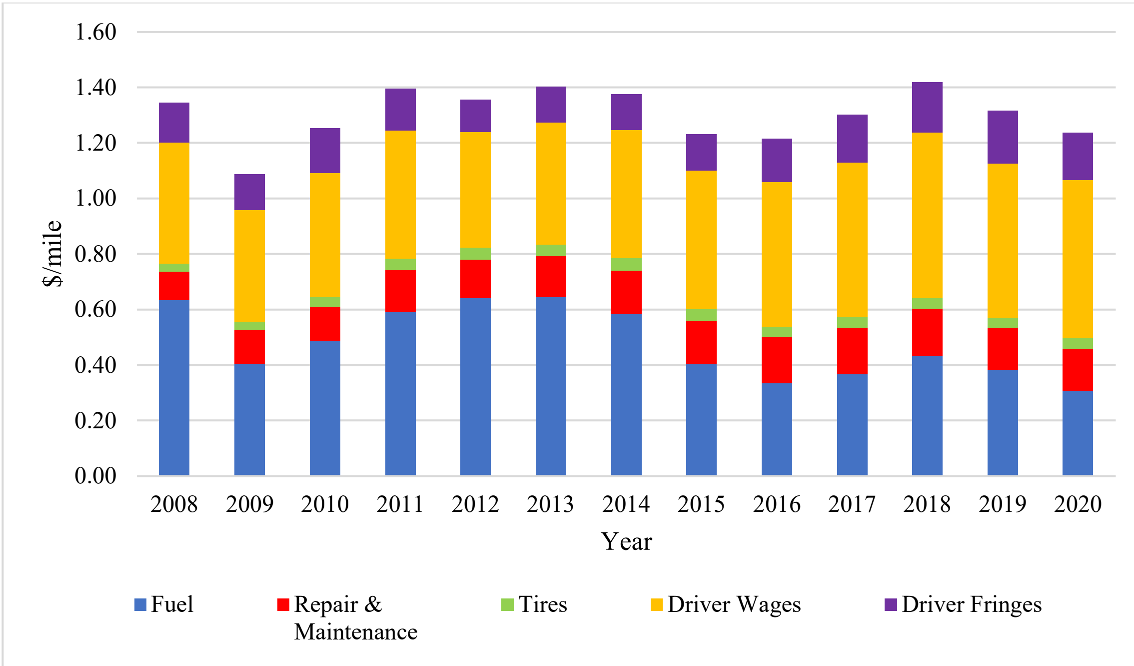


Figure 2.6. Average Marginal Operational Costs per Mile of Large Commercial Trucks. Data Source: An Analysis of the Operational Costs of Trucking: 2021 Update Report (Leslie and Murray 2021)

2.7 Shipping Inventory Cost

As changes in policies regulating truck weight limits greatly influence the loading behavior of shippers and carriers, changes in shipping inventory costs would likely occur. Shipping inventory costs refer to the carrying interest cost that a cargo owner incurs while the inventory is in transit. When a cargo is being transported, the owner is unable to invest the otherwise cash that the cargo is equivalent to, resulting in shipping inventory costs. Depending on the value of the cargo, speed of the truck, and the assumed interest carrying cost, the generated shipping inventory costs can be significant.

Studies have shown that higher prevailing opportunity cost of money, greater cargo value, higher cargo perishability, and slower speed of the truck are typically directly correlated to higher shipping inventory costs (Sinha and Labi 2007).

Estimates for the value and amount of shipment that is being moved within the state of Indiana provided by the FHWA's Freight Analysis Framework, FAF, (National Transportation Reserach Center 2022) are presented in Table 2.6 and can be used as input data for the value of cargo to assess the impacts of overweight truck permitting on inventory shipping costs.

Table 2.6. Shipments By Commodity Within the State of Indiana: 2022.

Commodity	Within IN				Outbound from IN				Inbound from IN				Average Commodity Value ($/ton)
	tons (1000)	ton-miles (million)	miles	value (million)	tons (1000)	ton-miles (million)	miles	value (million)	tons (1000)	ton-miles (million)	miles	value (million)	
Alcoholic beverages	922.26	57.41	62.24	2,297.62	961.08	615.69	640.62	1,912.36	708.62	274.05	386.73	1,028.22	5,125,272,022.45
Animal feed	7,298.26	741.08	101.54	2,814.84	12,321.57	7,517.44	610.10	4,451.38	4,451.49	1,471.78	330.63	2,699.10	10,858,497,852.01
Articles-base metal	1,966.45	197.02	100.19	5,584.99	7,119.08	2,582.78	362.80	9,645.37	2,500.49	1,042.11	416.76	9,047.14	30,174,411,894.11
Base metals	15,240.25	1,046.57	68.67	13,560.04	28,916.83	12,348.77	427.04	27,527.20	15,421.70	5,048.61	327.37	19,336.03	61,475,676,779.06
Basic chemicals	4,823.67	461.70	95.72	1,335.70	3,560.79	1,159.31	325.58	3,183.99	4,841.31	2,707.08	559.16	6,966.58	11,506,740,253.75
Building stone	384.06	32.58	84.84	100.78	433.34	252.97	583.76	168.19	77.32	24.61	318.28	13.38	245,614,135.72
Cereal grains	34,758.65	4,616.63	132.82	3,871.25	21,090.93	13,454.35	637.92	2,784.90	16,621.49	4,011.04	241.32	2,512.42	9,531,702,678.73
Chemical prods.	1,079.39	93.94	87.03	2,990.89	1,596.31	1,027.27	643.53	6,145.89	3,350.40	1,689.46	504.26	10,867.32	19,814,937,761.28
Coal	16,964.63	1,626.74	95.89	691.49	5,539.84	1,700.53	306.96	195.17	19,330.12	12,151.68	628.64	881.23	1,695,391,872.21
Coal-n.e.c.	25,703.61	2,330.98	90.69	5,931.41	51,201.21	10,883.42	212.56	9,953.84	68,084.60	12,324.94	181.02	12,594.24	29,488,307,712.37
Crude petroleum	6.77	0.91	133.59	2.14	10,295.36	2,708.50	263.08	3,244.97	32,807.28	27,582.26	840.74	10,480.49	13,648,891,819.10
Electronics	413.16	33.46	80.98	5,905.92	1,053.56	715.66	679.28	20,144.63	1,349.85	1,275.16	944.67	25,978.96	49,440,976,276.48
Fertilizers	3,934.24	405.32	103.02	1,314.18	714.14	197.43	276.45	245.67	4,080.64	3,713.12	909.94	1,022.26	2,701,812,632.43
Fuel oils	10,092.86	612.53	60.69	5,210.82	3,072.12	1,171.83	381.44	1,761.14	4,240.98	481.53	113.54	2,162.96	9,280,671,312.66
Furniture	710.64	56.99	80.20	4,259.92	1,082.62	647.32	597.92	5,459.51	946.35	783.87	828.30	4,225.88	14,157,210,280.69
Gasoline	14,856.47	861.80	58.01	7,836.78	17,177.26	5,378.78	313.13	8,870.58	17,649.79	3,352.50	189.95	10,002.74	26,674,220,388.08
Gravel	68,294.56	5,071.40	74.26	642.87	10,823.56	3,079.38	284.51	92.90	7,630.77	1,856.16	243.25	109.16	934,022,035.73
Live animals/fish	2,231.83	262.49	117.61	3,149.42	463.59	87.97	189.77	640.77	593.90	122.13	205.64	1,225.56	5,325,304,329.25
Logs	4,475.55	481.76	107.64	87.79	47.14	56.25	1,193.17	36.91	124.45	77.03	618.99	60.28	1,993,395,099.88
Machinery	1,245.97	92.01	73.85	12,899.32	2,967.31	1,828.52	616.22	26,684.35	2,743.44	1,575.43	574.25	27,417.69	68,035,617,368.80
Meat/seafood	338.37	33.82	99.96	1,155.92	1,657.00	1,079.75	651.63	5,263.75	1,239.68	572.22	461.59	4,648.46	11,152,929,606.43
Metallic ores	67.94	6.30	92.79	23.69	171.21	109.54	639.81	93.51	12,034.83	7,154.89	594.51	753.79	3,917,330,506.25

Commodity	Within IN				Outbound from IN				Inbound from IN				Average Commodity Value ($/ton)
	tons (1000)	ton-miles (million)	miles	value (million)	tons (1000)	ton-miles (million)	miles	value (million)	tons (1000)	ton-miles (million)	miles	value (million)	
Milled grain prods.	731.54	58.10	79.42	1,433.73	3,616.36	2,060.05	569.65	4,804.04	2,384.31	970.04	406.84	5,831.53	12,867,741,522.32
Misc. mfg. prods.	1,055.37	80.22	76.01	4,331.00	1,701.64	838.65	492.85	11,543.60	1,614.28	839.28	519.91	14,894.79	29,308,730,287.57
Mixed freight	4,785.72	381.92	79.80	17,071.08	6,795.43	2,169.26	319.22	30,553.37	5,926.24	1,646.68	277.86	22,476.03	69,188,505,225.64
Motorized vehicles	10,736.11	595.71	55.49	34,399.27	12,699.49	6,278.28	494.37	53,918.21	5,449.45	2,378.83	436.53	38,382.88	139,545,680,928.22
Natural sands	8,569.56	627.62	73.24	72.34	138.82	43.45	312.97	34.11	2,749.82	844.01	306.93	161.48	1,194,924,837.07
Newsprint/paper	404.71	28.49	70.40	486.57	1,747.05	898.76	514.44	1,934.83	3,586.63	2,030.58	566.15	3,591.25	6,333,342,882.24
Nonmetal min. prods.	16,406.44	1,231.75	75.08	3,276.96	8,553.84	3,069.71	358.87	4,330.36	5,966.43	2,060.07	345.28	3,159.67	12,737,247,845.24
Nonmetallic minerals	4,330.98	427.06	98.61	366.00	2,793.32	803.78	287.75	364.73	3,102.82	1,673.95	539.49	421.86	1,196,707,668.99
Other ag prods.	14,741.83	1,701.11	115.39	4,915.98	6,902.13	3,548.14	514.06	3,063.65	6,785.26	2,221.80	327.44	3,123.61	11,728,886,596.04
Other foodstuffs	8,078.14	786.35	97.34	5,597.19	12,940.96	7,274.65	562.14	7,720.64	6,773.45	4,532.64	669.18	8,637.12	23,759,191,124.77
Paper articles	737.14	54.00	73.26	1,104.35	955.55	428.38	448.30	1,876.52	1,348.71	441.29	327.19	2,959.99	5,734,715,808.78
Pharmaceuticals	31.26	2.04	65.24	4,806.62	119.61	91.95	768.80	30,949.37	503.61	345.10	685.25	34,300.83	104,851,678,140.11
Plastics/rubber	2,039.01	162.23	79.56	7,535.42	4,239.87	2,434.54	574.20	15,542.08	7,939.22	5,215.52	656.93	18,538.06	45,954,432,000.78
Precision instruments	45.55	3.28	72.01	2,346.56	170.73	130.32	763.32	13,547.23	224.30	205.92	918.06	11,644.89	26,843,399,528.89
Printed prods.	260.80	10.93	41.93	1,881.64	592.33	375.58	634.07	3,621.34	603.15	296.07	490.87	2,862.27	8,773,621,642.65
Textiles/leather	228.80	18.06	78.93	2,102.58	745.92	500.11	670.47	13,061.19	782.32	696.75	890.61	11,648.80	24,358,322,115.77
Tobacco prods.	7.23	0.39	54.57	308.58	1.54	0.23	147.96	35.21	12.55	4.54	361.49	523.85	762,252,376.27
Transport equip.	36.71	2.89	78.76	181.44	221.25	91.90	415.36	2,225.28	74.69	32.75	438.47	1,341.13	3,654,352,554.72
Waste/scrap	18,081.84	808.13	44.69	1,258.91	1,823.30	598.03	327.99	926.38	10,738.02	2,486.82	231.59	2,921.71	8,680,113,531.96
Wood prods.	5,049.38	374.58	74.18	4,283.42	1,732.86	846.73	488.63	2,671.78	6,256.88	2,639.58	421.87	4,394.06	13,440,783,813.98
												Average Commodity Value =	$1,095.17 per ton

2.8 Chapter Summary

In this chapter a literature review of published research and documented experiences of several states was conducted to highlight the state-of-the-art of impacts of overweight truck operations on highway infrastructure degradation, overweight permitting revenues, operational performance, and economic productivity.

It is well documented that overweight truck operations cause significant damage to highway infrastructure, consequently reducing the service life of pavement and bridges. Compared to legally loaded trucks, overweight trucks cause much greater damage to pavement surfaces and bridges (Straus et al. 2006). To date, several states have invested in efforts to quantify overweight trucks' pavement and bridge consumption. Results from those studies show that the damage cost of highway assets inflicted by overweight trucks is greatly affected by the type and age of the asset (Ahmed et al. 2012; Ali et al. 2020; Dey et al. 2015; Gungor et al. 2019). For pavement assets, vehicle type and weight were identified as the most significant factors in pavement deterioration, as heavy truck loads can develop excessive stress and strain on the structural layers of the pavement, causing distress and ultimately pavement fatigue failure (Chowdhury et al. 2013). Studies have shown that increments in trucks' number of axles and load magnitude provoke an exponential increase in pavement damage (David Luskin 2001). For bridge assets, the impact of trucks varies mainly with the weight of each group of axles and the distance between axle groups (USDOT 2000a; b).

To lessen their burden in terms of infrastructure asset maintenance and replacement, State transportation agencies exercise OSOW permit fees to collect funding from commercial oversize and overweight vehicles for their infrastructure consumption. An evaluation of the permit fee structures of different states in the Midwest region was conducted, and the comparison showed that the differences in truck dimensions and gross weight limits for the same type of permit are mainly determined by the characteristics of their existing infrastructure (road and bridges' dimensions, age, structural capacity, etc.), the type of load that is being transported, and its impact on the infrastructure for each state. Thus, OSOW permits types and fees vary greatly among these states; and these variations reflect the different priorities that highway agencies have regarding truck operations in their jurisdictions. Lastly, past research from different states showed that although the OSOW permit fees were established to collect sufficient revenues for recovering the infrastructure damage inflicted by overweight trucks, the collected revenues from OSOW permit sales do not fully cover the additional highway asset expenditures associated with their consumption. Consequently, a significant gap between revenue and consumption is reported by several states (Crockford 1993; Luskin et al. 2000; Dey et al. 2015; Everett 2015; Nassif et al. 2015; Al-Qadi et al. 2017).

While the impacts of overweight truck operations on infrastructure deterioration have been widely studied in the literature, the operational impacts such as safety degradation and mobility impairment due to over-dimensioned and overloaded trucks remain underexplored (Everett et al. 2014; Wang et al. 2018). In terms of traffic safety, studies showed that TS&W limits increase are a controversial issue. Some argue that an increase in TS&W would reduce the number of trucks on the roads, reducing the level of exposure to crash situations that ultimately can improve overall road safety (TRB 1990). Others argue that the increase in TS&W limits would increase the frequency and severity of crashes that can result in more fatal crashes, for overweight trucks have reduced maneuverability and stability (David Luskin 2001; Neff and Bai 2012). Despite this controversy, in general, overweight trucks pose a threat to all road users. Past studies found that crash frequency tends to increase as GVW increases (TRB 1990; USDOT 2015). Also, the probability of a truck being involved in an accident with severe consequences is higher for an overweight truck than for a legally loaded truck (Pigman and Agent 1999; Jacob and La 2010). The heavier a truck is, the higher its kinetic energy is, and therefore the greater the impact and damage are in the event of a collision. In terms of traffic mobility, overweight truck operations have a significant impact on road traffic conditions. Compared with legally loaded trucks, overloaded trucks have reduced maneuverability and inferior acceleration/deceleration capabilities that caused them to have lower running speeds that ultimately impose more significant impacts on the traffic (Wang et al. 2018).

Furthermore, overweight truck operations also have an important impact on the economic productivity of the freight industry. By allowing the movement of heavier loads, the same amount of goods can be transported with fewer trips which in turn reduces labor costs, vehicle operational, and overhead costs (Luskin et al. 2000; Adams et al. 2013). These savings in freight transportation costs result in reduced vehicle operation costs and increased productivity that benefits not only the trucking industry but also the entire economy of a region. For instance, carriers may pass cost savings on to shippers in the form of lower rates, and shippers may pass cost savings on to consumers in the form of lower prices for goods, and so on (Dey et al. 2015; Adams et al. 2013). While the assessment of the impacts of overweight truck operations on economic productivity has been proven to be relevant when addressing OSOW permitting policies, the lack of needed input data has been the main obstacle to quantifying it in a rigorous manner (Everett et al. 2014). Only a few studies have attempted to quantify the economic impacts of overweight truck operations on the productivity of the trucking industry. These studies found that increasing the maximum GVW limit has positive effects on the economy of the state, which are mainly attributed to the savings in transportation cost resulted from the reduction in the number of trips (Everett et al. 2014; Hewitt et al. 1999).

Ultimately, because overweight permitting policies have a great impact not only on highway infrastructure and permitting revenues but also on traffic operational performance, vehicle operation costs, shipping inventory costs, and economic development and productivity, states must evaluate them together in order to develop a reasonable and fair OSOW permitting fee structure that can allow highway agencies to collect sufficient funding for covering road asset expenditures, protect public safety, improve traffic mobility, and promote the economic development and productivity of the state.

3. FRAMEWORK: MULTI-CRITERIA DECISION ANALYSIS FOR EVALUATING CHANGES IN POLICIES RELATED TO OVERWEIGHT TRUCK OPERATIONS

The complex and wide range of criteria that are involved in the transport-related decision process makes the multi-criteria decision analysis (MCDA) one of the most appropriate methods for evaluating transportation projects (Macharis and Bernardini 2015). MCDA techniques allow the simultaneous evaluation of several alternatives through various qualitative and quantitative performance criteria to facilitate the decision-making process by the different stakeholders. Nowadays, with the increasing relevance of social (e.g., equity, safety, environmental justice) and environmental (e.g., air pollution, noise) factors in transportation projects, the decision-making process is becoming more and more complex, for the criteria needed to be considered to capture their full impacts are often conflicting and intrinsically difficult to quantify. On top of that, the ongoing trend of the diverse and increased number of stakeholders, who demand transportation agencies to consider their concerns and standpoints in the decision-making process, exacerbates the complexity of the evaluation process (Bai and Labi 2012). For instance, while transportation agencies, within budgetary constraints, may seek to provide the best possible service to road users for promoting the economic development of the region; road users expect improved traffic mobility and safety and better accessibility to local roads; environmentalists may advocate for the preservation of water resources, air quality, and ecology; and environmental justice groups may demand affordable and accessible transportation for socially disadvantage groups. The versatility of the MCDA techniques permits the consideration of the priorities of the different stakeholders, so disagreements on the objectives or relative importance of the criteria in regard can be avoided. Moreover, past studies revealed that conflicting viewpoints hinder the decision-making process and consequently, tend to lengthen the total amount of time needed for the evaluation of projects (Basbas and Makridakis 2007).

To date, MCDA techniques are increasingly (Figure 3.1) and broadly (Figure 3.2) used in many areas of the transportation sector (Macharis and Bernardini 2015). MCDA techniques have been widely used to evaluate transportation policies (Figure 3.2) in areas such as marine transportation (Gagatsi and Morfoulaki 2013), public transportation (Jain et al. 2014), infrastructure (Costa 2001; Rabello Quadros and Nassi 2015), environmental assessment and sustainability (Baláž et al. 2021; Dubash et al. 2013; Knoll et al. 2016; Salling et al. 2018; Sun et al. 2015; Tzeng et al. 2005), among others. As shown in Figure 3.2, other applications of the MCDA techniques in transportation decision-making include studies on mobility management (Campos et al. 2010; Knoll et al. 2016; Mathey 2019), highway infrastructure development (Scannella and Beuthe 2003; De Silva and Tatam 1996; Tabucanon and Lee 1995), public transit (Barbosa et al. 2017; Chen et al. 2020), technology (Chen et al. 2020; Mathey 2019), logistics (Bulatov 2021; Labadie and Prodhon 2014), maritime transportation (Celik et al. 2009), air (Park et al. 2009), rail (Macura et al. 2012; Vilke et al. 2020), and biking (Barfod 2012).

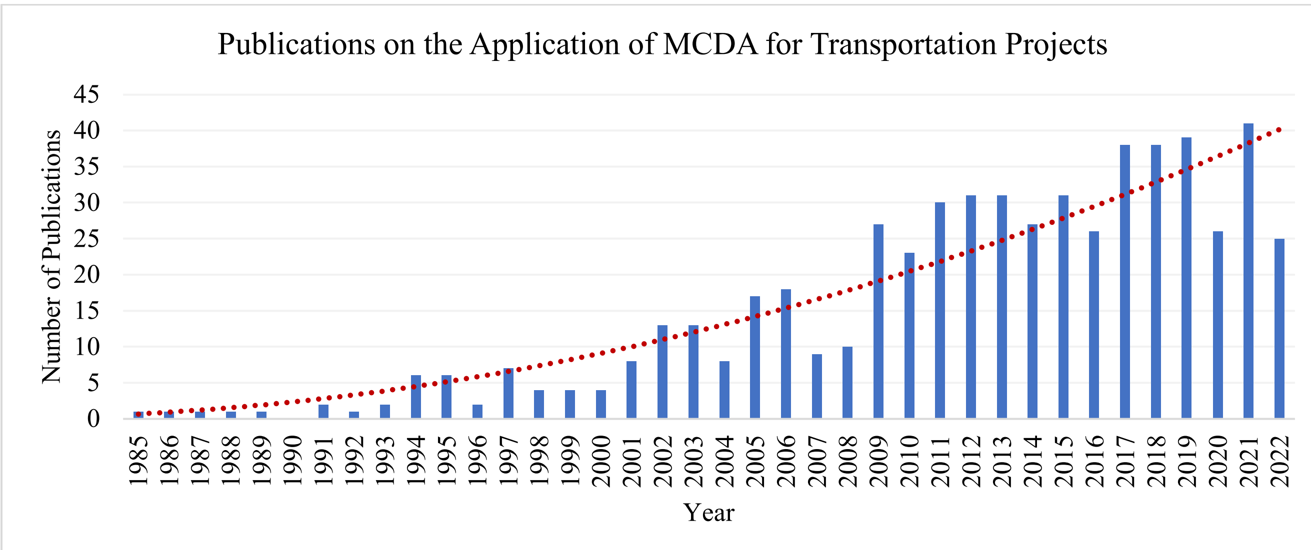


Figure 3.1. Historic trend of the application of MCDA in transportation projects.
Source: Updated from Macharis and Bernardini (2015).

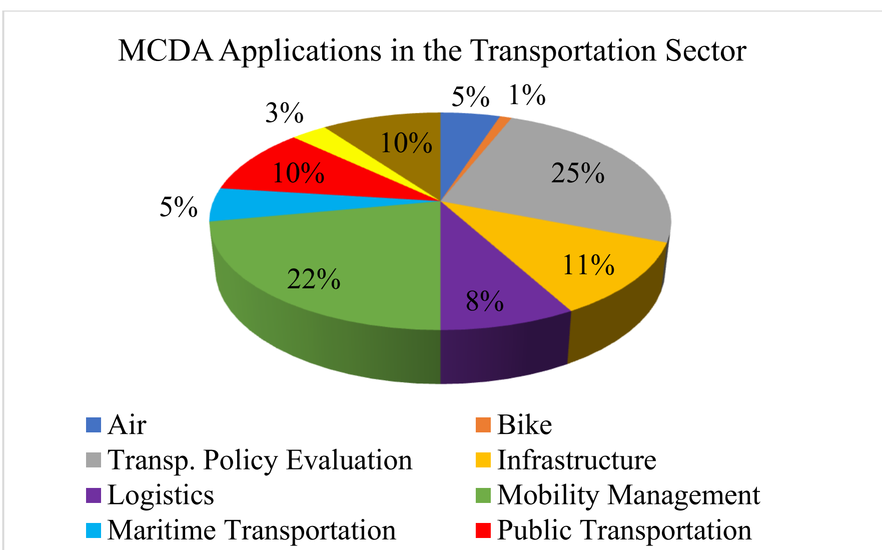


Figure 3.2. MCDA applications in the transportation sector.
Source: Macharis and Bernardini (2015).

In terms of highway infrastructure, applications of the MCDA techniques found in the literature range from infrastructure development projects that cover planning (Jeon et al. 2010; Salling et al. 2018; Tsigdinos and Vlastos 2021), design (Brauers et al. 2008; Kuzović et al. 2015; Santos et al. 2019), construction (Ahmadi et al. 2017; Purnus and Bodea 2016), maintenance (Sayadinia and Beheshtinia 2020; Suthanaya 2017) to policy measures design, evaluation, and implementation. It is important to note that a high number of recent research found in the literature related to the applications of MCDA techniques in transportation infrastructure development were focused on sustainable planning as well as on strategies for the implementation of new technologies such as autonomous vehicles, electric cars, and Internet of Things (IoT). However, to the best of the authors' knowledge the application of MCDA for evaluating changes in policies related to overweight truck operations has not been investigated in the context of overweight truck permitting before.

To address this gap, the authors propose a multi-criteria decision analysis framework (Figure 3.3) to enable prioritization of the wide range of criteria involved in changes in policies related to OW truck operations when considering the standpoints of different stakeholders (highway agencies and trucking industry) simultaneously. In this study, the focus is on the various costs and benefits associated with the operation of OW trucks. The resulted MCDA framework aims to assist highway agencies in the decision-making process for evaluating the possible effects on changes to the OW truck operation policies. As shown in Figure 3.3, the proposed MCDA framework consists of seven main steps: 1) Establishment of Decision Context, 2) Alternatives Identification, 3) Performance Criteria Identification, 4) Weighting, 5) Scaling, 6) Amalgamation, and 7) Decision Making. A description of each step is presented in the remaining of this chapter. Additionally, a literature review of the steps involved in a MCDA and the approaches found in past studies for quantifying relevant performance criteria in the evaluation of the impact of changes in policies related to overweight truck permitting are included for a better understanding of the methodology.

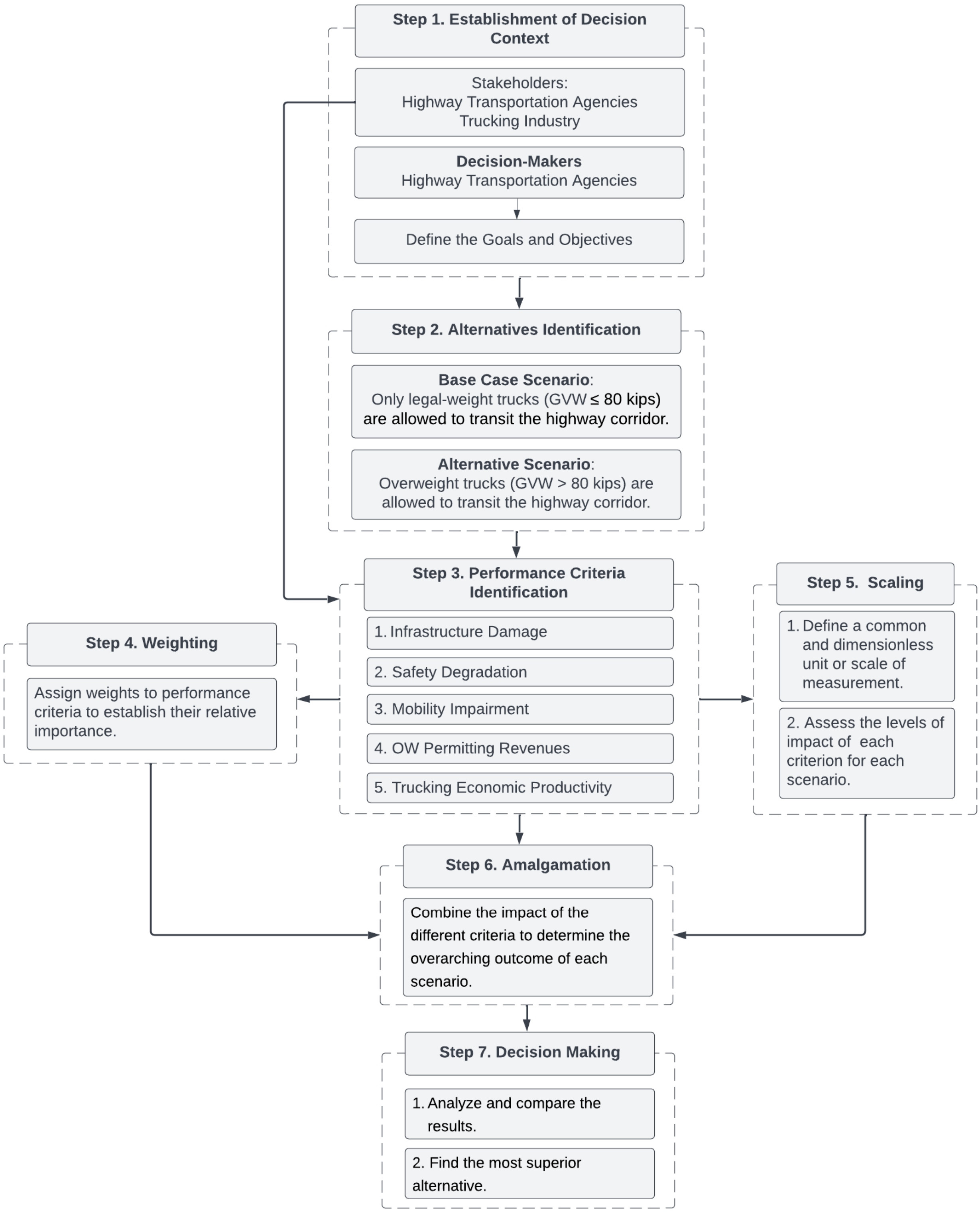


Figure 3.3. General framework of MCDA applied in the context of OW truck permitting.

