DEVELOPMENT OF A FRAMEWORK TO ESTIMATE SOCIAL AND ENVIRONMENTAL COSTS OF TRUCK, RAILROAD, AND UNDERGROUND FREIGHT TRANSPORTATION

by

AMIR TABESH

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment
of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF TEXAS AT ARLINGTON
August 2018

Dedication

TO MY WIFE, BEHESHTEH
For all her love, supports and encouragements

TO MY PARENTS, REZA AND SHAHNAZ
For raising me to believe that there is no limit to what I can accomplish

TO MY SISTER, DR. AZAR TABESH
For always being there, when I need her

Acknowledgements

I would like to express my sincere appreciation to all individuals who encouraged me and helped me during my studies to accomplish my goals in my graduate studies at the University of Texas at Arlington. I would like to express my sincere gratitude to my mentor, Dr. Mohammad Najafi, my Ph.D. dissertation advisor, for guiding and supporting me during my studies and for providing me with invaluable information, recommendations, and suggestions for accomplishing my research goals. Moreover, I would like to thank my Ph.D.'s committee members, Dr. Shahandashti, Dr. Sattler, Dr. Mehta, Dr. Tsung, and Dr. Ghandehari for their support and advices.

I would like to thank Dr. Alireza Norozi and Ms. Farwa Sultan for their special support and advices.

Most importantly, many thanks are due to my wife, Beheshteh Bagheri, my sister, Dr. Azar Tabesh, and my parents who patiently supported me throughout my studies at University of Texas at Arlington. Words alone cannot express my gratitude and my thanks that I always owe them. In this regard I would like to thank my father who always supports and encourages me and I would like to thank my mother, for all the support she has given me.

Lastly, I offer my regards to all Civil Engineering department faculty and staff at University of Texas at Arlington, and all CUIRE members who supported me in any respect during the completion of my studies.

Amir Tabesh

August 2018

Abstract

DEVELOPMENT OF A FRAMEWORK TO ESTIMATE SOCIAL AND ENVIRONMENTAL COSTS OF TRUCK, RAILROAD, AND UNDERGROUND FREIGHT TRANSPORTATION

Amir Tabesh, PhD

The University of Texas at Arlington, 2018

Supervising Professor: Dr. Mohammad Najafi

Increasing freight transportation capacity is the most important factor to keep US economy viable. Trucks moved 11.5 billion tons of goods, or 63.8 percent of total freight shipments in 2015, which is projected to grow to 16.6 billion tons by 2045. It is predicted truck travel may increase from 282 million miles per day in 2012 to 488 million miles per day by 2045. The U.S. railroad system includes 138,000 rail miles, which 93,500 miles owned and operated by Class I railroad and the rest of them owned and operated by regional and local railroads. While the miles of railroad are decreasing due to the poor condition of railroad and lower structural capacity of bridges, it is projected the annual tonnage of freight transportation by railroad increase by 24%. Existing and anticipated increases in the number of freight vehicles and other conveyances on both public and private infrastructure are stressing the system as more segments of the network approach or reach the capacity. The purpose of this dissertation is to estimate social and environmental benefits of three different alternatives, which are (1) widening the highway, (2) increase railroad capacity, and (3) implementation of underground freight transportation, to increase freight transportation capacity by using conceptual case study route. Underground Freight Transportation (UFT) is a class of automated inland freight transportation system, which vehicles carry freight through tunnels and pipelines between intermodal terminals. For this study, two traffic models, which are (1) Traffic Volume Distribution Model (TVDM) and (2) Traffic Flow Speed Prediction (TFSP) are developed. For estimating social and environmental cost of heavy-duty trucks, railroad, and UFT, following items are considered: (1) Air pollution, (2) Noise pollution, (3) Traffic accidents, and (4) Traffic congestion. Since the amount of emitted air pollution is dependent on the vehicle speed, new equations to estimate the social costs of air pollution are developed. As a result, UFT was found to have the lowest environmental and social costs compared with truck and railroad. UFT reduces air pollution, noise pollution, and traffic accidents reduce approximately 10%, 30%, and 30% respectively.

Table of Contents

Table of Figures

List of Tables

List of Acronyms and Symbols

a	Exponent Calibration Parameter
AADT	Average Annual Daily Traffic
$AADT_{peak}$	Average Annual Daily Traffic at Peak Hour
AADTT	Average Annual Daily Truck Traffic
A_i	Area at Time Interval i
A	Actual Value
ASCE	American Society of Civil Engineers
ATR	Automated Traffic Recorder
ATRI	American Transportation Research Institute
B/C	Benefit-Cost Ratio
BFFS	Base Free-Flow Speed
BP	Break Point
BTU	British Thermal Unit
c	Fraction of Fuel Sulfur Converted to SO_2
C	Carbon
C	Base Segment Capacity
C_{adj}	Adjusted segment capacity
C_{air}	Total Social Cost of Air Pollution
$C_{Air-HDT}$	Social Cost of Air Pollution by Heavy Duty Truck
C_{Air-PV}	Social Cost of Air Pollution by Passenger Vehicle
C_{AP-PV}	Annual Cost of Air Pollution by Passenger Vehicle
C_{AP-T}	Annual Cost of Air Pollution by Heavy Duty Truck
CCS	Continuous Count Station
C_{En}	Social Cost of Air Pollution by Generating 1MWh Electricity
$C_{Fuel-HDT}$	Cost of Excessive Fuel Consumption for HDT
$C_{Fuel-PV}$	Cost of Excessive Fuel Consumption for PV
CH_4	Methane
C_i	Social Cost of P_i
CLP	Coal Log Pipeline
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
C_{TL}	Cost of Time Value Loss
C_{UFT-AP}	Social Cost of Air Pollution by UFT
CUIRE	Center for Underground Infrastructure Research and Education
D	Distance
DB	Design-Build
D_c	Density at capacity

dB	Decibels
dBA	A-weighted Decibels
DBB	Design-Bid-Build
DBFOM	Design-Build-Finance-Operate-Maintain
DFW	Dallas-Fort Worth
DOT	Department of Transportation
E	Efficiency
EESI	Environmental and Energy Study Institute
E_{HDT}	Average Energy Consumption of Heavy Duty Truck
EI	Energy Intensiveness
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FAF	Freight Analysis Framework
FAST	Fixing America’s Surface Transportation
FFS	Free-Flow Speed
FFS_{adj}	Adjusted Free Flow Speed
F_{HDT}	Average Fuel Consumption of Heavy Duty Truck
f_{HV}	Adjustment Factor for Presence of Heavy Vehicles
FHWA	Federal Highway Administration
Fi	Forecasted Value
f_{LW}	Adjustment Factor for Lane Width
F_{PV}	Average Fuel Consumption of Passenger Vehicle
f_{RLC}	Adjustment for Right-Side Lateral Clearance
FSS	Freight Shuttle System
ft	Foot
ft^2	Square Foot
FTNC	Freight Transportation Network Capacity
γ	Fuel Density
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GWP	Global Warming Potential
HC	Hydrocarbons
HCP	Hydraulic Capsule Pipeline
HDT	Heavy Duty Truck
HF	Hydrofluorocarbons
HGV	Heavy Goods Vehicle
HP	Horse Power
IH	Interstate Highway
IRR	Internal Rate of Return

kW	Kilo Watt
kWh	Kilo Watt Hour
L	Limit Line
lbf	Pond Force
LIM	Linear Induction Motor
LOS	Level of Service
L_