3.1 Establishing the Decision Context

For a MCDA, the first thing needed to be done is to clearly define the context of the analysis. The context accounts for the current situation, goals to be achieved, stakeholders, and key participants or "key players" in the decision-making process. Key players are persons who can make a helpful and meaningful contribution to the analysis. Key players can be stakeholders, individuals with an interest or concern in the subject matter or can simply be experts with no investment in the final decision but with knowledge of the subject matter.

When analyzing the potential impacts of changes in policies regarding overweight truck operations, two different groups of stakeholders are generally involved. On one hand, we have the transportation agencies, responsible for the maintenance and preservation of the highway system, representing the public sector. On the other hand, we have the trucking industry composed by carriers and shippers who seek to profit from their services, representing the private sector. Because the highway transportation system is owned and managed by the federal, state, and local transportation agencies, the power of decision-making fall under their responsibility. In the context of overweight truck permitting, the goals are the preservation of infrastructure assets, provision of an acceptable level of operational performance in terms of road safety and traffic mobility, and minimization of road users' costs.

3.2 Identifying the Alternatives to be Evaluated

In a MCDA, various possibilities are compared to one another. At least two options are usually evaluated in a MCDA, the option of continuing as at present, known as the base case scenario, and an additional option, known as the alternative scenario. Options are frequently formulated on a go/no-go basis (Dodgson et al. 2009). Those performing the MCDA should be open to the potential of changing or expanding the alternatives as the analysis goes on, regardless of whether the options are provided or need to be generated (Dodgson et al. 2009). Whether an alternative is chosen or not depends on the outcomes/consequences associated with it.

To evaluate the impacts of overweight truck operations, the present study will analyze two scenarios:

- Base case scenario: all trucks in the traffic stream are loaded at 80,000 lbs.
- Alternative scenario: some of the trucks in the traffic stream are loaded at 100,000 lbs.

3.3 Identifying the Performance Criteria for Comparing Alternatives

Since the consequences tied to each alternative are the ones determining the outcome of the decision-making process; consequences play an important role in the MCDA (Dodgson et al. 2009). There are various ways that consequences might differ, and those that are important to help attain goals are known as criteria, performance criteria or performance measures (Dodgson et al. 2009). Performance criteria describe clearly delineated standards by which the various alternatives can be measured and compared (Toolshero 2022). In other words, criteria are the measures of performance used to evaluate the alternatives (Dodgson et al. 2009). Performance measures provide an effective method of informing decision-makers by converting data and statistics into a concise and uniform format. Consequently, transportation decision-making is characterized by its need of considering a broad range of performance measures to reflect the concerns and perspectives of all stakeholders for comparing different alternatives and ultimately identifying the optimal solution to the problem.

For purposes of transportation decision-making, the selection of performance measures is driven by the goals and objectives of the project. Attributes of a good individual performance measure are appropriateness, measurability, dimensionality, realistic, defensible, and forecastable (Turner et al. 1996). Appropriateness refers to the relevance and adequacy of the performance measure in reflecting at least one goal or objective of the transportation system action. Measurability means that the performance measure can be measured objectively, accurately, and reliably. Dimensionality allows the capture of the level required for each dimension when evaluating a problem and the comparison across different domains (e.g., special and temporal). Realistic facilitates the gathering, generation, and extraction of dependable data related to the performance measure without requiring an excessive amount of work, time, or money. Defensibility relates to the clarity and conciseness of the performance measure to enable the effective communication of the way in which it is interpreted and assessed by decision-makers, stakeholders, and the public. Finally, forecastable means that the performance measure should be predictable at a future time in a reliable manner using existing forecasting techniques.

Attributes for a good set of performance measures are (Sinha and Labi 2007): 1) Completeness: the set of performance measures is complete when it can adequately specify to what extent the objective is met; 2) Operational: the set of performance measures needs to be useful and meaningful so that the consequences of the alternatives can be understood while making the problem more manageable; 3) Non-redundancy: the set of performance measures should avoid double counting of consequences, and 4) Minimal: the set of performance measures should be as small as possible to reduce dimensionality.

In this study, typical performance measures used in the evaluation of policies related to OW truck operations such as infrastructure damage, safety degradation, mobility impairment, overweight truck permitting revenues, vehicle operation cost, and shipping inventory costs were selected for the analysis (Table 3.1). A description of the methodology used for quantifying these performance measures is presented below.

Table 3.1. Performance Measures for Overweight Truck Operations.

Goal	Category	Performance Measure
1. Agency Cost	Infrastructure damage cost Overweight permit revenues	Annual change in infrastructure damage cost (%) Annual change in revenues from sales of OW permits (%)
2. Safety	Crashes	Annual injury crash frequency (crashes/centerline-mile)
3. Mobility	Travel time	Average travel speed (mph)
4. User Cost	VOC Shipping Inventory Cost	Vehicle operation cost for trucks ($/truck-mile) Shipping inventory cost (cents/truck-mile)

3.3.1 Infrastructure Damage Assessment

Rather than estimating the impact of overweight trucks on highway infrastructure, this study adopts the unit pavement and bridge costs established in a report titled Costs and Revenues Associated with Overweight Trucks in Indiana, SPR-3502 Report, (Ahmed et al. 2012) and applied them to quantify the impacts of overweight trucks operations on pavement and bridge assets. In contrast to other studies found in the literature in which most of them considered only asset rehabilitation treatments at fixed intervals in the analysis, the SPR-3502 report estimated the unit cost of pavement and bridge consumption for overweight trucks using more realistic traffic volumes, growth projections, and lifecycle schedules for pavement and bridge maintenance, rehabilitation, and reconstruction (MR&R). Another reason why the asset unit consumption costs from the SPR-3502 report were chosen over the other studies is that the study was contextualized for the pavement and bridge assets in the state of Indiana.

To estimate the total additional infrastructure damage costs due to overweight truck operations along a given route, information on each individual overweight truck such as GVW, axle load, axle configuration, and number of axles can be obtained from the OW permit records.

While the functional class of the road segments (IS, non-Interstate NHS, and non-NHS), as well as the number of bridges in the route, can be identified using the National Highway Planning Network (NHPN). Moreover, to estimate the impacts of overweight truck operations on bridge assets, relevant characteristics of the bridges in the route such as the age, dimensions, length, and structural material that are required as input can be obtained from the National Bridge Inventory.

To calculate the pavement damage cost caused by different overweight truck classes **Error! Reference source not found.**(Figure 3.4), the present study adopts the methodology presented in the SPR-3502 report (Ahmed et al. 2012). The SPR-3502 report's (Ahmed et al. 2012) procedure is presented below:

- Step 1: Assessment of Unit Cost for Pavement Damage. The present study will apply the load-related overall marginal pavement damage cost due to truck operations in Indiana obtained from the report SPR-3502. In that report, the research team established the pavement consumption for Interstates (IS), non-Interstates National Highway System (NIS-NHS), and non-National Highway System (Non-NHS) as \$0.006, \$0.055, and \$0.218 per ESAL-mile, respectively (Ahmed et al. 2012).
- Step 2: Compute the average ESAL for legal-weight trucks (GVW ≤ 80,000 lbs.). Since the present study intents to compare the actual infrastructure consumption costs of trucks with permitting revenues, only trucks with a GVW greater than 80,000 lbs. that are required to buy an overweight permit will be considered in the analysis. Furthermore, for those overweight trucks, the load that is being charged, corresponds to the load over the 80,000 lbs. only, will be used in the calculations. So, for subtracting the pavement damage cost caused by the 80,000 lbs. legal weight from the total GVW of a truck, the average ESAL of 2.4 for a standard 5-axle semi-trailer with a weight of 80,000 lbs. was used to represent legal-weight trucks in the SPR-3502 report. In that report, the average ESAL of 2.4 for the 5-axle semi-trailer truck was estimated using the AASHTO fourth power law and assuming a load of 12,000 lbs. and 34,000 lbs. on the steering axle and each tandem axle, respectively.
- Step 3: Computation of the average GVW and average ESAL for all overweight trucks (GVW > 80,000 lbs.) classes (Class 4 - Class 13). To compare the actual

infrastructure consumption costs of overweight trucks with permitting revenues, trucks can be classified based on the current permit fee structure into categories. Within each category, trucks can be further classified based on the number of axles. Then total ESAL generated by each truck class can be estimated for the different axle configurations and GVW. The ESALs can be computed for each truck following INDOT's procedure outlined in 105 LAC 10-3-2 (INDOT 2013) (See (Equation 3.1).

$$Total\ Truck\ ESAL = \sum_{i=1} \left[\frac{W_i}{X}\right]^4 \qquad \text{(Equation 3.1)}$$

Where
n: total number of axle group in a truck
W_i: axle weight group
X: axle group divisor, defined as:

$$X = \begin{cases} 18{,}000\ lbs., & single\ axle \\ 33{,}200\ lbs., & tandem\ axle \\ 46{,}000\ lbs., & tridem\ axle \\ 57{,}000\ lbs., & quadrum\ axle \\ 65{,}000\ lbs., & quintuple\ axle \end{cases} \qquad \text{(Equation 3.2)}$$

Note: Anything more than a quintuple axle should be calculated as a single, tandem, or tridem.

- Step 4: Computation of the additional ESAL causing extra damage due to a load that exceeds the 80,000-lb limit. To calculate the additional ESAL of an overweight truck causing pavement damage, subtract the ESALs produced by an 80,000 lb., 5-axle vehicle (2.4) from its total ESALs (Equation 3.3).

$$Additional\ ESAL = Total\ ESAL\ of\ OW\ truck - 2.4 \qquad \text{(Equation 3.3)}$$

- Step 5: Computation of the additional pavement damage cost caused by an overweight truck on the system using the unit pavement damage costs in Step 1 (Equation 3.4).

$$Additional\ PDC = Additional\ ESAL\ x\ \$/ESAL\ mile \qquad \text{(Equation 3.4)}$$

Where
$Additional\ PDC$: additional pavement damage cost caused by an OW truck, \$/mi.

- Step 6: Estimation of the total additional pavement damage cost ($) caused by an overweight truck (GVW > 80,000 lbs.) by multiplying the additional damage with its miles traveled.

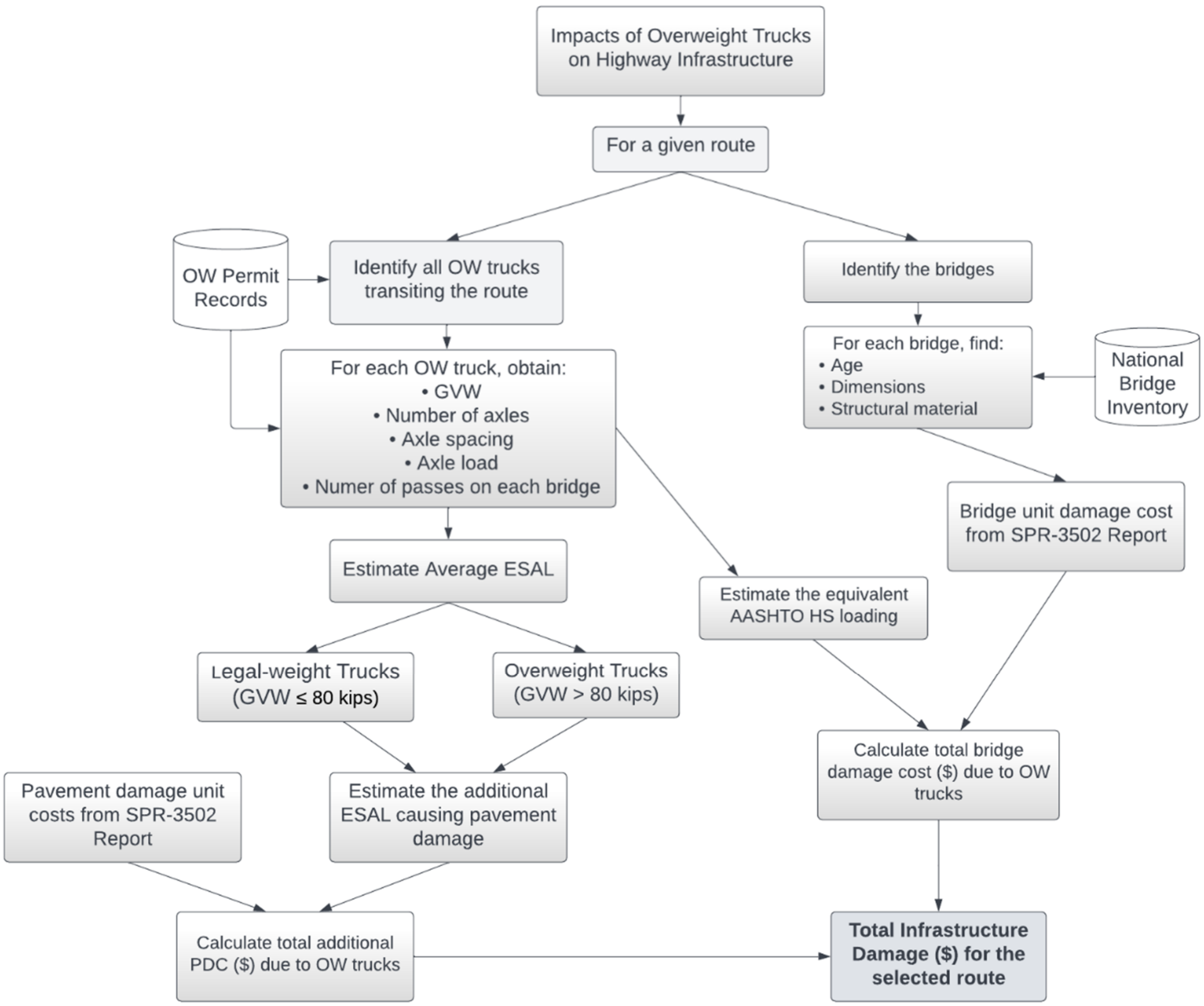


Figure 3.4. Methodology for estimating the additional infrastructure damage caused by overweight trucks.

For bridge assets, the authors of the SPR-3502 also establish unit consumption costs for bridges in $ per ft-pass (Ahmed et al. 2012). Appendix A shows the results obtained from the SPR-3502 for bridge damage caused by the overweight portion of an overweight vehicle (GVW > 80,000 lbs.).

A procedure to calculate the cost of bridge damage due to truck operations (Figure 3.4) presented in the SPR-3502 report is described below (Ahmed et al. 2012):

- Step 1: For a specific route, obtain the number of bridges and their characteristics such as bridge functional class (IS, NIS-NHS, Non-NHS), bridge material (steel, concrete, prestressed-concrete), bridge age (0-20, 21-35, 36-55, > 56 years), and bridge length (in feet).
- Step 2: Estimation of the equivalent AASHTO HS loading (Equation 3.5) using the GVW, average axle spacing (in inches), and the average axle load (in lbs.) of trucks transiting that route.

$$MEV = 0.0057 \left(\frac{GVW}{AAS}\right)^{0.} \times AAL^{0.64} \qquad \text{(Equation 3.5)}$$

Where
MEV: modified equivalent vehicle (AASHTO loading in HS);
AAS: calculated average axle spacing in inches; and
AAL: calculated average axle load in lbs.

- Step 3: Computation of the bridge damage costs by using the unit consumption cost ($/ft-pass) from the SPR-3502 report.

3.3.2 Safety Degradation Assessment

As mentioned in Section 2.2, increases in the allowable weight limits of trucks can be controversial (Neff and Bai 2012). Viewing it from multiple dimensions, overweight trucks have a bifurcated effect on traffic safety (Figure 3.5) (Everett et al. 2014). On one hand, an increase in truck weight would reduce the number of trucks on the roads, for fewer trips would be needed to move the same amount of freight, resulting in less traffic volume and thus less exposure to crash situations that ultimately can improve the overall road safety (TRB 1990). On the other hand, the inferior acceleration/deceleration capabilities and reduced maneuverability and stability of heavy trucks due to the extra load being carried cause disruptions in the traffic stream that ultimately lead to an increase in the frequency and severity of crashes (David Luskin 2001; Neff and Bai 2012).

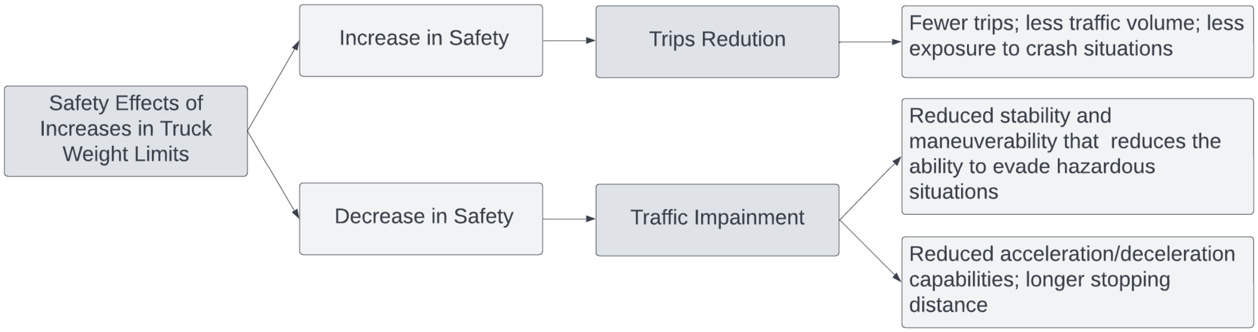


Figure 3.5. Safety impacts of overweight truck operations.
Source: Modified from SPR-3757 Report (Everett et al. 2014).

Thus, the net safety effects of overweight trucks should be estimated considering these two opposing effects, trip reduction effect and traffic impairment effects. A report titled Impact of HB-1481 on Indiana's Highway Revenue Generation, Asset Degradation, Modal Distribution, and Economic Development and Competitiveness (SPR-3757 Report) outlined a methodology to estimate the net impacts in crash frequency due to changes in policies related to overweight truck operations considering trip reduction and traffic impairment effects (Everett et al. 2014). Because the SPR-3757 report specifically considered the net impacts of overweight trucks on road safety, while most studies found in the literature only considered the impacts of heavy/large trucks which does not necessarily are overweight, the present study adopts the same methodology for evaluating the net safety impacts of overweight trucks operations.

The procedure proposed by the SPR-3757 report (Everett et al. 2014) to calculate the net safety impacts due to overweight truck operations (Figure 3.6) is described below. For a given route, relevant input information such as truck weight and configuration (e.g., GVW, axle load, axle spacing, and number of axles) and traffic volumes (AADT, ADT) are needed and can be obtained from the overweight permit records and the INDOT's Traffic Count Database System, respectively. Step 1 is for determining the crash frequency due to legal-weight trucks, while Steps 2-6 are for determining the crash frequency due to overweight truck operations, lastly Step 7 computes the percentage change in crash frequency due to overweight truck operations along the given route.

- Step 1: By using safety performance functions (SPF), estimate the expected number of crashes by the level of severity for the base case scenario ($C_{\text{fatal, Base Case}}$, $C_{\text{injury, Base Case}}$, $C_{\text{PDO, Base Case}}$) in which only legal-weight trucks (GVW ≤ 80,000 lbs.)

are present in the traffic stream. The SPR-3757 report suggested different safety performance functions for estimating crash frequency on different highway functional classes. However, since the present study only intends to apply this methodology to a rural interstate, (Equation 3.6 which was developed by (Hadi et al. 1995) for estimating crash frequency on rural freeways is presented below:

$$C_{RF} = 0.25 \times ADT^{0.9599}(1000L)^{0.9107}e^{B_{RF}} \quad \text{(Equation 3.6)}$$

Where,

$$B_{RF} = -14.032 - 0.0407W_{is} + 0.2127N_x \quad \text{(Equation 3.7)}$$

C_{RF}: frequency of mid − junction injury crashes, crashes/year.
ADT: average daily traffic, veh/day.
L: freeway segment lenght, mile.
W_{is}: inside shoulder width, ft (assumed to be 6 ft in the present study).
N_x: number of interchanges on freeway segment (assumed to be 1 in the present study).

Note that (Equation 3.6 and (Equation 3.7 can be replaced for a safety performance function that is considered more adequate at a future time.

- Step 2: Verify whether the safety performance functions being used include any variable for representing the volume of overweight trucks, if so calculate then the annual crash frequency for the specified highway segment; otherwise move on to the following step.
- Step 3: Determine the equivalent number of legal-weight trucks from the total number of OW trucks.

  A. For each overweight truck determine the equivalent number of legal-weight trucks by first estimating the maximum allowable weight, W, using the bridge formula (Equation 1.1). Then, for each overweight truck, compute the equivalent number of legal-weight trucks using (Equation 3.8).

$$\left(N_{eq}\right)_i = \left(\frac{GVW}{W}\right)_i \quad \text{(Equation 3.8)}$$

  Where,

  GVW: gross vehicle weight, lbs.
  W: maximum allowable weight, lbs. (estimated from (Equation 1.1).
  i: 1 to n where n is the total number of trucks in the traffic stream.

  B. Estimate the percentage of extra weight (APEW) compared to the maximum allowable weight of each truck can be calculated using (Equation 3.9).

$$APEW = \left(\frac{GVW - W}{W}\right) \times 100 \quad \text{(Equation 3.9)}$$

C. Compute the total number of equivalent legal-weight trucks in the traffic stream by summing up the equivalent number of legal-weight trucks obtained from the calculation in Step 3A for each individual overweight truck ((Equation 3.10) or(Equation 3.11).

$$N_{eq} = \sum_{i-1} \left(N_{eq}\right)_i \quad \text{(Equation 3.10)}$$

$$N_{eq} = N_{TT} + APEW \times N_{TT} = N_{TT}(1 + APEW) \quad \text{(Equation 3.11)}$$

Where,

N_{eq}: total number of equivalent legal weight trucks in the route, trucks/day.
N_{TT}: total number of legal weight trucks plus the number of OW trucks, trucks/day.

APEW: average percentage extra weight compared to the maximum allowable weight for all trucks.

- Step 4: For considering the opposing forces of overweight trucks on the traffic stream, traffic impairment (TIE) and trips reduction (TRE) effects are included in the analysis when estimating the net traffic volume, NE_{OW}.

A. Compute the reduced number of trucks on the highway segment due to the trip reduction effect caused by overweight truck operation (Equation 3.12).

$$TRE = APEW \times N_{TT} \times P_{OW} \quad \text{(Equation 3.12)}$$

Where,

APEW: average percentage extra weight compared to the maximum allowable weight for all trucks.
N_{TT}: total number of legal − weight trucks plus the number of OW trucks, trucks/day.
P_{OW}: percentage of overweight trucks in the entire truck traffic stream.

B. Estimate the Traffic Impairment Effect (TIE) of overweight truck operations using the concept of highway capacity.

As explained before, overweight trucks (GVW > 80,000 lbs.) have reduced maneuverability and inferior acceleration/deceleration capabilities that caused them to have lower running speeds that ultimately make them consume more highway capacity than legal-weight trucks (GVW ≤ 80,000 lbs.).

$$TIE = N_{TT} \times P_{OW} \times \frac{PCE_{OW} - PCE_N}{PCE_N} \quad \text{(Equation 3.13)}$$

Where,

N_{TT}: total number of legal weight trucks plus the number of OW trucks, trucks/day.
P_{OW}: percentage of overweight trucks in the entire truck traffic stream.
PCE_{OW}: passenger car equivalent of overweight trucks.
PCE_N: passenger car equivalent of normal (legal weight) trucks.

- Step 5: Considering the TRE and the TIE, compute the net total equivalent number of legal-weight trucks (NE_T).

A. Verify whether the safety performance functions being used in Step 1 include any variable for representing the volume of trucks, if so, calculate the NE_T using (Equation 3.14; otherwise move on to the following step.

$$NE_T = N_{TT} + TIE - TRE \quad \text{(Equation 3.14)}$$

Where,

NE_T: net total equivalent number of legal weight trucks, trucks/day.
N_{TT}: total number of legal weight trucks plus the number of OW trucks, trucks/day.
TIE: traffic impairment effect, trucks/day.
TRE: trip reduction effect, trucks/day.

B. If none of the variables in the safety performance function is representing trucks, convert the NE_T into equivalent number of autos by using PCE_N values.

$$NE_A = NE_T \times PCE_N \quad \text{(Equation 3.15)}$$

Where,

NE_A: net total equivalent number of autos, autos/day.
NE_T: net total equivalent number of legal weight trucks, trucks/day.
PCE_N: passenger car equivalent of normal (legal weight) trucks.

- Step 6: Calculate the expected number of crashes on the highway due to overweight truck operations ($C_{fatal,\ OW}$, $C_{injury,\ OW}$, $C_{PDO,\ OW}$) using either the net total equivalent number of legal trucks (NE_T) or autos (NE_A) in the safety performance functions.
- Step 7: Calculate the % change in crash frequency along the route caused by overweight vehicle operations for each crash severity (Equation 3.16).

$$\Delta C = \frac{C_{OW} - C_{base\ case}}{C_{base\ case}} \times 100 \qquad \text{(Equation 3.16)}$$

Where,

ΔC: change of crash frequency with and without overweight trucks consideration, %.
C_{OW}: crash frequency for the route accounting for the net effect of overweight trucks operations (from either Step 2 or Step 6), crashes/year.
$C_{base\ case}$: crash frequency for the route assuming that all trucks are legally loaded (from Step 1), crashes/year.

The procedure followed in the present study for estimating the net safety impacts of truck operations (no overweight and overweight) is presented in a flowchart in Figure 3.6.

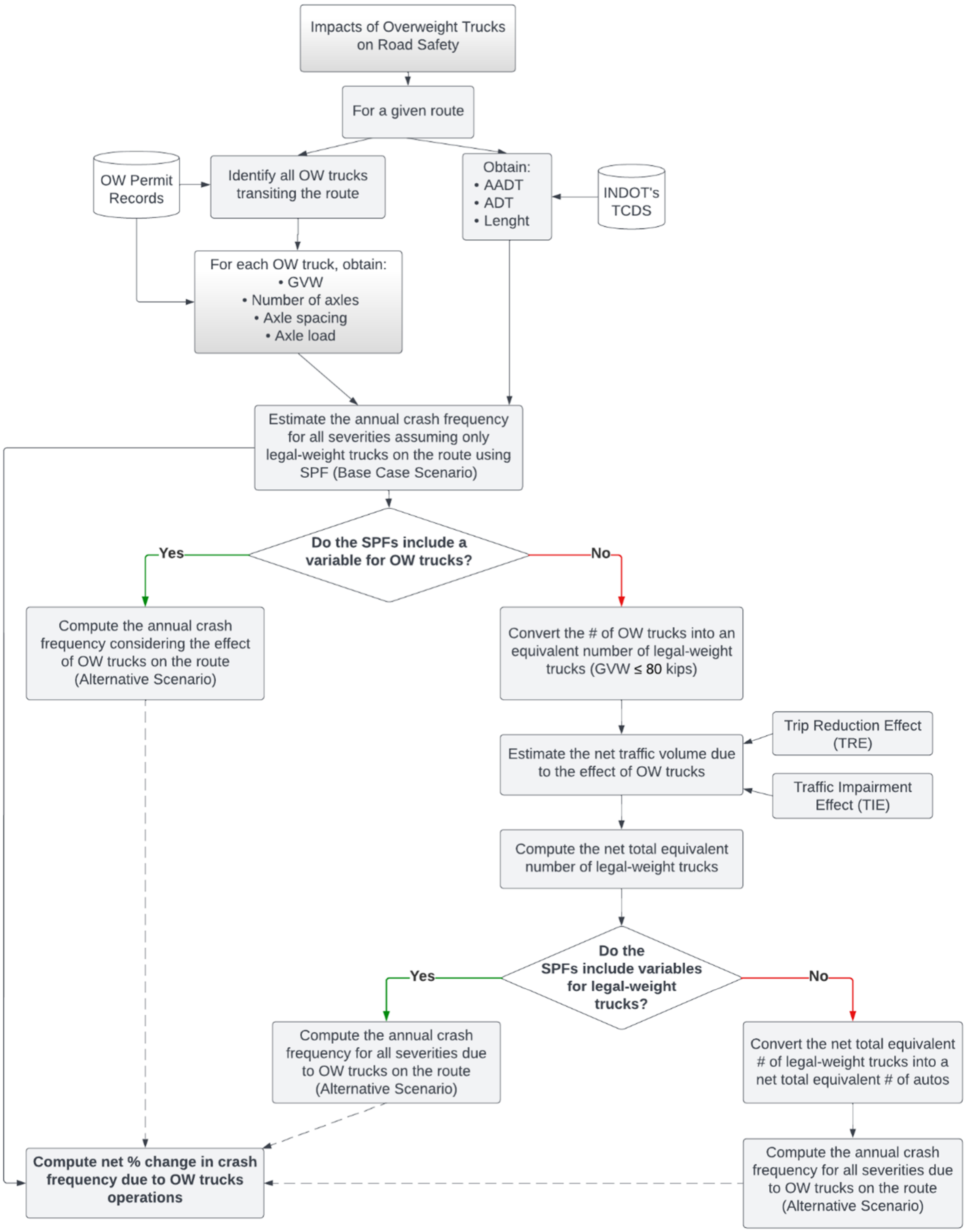


Figure 3.6. Methodology for estimating the impact of OW truck on traffic safety.
Source: Modified from the SPR-3757 report (Everett et al. 2014).

3.3.3 Mobility Impairment Assessment

Similar to safety, increases in the allowable weight limits of trucks can have opposing effects on traffic mobility. On one hand, an increase in truck weight would reduce the number of trucks on the roads, for fewer trips would be needed to move the same amount of freight, resulting in less traffic volume and thus less traffic congestion that ultimately improves the overall traffic mobility (Everett et al. 2014). On the other hand, the inferior acceleration/deceleration capabilities of heavy trucks due to the extra load being carried causes disruptions in the traffic stream that can potentially impede the efficient mobility of road users causing delays that in turn translates into loss in productivity for businesses and people in general (Aghabayk et al. 2012).

In contrast to the few research were the impacts of OW truck operations on traffic mobility were studied, the methodology proposed in the SPR-3757 report (Everett et al. 2014) considered the opposing effects of changes in policies related to overweight truck on traffic mobility (trip reduction and traffic impairment effects). Therefore, the present study adopts the same methodology for estimating the net impacts of overweight truck operations on traffic mobility.

To capture the net effect of trucks on the traffic mobility, the procedure proposed in the SPR-3757 report (Everett et al. 2014) is presented below:

- Step 1: Assuming that all trucks in the traffic stream are legally loaded (GVW ≤ 80,000 lbs.), calculate the average traffic speed on the highway segment, which will be the traffic speed for the base case scenario.

$$U_{base\ case} = \frac{V_{auto} + (N_{TT} \times PCE_N)}{k} \quad \text{(Equation 3.17)}$$

  Where

  $U_{base\ case}$: average traffic speed without the impacts of OW trucks, mph.
  V_A: number of autos, veh/h.
  k: density, veh/lane − mile.
  N_{TT}: total number of trucks, trucks/h.
  PCE_N: passenger car equivalent of normal (legal weight) trucks.

- Step 2: For the same highway segment, calculate the average traffic speed for the alternative scenario (with overweight trucks on the traffic stream) by using the net total equivalent number of legal-weight trucks (N_{ET}) previously obtained in Step 5.A of Section 3.3.2.

$$U_{OW} = \frac{V_{auto} + (NE_T \times PCE_N)}{k} \quad \text{(Equation 3.18)}$$

Where

U_{OW}: average traffic speed considering the impacts of OW trucks, mph;
V_A: number of autos, veh/h;
k: density, veh/lane − mile;
NE_T: net total equivalent number of legal weight trucks, trucks/h; and
PCE_N: passenger car equivalent of normal (legal weight) trucks.

- Step 3: For the base case scenario (only legal-weight trucks on the traffic stream) and alternative scenario (with overweight trucks on the traffic stream), calculate the average travel time using (Equation 3.19 and (Equation 3.20.

$$T_{base\ case} = \frac{L}{U_{base\ case}} \quad \text{(Equation 3.19)}$$

$$T_{OW} = \frac{L}{U_{OW}} \quad \text{(Equation 3.20)}$$

Where,

$T_{base\ case}$: travel time without OW trucks on the traffic stream, h.
T_{OW}: travel time with OW trucks on the traffic stream, h.
L: highway segment, mile.
$U_{base\ case}$: average traffic speed without the impacts of OW trucks, mph.
U_{OW}: average traffic speed considering the impacts of OW trucks, mph.

- Step 4: Compute the average percentage change in travel time caused by overweight trucks along a given route (Equation 3.21(Equation 3.18).

$$\Delta T = \frac{T_{OW} - T_{base\ case}}{T_{base\ case}} \times 100 \quad \text{(Equation 3.21)}$$

Where,

ΔT: average % change in travel time over a given route due to OW trucks.
$T_{base\ case}$: travel time without OW trucks on the traffic stream, h.
T_{OW}: travel time with OW trucks on the traffic stream, h.

The procedure followed in the present study for estimating the impacts of overweight truck operations on traffic mobility along a given route is presented in a flowchart in Figure 3.7.

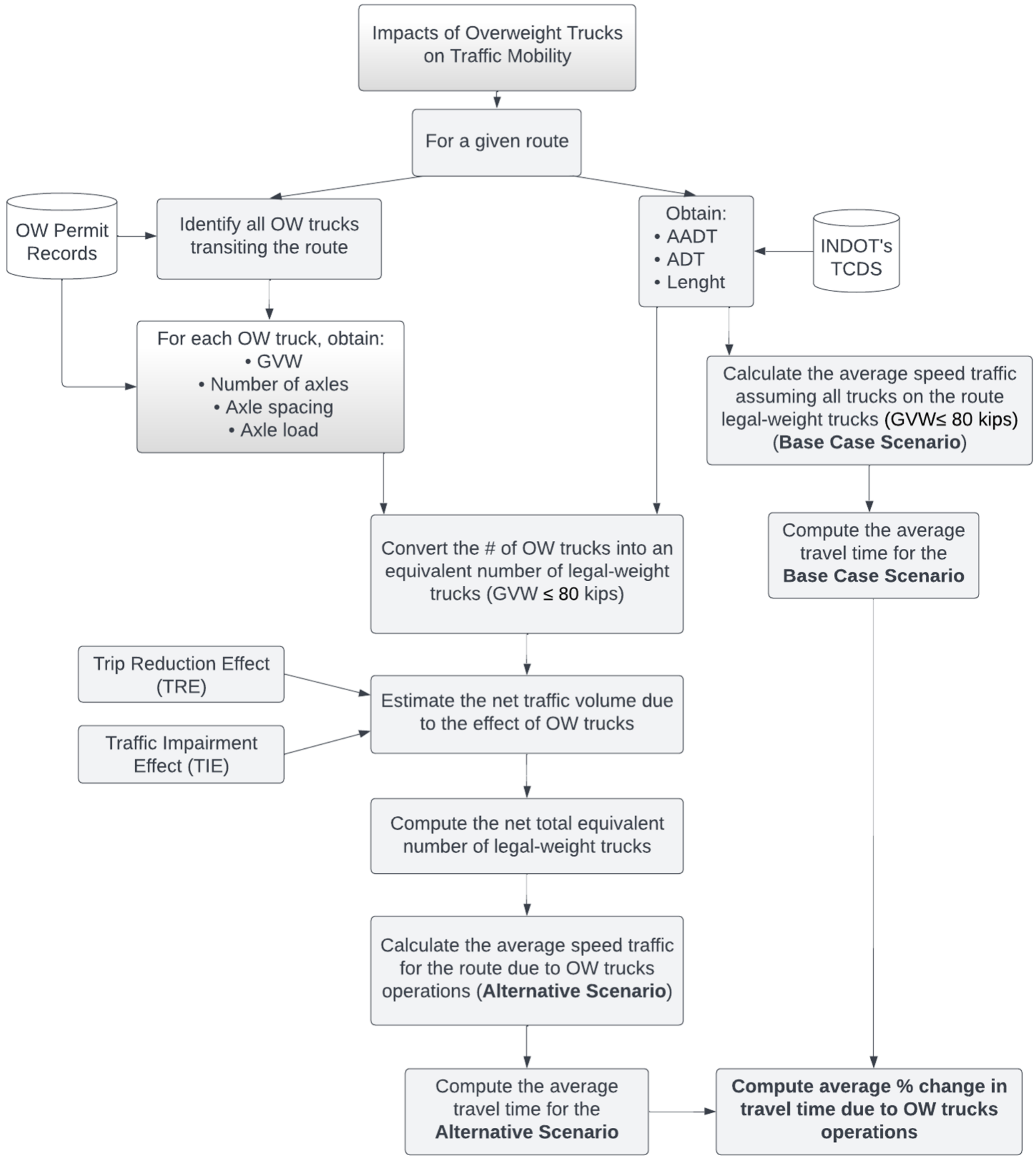


Figure 3.7. Methodology for estimating the impact of trucks on traffic mobility.
Source: Modified from the SPR-3757 report (Everett et al. 2014).

3.3.4 Overweight Truck Permitting Revenues Assessment

On a given route, records of overweight permits are needed to estimate the total revenues collected from the operation of overweight trucks. Each individual OW permit record contains information regarding the truck dimensions and weight, type of load being transported, and the route used. Based on this information, the number of permits sold by type and their actual amount charged can be extracted to estimate the total revenues collected from the sales of OW permits for a specific route and period. Figure 3.8 shows a general methodology for estimating overweight permitting revenues.

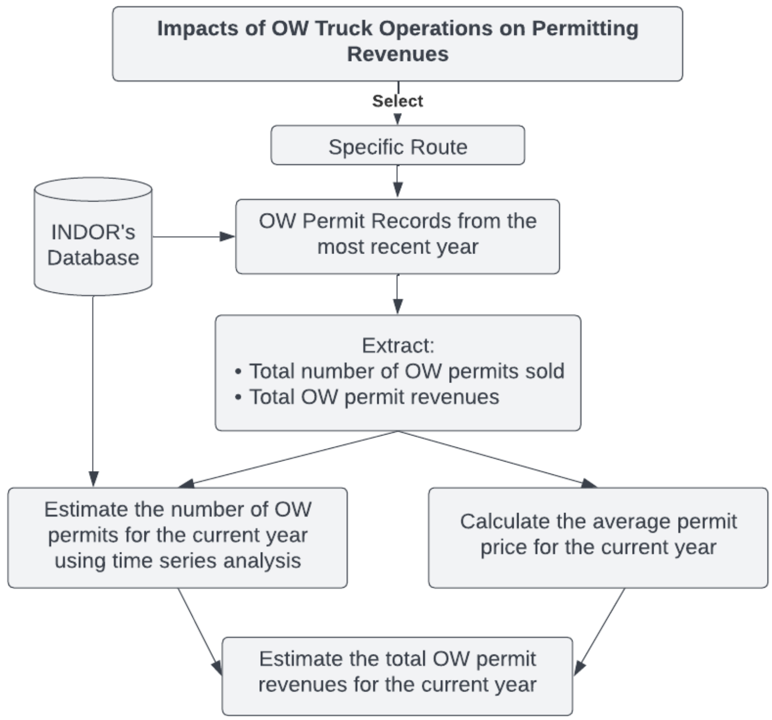


Figure 3.8. Methodology for estimating overweight permitting revenues.

3.3.5 Vehicle Operational Cost Assessment

Changes in policies regulating truck weight limits can lead to important changes in the vehicle operations costs of shippers and carriers. By allowing the movement of heavier loads, the same amount of goods can be transported with fewer trips which in turn reduces labor costs, vehicle operational costs (vehicle wear and tear, repair, fuel, etc.), and overhead costs (Luskin et al. 2000; Adams et al. 2013).

According to the American Transportation Research Institute (ATRI), the average marginal operational cost per mile of large commercial trucks was reported to be $1.24 in 2020, distributed as follows: fuel consumption cost ($0.31), maintenance and repair cost ($0.15), tire cost ($0.04), and driver's wages and fringes cost ($0.74) (Leslie and Murray 2021).

Since many factors that significantly influence the operational costs of vehicles (e.g., market price of fuel, vehicle fuel-efficiency/consumption rate, vehicle maintenance and repair costs) change over time, values of truck maintenance and repair, tires, and driver's wage and fringe from ATRI's report (Leslie and Murray 2021) will be updated to the current year using the CPI Inflation Calculator from the U.S. Bureau of Labor Statistics website (U.S. Bureau of Labor Statistics n.d.) and applied in the present study. However, because fuel prices are incredibly susceptible to any type of disruptions in the demand and supply chain, this is study opts for estimating the fuel consumption cost by utilizing current fuel price in the market and the fuel efficiency of semitrailers.

A conceptual methodology is presented below for estimating the impacts of overweight truck operations on the vehicle operational costs of the trucking industry (Figure 3.9) is presented below:

- Step 1: Estimate the total number of overweight trucks and their respective load weights. For a given route, the total number of overweight trucks and their corresponding load weights can be obtained from the OW permit records. This will yield the total number of trucks for the alternative scenario. The total load being carried constitutes the total output of the trucking industry for the base case scenario and the alternative scenario.
- Step 2: Convert each individual overweight truck into an equivalent number of legal-weight trucks with GVW = 80 kips, following the procedure described in Section 3.3.2 (Step 3A and Step 3C). This will yield the total number of trucks for the base case scenario.
- Step 3: Estimate the current average cost per mile of a large commercial truck' operator wage and fringe and calculate the total labor cost per mile for both scenarios, assuming one driver for each truck (Equation 3.22). In this study, the values of large commercial truck's operator wage and fringe from the most recent ATRI's report will be updated for inflation to the current year.

$$\text{Labor Cost}\left[\frac{\$}{\text{mile}}\right] = \text{operator wage}\left[\frac{\$}{\text{driver-mile}}\right] + \text{fringe}\left[\frac{\$}{\text{driver-mile}}\right]\Bigg\} \times \text{N. of drivers} \quad \text{(Equation 3.22)}$$

- Step 4: Estimate the fuel consumption cost for both scenarios using the fuel consumption of a truck and the fuel price (Equation 3.23). Since the 5-axle tractor semitrailer (also known as 18-wheeler) is the most common commercial truck in the United States (TRB 2003), this study found reasonable the use of the fuel efficiency of an average 5-axle semitrailer truck in the calculations of the fuel consumption cost. The fuel efficiency of an average 5-axle tractor semitrailer is about 5.5 miles per gallon of diesel (Top Mark Funfing. LLC 2020).

$$\text{Fuel Consumption Cost}\left[\frac{\$}{\text{mile}}\right] = \frac{\text{fuel price}\left[\frac{\$}{\text{gallon}}\right]}{\text{truck fuel efficiency}\left[\frac{\text{mile}}{\text{truck-gallon}}\right]} \times \text{N. of trucks} \qquad \text{(Equation 3.23)}$$

- Step 5: Estimate the truck tire (Equation 3.24) and maintenance and repair (M&R) (Equation 3.25) costs for both scenarios. In this step, the present study updated the values of truck's tires and maintenance & repair costs from the most recent ATRI's report and applied in the calculations.

$$\text{Truck Tire Cost}\left[\frac{\$}{\text{mile}}\right] = \text{tire cost}\left[\frac{\$}{\text{truck-mile}}\right] \times \text{N. of trucks} \qquad \text{(Equation 3.24)}$$

$$\text{Truck Maintenance \& Repair Cost}\left[\frac{\$}{\text{mile}}\right] = \text{M\&R cost}\left[\frac{\$}{\text{truck-mile}}\right] \times \text{N. of trucks} \qquad \text{(Equation 3.25)}$$

- Step 6: For each scenario, estimate the total input of the trucking industry by summing up all the operational costs previously obtained from Step 3 to Step 5 ((Equation 3.26).

$$\text{VOC}\ [\$] = (\text{Labor} + \text{Fuel Consumption} + \text{Tire} + \text{M\&R}) \times \text{Road Lenght} \qquad \text{(Equation 3.26)}$$

- Step 7: Calculate the percentage change in carriers and shippers' vehicle operational costs using (Equation 3.27.

$$\Delta\text{VOC}\ [\%] = \frac{\text{VOC}_{\text{OW}} - \text{VOC}_{\text{base case}}}{\text{VOC}_{\text{base case}}} \times 100 \qquad \text{(Equation 3.27)}$$

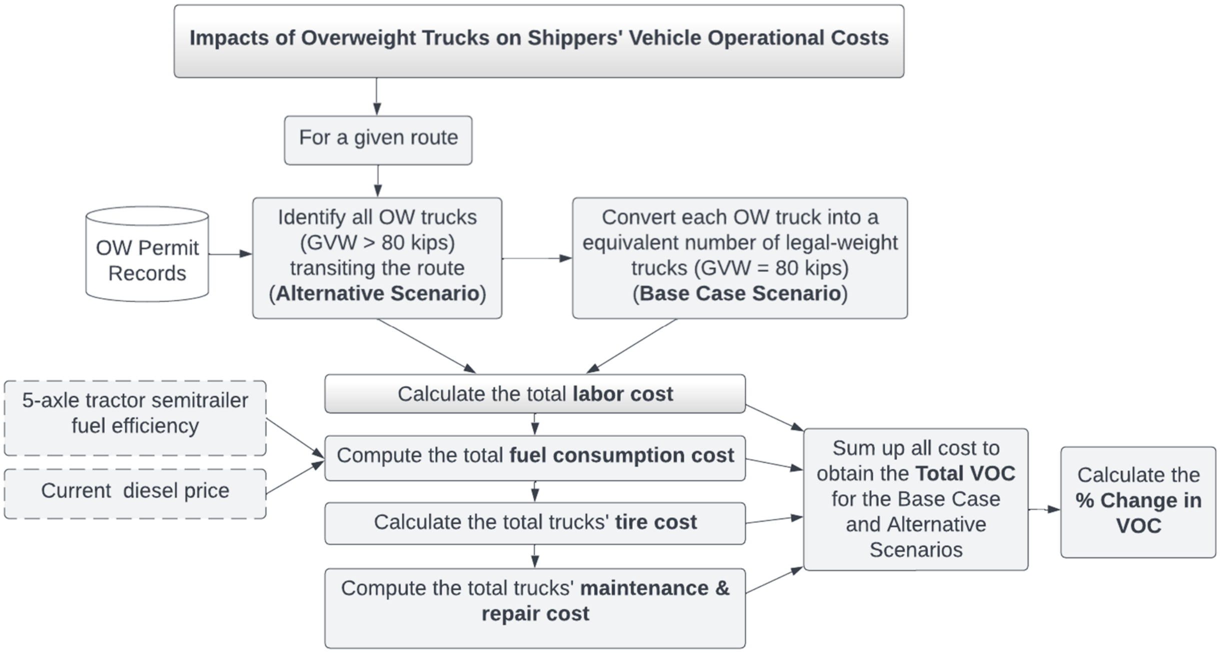


Figure 3.9. Methodology for estimating the impacts of OW truck operations on the vehicle operational costs.

3.3.6 Shipping Inventory Cost Assessment

To assess the impacts of overweight permitting policies on shipping inventory costs, the following procedure can be used:

- Step 1: Estimate the shipping inventory costs for the base case and alternative scenarios.

To estimate the shipping inventory cost per truck-mile, the hourly interest rate (r), value of the cargo (P_{cargo}), and the travel speed of the vehicle (S) are variables that need to be considered in the analysis (AASHTO 2003).

$$I = 100 \times \frac{r}{8760} \times \frac{1}{S} \times P_{cargo} \qquad \text{(Equation 3.28)}$$

Where,

I: inventory costs, cents/veh − mi.
r: annual interest rate, %.
P_{cargo}: value of the cargo, $.
S: speed of the truck, mi/h.

The value of cargo can be obtained using the estimates of FHWA's Freight Analysis Framework (National Transportation Reserach Center 2022) presented in Table 2.6. The speed of the truck can be calculated as described in Steps 1 and 2 of Section 3.3.3.

- Step 2: Calculate the percentage change in shipping inventory costs.

$$\Delta I = \frac{I_{OW} - I_{base\ case}}{I_{base\ case}} \times 100 \quad \text{(Equation 3.29)}$$

ΔI: percentage change in shipping inventory costs, %.
$I_{base\ case}$: shipping inventory cost without OW trucks on the traffic stream, $.
I_{OW}: shipping inventory cost with OW trucks on the traffic stream, $.

3.4 Weighting of Performance Criteria

One of the key steps in the MCDA includes the assignment of weights to the different performance measures to reflect their relative importance from the perspective of the decision-makers. The assignment of weights to the multiple criteria assists decision-makers in evaluating the different transportation alternatives in terms of their performance with respect to the selected criteria for meeting the specified goals and objectives. Moreover, the use of weights facilitates the decision-making process by assisting decision-makers in trade-off analysis, especially when conflicting criteria are considered, to determine the extent to which one performance criterion might be exchanged for another (Sinha et al. 2009).

Different weighting techniques or even slight changes to the weight distributions can significantly influence the outcome. A description of some common weighting techniques used in the MCDA is presented below.

3.4.1 Equal Weighting

Under the equal weighting approach, all performance measures are assigned the same weight, and the sum of all weights should be equal to one (Dawes and Corrigan 1974). This is mathematically represented in (Equation 3.30) and (Equation 3.31.

$$w_i = \frac{1}{n} \quad \text{(Equation 3.30)}$$

$$\sum_{i=1} w_i = 1 \quad \text{(Equation 3.31)}$$

Where

w_i: weight assigned to each performance measure.
n: number of performance measures.

Equal weighting is the simplest weighting approach. However, because all performance measures are assigned the same weight, this approach does not reflect the relative importance among the criteria. The equal weighting technique can be applied when there is no information about the weights of the performance measurements.

3.4.2 Direct Weighting

Decision-makers directly assign numerical weight values to the performance criteria under the Direct Weighting method (Dodgson et al. 2009). There are two approaches for the direct weighting:

- Point Allocation. The performance criteria are given a certain number of points (e.g., 100) based on how important they are. This is mathematically represented in (Equation 3.32 and (Equation 3.33.

$$w_i = \frac{p_i}{100} \quad \text{(Equation 3.32)}$$

$$\sum_{i=1} w_i = 1 \quad \text{(Equation 3.33)}$$

Where

w_i: weight assigned to each performance measure.
p_i: allocated points assigned to each performance measure.
n: number of performance measures.

The decision-makers may globally assign particular weights within a range with ends that denote the lowest and highest levels of importance (i.e., global assignment), or they may allocate points locally, where the performance criteria are first placed into categories and then weights are assigned to each category, and then those weights are further assigned to criteria within each category (i.e., local assignment).

- Ranking. The performance criteria are decreasingly ordered according to the perceived importance by decision makers.

Among these two methods, point allocation is often favored over ranking because it produces a cardinal scale of importance rather than an ordinal one. Cardinality is a helpful feature because it provides a more meaningful sense of the relative relevance of the criteria. Moreover, when there are several criteria, the local method of the point allocation strategy is especially helpful.

3.4.3 Swing Weighting Method

Steps in the swinging weighting method include (Goicoechea et al. 1982): 1) assume that all performance measures are at their worst values; 2) amongst the performance measures, select the preferred criterion that yield the best outcome while maintaining the other performance measures the same (at their worst values)and repeat these steps for all the remaining performance measures, 3) assign the highest weight of a defined scale (e.g., 100-point scale) to the most important performance measure, and 4) assign proportional weights to the remaining performances measures according to their rank of importance.

$$w_i = \frac{r_i}{\sum_{j=1} r_i} \quad \text{(Equation 3.34)}$$

$$\sum_{i=1} w_i = 1 \quad \text{(Equation 3.35)}$$

Where

w_i: weight assigned to each performance measure.
r_i: ratings assigned to each performance measure.
n: number of performance measures.

3.4.4 Analytical Hierarchy Process (AHP)

Analytical Hierarchy Process (AHP) is a common tool for performing pairwise comparison in the weight assigning process of the performance criteria. AHP allows decision makers to weigh objective and subjective factors when determining the relative relevance of each performance criterion (Saaty 1977). Decision-makers can make use of AHP to create weights that naturally and intuitively reflect their experience and expertise. In AHP, complex structures that represent performance criteria are arranged in hierarchical clusters to make it easier to compare the criteria in pairs at different levels of the hierarchy and calculate their respective weights. The Pairwise comparisons between two performance criteria i and j can be represented using the following matrix (Equation 3.36):

$$Z = \begin{bmatrix} 1 & z_{12} & \dots & z_1 \\ 1/z_{12} & 1 & \cdots & z_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1/z_1 & 1/z_2 & \cdots & 1 \end{bmatrix} \qquad \text{(Equation 3.36)}$$

Where

z_{ij}: relative importance between performance criteria i and j.
n: number of performance measures.

Each entry Zij in the matrix represents decision-makers' quantified judgement of the relative importance of two criteria i and j using a scale of 1 to 9 (Table 3.2) that shows the relative importance of each pair of performance measures.

Table 3.2. Ratios for Pairwise Comparison Matrix

Comparison	X/Y Ratio
Criterion X is extremely more important than criterion Y	9
Criterion X is strongly more important than criterion Y	7
Criterion X is moderately more important than criterion Y	5
Criterion X is slightly more important than criterion Y	3
Criterion X is equally important than criterion Y	1
Criterion X is slightly less important than criterion Y	1/3
Criterion X is moderately less important than criterion Y	1/5
Criterion X is strongly less important than criterion Y	1/7
Criterion X is extremely less important than criterion Y	1/9

Source: Sinha and Labi (2007)

3.4.5 Delphi Technique

The Delphi technique is a group decision-making tool that combines the assessment of experts for reaching consensus, resulting in a more holistic final assessment (Dalkey and Helmer 1963). The Delphi technique is a strategy used to refine the weight obtained from other methods and to reduce the variance of the weights assigned by allowing the respondents to review their responses. Initially, the set of survey are analyzed, summarized, and presented to the respondents. Then, based on difference between their individual responses and the summary statistic, the weights originally assigned can be adjustment if needed. This process is repeated until no significant differences in the score between two successive iterations.

3.5 Scaling of Performance Criteria

Scaling is another key component of the multi-criteria evaluation. It consists of establishing a common and dimensionless unit or scale of measurement that allows all performance criteria to be expressed in the same units (e.g., 0 to 100) to enable comparison of the performance criteria, making it easier for decision-makers to evaluate and combine various effects to yield the overall desirability of each alternative.

Two scenarios can be expected in the evaluation of any project, the certainty scenario, and the risk scenario. When a decision is being made under a certainty scenario, the value function technique is employed; however, when a risk scenario is being considered, the utility function approach is used (Sinha and Labi 2007).

Figure 3.10 shows these scenarios and their various scaling methods.

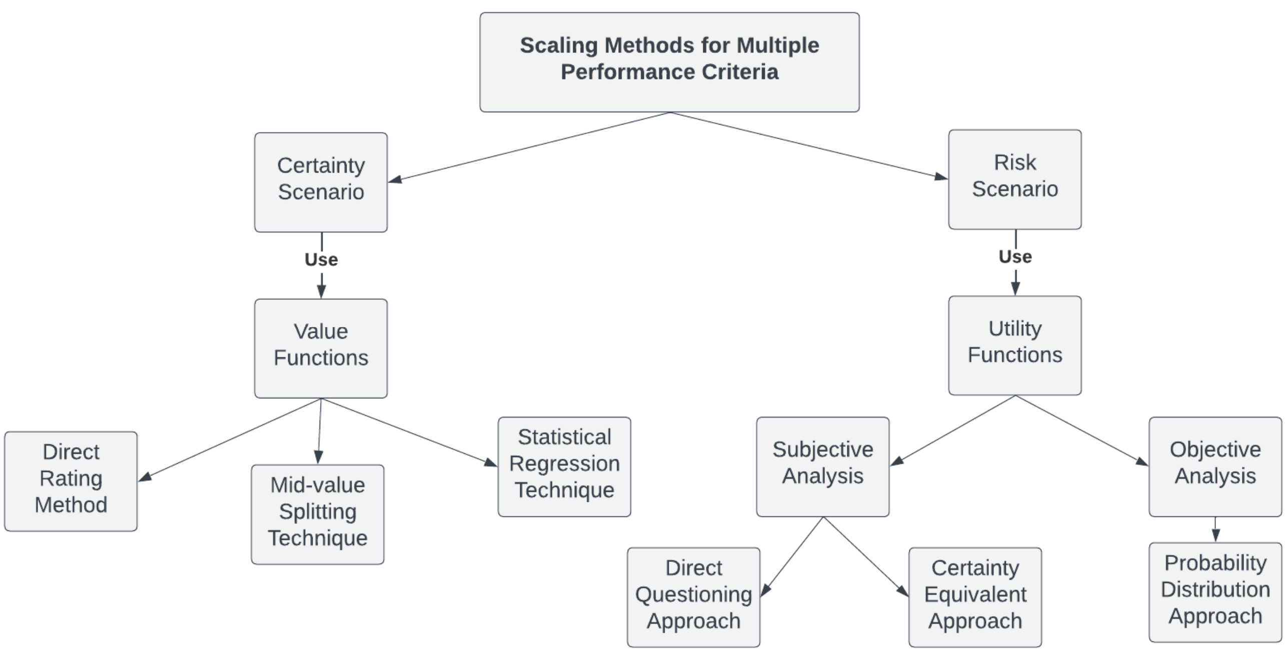


Figure 3.10. Scaling methods.
Source: Sinha and Labi (2007).

3.5.1 Scaling in Situations Where Decisions are Made Under Certainty

A value function is a scalar index of the preferences of the decision makers that captures the values they associate to each level of a performance measure (Sinha and Labi 2007). In other words, a value function, which can be linear or nonlinear, is a mathematical description of the decision makers' preference structure. Some techniques that can be used to develop value functions for a performance measure are described below:

- Direct Rating Method. The direct rating method is a straightforward technique that frequently entails surveys in order to produce value functions by asking decision makers to directly assign the values they associate to each level of a particular performance measure (Hobbs and Meier 2000). For performance criteria with a small number of discrete levels, the direct rating method has been proven to be helpful for the development of value functions. The procedure of direct rating is described by Bai and Labi (2012) as follows:

  Step 1: For each performance criterion, state all its possible outcomes. For instance, a performance measure named X, its outcomes will be $x_1, x_2, \dots, x$;

  Step 2: Set x_0 as the notation for the least preferred outcome of performance criterion X and $v_{(x_0)} = 0$ as its corresponding value function;

  Step 3: Set x as the notation for the most preferred outcome of performance criterion X and $v_{(x_n)} = 1$ as its corresponding value function;

  Step 4: For intermediate outcomes of performance criterion X (between x_0 and x), directly assign different values to the value function $v_{(x_i)}$ of the performance measure x_i;

  Step 5: For each performance criteria (e.g., X), state all its outcomes and its matching scaling value.

  Step 6: Check for consistency.

- Mid-value Splitting Technique. This technique requires a survey in which decision-makers are asked about their "indifference" to changes in levels of a performance measure (Keeney and Raiffa 1976). In order to determine points on the value function curve, the mid-value splitting technique finds the attribute level whose value is midway between two known attribute values. This technique is especially suitable for criteria that have a wide range of possible levels. The procedure for developing a value function based on the concept of mid-value splitting technique proposed by Bai and Labi (2012) is described below:

Step 1: Find the range of outcomes of performance measure X, and set $u_{X_{(x_0)}} = 0$ and $u_{X_{(x_1)}} = 1$, for the least preferred outcome x_0 and the most preferred outcome x_1, respectively;

Step 2: Establish the mid-value point between x_0 and x_1, and designate it as $x_{0.5}$ and set its value function ($u_{X_{(x_{0.5})}}$) as 0.5;

Step 3: Establish the mid-value point between x_0 and $x_{0.5}$, and designate it as $x_{0.25}$ and set its value function ($u_{X_{(x_{0.25})}}$) as 0.25;

Step 4: Establish the mid-value point of between$x_{0.5}$ and x_1, and designate it as $x_{0.75}$ and set its value function ($u_{X_{(x_{0.75})}}$) as 0.75;

Step 5: Verify that all the mid-value points are consistent; otherwise repeat steps 2 to 4; and

Step 6: Graph the value function curve of performance measure X using the set of points $\left[x_i, u_{X\,(x_i)}\right]$.

- Regression Analysis Method. Regression analysis can be used to find a global function that best represents the aggregated scaling preference orders of a large number of respondents. To do this, all data points from each decision-makers are gathered, and the replies are regressed to find the function that deviates the least from the responses. The functional form of the value function can be linear, convex, concave, S-shaped, etc.

3.5.2 Scaling in Situations Where Decisions are Made Under Risk

While the idea behind scaling is the creation of a suitable scale to accurately reflect the levels of the performance criteria accrued by a transportation action, the reality is that in most cases, the level of these outcomes cannot be precisely foreseen. Hence, it is indispensable for transportation agencies to incorporate the concepts of risk and uncertainty in scaling the performance measures.

In a risk scenario, the range and distribution of potential outcomes are known. Risk can be either subjective or objective. Unlike objective risk, which is based on theory, experiment, or observation, subjective risk is determined by one's own perceptions.

Utility functions are commonly used in the literature for considering the subjective risk factor in the scaling process of performance measures (Sinha and Labi 2007). A utility function offers a scale that displays the preferences of the decision-makers for various levels of a given performance criteria. Because it reflects the decision-makers' risky preferences for each performance criteria, the utility function can be thought of as a generalized version of the value function in this regard.

Techniques for developing utility functions in cases of subjective and objective risk are briefly described below.

- *Techniques for Developing Subjective-Risk Utility Functions*

Techniques that incorporate subjective risk factors into the analysis generally involve a survey of decision-makers to develop the utility functions. These techniques are described below:

A. Direct Questioning Technique.

Depending on whether the variable representing the performance criteria is discrete or continuous, there are two approaches for this method (Keeney and Raiffa 1976).

i. Discrete variable.

For those performance criteria that are represented by relatively few discrete variables, the following procedure proposed by Bai and Labi (2012) is presented below:

Step 1: For each performance criterion, state all its possible outcomes. For instance, a performance measure named X, its outcomes will be $x_1, x_2, \dots, x$;

Step 2: Set utilities for the least preferred outcome (x_0) and most preferred outcome (x_1) as $u_{X_{(x_0)}} = 0$ and $u_{X_{(x_1)}} = 1$, respectively to create the utility function for performance measure X;

Step 3: Find the probability (p_i) for each possible outcome (x_i) to contrast the following situations:

- A guaranteed prospect of an outcome x_i;
- A risk prospect of getting an outcome of x_b and x_w with probability p_i and $1 - p_i$, respectively;

Step 4: Use (Equation 3.37 to compute the utility of x_i

$$u(x_i) = p_i u(x_b) + (1 - p_i) u(x_w) \qquad \text{(Equation 3.37)}$$

Step 5: Compute the utilities of all remaining levels of the performance measure using step 3 and step 4;

Step 6: Verify that the values are consistent. Then, select any three levels of the performance measure and denote them as x_1, x_2, and x_3. Lastly, evaluate the following two situations:

- A guaranteed prospect of an outcome x_2;
- A risk prospect of obtaining an outcome of x_1 and x_3 with probability p and probability $1 - p_1$, respectively;

If the aforementioned two situations are viewed by the decision-maker as indifferent, p should be equal to (Equation 3.38.

$$p = \frac{u_{(x_2)} - u_{(x_3)}}{u_{(x_1)} - u_{(x_3)}} \qquad \text{(Equation 3.38)}$$

ii. Continuous variable

Since there are an endless number of possible levels for a continuous performance measure, the task of establishing utilities for all of those levels is impossible. In these situations, the continuum is broken down into a number of discrete levels to properly depict its spread. Then a survey is conducted to ascertain the utilities of these discrete values. Following are the specific steps proposed by Bai and Labi (2012):

Step 1: For each performance criterion, state all its possible outcomes. For instance, a performance measure named X, its outcomes will be $x_1, x_2, \dots, x$;

Step 2: Set utilities for the least preferred outcome (x_w) and most preferred outcome (x_b) as $u_{(x_w)} = 0$ and $u_{(x_b)} = 1$, respectively to create the utility function for the performance measure X;

Step 3: Evaluate the following situations:

- A guaranteed prospect of an outcome $X = 0.5(x_b - x_w)$;
- A risk prospect of getting an outcome of x_b and x_w with probability p and $1 - p$, respectively;

This is to ascertain the probability p that makes the aforementioned situations indifferent. Then p is $p_{0.5}$;

Step 4: Setting the guaranteed prospect as $0.25(x_b - x_w)$ and $0.75(x_b - x_w)$ and repeat step 3 to obtain $p_{0.25}$ and $p_{0.75}$;

Step 5: Check that the values are consistent. Evaluate the following two situations:

- A guaranteed prospect of an outcome $X = 0.5(x_b - x_w)$;
- A risk prospect of obtaining an outcome of $0.25(x_b - x_w)$ and $0.75(x_b - x_w)$ with probability p and $(1 - p)$, respectively;

This is to ascertain the probability p that makes the aforementioned situations indifferent;

- If $p = \frac{p_{0.5} - p_{0.25}}{p_{0.75} - p_{0.25}}$, move on to the next step; otherwise, go back to Step 3;

Step 6: Graph the following set of points $(x_w, 0)$, $(0.25(x_b - x_w), p_{0.25})$, $(0.5(x_b - x_w), p_{0.5})$, $(0.75(x_b - x_w), p_{0.75})$, and $(x_b, 1)$. Next, obtain the utility function using statistical regression.

When there are several survey respondents, additional regression can be employed to find the best fit for all observations. This consequently improves the scaling function further.

B. Certainty Equivalency Approach.

According to the literature (Keeney and Raiffa 1976), this approach seems to be the most widely used method for creating utility functions under the risk scenario. The steps listed below are used to create the utility function for a performance metric X (Bai and Labi 2012):

Step 1: Set utilities for the least preferred outcome (x_w) and most preferred outcome (x_b) as $u_{(x_w)} = 0$ and $u_{(x_b)} = 1$, respectively to create the utility function for the performance measure X;

Step 2: Evaluate the following situations:

- A guaranteed prospect of an outcome $x_{0.5}$;
- A risk prospect of obtaining an outcome of x_w and x_b, each with a probability of 50%;

Estimate $x_{0.5}$ that makes the aforementioned situations indifferent;

Step 3: Set the guaranteed prospect as $x_{0.25}$ and $x_{0.75}$ and repeat step 2 to obtain $p_{0.25}$ and $p_{0.75}$;

Step 4: Verify that the values are consistent. Evaluate the following two situations:

- A guaranteed prospect of an outcome $x_{0.5}$;
- A risk prospect of obtaining an outcome of $x_{0.25}$ and $x_{0.75}$, each with a probability of 50%;

Move on to the next step if the decision-makers consider the above situations to be equally important; otherwise, go back to step 2;

Step 5: Graph the following set of points $(x_w, 0)$, $(x_{0.25}, 0.25)$, $(x_{0.5}, 0.5)$, $(x_{0.75}, 0.75)$, and $(x_b, 1)$. Then select the utility function form to use and calibrate the parameters of the function.

- *Techniques for Developing Objective-Risk Utility Functions*

A. Probability Distributions.

To objectively account for the uncertainties of the effects of a transportation action on a particular performance criterion, the *expected utility value* can be employed. By assuming a probability distribution function (p.d.f.) of the potential outcomes, the expected utility value can be computed (Sinha and Labi 2007).

The expected utility value for a given probability that a particular outcome for a specific performance criterion will occur can be estimated as follows (Sinha and Labi 2007):

$$E[u_{(X)}] = \begin{cases} \sum_{x=mi}^{max} u_{(x)} P_{(X=x)}, & \text{when the p.d.f. is discrete} \quad \text{(Equation 3.39)} \\ \int_{mi}^{max} u_{(x)} f_{(x \backslash mi \ < x < x \backslash max) dx}, & \text{when the p.d.f. is continuous} \quad \text{(Equation 3.40)} \end{cases}$$

Where

$u_{(x)}$: utility function for the outcome level corresponding to performance criterion X.
P: probability of occurrence of a given outcome.
X: performance criterion.

The selection of the probability distribution that best fit the possible outcomes of a performance criterion will depend on the performance criterion in regard. Performance criteria that are represented by discrete variables with a small range of outcomes such as crash severity, deck condition, and traffic level of service, the binomial distribution can be used. However, for discrete criteria with a large range of outcomes (>30), the Poisson distribution can be a better fit. For performance criteria that are represented by continuous variables spread over a given range such as agency costs, travel time, emissions, the Beta distribution can be used to consider the degree of skewness and kurtosis of the possible outcomes of the performance criterion in regard (Sinha and Labi 2007).

3.6 Amalgamation

Once all the performance measures are scaled into a common and uniform unit, the next step is to combine them to determine the overarching outcome of an alternative. This process is known as amalgamation. To amalgamate the performance measures, several methods such as the weighted sum method, benefit/cost ratio method, the goal programming method, and the utility function method, can be used. Following, a brief description of the mentioned methods is provided next.

3.6.1 Weighted Sum Method (WSM)

A simple and easy method to combine the scaled performance measures is the weighed sum measure. However, a downside of this method is that it does not take into consideration the preference amongst the attributes. This method sums up all the individual weighted value to obtain the final value of an alternative ((Equation 3.41):

$$U_i = \sum_{j=1}^{m} w_j s_{ij}$$ (Equation 3.41)

Where,

w_j: weight of the performance measure j.
s_{ij}: scaled value of the performance measure j for alternative i.
m: number of performance measures.

Note that the highest value of U_i corresponds the best choice of that alternative. In addition, the performance measures need to be utility independent and preference independent if preference-based methods are used in the scaling of the values. Performance criteria are utility independent when each criterion does not depend on the levels of other performance criteria. In the case where the trade-offs of two performance measures do not depend on the level of other performance criteria, they are preference independent. The relative weights of each performance measures used in (Equation 3.41 can be obtained using a variety of scaling methods such as the observer-derived wights approach, direct weighing method, analytic hierarchy process (AHP) and gamble method.

3.6.2 Multiplicate Utility Function

Amalgamation can also be conducted through the use of multiplicative utility function of an alternative i as defined in (Equation 3.42:

$$U_i \frac{1}{k}([1 + kw_1 u(x_{i1})] * [1 + kw_2 u(x_{i2})] * \dots * [1 + kw_m u(x_{im})] - 1)$$ (Equation 3.42)

Where,

$u(x_{ij})$: utility of alternative i on the jth performance measure.
w_j: relative weight of performance measure j.
m: number of performance measures.
k: scaling constant, and it is defined as (Equation 3.43:

$$1 + k = (1 + k \quad _1) * (1 + k \quad _2) * \dots * (1 + k \quad _m)$$ (Equation 3.43)

In order to use this utility function, all the performance measures need to be mutually utility independent. The higher the final utility is, the better the project alternative is compared to a lesser final utility.

3.6.3 Benefit/Cost Ratio Method

This method consists of determining the benefit/cost ratio between the weighed sum of the performance measures (benefit) and the alternative cost (Equation 3.44). The greater this ratio is, the better the alternative is.

$$U_i = \frac{\sum_{j=1}^{m} \quad {}_j s_{ij}}{C_i} \qquad \text{(Equation 3.44)}$$

Where,

U_i: benefit/cost ratio of project i.
n: number of performance measures.
c_i: agency cost of implementing project i.
w_j: weight of performance measure j.
s_{ij}: scaled value of performance measure j for alternative i.

3.6.4 Goal Programming Method

The goal programming function is another amalgamation method that consist of defining goals (target levels) that need to be reached by using the distance from the goals for each alternative, which is given in (Equation 3.45.

$$U_i = \left(\sum_{j=1}^{m} (s_{ij} - M_j)^p \right)^{/p} \qquad \text{(Equation 3.45)}$$

Where,

U_i: sum of the deviation from the goals.
s_{ij}: scaled value of performance measure j for alternative i.
M_j: target value of the jth performance measure.
m: number of performance measures.

To minimize this function, different metric norms can be used. For instance, to determine the type of distance metric that is being measured, the value for the parameter p can be modified. Three most commonly used values for parameter p include $p = 1$, $p = 2$, and $p = \infty$ that correspond to the metric norms “city block” distance, “Euclidean” distance, and “Minmax” distance (or infinity norm).

3.7 Analysis of Results and Decision Making

In this last step, alternatives are compared by examining the results obtained from the MCDA. At this point, the decision-makers can better visualize the potential impacts of the alternative transportation projects in consideration, so the alternative with the highest level of desirability can be chosen.

In cases where there is not a truly dominant alternative (one that is better than all others on every criterion) and different transportation alternatives may excel in different performance criteria. The decision-maker can perform a trade-off analysis to determine how much of one criterion can be "exchanged" for a specific level of another.

3.8 Chapter Summary

The complex and wide range of criteria that are involved in transport-related decision problems makes the multi-criteria analysis one of the most appropriate methods for evaluating transportation projects (Macharis and Bernardini 2015). MCDA techniques allow the simultaneous evaluation of several alternatives through various qualitative and quantitative performance criteria to facilitate the decision-making process by the different stakeholders.

To date, MCDA techniques have been broadly used in many areas of the transportation sector, with applications on transportation projects ranging from infrastructure development projects that cover planning, design, construction, maintenance to policy measures design, evaluation, and implementation.

Steps in a MCDA include establishment of the decision context, identification of alternatives, identification of performance criteria, assignment of criteria’s weights, definition of criteria’s scales, and amalgamation. A general description of each of these steps along with some common weighting, scaling, and amalgamating techniques found in the literature was presented.

Ultimately, a general multi-criteria decision analysis framework is developed to enable prioritization of the wide range of criteria involved in changes in policies related to OW truck operations when considering the standpoints of different stakeholders (highway agencies and trucking industry) simultaneously. The resulted framework aims to assist highway agencies in the decision-making process for evaluating the possible effects due to changes on OW truck operation policies. As a part of the framework, a review of methodologies found in the literature for evaluating the impacts of overweight truck operations on infrastructure damage, traffic mobility, road safety, OW permitting revenues, and trucking economic productivity were presented to assist in the decision-making process.

4. CASE STUDY AT THE CORRIDOR LEVEL

To validate the methodology proposed in this study, the resulted multi-criteria decision analysis framework is applied to the Interstate 70 (I-70), a highway corridor with some of the highest overweight truck traffic in the state of Indiana (Figure 4.1). The I-70, with a total length of 156.6 miles, travels from east to west across the state of Indiana, passing through Indianapolis (Wikipedia 2022a).

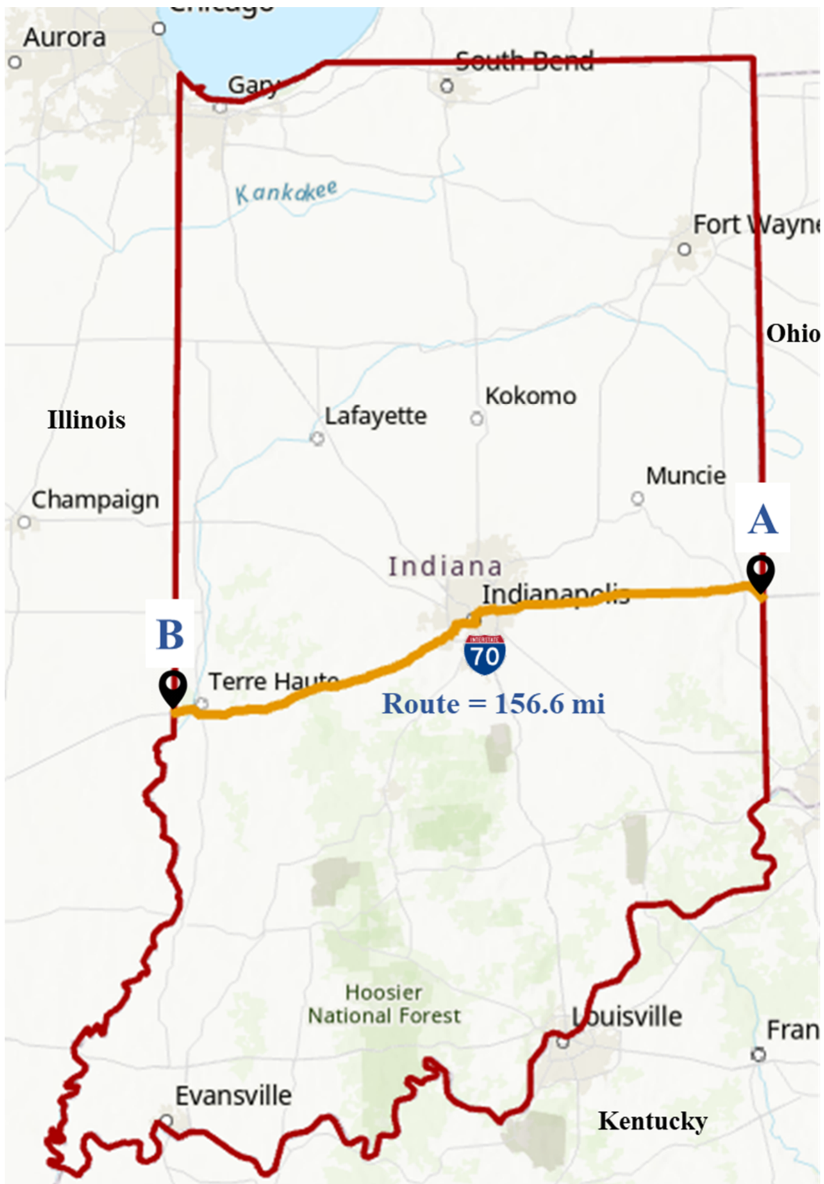


Figure 4.1. Indiana map with route I-70.

Due to the lack of specific data regarding overweight permit records, this study uses a slightly different approach for estimating the impacts of overweight truck operations on infrastructure, road safety, traffic mobility, overweight permitting revenues, vehicle operational costs, and shipping inventory costs. The analysis considers a total load of 339.8 million pounds that need to be transported from point A to point B on the I-70 (Figure 4.1) and compare the impacts of transporting this total load using legal weight-trucks only (GVW = 80,000 lbs.) and overloading some of the trucks (GVW = 100,000 lbs.), assuming that these trucks operate 7 days a week (365 trips a year).

4.1 Decision Context

When analyzing the potential impacts of changes in policies regarding overweight truck operations, two different groups of stakeholders are involved. On one hand, we have the transportation agencies, responsible for the maintenance and preservation of the highway system, representing the public sector. On the other hand, we have the trucking industry composed by carriers and shippers who seek to profit from their services, representing the private sector. Because the highway transportation system is owned and managed by the federal, state, and local transportation agencies, the power of decision-making fall under their responsibility. Thus, in this study the decision maker is INDOT. In the context of overweight truck permitting, INDOT's overall goals include the preservation of infrastructure assets, enhancement of the highway system operational performance, improve the safety of road users, reduction of road user costs and economic productivity promotion.

4.2 Alternatives to be Evaluated

Two scenarios are compared, a base case scenario in which the total load is being transported by legal-weight trucks (GVW = 80,000 lbs.) only and an alternative scenario in which the total load is being transported by 65% of the total number of trucks in the traffic stream being legal-weight trucks (GVW = 80,000 lbs.) and 35% being overweight trucks (GVW = 100,000 lbs.).

4.2.1 Conditions for the Base Case Scenario

Since the 5-axle tractor semitrailer (also known as 18-wheeler) is the most common commercial truck used in the United States, it is selected in this study as the operational truck for the calculations in this scenario. The 5-axle tractor semitrailer is widely utilized to transport and distribute various kinds of materials, commodities, and goods over long and short distances in both urban and rural locations (TRB 2003).

The 5-axle tractor semitrailer truck is composed of two units, a tractor or straight truck and a detachable semi-trailer. When the two units are attached, the 5-axle tractor semitrailer has 18 wheels, and weighs approximately 35,000 lbs. when it is empty (Tarradell 2020). Figure 4.2 shows the components of a standard 5-axle tractor semitrailer truck. The dimensions of a standard 5-axle semitrailer truck (WB-65) is presented in Figure 4.3.

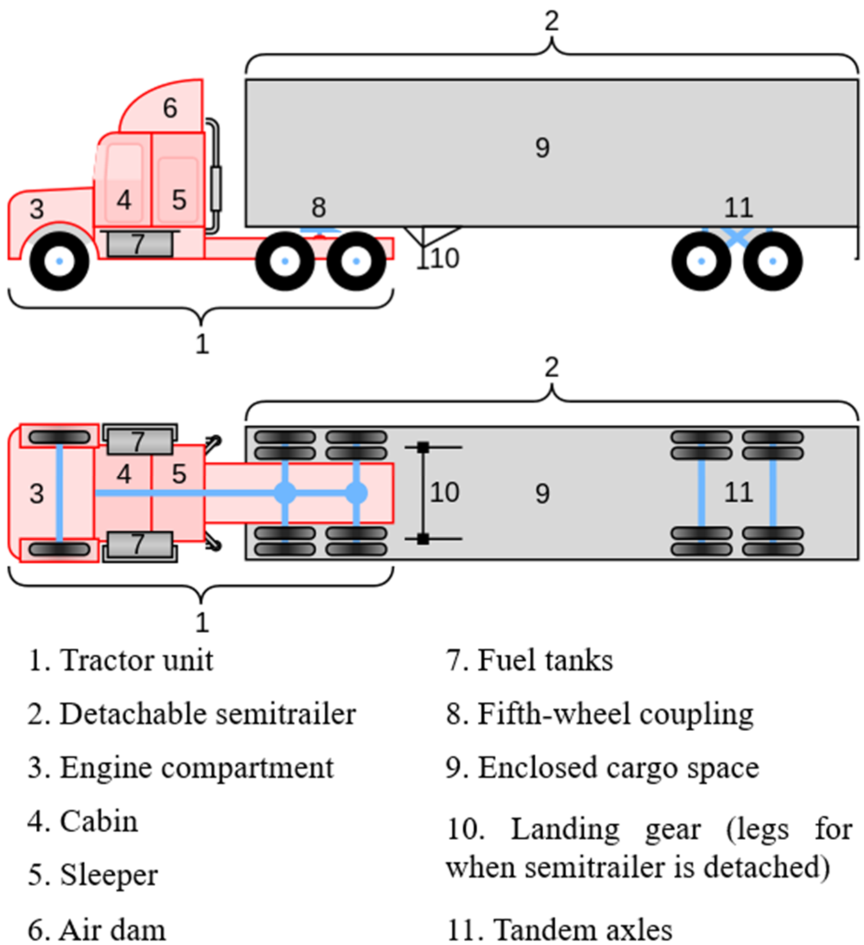


Figure 4.2. Standard 5-axle tractor semitrailer truck diagram.
Source: Wikipedia (2011).

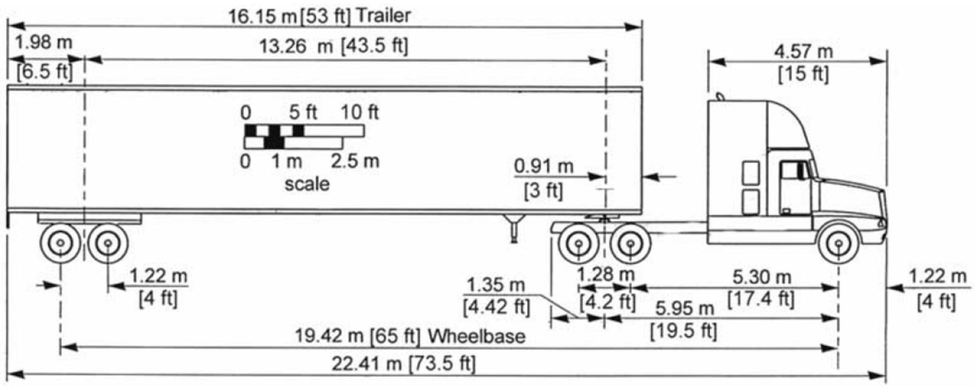


Figure 4.3. Dimensions of a standard 5-axle semitrailer truck (WB-65).
Source: Policy on Geometric Design of Highways and Streets (AASHTO 2001).

As explained in Section 1.1.2, in Indiana, trucks grossly weighting 80,000 lbs. or less are allowed to use the state's highway system without an overweight permit. However, in addition to the gross vehicle weight restriction, the state also has established axle weight limits for overweight trucks to complied with. The maximum allowable axle weight limits in the state of Indiana are 12 kips and 34 kips on a single axle and a tandem axle, respectively. Because carriers try to maximize their profits, it is assumed that carriers load their trucks as close as possible to the maximum allowable weights. Thus, for the base case scenario, the operational truck is assumed to carry the total gross weight of 80,000 lbs., distributed in 12,000 lbs. on its single axle and 34,000 lbs. on each of its tandem axles (Figure 4.4).

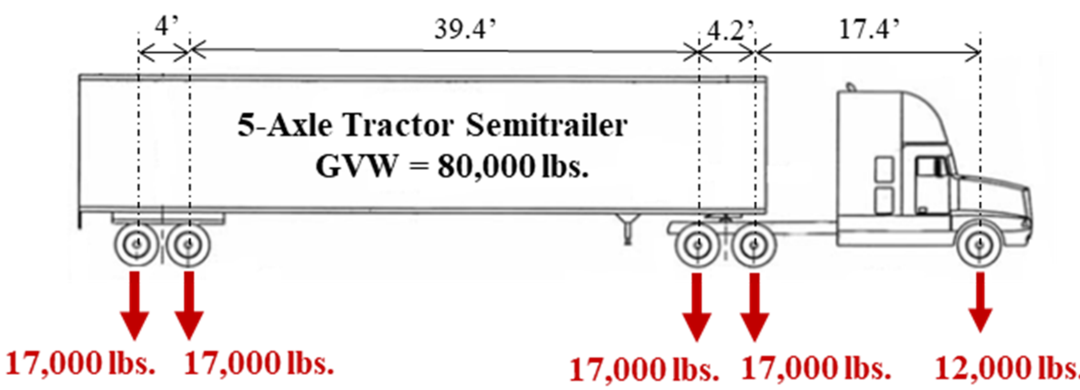


Figure 4.4. Axle weights of the legal-weight 18-wheeler truck for the Base Case Scenario.

Then the total number of legal-weight 5-axle tractor semitrailer trucks needed to transport the total load of 382,500,000 lbs. can be estimated by dividing it over the difference between the maximum allowable weight and the weight of an empty truck (30,000 lbs.) as follows:

$$\text{Number of Trucks}_{Base\ Case\ Scenario} = \frac{839{,}800{,}000 \text{ lbs}}{80{,}000 \text{ lbs } - 30{,}000 \text{ lbs}} = 16{,}796 \ \text{trucks}$$

Ultimately, the base case scenario considers 16,796 five-axle semitrailer trucks weighting 80,000 lbs. each.

4.2.2 Conditions for the Alternative Scenario

Since the alternative scenario considers that 65% of all trucks in traffic stream are loaded at 80,000 lbs. and 35% are loaded at 100,000 lbs., two truck configurations were used. For those trucks loaded at 80,000 lbs., the same 5-axle tractor semitrailer truck as in the base case scenario was used. For those trucks loaded at 100,000 lbs., a 6-axle tractor semitrailer truck was selected to reflect changes in the loading behavior of shippers and carriers due to increments of truck weight limit restrictions. Figure 4.5 shows the load distribution of the 6-axle tractor semitrailer truck (GVW = 100,000 lbs.) as follows: 14,000 lbs. on its single axle, 34,400 lbs. on its tandem axle, and 51,6000 lbs. on its tridem axle.

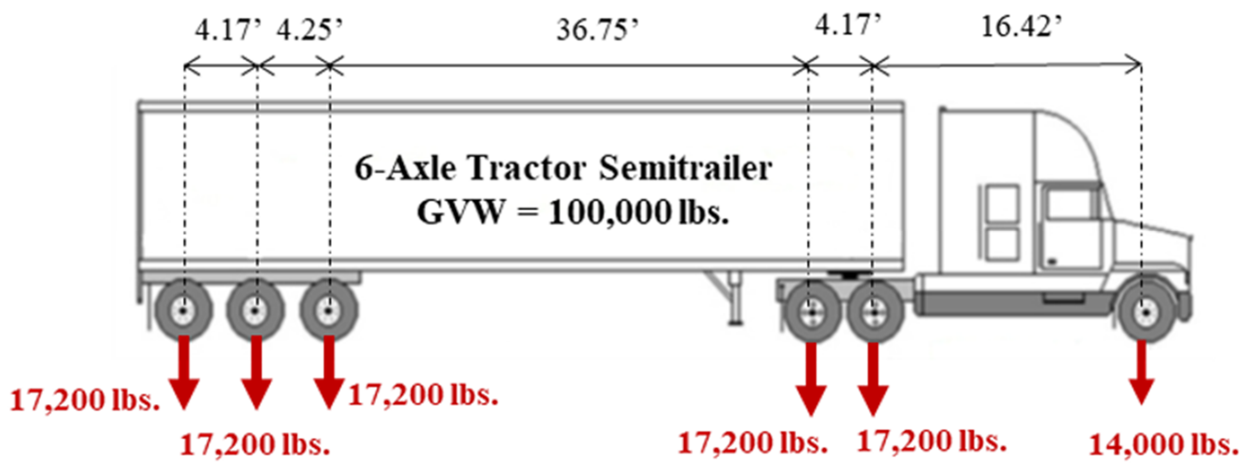


Figure 4.5. Axle weights of the overweight 6-axle semitrailer truck for the Alternative Scenario.

Then the total number of overweight 6-axle tractor semitrailer trucks needed to transport the total load of 382,500,000 lbs. can be estimated by dividing it over the difference between 100,000 lbs. and the weight of an empty truck (35,000 lbs.) as follows:

$$\text{Nr. Legal Weight Trucks}_{Alter\ \ ative\, Sce\ \ ario} = 0.65\,\frac{839{,}800{,}000\ \text{lbs}}{80{,}000\ \text{lbs}\ - 30{,}000\ \text{lbs}} = 9{,}880\ \text{trucks}$$

$$\text{Nr. OW Trucks}_{Alter\ \ ative\, Sce\ \ ario} = 0.35\,\frac{839{,}800{,}000\ \text{lbs}}{100{,}000\ \text{lbs}\ - 35{,}000\ \text{lbs}} = 5{,}320\ \text{trucks}$$

Ultimately, the alternative scenario considers a total number of 15,200 trucks in which 9,880 trucks are five-axle semitrailer trucks weighting 80,000 lbs. each and 5,320 trucks are six-axle semitrailer trucks weighting 100,000 lbs.

4.3 Performance Criteria Assessment

4.3.1 Infrastructure Damage

Rather than estimating the impact of overweight trucks on Indiana's pavement surfaces and bridges, this study adopts the unit pavement and unit bridge costs established in previous studies found in the literature. In Indiana, some relevant studies have been conducted to estimate the impacts of overweight truck operations on highway infrastructure. Among these studies, the SPR-3502 report established the unit cost of pavement and bridge consumption for overweight vehicles using practical lifecycle schedules for pavement and bridge maintenance, rehabilitation, and reconstruction (MR&R) (Ahmed et al. 2012). This study will use the unit costs established in the SPR-3502 report and apply them to quantify the impacts of overweight trucks on the pavement and bridge structures of the I-70.

A. Pavement Damage Cost

To estimate the pavement damage cost for the base case and alternative scenarios, the procedure described in Section 3.3.1. is used.

- Step 1: Assessment of Unit Cost for Pavement Damage.

For pavement assets, the researchers in the SPR-3502 report estimated the pavement unit costs for Interstates (IS), non-Interstate National Highway System (NIS-NHS), and non-National Highway System (Non-NHS) in the state of Indiana. Moreover, the authors further split the unit pavement damage costs between traffic loading (85%) and climate (15%) (Ahmed et al. 2012). Table 4.1 shows the traffic-load-related unit pavement consumption costs for the different highway functional classes.

Table 4.1. Traffic-Load-Related Unit Pavement Consumption Cost.

Highway Functional Class	Load Share of Unit Consumption Cost	
	2010 $/ESAL-mi	2022 $/ESAL-mi
Interstate	0.006	**0.010**
Non-Interstate NHS	0.055	0.088
Non-NHS	0.218	0.347
Mean	0.093	0.148

Source: SPR-3502 Report, Costs and Revenues Associated with Overweight Trucks in Indiana (Ahmed et al. 2012).

- Step 2: Compute the number of ESALs for the base case scenario (GVW = 80,000 lbs.).

In

Figure 4.4, the operational truck for the base case scenario weighs 12,000 lbs. on its single axle and 34,000 lbs. on each of its tandem axles, the number of ESALs can be obtained using (Equation 3.1.

$$\text{ESAL}_{\text{Base Case Scenario}} = \left[\frac{34{,}000\text{ lbs}}{33{,}200\text{ lbs}}\right]^4 + \left[\frac{34{,}000\text{ lbs}}{33{,}200\text{ lbs}}\right]^4 + \left[\frac{12{,}000\text{ lbs}}{18{,}000\text{ lbs}}\right]^4 = 2.4\text{ ESAL/truck}$$

Then the total ESALs for the base case scenario is estimated multiplying the total number of legal-weight trucks (GVW = 80,000 lbs.) transporting the total load of 839,800,000 lbs. on I-70 with the number of ESALs.

$$\text{Total ESAL}_{\text{Base Case Scenario}} = (16{,}796\ \text{ trucks}) \times \left(2.4\frac{\text{ESAL}}{\text{truck}}\right) = 40{,}310.4\text{ ESALs}$$

- Step 3: Compute the number of ESALs for the alternative scenario (GVW = 100,000 lbs.).

In Figure 4.5, the operational truck for the alternative scenario is assumed to weigh 14,000 lbs. on its single axle and 34,000 lbs. on each of its tandem axles, the number of ESALs can be also obtained using (Equation 3.1).

$$\text{ESAL}_{\text{Alternative Scenario}} = \left[\frac{51{,}600\text{ lbs}}{46{,}000\text{ lbs}}\right]^4 + \left[\frac{34{,}400\text{ lbs}}{33{,}200\text{ lbs}}\right]^4 + \left[\frac{14{,}000\text{ lbs}}{18{,}000\text{ lbs}}\right]^4 = 3.1\text{ ESAL/truck}$$

Then the total ESALs for the alternative scenario is estimated for the total number of trucks considered (i.e., 9,880 legal weight trucks and 5,320 OW trucks) as follows:

$$\text{Total ESAL}_{\text{Alternative Scenario}} = (9{,}880\text{ trucks}) \times \left(2.4\frac{\text{ESAL}}{\text{truck}}\right)(5{,}320\text{ trucks}) \times \left(3.1\frac{\text{ESAL}}{\text{truck}}\right)$$

$$\text{Total ESAL}_{\text{Alternative Scenario}} = 40{,}204\text{ ESALs}$$

- Step 4: Compute the pavement damage cost for base case scenario by multiplying the unit pavement damage cost for interstates ($0.010/ESAL-mi) established in the SPR-3502 report with the total ESALs and the total miles traveled a year.

$$\text{PDC}_{Base\ Case\ Sce\ \ ario} = 40{,}204\text{ ESALs} \times \left(\frac{\$0.01}{ESAL - mi}\right) \times 156.6\text{ mi} \times 365\frac{\text{days}}{\text{year}}$$

$$\text{PDC}_{Base\ Case\ Sce\ \ ario} = \ \$23{,}041{,}021.54\ \text{ per year}$$

- Step 5: Compute the pavement damage cost for alternative scenario.

$$\text{PDC}_{Alter\ \ ative\ Sce\ \ ario} = \left(\frac{\$0.01}{ESAL - mi}\right) \times 156.6\text{ mi} \times 365\frac{\text{days}}{\text{year}}\left[(9{,}880\text{ trucks}) \times \left(2.4\frac{\text{ESAL}}{\text{truck}}\right)(5{,}320\text{ trucks}) \times \left(3.1\frac{\text{ESAL}}{\text{truck}}\right)\right.$$

$$\text{PDC}_{\ Alter\ \ ative\ Sce\ \ ario} = \ \$22{,}980{,}204.36\text{ per year}$$

- Step 6: Compute the percentage change in pavement damage cost.

$$Change\ in\ PDC = \frac{\$22{,}980{,}204.36 - \$23{,}041{,}021.54}{\$22{,}980{,}204.36} \times 100 = -0.3\%$$

Under these conditions, the reduction in total truck-miles traveled due to the increase in payload per truck along with the change of using 6-axle truck instead of the conventional 5-axle truck that spreads the truck's load over a larger number of axles ultimately leads to a reduction of pavement damage cost of 0.3%. This result is consistent with findings presented in a study sponsored by TxDOT in which stated that increases of truck size and weight limit that encourage the use of trucks with more axles do not necessarily lead to higher pavement damage costs, but it can even produce savings in pavement damage costs (David Luskin 2001).

B. Bridge Damage Cost

For bridge assets, the SPR-3502 also establishes unit consumption costs in $ per ft-pass for the overweight portion of an overweight truck (GVW > 80,000 lbs.) crossing a bridge (Ahmed et al. 2012). Appendix A shows the bridge damage costs from the SPR-3502 report. To estimate the pavement damage cost for the base case and alternative scenarios, the procedure described in Section 3.3.1. is used.

- Step 1: For a specific route, obtain the number of bridges and their characteristics such as bridge functional class (IS, NIS-NHS, Non-NHS), bridge material (steel, concrete, prestressed-concrete), bridge age (0-20, 21-35, 36-55, > 56 years), and bridge length (in feet). For the route under consideration, I-70 westbound, a total of 50 bridges were identified and categorized by the type of material and age group (Table 4.2).

Table 4.2. Distribution of bridges in the study route by material type and age group.

Highway Type	Bridge Type	Age Group	Number	Length (ft)
Interstate	Steel	0 to 20	0	-
		21 to 35	0	-
		36 to 55	1	250.0
		56 to 70	17	3,873.9
	Reinforced Concrete	0 to 20	1	32.5
		21 to 35	0	-
		36 to 55	3	361.9
		56 to 70	24	2,992.3
	Prestressed Concrete	0 to 20	0	-
		21 to 35	0	-
		36 to 55	1	176.2
		56 to 70	3	551.9
		Total =	50	8,238.6

Data Source: National Bridge Inventory (ARTBA 2022).

- Step 2: Estimate the equivalent AASHTO HS loading for the base case scenario using (Equation 3.5).

$$\text{Average Axle Spacing}_{Alter\ \ ative\ Sce\ \ ario} = \text{AAS} = \frac{(4.17 + 41 + 4.17 + 16.42)\text{ft}}{4} \times \left[\frac{12\text{ in}}{1\text{ ft}}\right.$$

$$\text{Average Axle Spacing}_{Alter\ \ ative\ Sce\ \ ario} = 197.25\text{ in}$$

$$\text{Average Axle Load}_{Alter\ \ ative\ Sce\ \ ario} = \text{AAL} = \frac{(17 + 17 + 17 + 17 + 12) \times 10^3\text{ lbs}}{5}$$

$$\text{Average Axle Load}_{Alter\ \ ative\ Sce\ \ ario} = \text{AAL} = 16000\text{ lbs.}$$

$$\text{MEV}_{\text{Alternative Scenario}} = 0.0057\left(\frac{80{,}000}{197.25}\right)^{0.313} \times 16{,}000^{0.64} = 19\text{ HS}$$

- Step 3: Estimate the equivalent AASHTO HS loading for the alternative scenarios using (Equation 3.5).

$$\text{Average Axle Load}_{Base\ Case} = \text{AAS} = \frac{(4.17 + 4.17 + 36.83 + 4.17 + 16.42)\text{ft}}{5} \times \left[\frac{12 \text{ in}}{1 \text{ ft}}\right.$$

$$\text{Average Axle Load}_{Base\ Case} = 157.8 \text{ in}$$

$$\text{Average Axle Load}_{Base\ Case} = \text{AAL} = \frac{(17.2 + 17.2 + 17.2 + 17.2 + 17.2 + 14) \times 10^3 \text{ lbs}}{6}$$

$$\text{Average Axle Load}_{Alter\ \ ative\ Sce\ \ ario} = 16{,}667 \text{ lbs.}$$

$$\text{MEV}_{\text{Alternative Scenario}} = 0.0057 \left(\frac{100{,}000}{157.8}\right)^{0.313} \times 16{,}667^{0.64} = 21.53 \text{ HS} = 22 \text{ HS}$$

Unit bridge damage costs due to the total load carried by a truck were taken from the SPR-3502 report, updated to the current year, and presented in Table 4.3.

Table 4.3. Unit bridge consumption costs for 19 HS and 22 HS.

Highway Type	**Bridge Type**	**Age Group**	**100% Load Share of Unit Consumption Cost for HS-19**		**100% Load Share of Unit Consumption Cost for HS-27**	
			2010 $/ft-pass	**2022 $/ft-pass**	**2010 $/ft-pass**	**2022 $/ft-pass**
Interstate	Steel	0 to 20	0.0119	0.0192	0.022	0.035
		21 to 35	0.0120	0.0193	0.023	0.037
		36 to 55	0.0122	0.0197	0.023	0.037
		56 to 70	0.0125	0.0201	0.025	0.040
	Reinforced Concrete	0 to 20	0.0119	0.0192	0.022	0.035
		21 to 35	0.0120	0.0193	0.023	0.037
		36 to 55	0.0122	0.0197	0.024	0.039
		56 to 70	0.0125	0.0201	0.025	0.040
	Prestressed Concrete	0 to 20	0.0119	0.0191	0.023	0.037
		21 to 35	0.0158	0.0255	0.024	0.039
		36 to 55	0.0174	0.0280	0.024	0.039
		56 to 70	0.0191	0.0308	0.026	0.042

Because the load is not the only factor in bridge consumption costs, consideration should be also given to non-load factors such as the environment and the minimum design capacity required for the bridge to withstand its own weight. Hence, it is not appropriate to attribute the 100 percent of the damage to overweight trucks. Based on the findings from the Federal Highway Cost

Allocation Study (FHWA 1997), a 30 and 70 percent split for load-share and non-load share, respectively, were assumed in the present study.

- Step 3: Estimate the total bridge consumption cost due to legal-weight trucks in the base case scenario.

The total bridge damage costs caused by the load carried by the legal-weight trucks on the route was computed multiplying the unit cost (30% load-share) and the total bridge length. Results are presented in Table 4.4.

Table 4.4. Total bridge damage cost due to the total load carried by legal-weight trucks (19 HS).

Highway Type	**Bridge Type**	**Age Group**	**Length (ft)**	**30 % Load-Share**	**Cost (2022$/truck-pass)**	**Cost (2022$/truck-year)**
				Unit Cost 2022$/ft		
Interstate	Steel	0 to 20	-	0.006	-	
		21 to 35	-	0.006	-	-
		36 to 55	250.0	0.006	$1.48	-
		56 to 70	3,873.9	0.006	$23.36	$539.31
	Reinforced Concrete	0 to 20	32.5	0.006	$0.19	$8,526.21
		21 to 35	-	0.006	-	$68.29
		36 to 55	361.9	0.006	$2.14	-
		56 to 70	2,992.3	0.006	$18.04	$780.66
	Prestressed Concrete	0 to 20	-	0.006	-	$6,585.84
		21 to 35	-	0.008	-	-
		36 to 55	176.2	0.008	$1.48	-
		56 to 70	551.9	0.009	$5.10	$540.20
			8,238.6		$51.79 per truck/pass	$18,901.73 per truck $317,473,437.86 per year

$$Bridge\ Cost_{Base\ Case} = \frac{\$51.79}{truck - pass} \times 16796\ trucks \times \frac{365\ passes}{year} = \frac{\$317{,}473{,}437.86}{year}$$

- Step 4: Estimate the total bridge consumption cost for the alternative scenario.

The total bridge damage costs caused by the load carried by the overweight trucks on the route was computed multiplying the unit cost (30% load-share) and the total bridge length. The results are presented in Table 4.5.

Table 4.5. Total bridge damage cost due to the total load carried by overweight trucks (22 HS).

Highway Type	Bridge Type	Age Group	Length (ft)	30 % Load-Share	Cost (2022$/truck-pass)	Cost (2022$/truck-year)
				Unit Cost 2022$/ft		
Interstate	Steel	0 to 20	-	0.011	-	-
		21 to 35	-	0.011	-	-
		36 to 55	250.0	0.011	$2.78	$1,012.92
		56 to 70	3,873.9	0.012	$46.49	$16,967.58
	Reinforced Concrete	0 to 20	32.5	0.011	$0.34	$124.49
		21 to 35	-	0.011	-	-
		36 to 55	361.9	0.012	$4.23	$1,545.47
		56 to 70	2,992.3	0.012	$35.91	$13,106.15
	Prestressed Concrete	0 to 20	-	0.011	-	-
		21 to 35	-	0.012	-	-
		36 to 55	176.2	0.012	$2.06	$752.42
		56 to 70	551.9	0.013	$6.95	$2,538.02
			8,238.6		$98.76 per truck/pass	$36,047.05 per OW truck

Then, the total bridge damage cost for the alternative scenario is computed considering the damage inflicted by the 9,880 legal-weight trucks and the 5,320 overweight trucks as follows:

$$Bridge\ Cost_{Base\ Case} = \left[\frac{\$51.79}{truck-pass} \times 9{,}880\ trucks + \frac{\$98.76}{truck-pass} \times 5{,}320\ trucks\right] \times \frac{365\ passes}{year} = \ \$378{,}519{,}407.27\ per\ year$$

- Step 5: Compute the percentage change in bridge damage cost.

$$Change\ in\ PDC = \frac{\$378{,}519{,}407.27 - \$317{,}473{,}437.86}{\$317{,}473{,}437.86} \times 100 = +19\%$$

The total bridge consumption is greater for an OW truck ($36,047.05) than for a legal weight truck ($18,901.73). Nevertheless, when carriers and shippers are allowed to load their trucks at greater weights, there is reduction in the number of trucks traversing I-70 (i.e., 1,500 trucks less). This trip reduction effect, in turn, has an impact on the total annual bridge damage cost. This reduction in the number of trips in some way counterbalances the increment in the damage cost caused by the operation of overweight trucks, yielding an increase of 19 percent in the total annual bridge damage costs.

C. Total Infrastructure Damage Cost

The total annual infrastructure damage cost due to all trucks on the route for each scenario was estimated by summing up the pavement damage cost and the bridge damage cost. Table 4.6 presents the results of both scenarios for the performance criterion of infrastructure damage.

Table 4.6. Results for the Performance Measure of Infrastructure Damage

Performance Measure	Base Case Scenario	Alternative Scenario
Annual Pavement Damage Cost	$23,041,021.54	$22,980,204.36
Annual Bridge Damage Cost	$317,473,437.86	$378,519,407.27
Total Annual Infrastructure Damage Cost	$340,514,459.39	$401,499,611.63
% Change in Infrastructure Damage Cost	-	18%

Ultimately, an increase of 18 percent in annual infrastructure damage costs is expected to occur under these scenarios.

4.3.2 Operational Impacts

In general, when traffic safety and mobility analysis are performed, relevant input such as traffic volumes (AADT, ADT), truck percentage in the traffic stream, and hourly flow rate of autos and trucks, are required for each link of the route. From INDOT's Traffic Count Database System, 5 WIM stations are currently functioning along the I-70. Data from those 5 WIM stations showed great variations in AADT, truck percentages, and hourly flow rates of autos and trucks along the I-70 throughout the year.

The present study aims to assess and compare the operational impacts of transporting the same load of 839,800,000 lbs. using only legal-weight trucks loaded at 80,000 lbs. (Base Case Scenario) and some overweight trucks loaded at 100,000 lbs. (Alternative Scenario). Hence, for better capturing and reflecting the effects of overweight truck operations on traffic safety and mobility, the ADT, truck percentage, and hourly flow rates of autos and trucks were assumed to be constant along the highway corridor (I-70) throughout the analysis period.

The task of selecting a single value for the traffic volume, truck percentage, and hourly flow rates of autos and trucks to represent the overall condition and composition of the traffic stream in the entire route was not possible due to the wide range of variation in the traffic data among the different segments. Thus, in the present study, an AADT of 55,987 vehicles per day with trucks representing about 30% of the total traffic stream were selected for the analysis as three out of the five WIM stations in the I-70 showed an annual average daily traffic (AADT) ranging between 15,000 and 19,000 vehicles per day with trucks representing about 30 percent of the traffic stream in the both directions on the present year. Moreover, based on the volume count data from the same WIM stations, the flow rate of autos was observed to be 866 vehicles per hour during peak hours. Hence, this study assumed this value as the constant hourly flow rate of automobiles in the analysis for quantifying the impacts of overweight truck operations on traffic mobility.

A. Safety Impacts

To compute the net impacts of overweight truck operations on traffic safety, the procedure described in Section 3.3.2. was followed.

- Step 1: Estimate the crash frequency for the base case scenario. Because the safety performance function (Equation 3.6) being used in this study does not have any variable representing trucks, the percentage of trucks are converted into an equivalent number of passenger car assuming PCE as 1.5.

$$\text{ADT}_{Base\ Case\ Sce\ \ ario} = \frac{\text{39,191 passenger cars} + \left(\text{16796 legal trucks} \times \frac{\text{1.5 passenger cars}}{\text{1 legal truck}}\right)}{\text{1 day}}$$

$$\text{ADT}_{Base\ Case\ Sce\ \ ario} = \text{64,385 passenger cars/day}$$

Using (Equation 3.6 and (Equation 3.7, the crash frequency for the base case scenario was calculated assuming number of interchanges (N_x) as 1 and an inside shoulder (W_{is})width of 6 ft.

$$B_{RF} = -14.032 - 0.0407W_{is} + 0.2127N_x = -14.0635$$

$$C_{RF-Base\ Case\ Sce\ \ ario} = 0.25 \times ADT^{0.9599}(1000L)^{0.9107}e^{B_{RF}} = \text{434 injury crashes/year}$$

$$C_{RF-Base\ Case\ Sce\ \ ario} = \frac{\text{434 crashes/year}}{\text{156.6 centerline miles}} = \text{2.8 crashes/centerline} - \text{mile}$$

- Step 2: To estimate the expected number of crashes due to the presence of the 5,320 overweight trucks (GVW=100,000 lbs.) considered in the alternative scenario, steps 3 to 5 must be completed first in order to use the safety performance function presented in Step 1. Because the safety performance function that is being used does not have any variable representing overweight trucks neither legal-weight trucks, all overweight trucks must be converted into an equivalent number of legal-weight trucks first and then into an equivalent number of passenger cars.
- Step 3: Convert the number of overweight trucks into an equivalent number of legal-weight trucks.
    i. Knowing that the maximum allowable weight in the state of Indiana is 80,000 lbs., the equivalent number of legal weight trucks is calculated as:

$$N_{eq} = \frac{GVW - W_{Empty\ Truck}}{W - W_{Empty\ Truck}} = \frac{100{,}000\ lbs - 35{,}000\ lbs}{80{,}000\ lbs - 30{,}000\ lbs} = 1.44$$

    ii. Estimate the percentage of extra weight compared to the maximum allowable weight of each truck (APEW), using (Equation 3.9.

$$APEW = \frac{(GVW - W_{Empty\ Truck}) - (W - W_{Empty\ Truck})}{W - W_{Empty\ Truck}} = 30\%$$

    iii. Compute the total number of equivalent legal-weight trucks from the total number of overweight trucks in the traffic stream using (Equation 3.10.

$$N_{eq} = \sum_{i-1}^{n} (N_{eq})_i = 7{,}684\ legal - weight\ trucks/day$$

  This means that the 5,320 overweight trucks (GVW=100,000 lbs.) in the alternative scenario equivalent to 7,684 trucks loaded with 80,000 lbs.
- Step 4: Estimate the net effects of overweight trucks on traffic safety.
    i. Compute the reduced number of trucks on the I-70 due to the trip reduction effect caused by overweight truck operation using (Equation 3.12. Because the alternative scenario considers that some trucks are overweight (GVW = 100,000 lbs.), the percentage of overweight trucks (P_{OW}) in the truck traffic stream is 35% and thus, the total number of trucks (N_{TT}) on the I-70 is 15,200 trucks.

$$TRE = APEW \times N_{TT} \times P_{OW} = 0.3 \times 15{,}200 \times 0.35 = 1{,}596\ trucks/day$$

This means that under the given conditions, the 5,320 overweight trucks carry the same load as 7,684 legal-weight trucks; thus, a reduction of 1,596 trucks occurs due to the operation of overweight trucks.

ii. Estimate the Traffic Impairment Effect (TIE) of overweight truck operations using the concept of highway capacity. For this purpose, the passenger car equivalent of overweight trucks (PCE_{OW}) is needed. Webster and Elefteriadou (1999) estimated that the PCE for 5-axle tractor semitrailer trucks ranges between 2 to 4 depending on the traffic flow rate, percentage of trucks, vertical alignment of the road (e.g., level, upgrade, or downgrade), and length of the grade. The present study assumed a PCE_{OW} of 3 for overweight 5-axle tractor semitrailer trucks.

$$\mathrm{TIE} = \mathrm{N_{TT}} \times \mathrm{P_{OW}} \times \frac{\mathrm{PCE_{OW}} - \mathrm{PCE_N}}{\mathrm{PCE_N}} = 15{,}200 \times 0.35 \times \frac{3 - 1.5}{1.5}$$
$$= 5{,}320 \text{ trucks/day}$$

This means that under the given conditions, the moving behavior of 5,320 OW trucks represent an equivalent of 5,320 additional legal-weight trucks; thus, an increment of 5,320 trucks occurs due to the operation of overweight trucks.

- Step 5: Considering the TRE and the TIE, compute the net total equivalent number of legal-weight trucks (NE_T) and then the total equivalent number of passenger cars (NE_A).

i. Estimate the net total equivalent number of legal-weight trucks (NE_T) using (Equation 3.14.

$$\mathrm{NE_T} = \mathrm{N_{TT}} + \mathrm{TIE} - \mathrm{TRE} = 15{,}200 + 5{,}320 - 1{,}596 = 18{,}924 \text{ trucks/day}$$

This means that the under that under the given conditions, the total net volume of equivalent legal-weight trucks is 18,924 trucks per day.

ii. Estimate the net total equivalent number of passenger cars (NE_A) using (Equation 3.15.

$$\mathrm{NE_A} = \mathrm{NE_T} \times \mathrm{PCE_N} = 18{,}924 \times 1.5 = 28{,}386 \text{ passenger cars/day}$$

This means that under the given conditions, the total net volume of equivalent passenger cars is 28,386 vehicles per day.

iii. Estimate the ADT for Alternative Scenario adding the actual number of cars in the traffic stream (8,500 cars) and net total equivalent number of autos (NE_A) obtained from the conversion of OW trucks.

$$\text{ADT}_{\text{Alternative Scenario}} = 35{,}467 + \text{NE}_{\text{A}} = 35{,}467 + 28{,}386$$
$$= 63{,}853 \text{ passenger cars/day}$$

- Step 6: Calculate the expected number of crashes due to overweight truck operations (Alternative Scenario) using (Equation 3.6(Equation 3.7.

$$B_{RF} = -14.032 - 0.0407W_{is} + 0.2127N_x = -14.0635$$
$$C_{RF-Alter\ \ ative\,Sce\ \ ario} = 0.25 \times ADT^{0.9599}(1000L)^{0.9107}e^{B_{RF}} = 430 \text{ crashes/year}$$
$$C_{RF-Alter\ \ ative\,Sce\ \ ario} = \frac{430 \text{ crashes/year}}{156.6 \text{ centerline miles}} = 2.7 \text{ crashes/centerline} - \text{mile}$$

B. Traffic Mobility

To compute the net impacts of overweight truck operations on traffic safety, the procedure described in Section 3.3.3. was followed.

- Step 1: Using (Equation 3.17 calculate the average speed on the route for the base case scenario in which the total load of 839.8 million pounds is being transported by legal-weight trucks (GVW = 80,000 lbs.) only.
  Having the flow rate of autos (V_A) in the I-70 as 866 vehicles per hour and assuming a uniform hourly distribution of trucks, the total number of legal-weight trucks (N_{TT}) was estimated as 175 trucks per lane per hour (assumes 4 lanes on I-70). Based on the speed flow curves and level of service for basic freeway segments in the Highway Capacity Manual (TRB 2000), the traffic density of 18 vehicles per mile per lane was assumed for the analysis.

$$\text{U}_{\text{base case}} = \frac{\text{V}_{\text{auto}} + (\text{N}_{\text{TT}} \times \text{PCE}_{\text{N}})}{\text{k}}$$
$$\text{U}_{\text{base case}} = \frac{866 \text{ veh/h} + \left(175 \text{ legal weight truck/ln/h} \times \frac{1.5 \text{ veh}}{1 \text{ legal weight truck}}\right)}{18 \text{ veh/mi} - \text{lane}}$$
$$= 63 \text{ mph}$$

- Step 2: Using (Equation 3.18, calculate the average speed on the route for the alternative scenario in which the total load of 839.8 million pounds is being transported by some legal-weight trucks (GVW = 80,000 lbs.) and some overweight trucks (GVW = 100,000 lbs.).

Similar to the base case scenario, the net total equivalent number of legal-weight trucks (NE_T) was estimated assuming a uniform hourly distribution of trucks, resulting in 197 trucks per lane per hour. Moreover, in this scenario, the trip reduction and traffic impairment effects are reflected in the traffic density with a slight increase that resulted in a density of 21 vehicles per mile per lane.

$$U_{OW} = \frac{V_{auto} + (NE_T \times PCE_N)}{k}$$

$$\mathrm{U_{OW}} = \frac{866\ \mathrm{veh/h} + \left(197\ \mathrm{legal\ weight\ truck/h} \times \frac{1.5\ \mathrm{veh}}{1\ \mathrm{legal\ weight\ truck}}\right)}{21\ \mathrm{veh/mi-lane}} = 55\ \mathrm{mph}$$

Compared to the base case scenario, the presence of 5,320 OW trucks in the traffic stream results in a reduction of approximately 12 percent in the average travel speed. This result is consistent with findings from a study conducted by Zhou et al. (2012) that stated that overweight trucks experience an average travel speed reduction of 16 percent compared with legally loaded trucks.

4.3.3 Revenues from Overweight Permit Sales

Assuming that the aforementioned load being carried in both scenarios fall into the category of divisible loads, the permit fee structure for overweight loads in the state of Indiana presented in Table 2.3 was used for calculating the revenues for the base case and alternative scenario. Since legal-weight trucks generally are not required to issue an overweight permit, total revenue for the base case scenario is estimated as $0.

According to the current permit fee structure, all single trip permits for divisible loads allow trucks to transit the State's highway network once in a time window of 7 days. The cost of this type of permit for trucks loaded at 100,000 lbs. includes a flat fee of $20 and an additional fee of $0.25 per ESAL per mile traveled on the road network. Based on this information, the revenues for the alternative scenario were estimated to be $115,955,685.00 per year.

$$\text{Revenues}_{Alter\quad ative\ Sce\quad ario}$$
$$= 5{,}320\ \text{OW trucks}\left[\left(\$20 \times \frac{365\ \text{days}}{1\ \text{year}}\right) + \left(\frac{\$0.25}{\text{ESAL mi}} \times 0.70\ \text{ESAL} \times 156.6\ \text{mi} \times \frac{365\ \text{trips}}{1\ \text{year}}\right)\right]$$

$$\text{Revenues}_{Alter\quad ative\ Sce\quad ario} = \$92{,}248{,}655.60\ \text{per year}$$

This result shows a significant increase in revenues collection from previous years, which for I-70 this value was about $7.7 million in fiscal year 2020.

$$\text{Change in Revenues Collection} = \frac{\$92{,}248{,}655.60 - \$7{,}700{,}000}{\$7{,}700{,}000} \times 100 = 1098\%$$

This significant increase in revenues of 1098% can be explained by:

1) The recent change in the permit fee for divisible loads from $0.07/ESAL-mi to $0.25/ESAL-mi that started to regulate on January 1st, 2022 (INDOR 2021a). This alone represents a fee increase of 257% for divisible loads.
2) According to WIM station data, overweight trucks have found to be about 9 percent of the total truck traffic stream. However, to capture the pure effects of changes in truck weight limit restrictions on infrastructure, revenues collection, safety, mobility, and road user, this study intentionally assume that overweight trucks (all being loaded at 100,000 lbs.) represent 35 percent of the truck traffic stream. This assumption leads to high revenues as permit fees increases as the weight of trucks increases.
3) Lastly, this study assumes that all overweight trucks are 20,000 lbs. over the maximum legal weight (i.e., 80,000 lbs.) while in reality, shippers and carriers try to conform or stay close to this maximum weight limit, so that they can avoid paying additional amounts on overweight permits. This assumption also contributes to the resulting high percentage change in revenues.

4.3.4 Vehicle Operating Costs

In this section, the present study intends to assess and compare the carriers' vehicle operational costs of transporting the same load of 382,500,000 lbs. using only legal-weight trucks loaded at 80,000 lbs. (Base Case Scenario) and some overweight trucks loaded at 100,000 lbs. (Alternative Scenario). To estimate the percentage change in vehicle operating costs due to the operation of overweight trucks, the following procedure was followed:

- Step 1: Estimate the total number of overweight trucks and their respective load weights.

$$\text{Total number of trucks}_{\textit{Base Case Sce ario}} = 16{,}796 \text{ legal weight trucks}$$

$$\text{GVW}_{\text{Legal-Weight Trucks}} = 80{,}000 \text{ lbs.}$$

- Step 2: Convert all overweight trucks into an equivalent number of legal-weight trucks with a gross vehicle weight of 80,000 lbs. This was previously calculated in Step 3 of Section 4.3.2.A.

$$\text{Nr of legal} - \text{weight trucks}_{\textit{Alter ative Sce ario}} = 9{,}880 \text{ legal} - \text{weight trucks}$$

$$\text{GVW}_{\text{Legal-weight Trucks}} = 80{,}000 \text{ lbs.}$$

$$\text{Nr of OW trucks}_{\textit{Alter ative Sce ario}} = 5{,}320 \text{ overweight trucks}$$

$$\text{GVW}_{\text{OW Trucks}} = 100{,}000 \text{ lbs.}$$

- Step 3: Estimate the current average cost per mile of a large commercial truck' operator wage and fringe and calculate the total labor cost per mile for both scenarios, assuming one driver for each truck. In this study, the values of large commercial truck's operator wage and fringe from the most recent ATRI's report were updated for inflation to the current year and used in the analysis.

  Driver Wage = \$0.65 per mile Updated to 2022 from Leslie and Murray (2021)

  Driver fringe = \$0.22 per mile Updated to 2022 from Leslie and Murray (2021)

$$\text{Labor Cost}_{\text{Base Case}} = \left.\frac{\$0.65 + \$0.22}{\text{driver-mi}}\right\} \times 16{,}796 \text{ driver} \times \frac{156.6 \text{ mi}}{\text{trip}} \times \frac{365 \text{ trip}}{1 \text{ year}}$$

$$\text{Labor Cost}_{\text{Base Case}} = \$835{,}237{,}030.68 \text{ per year}$$

$$\text{Labor Cost}_{\text{Alternative Scenario}}$$

$$= \left.\frac{\$0.65 + \$0.22}{\text{driver-mi}}\right\} \times (9{,}880 + 5{,}320) \text{ driver} \times \frac{156.6 \text{ mi}}{\text{trip}} \times \frac{365 \text{ trip}}{1 \text{ year}}$$

$$\text{Labor Cost}_{\text{Alternative Scenario}} = \$755{,}870{,}616.00 \text{ per year}$$

- Step 4: Estimate the fuel consumption cost for both scenarios using the fuel consumption of a truck and the fuel price (Equation 3.23).

  $\text{Fuel efficiency}_{5-\text{axle truck}} = 5.5 \text{ mi/gallon of diesel}$ (Top Mark Funfing. LLC 2020)

  $\text{Fuel efficiency}_{6-\text{axle truck}} = 4.5 \text{ mi/gallon of diesel}$ (Top Mark Funfing. LLC 2020)

  $\text{Diesel price} = \$5.049 \text{ per gallon}$ (U.S. Energy Information Administration 2022)

$$\text{Fuel Cons Cost}_{\text{Base Case}} = \frac{\$5.049/\text{gallon}}{5.5 \text{ mi/gallon}} \times 156.6 \text{ mi} \times \frac{365 \text{ trip}}{1 \text{ year}} \times 16{,}796 \text{ trucks}$$

$$\text{Fuel Cons Cost}_{Base\ Case} = \$865{,}783{,}839.53 \text{ per year}$$

$$\text{Fuel Cons Cost}_{Alter\ \ ative} = \frac{\$5.049/\text{gallon}}{4.5 \text{ mi/gallon}} \times 156.6 \text{ mi} \times \frac{365 \text{ trip}}{1 \text{ year}} \times (9{,}880 + 5{,}320) \text{ trucks}$$

$$\text{Fuel Cons Cost}_{Alter\ \ ative} = \$844{,}454{,}825.89 \text{ per year}$$

- Step 5: Estimate the truck tire (Equation 3.24) and maintenance and repair (M&R) (Equation 3.25) costs for both scenarios. In this study, the values of truck's tires and maintenance & repair costs from the most recent ATRI's report were updated for inflation to the current year and used in the analysis.

$$\text{Truck Tire Cost}_{5-\text{axle truck}} = \$0.05 \text{ per mile}$$

$$\text{Truck M\&R Cost}_{5-\text{axle truck}} = \$0.18 \text{ per mile}$$

$$\text{Truck Tire Cost}_{\text{Base Case}} = \frac{\$0.05}{\text{mi}} \times 16{,}796 \text{ truck} \times \frac{156.6 \text{ mi}}{\text{trip}} \times \frac{365 \text{ trip}}{1 \text{ year}}$$

$$\text{Truck Tire Cost}_{\text{Base Case}} = \$48{,}002{,}128.20 \text{ per year}$$

$$\text{Truck Tire Cost}_{\text{Alternative Scenario}} = \frac{\$0.05}{\text{mi}} \times (9{,}880 + 5{,}320) \text{ truck} \times \frac{156.6 \text{ mi}}{\text{trip}} \times \frac{365 \text{ trip}}{1 \text{ year}}$$

$$\text{Truck Tire Cost}_{\text{Alternative Scenario}} = \$43{,}440{,}840.00 \text{ per year}$$

$$\text{Truck M\&R Cost}_{\text{Base Case}} = \frac{\$0.18}{\text{mi}} \times 16{,}796 \text{ truck} \times \frac{156.6 \text{ mi}}{\text{trip}} \times \frac{365 \text{ trip}}{1 \text{ year}}$$

$$\text{Truck M\&R Cost}_{\text{Base Case}} = \$172{,}807{,}661.52 \text{ per year}$$

$$\text{Truck M\&R Cost}_{\text{Alternative Scenario}} = \frac{\$0.18}{\text{mi}} \times (9{,}880 + 5{,}320) \text{truck} \times \frac{156.6 \text{ mi}}{\text{trip}} \times \frac{365 \text{ trip}}{1 \text{ year}}$$

$$\text{Truck M\&R Cost}_{\text{Alternative Scenario}} = \$156{,}387{,}024.00 \text{ per year}$$

- Step 6: For each scenario, estimate the total input of the trucking industry by summing up all the operational costs previously obtained from Step 3 to Step 5 ((Equation 3.26).

$$\text{VOC}_{\text{Base Case}} = \$1{,}921{,}830{,}659.93 \text{ per year}$$

$$\text{Unit VOC}_{\text{Base Case}} = \frac{\$1{,}921{,}830{,}659.93 \text{ per year}}{16{,}796 \text{ truck} \times 165\ mi \times 365\ days} = \$2.00/\text{truck/mi}$$

$$\text{VOC}_{\text{Alternative}} = \$1{,}800{,}153{,}305.89 \text{ per year}$$

$$\text{Unit VOC}_{\text{Alternative Scenario}} = \frac{\$1{,}800{,}153{,}305.89 \text{ per year}}{(9{,}880 + 5{,}320) \text{ truck} \times 165\ mi \times 365\ days}$$

$$= \$2.07/\text{truck/mi}$$

- Step 7: Calculate the percentage change in vehicle operational costs.

$$\Delta\text{VOC} = \frac{\text{VOC}_{\text{OW}} - \text{VOC}_{\text{base case}}}{\text{VOC}_{\text{base case}}} \times 100 = -6.33\%$$

This means that the operation of overweight trucks on the I-70 decreases carrier's vehicle operational costs by 6.33 percent.

4.3.5 Shipping Inventory Cost

The impacts of overweight permitting policies on shipping inventory costs were estimated following the procedure described in Section 3.3.6.

- Step 1: Estimate the shipping inventory costs for the base case and alternative scenarios. Assuming that all trucks (legal-weight trucks and overweight trucks) are loaded with base metal, the value of the cargo (P_{cargo}) was calculated using the FAF estimates for the value and amount of shipment moved within the state of Indiana (National Transportation Reserach Center 2022) shown in Table 2.6. The average truck speed (S) in each scenario was estimated and previously described in Section 4.3.2.B. Then, with an annual interest rate (r) of 4.5 percent the shipping inventory costs for both scenarios were estimated using (Equation 3.28.

Base Case Scenario

Number of trucks = 16,796 trucks

GVW = 80,000 lbs.

Miles traveled per truck per trip = 156.6 mi

Number of trips per year = 260 trips

$r = 4.5\%$

$S = 63\ \text{mi/h}$

$\text{Average value of comodities in IN} = \frac{\$0.96}{\text{lb}}$

$$P_{\text{cargo}} = \frac{\$0.96}{\text{lb}} \times \frac{(80{,}000 - 30{,}000)\ \text{lbs}}{1\ \text{truck}}$$

$$P_{\text{cargo}} = \$48{,}038.75\ /\text{truck}$$

$$\text{Shipping Inventory} = 100 \times \frac{0.045}{8760} \times \frac{1}{63} \times 48{,}038.75$$

$$\text{Shipping Inventory Cost} = \mathbf{0.39}\,\frac{\textbf{cents}}{\textbf{truck} - \textbf{mi}}$$

Alternative Scenario

Number of trucks = 15,200 legal-weight + 9,880 OW

$GVW_{\text{legal-weight}}$ = 80,000 lbs. GVW_{OW} = 100,000 lbs.

Miles traveled per truck per trip = 156.6 mi

Number of trips per year = 260 trips

$r = 4.5\%$

$S = 55\ \text{mi/h}$

$\text{Average value of comodities in IN} = \frac{\$0.96}{\text{lb}}$

$$P_{\text{cargo}} = \frac{\$0.54}{\text{lb}} \times \frac{(100{,}000 - 35{,}000)\text{lbs}}{1\ \text{truck}}$$

$$P_{\text{cargo}} = \$62{,}450.38\ /\text{truck for OW trucks}$$

$$P_{\text{cargo}} = \$48{,}038.75\ /\text{truck for legal-weight trucks}$$

$$\text{Shipping Inventory} = 100 \times \frac{0.045}{8760} \times \frac{1}{55} \times 62{,}450.38$$

$$\text{Shipping Inventory Cost} = 0.5799\,\frac{\text{cents}}{\text{truck}-\text{mi}}\ \text{for legal-weight trucks}$$

$$\text{Shipping Inventory} = 100 \times \frac{0.045}{8760} \times \frac{1}{55} \times 48{,}038.75$$

$$\text{Shipping Inventory Cost} = 0.4461\,\frac{\text{cents}}{\text{truck}-\text{mi}}\ \text{for OW trucks}$$

$$\text{Average Shipping Inventory Cost} = (0.5799 + 0.4461)/2$$

$$\text{Average Shipping Inventory Cost} = \mathbf{0.49}\,\frac{\textbf{cents}}{\textbf{truck} - \textbf{mi}}$$

- Step 2: Calculate the percentage change in shipping inventory costs using (Equation 3.29.

$$\Delta I = \frac{0.49 - 0.39}{0.39} \times 100 = +25.6\%$$

This means that the operation of overweight trucks on I-70 increases unit shipping inventory costs by 25.6 percent.

4.3.6 Summary of the Performance of Scenarios

In this section, a summary with the expected impacts of the base case and alternative scenarios on each of the performance criterion is presented in Table 4.7 to facilitate the visualization of the results and comparison among alternatives.

Table 4.7. Performance of Alternatives.

Goal	Performance Criterion	Unit	Expected Impact on Performance Criterion	
			Base Case Scenario	Alternative Scenario
Agency Costs	Annual percentage change in infrastructure damage costs	%	0	18
	Annual percentage change in revenues from sales of overweight permits	%	0	1098
Safety	Annual injury crash frequency	crashes/centerline mile	2.8	2.75
Mobility	Average travel speed	mph	63	55
User Costs	Vehicle operational cost for trucks	$/truck-mile	2.00	2.07
	Inventory Shipping Cost	cents/truck-mile	0.39	0.49

4.4 Weighting

To assign weights to the different performance criteria considered in the analysis, the present study reviewed past research in which relative weights for common performance criteria used in transportation decision-making were determined from the agency perspective. For bridge management, Sinha et al. (2009) developed relative weights for multiple criteria using direct-questioning and Analytic Hierarchy Process (AHP) techniques. For highway asset management, Li and Sinha (2004) developed agency perspective relative weights for six overall agency goals in Indiana (infrastructure preservation, safety, mobility, agency costs, user costs, and environment) using the direct-questioning approach. The weights were determined as 0.2259 for infrastructure preservation, 0.2319 for safety, 0.2112 for mobility, 0.1922 for agency costs, 0.1776 for user costs, and 0.1715 for environment. These weights were calibrated in 2009 using an AHP technique (Sinha et al. 2009). Moreover, in the context of truck operations, Yang and Regan (2013) proposed a multi-criteria methodology to prioritize different transportation system alternatives involving trucks operations in California. The authors of that study surveyed public agencies and trucking industry to develop relative weights for the following performance criteria: project cost (0.405), safety hazards (0.2564), traffic congestion (0.1424), air pollution (0.0486), pavement damage

(0.0337), productivity (0.0855), and travel time reliability (0.0285). It should be noted from the studies by Li and Sinha (2004), Sinha et al. (2009), and Yang and Regan (2013), that from the agency perspective, the safety and mobility performance criteria are considered top two priorities whereas the performance criteria related to road user cost (trucking productivity and travel time reliability) are considered the least in importance.

To define the relative importance of the multiple performance criteria involved in the analysis of overweight truck permitting, the present study adopted the agency perspective weights developed by Li and Sinha (2004) for those weights were developed from the responses of INDOT officials, who are the decision-makers in this study. Although these weights were not specifically developed in the context of overweight truck permitting, the fact that the performance criteria under consideration in this study were also derived from the same overall agency goals, the adoption of those relative weights in the present study is justified. Thus, the weight of 0.2319 and 0.2112 corresponding to the overall goals of safety and mobility, respectively, were assigned to the same corresponding performance criteria of this study. Similarly, for the vehicle operational costs and shipping inventory costs criteria, the weight of 0.1776 corresponding to the overall goal of road user cost was assigned because carriers and shippers are users of the road network. Lastly, the infrastructure damage and the revenue criteria were assigned the weight of 0.1922 corresponding to the overall goal of agency cost.

On one hand, operation of overweight trucks lead to a premature and accelerated deterioration of highway assets that are translated into additional construction, rehabilitation and maintenance cost that are assumed by the agency. On the other hand, the revenue from the sales of overweight permits is represented as a negative cost to the agency as they were established to recover highway assets repair/replace expenditures from their users. For consistency, each of these weights was then normalized to fall within a scale between 0 and 1. Table 4.8 presents the normalized relative weights for the different performance criteria used in the present study for overweight truck permitting policies.

Table 4.8. Agency Perspective Relative Weights in Overweight Truck Permitting Policies.

Performance Criteria	**Weights** (Li and Sinha 2004)	**Normalized Weights**
Infrastructure damage	0.1922	0.1625
Safety	0.2319	0.1961
Mobility	0.2112	0.1786
Revenues from the sales of OW permits	0.1922	0.1625
Vehicle Operational Costs	0.1776	0.1502
Shipping Inventory Costs	0.1776	0.1502
Total	1.1827	1.0000

In Table 4.8, it can be seen that from INDOT's perspective, safety, mobility, and infrastructure damage criteria are the top three priorities of the agency, for they were assigned the highest weights.

4.5 Scaling

For scaling the performance measures, a survey (Appendix C) was designed to collect information from different stakeholders to develop a value function for each individual criterion. Assuming that the decision is being made under the certainty scenario, the technique used for scaling each individual performance criterion considered in this study was the Direct Rating method. Through the designed survey, decision makers were asked to directly assign the values they associate to each level of a particular performance measure and their responses were used to develop a value function for each performance criterion. Figure 4.6 shows the developed value functions. These value functions were used to convert the different impacts of each scenario on individual performance measure into a common scale of measurement (Table 4.9), so that these impacts can later be combined in the next step (i.e., amalgamation) to yield a composite outcome that can represent the overall performance of each scenario.

Table 4.9. Scaled values.

Performance Criteria	Relative Weight	Unweighted Utilities $u_i (x_{ij})$		Weighted Utilities $w*u_i (x_{ij})$	
		Base Case Scenario	Alternative Scenario	Base Case Scenario	Alternative Scenario
Annual percentage change in infrastructure damage costs	0.1625	100	77.00	16.25	12.51
Annual percentage change in revenues from sales of overweight permits	0.1961	0	24.92	0.00	4.89
Annual injury crash frequency	0.1786	0	2.00	0.00	0.36
Average travel speed	0.1625	98.60	87.50	16.02	14.22
Vehicle operational cost for trucks	0.1502	16.66	10.83	2.50	1.63
Inventory Shipping Cost	0.1502	76.25	63.75	11.45	9.57

4.6 Amalgamation

Using the Weighted Sum Method (WSM) the various impacts of the performance measures considered in the analysis were combined to yield a composite value to represent the overall performance of each scenario with respect to the selected performance measures. Results are presented in Table 4.10.

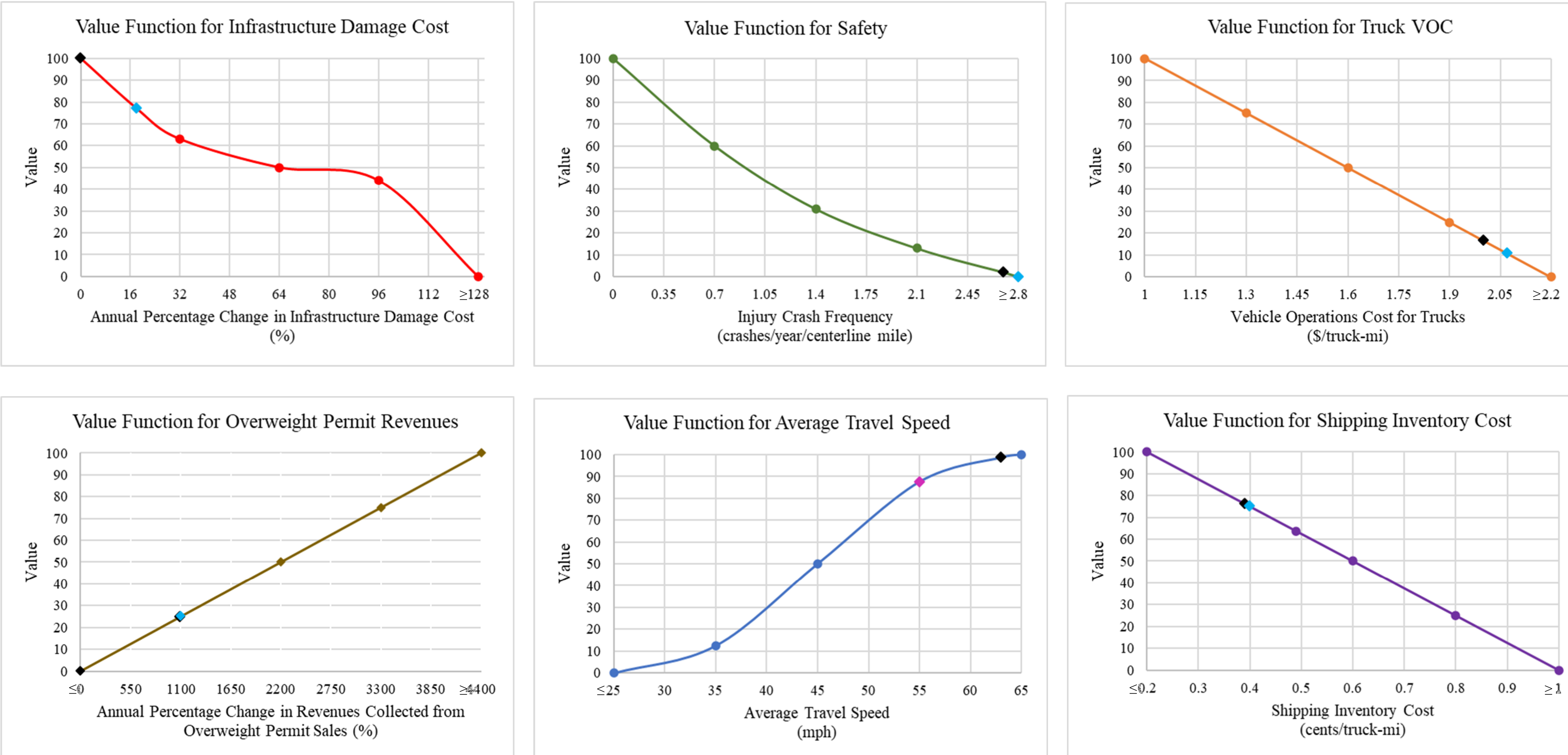


Figure 4.6. Value functions for all performance measures.

Table 4.10. Results

Performance Criteria	Relative Weight	Unweighted Utilities $u_i (x_{ij})$		Weighted Utilities $w*u_i (x_{ij})$	
		Base Case Scenario	**Alternative Scenario**	**Base Case Scenario**	**Alternative Scenario**
Annual percentage change in infrastructure damage costs	0.1625	100	77.00	16.25	12.51
Annual percentage change in revenues from sales of overweight permits	0.1961	0	24.92	0.00	4.89
Annual injury crash frequency	0.1786	0	2.00	0.00	0.36
Average travel speed	0.1625	98.60	87.50	16.02	14.22
Vehicle operational cost for trucks	0.1502	16.66	10.83	2.50	1.63
Inventory Shipping Cost	0.1502	76.25	63.75	11.45	9.57
Total	**1**			**46.23**	**43.18**

4.7 Decision Making

Results from Table 4.10 shows that under these conditions, the overall performance of the Base Case Scenario (having only legal-weight trucks traversing on I-70) is slightly more beneficial than the Alternative Scenario in which some of the trucks are overweight.

5. CONCLUSION, LIMITATIONS, AND FUTURE WORK

In this study, a general MCDA framework has been proposed to assist transportation agencies in the evaluation of the wide range of performance criteria involved in decisions regarding overweight truck operations policies. This framework allows the simultaneous consideration of different standpoints such as economic, public, and private sector standpoints that ultimately can help agencies achieve a more balance, rational, and defensible decision. In this study, the proposed MCDA framework was validated through a case study on I-70 to demonstrate its implementation.

This study only evaluated two scenarios, the base case scenario in which all trucks were loaded at 80,000 lbs. and the alternative scenario in which 35 percent of the trucks were loaded at 100,000 lbs. For future studies, it is recommended to consider more scenarios in which different percentages of overweight trucks in the traffic stream can be evaluated as well as different loading scenarios.

REFERENCE

AASHTO. (2001). *A Policy on Geometric Design of Highways and Streets*. Washington, D.C.

AASHTO. (2003). *User Benefit Analysis for Highways*.

AASHTO. (2009). *A Synthesis of Safety Implications of Oversize/overweight Commercial Vehicles*.

Adams, T. M., Perry, E., Schwartz, A., Gollnik, B., Kang, M., Bittner, J., and Wagner, S. (2013). *Aligning Oversize/Overweight Fees with Agency Costs: Critical Issues*.

Aghabayk, K., Sarvi, M., and Young, W. (2012). "Understanding the Dynamics of Heavy Vehicle Interactions in Car-Following." *Journal of Transportation Engineering*, 138(12), 1468–1475.

Ahmadi, M., Behzadian, K., Ardeshir, A., and Kapelan, Z. (2017). "Comprehensive Risk Management Using Fuzzy FMEA and MCDA Techniques in Highway Construction Projects." *Journal of Civil Engineering and Management*, 23(2), 300–310.

Ahmed, A. (2012). "Pavement Damage Cost Estimation Using Highway Agency Maintenance, Rehabilitation, and Reconstruction Strategies." *Purdue University*, Purdue University.

Ahmed, A., Agbelie, B. R., Lavrenz, S., Keefer, M., Labi, S., and Sinha, K. C. (2012). *Costs and Revenues Associated With Overweight Trucks in Indiana. Fhwa/in/Jtrp-2013/01*.

Ahmed, U., Drakopoulos, A., and Ng, M. (2013). "Impact of Heavy Vehicles on Freeway Operating Characteristics under Congested Conditions." *Transportation Research Record*, (2396), 28–37.

Al-Qadi, I., Ouyang, Y., Wang, H., Meidani, H., Gungor, O. E., PEtit, A., Zhao, J., and Qiu, J. (2017). *Development of a Proposed Overweight Vehicle Permit Fee Structure in Illinois*.

Ali, H., Nowak, A. S., Stallings, J. M., Chmielewski, J., and Stawska, S. (2020). *Impact of Heavy Trucks and Permitted Overweight Loads on Highways and Bridges Now and in the Future versus Permit Fees , Truck Registration Fees , and Fuel Taxes*.

ARTBA. (2022). "National Bridge Inventory: Indiana." <https://artbabridgereport.org/state/profile/IN> (Jun. 27, 2022).

Babu, A. M. R. (2019). "Quantifying the Fatigue Damage Accumulation in Bridges." Auburn University, Aubum, Alabama.

Bai, Q., and Labi, S. (2012). *Updating, Upgrading, Refining, Calibration and Implementation of*

Trade-Off Analysis Methodology Developed for INDOT.

Baláž, V., Dokupilová, D., and Filčák, R. (2021). "Participatory multi-criteria methods for adaptation to climate change." *Mitigation and Adaptation Strategies for Global Change*, Springer Netherlands, 26(4), 1–22.

Banerjee, A., Prozzi, J., and Prozzi, J. (2012). "Evaluating the effect of natural gas developments on highways." *Transportation Research Record*, 202(2282), 49–56.

Barbosa, S. B., Ferreira, M. G. G., Nickel, E. M., Cruz, J. A., Forcellini, F. A., Garcia, J., and Guerra, J. B. S. O. de A. (2017). "Multi-criteria analysis model to evaluate transport systems: An application in Florianópolis, Brazil." *Transportation Research Part A: Policy and Practice*, Elsevier Ltd, 96, 1–13.

Barfod, M. B. (2012). "An MCDA approach for the selection of bike projects based on structuring and appraising activities." *European Journal of Operational Research*, Elsevier B.V., 218(3), 810–818.

Barnes, G., and Langworthy, P. (2003). *The Per-Mile Costs of Operating Automobiles and Trucks*.

Basbas, S., and Makridakis, C. M. (2007). "A Review of the Contribution of Multi-Criteria Analysis to the Evaluation Process of Transportation Projects." *International Journal of Sustainable Development and Planning*, 2(4), 387–407.

Brauers, W. K. M., Zavadskas, E. K., Peldschus, F., and Turskis, Z. (2008). "Multi-Objective Decision-Making for Road Design." *Transport*, 23(3), 183–193.

Bulatov, N. K. (2021). "Development of the model (algorithm) of the efficient transportation logistics with the purpose of collection and transportation of the solid municipal waste to the places of their recycling." 2015–2037.

Cambridge Systematics, and SRF Consulting Group. (2006). *Minnesota Truck Size and Weight Project*.

Campbell, S., Swearingen, K. C., Honefanger, J. G., Keller, T., Ray, D., Humphrey, D., Miller, D., Hisem, J. M., Pritchard, T., Guckes, A. C. M., Nelson, D., Fejes, A., and Varner, S. (2009). *Impacts of Permitted Trucking on Ohio ' s Transportation System and Economy*.

Campos, V. B. G., Ramos, R. A. R., Miranda, D. de, and Correia, S. (2010). "Multi-criteria analysis procedure for sustainable mobility evaluation in urban areas." *Journal of Advanced Transportation*, 43(4), 371–390.

Celik, M., Cebi, S., Kahraman, C., and Er, I. D. (2009). “Application of Axiomatic Design and TOPSIS Methodologies under Fuzzy Environment for Proposing Competitive Strategies on Turkish Container Ports in Maritime Transportation Network.” *Expert System with Applicattions*, 36, 4541–4557.

Chen, X., Wang, Y., Tang, J., Dai, Z., and Ma, X. (2020). “Examining regional mobility patterns of public transit and automobile users based on the smart card and mobile Internet data: A case study of Chengdu, China.” *IET Intelligent Transport Systems*, 14(1), 45–55.

Chowdhury, M., Putman, B. J., Pang, W., Dunning, A., Dey, K. C., and Chen, L. (2013). *Rate of Deterioration of Bridges and Pavements as Affected by Trucks*.

Costa, C. A. B. E. (2001). “The use of multi-criteria decision analysis to support the search for less conflicting policy options in a multi-actor context: case study.” *Journal of Multi-Criteria Decision Analysis*, 10(2), 111–125.

Crockford, W. W. (1993). *Weight Tolerance Permits*. Austin, Texas.

Dalkey, N., and Helmer, O. (1963). “An Experimental Application of the DELPHI Method to the Use of Experts.” *Managment Science*, 9(3), 458–467.

David Luskin, C. M. W. (2001). *Effects of Truck Size and Weights on Highway Infrastructure and Operations: A Synthesis Report*. Austin, Texas.

Dawes, R. M., and Corrigan, B. (1974). “Linear models in decision making.” *Psychological Bulletin*, 81(2), 95–106.

Dehghan-Niri, E., Cortes, D. D., Zamen, S., Alvidrez, F., and Jauregui, D. (2020). “Simplified Comparison of Oversize and Overweight Vehicles Permit Fee Structure in the U.S. Western States.” *Transportation Research Record*, 2674(10), 963–988.

Dey, K. C., Chowdhury, M., Pang, W., Putman, B. J., and Chen, L. (2014). “Estimation of Pavement and Bridge Damage Costs Caused by Overweight Trucks.” *Transportation Research Record: Journal of the Transportation Research Board*, 2411(1), 62–71.

Dey, K. C., Chowdhury, M., Wiecek, M. M., and Dunning, A. (2015). “Infrastructure damage-cost-recovery fee for overweight trucks: Tradeoff analysis framework.” *Journal of Transportation Engineering*, 141(7), 04015008.

Dodgson, J. S., Spackman, M., Pearman, A., and Phillips, L. D. (2009). *Multi-Criteria Analysis : A Manual*. *Appraisal*.

Dong, C., Ph, D., Dong, Q., Ph, D., Huang, B., Ph, D., Asce, M., Hu, W., Nambisan, S. S., and

Ph, D. (2017). “Estimating Factors Contributing to Frequency and Severity of Large Truck – Involved Crashes.” 143(1996), 1–9.

Dubash, N. K., Raghunandan, D., Sant, G., and Sreenivas, A. (2013). “Indian Climate Change Policy: Exploring a Co-Benefits Based Approach.” *Indian Climate Change Policy*, xlviiI(22), 47–62.

Everett, S. R. (2015). “Overweight Vehicle Permitting Alternatives.”

Everett, S. R., Athigakunagorn, N., Woldemariam, W., Varadarajan, V., Arman, M., Roshandeh, A., Gkritza, K., Labi, S., and Sinha, K. C. (2014). *Impact of HB-1481 on Indiana’s Highway Revenue Generation, Asset Degradation, Modal Distribution, and Economic Development and Competitiveness*.

Federal Motor Carrier Safety Administration. (2020). *Emergency Declaration Under 49 CFR § 390.23*. 0–1.

FHWA. (1997). *1997 Federal Highway Cost Allocation Study Final Report*.

FHWA. (2015). *Compilation of Existing State Truck Size and Weight Limit Laws*. Washington DC.

FHWA. (2019). “Bridge Formula Weights.” <https://ops.fhwa.dot.gov/freight/publications/brdg_frm_wghts/> (May 23, 2022).

Florida Transportation Commission. (1993). *Truck Weights and Penalties in Florida*. Tallahassee, Florida.

Gagatsi, E., and Morfoulaki, M. (2013). “MultiActors Multi-Criteria Analysis for supporting policy making in the Greek Coastal Transport System.” *13th Special Conference of HELORS*, Thessaloniki, Greece.

Gao, J., Liu, B., Kong, L., and Guo, Z. (2004). “Study on the Influence of Heavy Vehicles on Freeway Safety.” *Proceedings 8th International Symposium on Heavy Vehicle Weights and Dimensions*, 7.

Goicoechea, A., Hansen, D. R., and Duckstein, L. (1982). *Multiobjective Decision analysis with Engineering and Business Applications*. John Wiley & Sons Incorporated.

Gungor, O. E., Petit, A. M. A., Qiu, J., Zhao, J., Meidani, H., Wang, H., Ouyang, Y., Al-Qadi, I. L., and Mann, J. (2019). “Development of an overweight vehicle permit fee structure for Illinois.” *Transport Policy*, Elsevier Ltd, 82(August), 26–35.

Hadi, M. A., Aruldhas, J., Chow, L. F., and Wattleworth, J. A. (1995). “Estimating safety effects of cross-section design for various highway types using negative binomial regression." *Transportation Research Record*, (1500), 169–177.

Hewitt, J., Stephens, J., Smith, K., and Menuez, N. (1999). "Infrastructure and Economic Impacts of Changes in Truck Weight Regulations in Montana." *Journal of the Transportation Research Board*, 1653(1), 42–51.

Hobbs, B., and Meier, P. (2000). *Energy Decisions and the Environment: A Guide to the Use of Multicriteria Methods*. Springer.

IDOT. (2022). "Oversize/Overweight Permits." <https://idot.illinois.gov/doing-business/permits/Oversize-and-Overweight-Permits/index> (May 23, 2022).

Indiana General Assembly. (2021). "Indiana Code 2021." <http://iga.in.gov/legislative/laws/2021/ic/titles/009> (May 18, 2022).

INDOR. (2017). *Oversize/Overweight Vehicle Permitting Handbook*.

INDOR. (2021a). "Overweight Permit Fees Oversize Permit Fees." <https://www.in.gov/dor/files/osw-permitting-memo-aug-2018.pdf> (Apr. 19, 2022).

INDOR. (2021b). "Indiana Department of Revenues: Annual Reports." <https://www.in.gov/dor/news-media-and-publications/annual-reports/> (May 28, 2022).

INDOR. (2022a). "Oversize/Overweight (OSW)." <https://www.in.gov/dor/motor-carrier-services/oversizeoverweight-osw> (Apr. 4, 2022).

INDOR. (2022b). *FY21 Annual Report*.

INDOT. (2013). *Title 105 Indiana Department of Transportation*.

INDOT. (2022). "Indiana Extra Heavy Duty Highways." <https://www.in.gov/indot/resources/maps/> (May 19, 2022).

Jacob, B., and La, V. F. (2010). "Improving truck safety: Potential of weigh-in-motion technology." 34, 9–15.

Jain, S., Aggarwal, P., Kumar, P., Singhal, S., and Sharma, P. (2014). "Identifying public preferences using multi-criteria decision making for assessing the shift of urban commuters from private to public transport: A case study of Delhi." *Transportation Research Part F: Traffic Psychology and Behaviour*, Elsevier Ltd, 24, 60–70.

Jeon, C. M., Amekudzi, A. A., and Guensler, R. L. (2010). "Evaluating Plan Alternatives for Transportation System Sustainability: Atlanta Metropolitan Region, International Journal of Sustainable Transportation." *International Journal of Sustainable Transportation*, 227–247.

Keeney, R. L., and Raiffa, H. (1976). *Decisions with Multiple Objectives: Preferences and Value Trade-Offs*. *IEEE Transactions on Systems, Man and Cybernetics*, Cambridge University Press.

Knoll, B., Buawald, P., Dopheide, R., Hofmann, R., Link, C., Pfaffenbichler, P., and Spreitzer, G. (2016). "Multi-perspective ICT-toolkit supporting inclusive and sustainable mobility planning in rural areas." *4th International Conference on ICT for Sustainability*, 134–140.

Krammes, R. A., and Crowley, K. W. (1986). "Passenger Car Equivalents for Trucks on Level Freeway Segments." *Transportation Research Record*, 10–17.

Kuzović, L. T., Aleksić, B. L., and Glavić., D. N. (2015). "The Application of the Multi-Criteria Analysis in Evaluating of the road Designs." *Tehnika*, 70(1), 143–150.

Labadie, N., and Prodhon, C. (2014). "A Survey on Multi-criteria Analysis in Logistics: Focus on Vehicle Routing Problems." *Applications of Multi-Criteria and Game Theory Approaches*, 3–29.

Leslie, A., and Murray, D. (2021). *An Analysis of the Operational Costs of Trucking: 2021 Update*. Minneapolis, MN.

Li, Z., and Sinha, K. C. (2004). "Methodology for multicriteria decision making in highway asset management." *Journal of the Transportation Research Board*, (1885), 79–87.

Luskin, D. L., Harrison, R., Walton, C. M., Zhang, Z., and Jerry L. Jamieson, J. (2000). *Alternatives to Weight Tolerance Permits*. Austin, Texas.

Macharis, C., and Bernardini, A. (2015). "Reviewing the Use of Multi-criteria Decision Analysis for the Evaluation of Transport Projects: Time for a Multi-actor Approach." *Transport Policy*, Elsevier, 37, 177–186.

Macura, D., Bojović, N., Nuhodžić, R., Šelmić, M., and Bošković, B. (2012). "Evaluation of Transport Projects Using Multi-Criteria Decision Making Method." *International Conference on Traffic and Transport Engineering*, Belgrade, 547–554.

Mathey, M. (2019). "One app to rule them all? Assessing mobility service providers for sustainable private Mobility as a Service platforms."

McDonald, M., Brackstone, M. A., Sultan, B., and Roach, C. (1997). "Close Following on the Motorway Initial Findings of an instrumented Vehicle Study." *Seventh International Conference series on Vision in Vehicles*, Elsevier, Marseille, France.

MDOT. (2019). "MiTRIP - Overweight or Oversize Permits."

<https://www.michigan.gov/mdot/business/permits/mitrip---overweight-or-oversize-permits#2> (May 23, 2022).

Nassif, H., Ozbay, K., Wang, H., Noland, R., Lou, P., Demiroluk, S., Su, D., Na, C., Zhao, J., and Beltran, M. (2015). *Impact of freight on highway infrastructure in New Jersey*.

National Transportation Reserach Center. (2022). "FHWA's Freight Analysis Framework 5 Summary Statistics." <https://faf.ornl.gov/faf5/SummaryTable.aspx> (Jul. 28, 2022).

Neff, R., and Bai, Y. (2012). "Developing a Sustainable Freight Transportation Framework with the Consideration of Improving Safety and Minimizing Carbon Emissions." 8.

ODOT. (2019). "Special Hauling Permit Fee Schedule." <https://www.transportation.ohio.gov/working/permits/special-hauling-permits/permit-information/fee-schedule> (May 23, 2022).

ODOT. (2020). "Operational Guide for Vehicles Operating with an Oversize/Overweight Special Hauling Permit." <https://dx-authoring.myohio.gov/wps/portal/gov/odot/working/publications/shp-op-guide#Section10FEESCHEDULE> (May 23, 2022).

Park, Y., Choi, J. K., and Zhang, A. (2009). "Evaluating competitiveness of air cargo express services." *Transportation Research Part E: Logistics and Transportation Review*, Elsevier Ltd, 45(2), 321–334.

Pigman, J. G., and Agent, K. R. (1999). *Heavy Truck Involvement in traffic Accidents and Related Countermeasures*.

Prozzi, M., Loftus-Otway, M., Banerjee, L., Wu, K., Prozzi, J. P., Hutchison, R., Harrison, R., Walton, C. M., Weissmann, J., and Weissmann, A. (2012). *Oversize/Overweight Vehicle Permit Fee Study*. Austin, Texas.

Purnus, A., and Bodea, C.-N. (2016). "Cash Flow Multi-Criteria Analysis in Construction Projects." *Creative Construction Conference*, Budapest, Hungary, 462–468.

Rabello Quadros, S. G., and Nassi, C. D. (2015). "An evaluation on the criteria to prioritize transportation infrastructure investments in Brazil." *Transport Policy*, Elsevier, 40, 8–16.

Saaty, T. L. (1977). "A Scaling Method for Priorities in Hierarchical Structures." *Journal of Mathematical Psychology*, 15(3), 234–281.

Salen, H. M. A. (2008). "Effect of excess axle weights on pavement life." *Emirates Journal for Engineering Research*, 13(1), 21–28.

Salling, K. B., Barfod, M. B., Pryn, M. R., and Leleur, S. (2018). “Flexible decision support for sustainable development: The SUSTAIN framework model.” *European Journal of Transport and Infrastructure Research*.

Santos, J., Bressi, S., Cerezo, V., and Lo Presti, D. (2019). “SUP&R DSS: A sustainability-based decision support system for road pavements.” *Journal of Cleaner Production*, 206, 524–540.

Sayadinia, S., and Beheshtinia, M. A. (2020). “Proposing a new hybrid multi-criteria decision-making approach for road maintenance prioritization.” *International Journal of Quality and Reliability Management*, 38(8), 1661–1679.

Scannella, G., and Beuthe, M. (2003). “Valuation of road projects with uncertain outcomes.” *Transport Reviews*, 23(1), 35–50.

De Silva, H., and Tatam, C. (1996). “An empirical procedure for enhancing the impact of road investments.” *Transport Policy*, 3(4), 201–211.

Sinha, K. C., and Labi, S. (2007). *Transportation Decision Making: Principles of Project Evaluation and Programming*. *Transportation Decision Making*, Wiley, New Jersey.

Sinha, K. C., Patidar, V., Li, Z., Labi, S., and Thompson, P. D. (2009). “Establishing the Weights of Performance Criteria : Case Studies in Transportation Facility Management.” *Journal of Transportation Engineeering*, 135(September), 619–631.

Specialized Carriers & Rigging Association. (2020). “How Covid-19 affects OS/OW Permits across States and Provinces.” <https://www.scranet.org/SCRA/Content/advocacy/2020-OSOW-Permit-Alerts.aspx> (May 28, 2022).

Straus, S. H., Raton, B., and Semmens, J. (2006). *Estimating the Cost of Overweight Vehicle Travel on Arizona Highways*.

Sun, H., Zhang, Y., Wang, Y., Li, L., and Sheng, Y. (2015). “A social stakeholder support assessment of low-carbon transport policy based on multi-actor multi-criteria analysis: The case of Tianjin.” *Transport Policy*, Elsevier, 41, 103–116.

Suthanaya, P. A. (2017). “Road Maintenance Priority Based On Multi-Criteria Approach (Case Study of Bali Province, Indonesia).” *International Journal of Engineering and Technology*, 9(4), 3191–3196.

Tabucanon, M. T., and Lee, H.-M. (1995). “Multiple Criteria Evaluation of Transportation System Improvement Projects: The Case of Korea.” *Journal of Advanced Transportation*, 29(1), 127–143.

Tarradell, M. (2020). “A Guide to Truck Weight, Classification, and Uses.” <https://www.tcsfuel.com/blog/truck-weight-classification/> (Jul. 13, 2022).

Toolshero. (2022). “Multiple Criteria Decision Analysis (MCDA).” *October 26, 2018*, <https://www.toolshero.com/decision-making/multiple-criteria-decision-analysis-mcda/> (Jun. 26, 2022).

Top Mark Funfing. LLC. (2020). “The Elusive 10 Miles per Gallon.” <https://www.topmarkfunding.com/the-elusive-10-miles-per-gallon/> (Jul. 13, 2022).

TRB. (1990). *Truck Size and Weight Limits: Issues and Options*. Washington DC.

TRB. (2000). *Highway Capacity Manual*. *National Research Council, Washington, DC*, Washington DC.

TRB. (2003). *NCHRP Report 505: Review of Truck Characteristics as Factors in Roadway Design*. *Review of Truck Characteristics as Factors in Roadway Design*.

Tsigdinos, S., and Vlastos, T. (2021). “Exploring ways to determine an alternative strategic road network in a metropolitan city: A multi-criteria analysis approach.” *IATSS Research*, International Association of Traffic and Safety Sciences, 45(1), 102–115.

Turner, S., Best, M. E., and Schrank, D. L. (1996). *Measures of Effectiveness for Major Investment Studies*.

TxDOT. (2005). “Construction and Materials Tips.” <https://ftp.dot.state.tx.us/pub/txdot-info/cst/tips/flex_pave_des_faq.pdf> (Jun. 26, 2022).

Tzeng, G. H., Lin, C. W., and Opricovic, S. (2005). “Multi-criteria analysis of alternative-fuel buses for public transportation.” *Energy Policy*, 33(11), 1373–1383.

U.S. Bureau of Labor Statistics. (n.d.). “CPI Inflation Calculator.” <https://www.bls.gov/data/inflation_calculator.htm> (Jul. 12, 2022).

U.S. Department of Transportation; Bureau of Transportation Statistics. (2020). *Transportation Statistics Annual Report 2020*. Washington DC.

U.S. Department of Transportation. (1997). “Truck Size and Weight Limits.” *1997 U.S. DOT Comprehensive TS&W Study*, 19.

U.S. Energy Information Administration. (2022). “Petroleum & Other Liquids.” <https://www.eia.gov/petroleum/gasdiesel/> (Jul. 19, 2022).

USDOT. (2000a). *Comprehensive Truck Size and Weight Study: Volume II: Issues and*

Background, Publication FHWA-PL-00-029 (Volume II).

USDOT. (2000b). *Comprehensive Truck Size and Weight Study, Vol. III: Scenario Analysis, Publication FHWA-PL-00-029 (Volume III)*.

USDOT. (2015). *Highway Safety and Truck Crash Comparative Analysis*.

Vilke, S., Debelić, B., and Mance, D. (2020). "Application Of The Multi-Criteria Analysis For The Railway Route Evaluation And Selection." *Business Logistics in Modern Management*, Osijek, Croatia.

Wang, X., Zhao, P., and Tao, Y. (2018). "Evaluating Impacts of Overloaded Heavy Vehicles on Freeway Traffic Condition by a Novel Multi-Class Traffic Flow Model." *Sustainability (Switzerland)*, 10(12).

Webster, N., and Elefteriadou, L. (1999). "A simulation study of truck passenger car equivalents (PCE) on basic freeway sections." *Transportation Research Part B: Methodological*, 33(5), 323–336.

Weisbrod, G. (2016). *Productivity: The Connection Between Transportation Performance and the Economy*.

Wikipedia. (2011). "Conventional 18-Wheeler Truck Diagram." <https://en.wikipedia.org/wiki/File:Conventional_18-wheeler_truck_diagram.svg> (Jul. 14, 2022).

WisDOT. (2021a). "Oversize/Overweight Multiple Trip Permit Information." <https://wisconsindot.gov/Documents/formdocs/mv2614.pdf> (May 22, 2022).

WisDOT. (2021b). "Oversize/Overweight Single Trip Permit Information." <https://wisconsindot.gov/Documents/formdocs/mv2600.pdf> (May 22, 2022).

Yang, C. H., and Regan, A. C. (2013). "A multi-criteria decision support methodology for implementing truck operation strategies." *Transportation*, 40(3), 713–728.

Yoo, H., and Green, P. (1999). *Driver Behavior While Following Cars, Trucks, and Buses*. *Report*, Ann Arbor, Michigan.

Zhao, J., and Tabatabai, H. (2009). *Analysis of Permit Vehicle Loads in Wisconsin*.

Zhou, H. W., Li, G. X., and Shi, K. T. (2012). *Jiangsu Freeway Traffic Condition Analyzing Report*. Nanjing, China.

APPENDIX A. BRIDGE CONSUMPTION COST FROM SPR-3502

Highway Type	Bridge Type	Age Group	Cost per Length per Pass for AASHTO Loadings (HS/2010$/ft)										
			20	21	22	23	24	25	26	27	28	29	30
Interstate	Steel	0 to 20	0.015	0.021	0.022	0.047	0.076	0.107	0.138	0.170	0.213	0.276	0.348
		21 to 35	0.016	0.022	0.023	0.050	0.080	0.112	0.145	0.178	0.223	0.290	0.365
		36 to 55	0.016	0.022	0.023	0.050	0.080	0.112	0.145	0.178	0.223	0.290	0.365
		56 to 70	0.018	0.024	0.025	0.054	0.086	0.121	0.156	0.192	0.240	0.312	0.394
	Prestressed Concrete	0 to 20	0.016	0.022	0.023	0.049	0.078	0.110	0.142	0.175	0.218	0.284	0.358
		21 to 35	0.017	0.023	0.024	0.051	0.082	0.114	0.148	0.182	0.227	0.295	0.373
		36 to 55	0.018	0.023	0.024	0.052	0.084	0.118	0.152	0.187	0.234	0.304	0.384
		56 to 70	0.020	0.025	0.026	0.057	0.091	0.128	0.165	0.203	0.254	0.330	0.417
	Reinforced Concrete	0 to 20	0.015	0.021	0.022	0.047	0.075	0.106	0.137	0.168	0.211	0.274	0.345
		21 to 35	0.016	0.022	0.023	0.049	0.078	0.110	0.142	0.175	0.219	0.284	0.358
		36 to 55	0.017	0.022	0.024	0.050	0.081	0.114	0.147	0.181	0.226	0.294	0.370
		56 to 70	0.019	0.024	0.025	0.055	0.088	0.123	0.159	0.196	0.245	0.318	0.401
NHS Non-Interstate	Steel	0 to 20	0.046	0.053	0.059	0.127	0.204	0.286	0.370	0.455	0.569	0.739	0.932
		21 to 35	0.049	0.055	0.062	0.133	0.214	0.300	0.387	0.477	0.597	0.775	0.977
		36 to 55	0.049	0.055	0.062	0.133	0.214	0.300	0.387	0.477	0.597	0.775	0.978
		56 to 70	0.054	0.060	0.067	0.143	0.230	0.323	0.417	0.514	0.643	0.835	1.530
	Prestressed Concrete	0 to 20	0.047	0.054	0.061	0.130	0.209	0.293	0.379	0.467	0.584	0.759	0.957
		21 to 35	0.05	0.057	0.063	0.136	0.218	0.306	0.395	0.487	0.609	0.791	0.997
		36 to 55	0.052	0.059	0.065	0.140	0.225	0.315	0.407	0.501	0.627	0.815	1.027
		56 to 70	0.057	0.064	0.071	0.152	0.244	0.342	0.442	0.544	0.681	0.884	1.115
	Reinforced Concrete	0 to 20	0.045	0.052	0.059	0.126	0.202	0.283	0.366	0.451	0.564	0.732	0.923
		21 to 35	0.047	0.054	0.061	0.130	0.210	0.294	0.380	0.468	0.585	0.760	0.959
		36 to 55	0.05	0.056	0.063	0.135	0.217	0.304	0.393	0.484	0.605	0.786	0.992
		56 to 70	0.055	0.061	0.068	0.146	0.235	0.329	0.425	0.524	0.655	0.851	1.073
Non-NHS Roads	Steel	0 to 20	0.153	0.180	0.208	0.445	0.715	1.001	1.295	1.595	1.994	2.591	3.267
		21 to 35	0.163	0.190	0.218	0.466	0.749	1.050	1.358	1.672	2.091	2.716	3.425
		36 to 55	0.163	0.19	0.218	0.466	0.750	1.050	1.358	1.672	2.091	2.717	3.426
		56 to 70	0.18	0.207	0.235	0.503	0.808	1.131	1.463	1.802	2.253	2.928	3.692
	Prestressed Concrete	0 to 20	0.158	0.186	0.213	0.457	0.734	1.028	1.329	1.637	2.047	2.660	3.354
		21 to 35	0.167	0.195	0.222	0.476	0.765	1.071	1.385	1.706	2.133	2.772	3.495
		36 to 55	0.174	0.201	0.229	0.490	0.788	1.103	1.427	1.757	2.197	2.855	3.600
		56 to 70	0.193	0.221	0.248	0.532	0.855	1.198	1.549	1.907	2.385	3.099	3.907
	Reinforced Concrete	0 to 20	0.151	0.178	0.206	0.441	0.708	0.992	1.283	1.580	1.975	2.566	3.236
		21 to 35	0.159	0.186	0.214	0.457	0.735	1.029	1.331	1.639	2.050	2.664	3.359
		36 to 55	0.166	0.193	0.221	0.473	0.760	1.065	1.377	1.696	2.121	2.756	3.475
		56 to 70	0.184	0.212	0.239	0.512	0.823	1.152	1.490	1.835	2.295	2.982	3.760

Figure A.1. Bridge Damage Cost for HS20-HS30.

Highway Type	Bridge Type	Age Group	Cost per Length per Pass for AASHTO Loadings (HS/2010$/ft)									
			31	32	33	34	35	36	37	38	39	40
Interstate	Steel	0 to 20	0.430	0.517	0.619	0.738	0.879	1.042	1.278	1.715	2.345	3.384
		21 to 35	0.451	0.542	0.649	0.774	0.922	1.093	1.340	1.798	2.459	3.548
		36 to 55	0.451	0.542	0.649	0.774	0.922	1.093	1.340	1.799	2.459	3.549
		56 to 70	0.486	0.584	0.699	0.834	0.994	1.178	1.444	1.938	2.650	3.824
	Prestressed Concrete	0 to 20	0.442	0.530	0.635	0.758	0.903	1.070	1.312	1.761	2.408	3.474
		21 to 35	0.460	0.553	0.662	0.790	0.941	1.115	1.367	1.835	2.509	3.620
		36 to 55	0.474	0.569	0.682	0.813	0.969	1.148	1.408	1.890	2.584	3.729
		56 to 70	0.515	0.618	0.740	0.883	1.052	1.247	1.529	2.051	2.805	4.047
	Reinforced Concrete	0 to 20	0.426	0.512	0.613	0.731	0.871	1.032	1.266	1.699	2.323	3.352
		21 to 35	0.442	0.531	0.636	0.759	0.904	1.072	1.314	1.764	2.411	3.479
		36 to 55	0.458	0.550	0.658	0.785	0.935	1.109	1.360	1.825	2.495	3.600
		56 to 70	0.495	0.595	0.712	0.850	1.012	1.200	1.471	1.974	2.699	3.895
NHS Non-Interstate	Steel	0 to 20	1.152	1.383	1.656	1.976	2.354	2.790	3.422	4.592	6.278	9.059
		21 to 35	1.207	1.450	1.736	2.072	2.468	2.925	3.587	4.814	6.582	9.497
		36 to 55	1.208	1.450	1.736	2.072	2.469	2.926	3.588	4.815	6.583	9.499
		56 to 70	1.301	1.562	1.871	2.233	2.660	3.153	3.866	5.188	7.093	10.235
	Prestressed Concrete	0 to 20	1.182	1.420	1.700	2.028	2.417	2.864	3.513	4.714	6.445	9.299
		21 to 35	1.232	1.479	1.771	2.114	2.518	2.985	3.660	4.912	6.716	9.691
		36 to 55	1.269	1.524	1.824	2.177	2.594	3.074	3.770	5.059	6.917	9.981
		56 to 70	1.377	1.654	1.980	2.363	2.815	3.337	4.092	5.491	7.508	10.833
	Reinforced Concrete	0 to 20	1.141	1.370	1.640	1.957	2.332	2.764	3.389	4.548	6.218	8.973
		21 to 35	1.184	1.422	1.702	2.031	2.420	2.869	3.518	4.721	6.454	9.313
		36 to 55	1.225	1.471	1.761	2.102	2.504	2.968	3.640	4.884	6.678	9.636
		56 to 70	1.325	1.591	1.906	2.274	2.709	3.211	3.938	5.284	7.225	10.425
Non-NHS Roads	Steel	0 to 20	4.036	4.846	5.803	6.925	8.250	9.779	11.991	16.092	22.001	31.747
		21 to 35	4.231	5.081	6.084	7.260	8.649	10.252	12.571	16.870	23.065	33.282
		36 to 55	4.232	5.081	6.085	7.261	8.651	10.254	12.573	16.873	23.069	33.288
		56 to 70	4.560	5.475	6.556	7.824	9.321	11.048	13.548	18.181	24.857	35.868
	Prestressed Concrete	0 to 20	4.143	4.975	5.957	7.109	8.469	10.038	12.309	16.519	22.585	32.589
		21 to 35	4.317	5.184	6.208	7.408	8.825	10.461	12.827	17.214	22.535	33.961
		36 to 55	4.446	5.339	6.393	7.629	9.089	10.773	13.211	17.729	24.239	34.976
		56 to 70	4.826	5.795	6.940	8.281	9.866	11.694	14.340	19.244	26.310	37.965
	Reinforced Concrete	0 to 20	3.997	4.800	5.748	6.859	8.171	9.685	11.877	15.938	21.791	31.444
		21 to 35	4.149	4.982	5.966	7.119	8.481	10.053	12.327	16.543	22.617	32.636
		36 to 55	4.293	5.155	6.173	7.366	8.775	10.401	12.755	17.116	23.401	33.768
		56 to 70	4.645	5.577	6.678	7.969	9.494	11.253	13.800	18.519	25.319	36.535

Figure A.2. Bridge Damage Cost for HS31-HS40.

Highway Type	Bridge Type	Age Group	Cost per Length per Pass for AASHTO Loadings (HS/2010$/ft)									
			41	42	43	44	45	46	47	48	49	50
Interstate	Steel	0 to 20	5.397	5.667	5.937	6.207	6.478	7.632	8.960	10.484	12.227	14.217
		21 to 35	5.658	5.864	6.070	6.277	6.483	7.638	8.938	10.494	12.241	14.233
		36 to 55	5.659	5.865	6.071	6.277	6.483	7.638	8.968	10.494	12.241	14.234
		56 to 70	6.098	6.196	6.294	6.393	6.491	7.650	8.982	10.512	12.263	14.262
	Prestressed Concrete	0 to 20	5.540	5.775	6.010	6.245	6.480	7.635	8.965	10.490	12.235	14.226
		21 to 35	5.773	5.951	6.129	6.307	6.485	7.641	8.972	10.499	12.247	14.241
		36 to 55	5.946	6.082	6.217	6.353	6.488	7.646	8.977	10.506	12.256	14.252
		56 to 70	6.454	6.465	6.473	6.487	6.498	7.659	8.993	10.526	12.282	14.285
	Reinforced Concrete	0 to 20	5.345	5.629	5.912	6.196	6.479	7.634	8.963	10.488	12.232	14.223
		21 to 35	5.548	5.782	6.016	6.250	6.483	7.639	8.969	10.496	12.243	14.236
		36 to 55	5.741	5.927	6.114	3.600	6.487	7.644	8.975	10.503	12.252	14.248
		56 to 70	6.211	6.282	6.354	6.425	6.496	7.656	8.990	10.522	12.276	14.278
NHS Non-Interstate	Steel	0 to 20	14.466	15.693	16.939	18.186	19.433	22.895	26.880	31.452	36.682	42.650
		21 to 35	15.145	16.220	17.296	18.371	19.446	22.913	26.902	31.479	36.718	42.695
		36 to 55	15.148	16.222	17.297	18.372	19.466	22.913	26.902	31.480	36.718	42.695
		56 to 70	16.322	17.109	17.896	18.683	19.470	22.943	26.939	31.526	36.778	42.771
	Prestressed Concrete	0 to 20	14.830	15.982	17.135	18.288	19.440	22.905	26.892	31.467	36.702	42.675
		21 to 35	15.454	16.453	17.453	18.453	19.453	22.921	26.012	31.492	36.734	42.715
		36 to 55	15.916	16.802	17.689	18.575	19.452	22.933	26.926	31.510	36.758	42.745
		56 to 70	17.276	17.829	18.382	18.935	19.489	22.968	26.969	31.563	36.827	42.833
	Reinforced Concrete	0 to 20	14.308	15.591	16.873	18.155	19.437	22.902	26.888	31.462	36.695	42.666
		21 to 35	14.851	16.000	17.150	18.299	19.448	22.915	26.905	31.484	36.723	42.701
		36 to 55	15.366	16.389	17.412	18.435	19.458	22.929	26.921	31.503	36.749	42.734
		56 to 70	16.625	17.340	18.054	18.769	19.483	22.961	26.961	31.553	36.814	42.815
Non-NHS Roads	Steel	0 to 20	50.626	54.163	57.701	61.238	64.775	76.318	89.600	104.840	122.275	142.166
		21 to 35	53.074	56.012	58.949	61.886	64.824	76.380	89.677	104.936	122.400	142.324
		36 to 55	53.084	56.019	58.954	61.889	64.824	76.381	89.678	104.937	122.400	142.325
		56 to 70	57.198	59.125	61.052	62.979	64.905	76.486	89.807	105.099	122.611	142.590
	Prestressed Concrete	0 to 20	51.969	55.178	58.386	61.594	64.802	76.352	89.643	104.893	122.343	142.253
		21 to 35	54.157	56.829	59.501	62.173	64.845	76.408	89.711	104.979	122.455	142.394
		36 to 55	55.776	58.051	60.327	62.602	64.877	76.449	89.762	105.043	122.538	142.499
		56 to 70	60.542	61.649	62.757	63.864	64.971	76.571	89.913	105.230	122.782	142.806
	Reinforced Concrete	0 to 20	50.143	53.805	57.468	61.130	64.792	76.340	89.627	104.874	122.319	142.222
		21 to 35	52.045	55.241	58.437	61.634	64.830	76.388	89.687	104.949	122.416	142.345
		36 to 55	53.489	56.603	59.357	62.111	64.866	76.434	89.744	105.020	122.508	142.461
		56 to 70	58.262	59.934	61.607	63.280	64.953	76.547	89.883	105.193	122.734	142.746

Figure A.3. Bridge Damage Cost for HS41-HS50.

APPENDIX B. BRIDGE DAMAGE COSTS RESULTS

Highway Type	Bridge Type	Age (years)	Bridge Length (ft)	Unit Cost HS 27 100% Load-Share (2010 $/ft-pass)	Unit Cost HS 27 100% Load-Share (2022 $/ft-pass)	Cost ($/truck)	Total Cost
Interstate	Prestressed Concrete	55	176.2	0.17	0.274	$ 48.28	$ 434.48
Interstate	Prestressed Concrete	56	272.0	0.184	0.296	$ 80.51	$ 724.59
Interstate	Prestressed Concrete	56	111.9	0.184	0.296	$ 33.12	$ 298.05
Interstate	Prestressed Concrete	58	168.0	0.184	0.296	$ 49.72	$ 447.52
Interstate	Reinforced Concrete	13	32.5	0.153	0.246	$ 7.99	$ 71.91
Interstate	Reinforced Concrete	55	91.9	0.164	0.264	$ 24.25	$ 218.28
Interstate	Reinforced Concrete	55	105.0	0.164	0.264	$ 27.72	$ 249.46
Interstate	Reinforced Concrete	55	165.0	0.164	0.264	$ 43.57	$ 392.12
Interstate	Reinforced Concrete	56	103.0	0.177	0.285	$ 29.36	$ 264.26
Interstate	Reinforced Concrete	56	87.9	0.177	0.285	$ 25.06	$ 225.54
Interstate	Reinforced Concrete	56	134.8	0.177	0.285	$ 38.43	$ 345.89
Interstate	Reinforced Concrete	56	113.9	0.177	0.285	$ 32.45	$ 292.03
Interstate	Reinforced Concrete	56	457.4	0.177	0.285	$ 130.35	$ 1,173.16
Interstate	Reinforced Concrete	56	82.0	0.177	0.285	$ 23.38	$ 210.39
Interstate	Reinforced Concrete	56	73.2	0.177	0.285	$ 20.85	$ 187.67
Interstate	Reinforced Concrete	56	90.9	0.177	0.285	$ 25.90	$ 233.12
Interstate	Reinforced Concrete	56	152.9	0.177	0.285	$ 43.57	$ 392.17
Interstate	Reinforced Concrete	56	101.1	0.177	0.285	$ 28.80	$ 259.21
Interstate	Reinforced Concrete	57	138.1	0.177	0.285	$ 39.37	$ 354.30
Interstate	Reinforced Concrete	57	151.6	0.177	0.285	$ 43.20	$ 388.81
Interstate	Reinforced Concrete	57	70.5	0.177	0.285	$ 20.10	$ 180.94
Interstate	Reinforced Concrete	57	201.1	0.177	0.285	$ 57.32	$ 515.89
Interstate	Reinforced Concrete	57	85.6	0.177	0.285	$ 24.41	$ 219.65

Highway Type	Bridge Type	Age (years)	Bridge Length (ft)	Unit Cost HS 27 100% Load-Share (2010 $/ft-pass)	Unit Cost HS 27 100% Load-Share (2022 $/ft-pass)	Cost ($/truck)	Total Cost
Interstate	Reinforced Concrete	57	107.6	0.177	0.285	$ 30.67	$ 276.04
Interstate	Reinforced Concrete	57	164.7	0.177	0.285	$ 46.94	$ 422.47
Interstate	Reinforced Concrete	57	155.8	0.177	0.285	$ 44.42	$ 399.75
Interstate	Reinforced Concrete	58	112.9	0.177	0.285	$ 32.17	$ 289.50
Interstate	Reinforced Concrete	58	79.1	0.177	0.285	$ 22.54	$ 202.82
Interstate	Reinforced Concrete	58	65.6	0.177	0.285	$ 18.70	$ 168.32
Interstate	Reinforced Concrete	58	81.4	0.177	0.285	$ 23.19	$ 208.71
Interstate	Reinforced Concrete	60	75.5	0.177	0.285	$ 21.51	$ 193.56
Interstate	Reinforced Concrete	63	105.6	0.177	0.285	$ 30.11	$ 270.99
Interstate	Steel	55	250.0	0.162	0.261	$ 65.25	$ 587.28
Interstate	Steel	56	364.8	0.174	0.280	$ 102.16	$ 919.41
Interstate	Steel	56	227.0	0.174	0.280	$ 63.57	$ 572.15
Interstate	Steel	57	173.9	0.174	0.280	$ 48.69	$ 438.21
Interstate	Steel	57	182.4	0.174	0.280	$ 51.08	$ 459.71
Interstate	Steel	57	213.9	0.174	0.280	$ 59.90	$ 539.08
Interstate	Steel	57	363.9	0.174	0.280	$ 101.88	$ 916.93
Interstate	Steel	57	227.7	0.174	0.280	$ 63.76	$ 573.81
Interstate	Steel	57	207.0	0.174	0.280	$ 57.97	$ 521.72
Interstate	Steel	57	188.7	0.174	0.280	$ 52.82	$ 475.42
Interstate	Steel	58	178.8	0.174	0.280	$ 50.07	$ 450.61
Interstate	Steel	58	365.2	0.174	0.280	$ 102.25	$ 920.24
Interstate	Steel	59	184.4	0.174	0.280	$ 51.63	$ 464.67
Interstate	Steel	60	221.1	0.174	0.280	$ 61.92	$ 557.27
Interstate	Steel	60	106.6	0.174	0.280	$ 29.86	$ 268.71
Interstate	Steel	60	284.1	0.174	0.280	$ 79.56	$ 716.02
Interstate	Steel	63	162.1	0.174	0.280	$ 45.38	$ 408.45
Interstate	Steel	63	222.1	0.174	0.280	$ 62.19	$ 559.75
			8238.6			$ 2,317.89	$ 20,861.05

APPENDIX C. SURVEY

Section A: Developing Value Function for Average Travel Speed

This section is designed to evaluate the impact of changes in policies regulating the operation of overweight trucks on traffic mobility. For that purpose, a value function for the average speed on Interstate 70 (I-70), in which the average speed limit is 65 mph, will be developed based on the responses. *In Figure C1, the x-axis represents the* average travel speed *(mph) and the y-axis represents your level of satisfaction on a scale of 0 to 100.*

Figure C1. Value function for the traffic mobility performance criterion.

Assuming that an average speed of 25 mph or less is assigned a level of satisfaction of 0 percent and an average speed of 65 mph is assigned to a level of satisfaction of 100 percent, answer the question below.

Does the linear function show in Figure C1 fit your personal degree of satisfaction towards the different values presented for the following average travel speed: 35 mph, 45 mph, and 55 mph?
Yes __________ No___________

If your answer is No:

- To reflect your level of satisfaction, what value (on a scale of 0 to 100) would you assign to an average travel speed of 35 mph on I-70, considering that the speed limit on the interstate is 65 mph?

  ____

- To reflect your level of satisfaction, what value (on a scale of 0 to 100) would you assign to an average travel speed of 45 mph on I-70, considering that the speed limit on the interstate is 65 mph?

  ____

- To reflect your level of satisfaction, what value (on a scale of 0 to 100) would you assign to an average travel speed of 55 mph on I-70, considering that the speed limit on the interstate is 65 mph?

  ____

Section B: Developing Value Function for Traffic Safety

To support national and state goals of reducing the freight-involved crashes in Indiana, INDOT established safety performance measures in its 2014 Multimodal Freight and Mobility Plan. In that plan, INDOT defined the following annual safety targets for the national freight network for Indiana by 2035: 0.01 fatal crashes per centerline mile, 2.8 injury crashes per centerline mile, and 9.5 property damage crashes per centerline mile.

In Figure C2, the x-axis represents the annual injury crashes expected to occur per centerline mile due to overweight truck operations and the y-axis represents your level of satisfaction on a scale of 0 (extremely unsatisfied) to 100 (extremely satisfied).

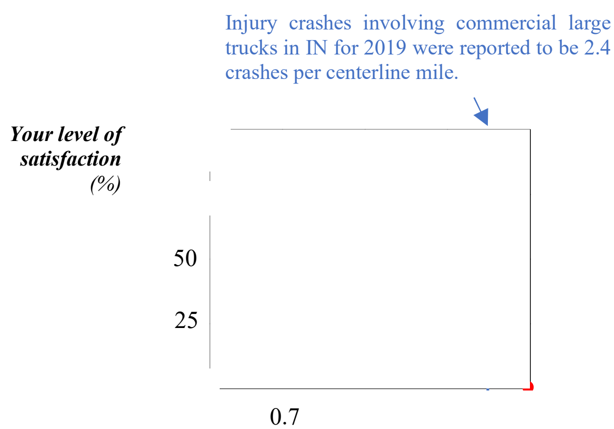


Figure C2. Value function for the road safety performance criterion.

Assuming that an annual number of freight related injury crashes of 0 per centerline mile is assigned to a level of satisfaction of 100 percent and an annual number of freight related injury crashes of 2.8 per centerline mile is assigned to a level of satisfaction of 0 percent, answer the question below:

Does the linear function in Figure C2 fit your personal degree of satisfaction towards the different values presented for annual injury crashes involving large commercial trucks (0.7 injury crashes per centerline mile, 1.4 injury crashes per centerline mile, and 2.1 injury crashes per centerline mile)?
Yes ___________ No___________

If your answer is No:

- To reflect your level of satisfaction, on a scale of 0 to 100, what value would you assign to an annual crash frequency of 0.7 injury crashes per centerline mile on I-70?

  ____

- To reflect your level of satisfaction, on a scale of 0 to 100, what value would you assign to an annual crash frequency of 1.4 injury crashes per centerline mile on I-70?

  ____

- To reflect your level of satisfaction, on a scale of 0 to 100, what value would you assign to an annual crash frequency of 2.1 injury crashes per centerline mile on I-70?

  ____

Section C: Developing Value Function for the Infrastructure Damage Cost

Infrastructure damage costs refer to the cost INDOT incurred in the maintenance, rehabilitation, and reconstruction of pavement and bridge assets due to the operation of overweight trucks. Past studies have estimated that the unit damage costs of overweight trucks on interstates is $0.010/ESAL-mile for pavement assets and $1.182/ft-pass for bridge assets on average.

To provide a baseline assessment of likely outcomes for the annual percentage change in infrastructure damage cost, the extreme condition of only having legal-weight trucks (trucks with gross vehicle weight, GVW, of 80,000 lbs. or less) traversing I-70 was defined as the baseline condition. Estimates of the potential effects of overweight trucks on I-70 suggests an annual increase of approximately 128% higher infrastructure damage cost than having only legal-weight trucks traveling on the interstate.

In Figure C3, the x-axis represents the annual percentage change in infrastructure damage costs *for I-70 and the y-axis represents your level of satisfaction on a scale of 0 (extremely unsatisfied) to 100 (extremely satisfied).*

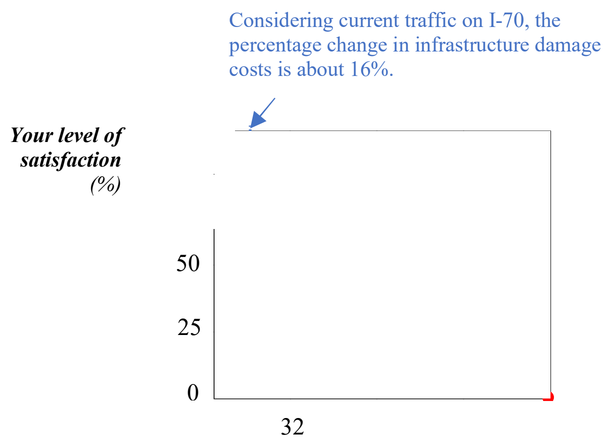


Figure C3. Value function for the infrastructure damage cost performance criterion.

Assuming that a 0 percent annual change in infrastructure damage cost is assigned to a level of satisfaction of 100 percent and a 128 percent annual change in infrastructure damage cost is assigned to a level of satisfaction of 0 percent, answer the question below.

Does the linear function in Figure C3 fit your personal degree of satisfaction towards the different values presented for annual percentage change in infrastructure damage cost (32%, 64%, and 96%)?
Yes ___________ No____________

If your answer is No:

- To reflect your level of satisfaction, on a scale of 0 to 100, what value would you assign to an annual increase of 32 percent in infrastructure damage cost for I-70?

____

- To reflect your level of satisfaction, on a scale of 0 to 100, what value would you assign to an annual increase of 64 percent in infrastructure damage cost for I-70?

____

- To reflect your level of satisfaction, on a scale of 0 to 100, what value would you assign to an annual increase of 96 percent in infrastructure damage cost for I-70?

Section D: Developing Value Function for the Overweight Permitting Revenues

Overweight permitting revenues refer to the total amount of income generated by the sale of overweight permits that allow trucks exceeding the maximum allowable weight to travel on Indiana's roads and bridges.

Assuming that the revenues collected from the sales of overweight permits are enough to cover the total pavement and bridge consumption costs incurred by the overweight portion of the load (beyond 80,000 lbs.) carried by overweight trucks, the following two extreme conditions were considered to provide a baseline assessment of likely outcomes for the annual percentage change in overweight permit revenues:

1) Only legal weight trucks traverse I-70. Thus, the annual percentage change in overweight permit revenues needed for covering their corresponding additional pavement and bridge consumption is estimated to be less than or equal to 0%, as trucks with a gross vehicle weight of 80,000 lbs. or less are not required to purchase any overweight permit.
2) Overweight trucks traverse I-70. Thus, the annual percentage change in overweight permit revenues needed for covering their corresponding additional pavement and bridge consumption is estimated to be 4400% higher than the estimated baseline value of $7.7 million revenues in 2021.

In Figure C4, the x-axis represents the annual percentage change in overweight permit revenues for I-70, and the y-axis represents your level of satisfaction on a scale of 0 (extremely unsatisfied) to 100 (extremely satisfied).

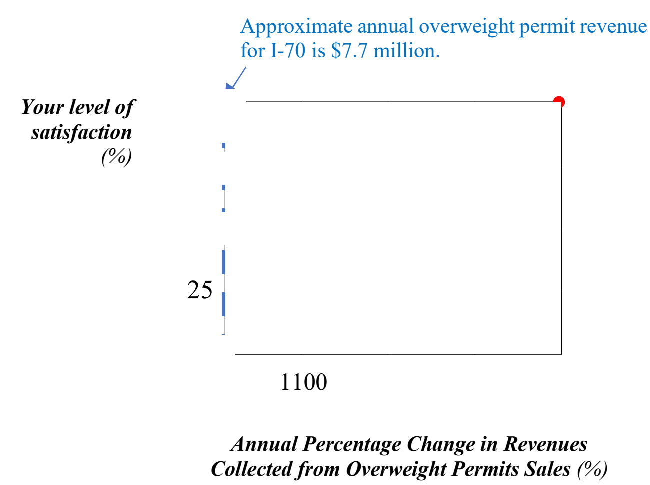


Figure C4. Value function for the overweight permitting revenues performance criterion.

Assuming that a 0 percent annual change in overweight permit revenues is assigned to a level of satisfaction of 0 percent and a 4400 percent annual change in overweight permit revenues is assigned to a level of satisfaction of 100 percent, answer the question below.

Does the linear function in Figure 4A fit your personal degree of satisfaction towards the different values presented for annual percentage change in overweight permit revenues (1100%, 2200%, and 3300%)?
Yes __________ No___________

If your answer is No:

- To reflect your level of satisfaction, on a scale of 0 to 100, what value would you assign to an annual increase of 1100 percent in revenues collected from the sale of overweight permits for I-70?

____

- To reflect your level of satisfaction, on a scale of 0 to 100, what value would you assign to an annual increase of 2200 percent in revenues collected from the sale of overweight permits for I-70?

____

- To reflect your level of satisfaction, on a scale of 0 to 100, what value would you assign to an annual increase of 3300 percent in revenues collected from the sale of overweight permits for I-70?

____

Section E: Developing Value Function for Trucks Vehicle Operation Costs

This section was designed to evaluate the impact of changes in policies regulating the operation of overweight trucks on shippers and carriers' operational costs traveling I-70.
Real-world data collected from commercial motor carriers by the American Transportation Research Institute in 2018 has shown that the average marginal operational costs of the trucking industry is $2.20 per truck per mile traveled. However, ongoing major freight transportation projects on Indiana's primary highway freight network are expected to lower this marginal truck vehicle operation cost to $1 by 2035, as established in the 2014 Indiana Multimodal Freight and Mobility Plan. For the purpose of this survey, these values were used to provide a baseline assessment of likely outcomes for I-70.

In Figure C5, the x-axis represents the truck vehicle operation costs *of shippers and carriers (dollars per truck-mile), and the y-axis represents your level of satisfaction on a scale of 0 (extremely unsatisfied) to 100 (extremely satisfied).*

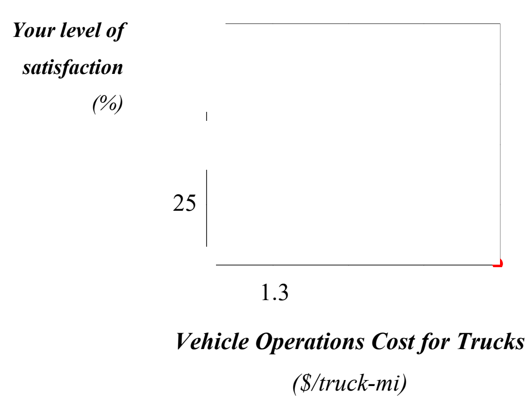


Figure C5. Value function for truck VOC performance criterion.

Assuming that a truck vehicle operation cost of $1 per truck-mile is assigned to a level of satisfaction of 100 percent and a truck vehicle operation cost of $2.2 per truck-mile is assigned to a level of satisfaction of 0 percent, answer the question below.

Does the linear function presented in Figure C5 fit your personal degree of satisfaction towards the different values presented for truck vehicle operation cost ($1.3 per truck-mile, $1.6 per truck-mile, and $1.9 per truck-mile)?
Yes __________ No___________

If your answer is No:

- To reflect your level of satisfaction, what value would you assign to a truck vehicle operation cost of $1.3 per truck per mile on a scale of 0 to 100?

  ____

- To reflect your level of satisfaction, what value would you assign to a truck vehicle operation cost of $1.6 per truck per mile to reflect your level of satisfaction on a scale of 0 to 100?

  ____

- To reflect your level of satisfaction, what value would you assign to a truck vehicle operation cost of $1.9 per truck per mile to reflect your level of satisfaction on a scale of 0 to 100?

  ____

Section F: Developing Value Function for Shipping Inventory Cost

This section was designed to evaluate the impact of changes in policies regulating the operation of overweight trucks on the trucking industry in terms of shipping inventory cost. Shipping inventory costs refer to the carrying interest cost that a cargo owner incurs while the inventory is in transit. When a cargo is being transported, the owner is unable to invest the otherwise cash that the cargo is equivalent to, resulting in shipping inventory costs. Shipping inventory costs is influenced by factors such as the travel speed, the value of the cargo being transported, and the interest rate.

According to the national Freight Analysis Framework database, I-70 is projected to move between 60 and 315 million tons of freight, representing approximately $66 and $345 billion worth of goods, respectively. These projections along with the current annual average daily truck traffic were used to provide a baseline assessment of likely outcomes for shipping inventory cost, considering a 4.5% interest rate and truck travel speeds between 25 mph and 60 mph. Ultimately, estimates for shipping inventory cost of cargo in Indiana varies from 0.20 cents to 1.0 cents per truck-mile.

In Figure C6, the x-axis represents the shipping inventory cost that shippers and carriers incur when their cargo is in transit (cents per truck-mile), and the y-axis represents your level of satisfaction on a scale of 0 to 100.

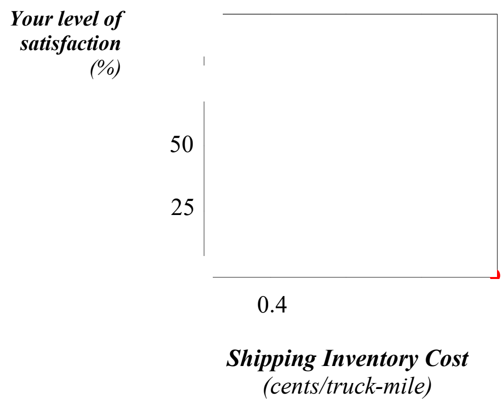


Figure C6. Value function for the shipping inventory cost performance criterion

Assuming that a shipping inventory cost of 0.20 cents per truck-mile reflects a level of satisfaction of 100 percent and a shipping inventory cost of 1.00 cents per truck-mile reflects a level of satisfaction of 0 percent, answer the question below.

Does the linear function presented in Figure C6 fit your personal degree of satisfaction towards the different values presented for shipping inventory cost (0.4 cents/truck-mile, 0.6 cents/truck-mile, and 0.8 cents/truck-mile)?
Yes __________ No___________

If your answer is No:

- To reflect your level of satisfaction, what value would you assign to a shipping inventory cost of 0.4 cents per truck per mile on a scale of 0 to 100?

  ____

- To reflect your level of satisfaction, what value would you assign to a shipping inventory cost of 0.6 cents per truck per mile on a scale of 0 to 100?

  ____

- To reflect your level of satisfaction, what value would you assign to a shipping inventory cost of 0.8 cents per truck per mile on a scale of 0 to 100?

  ____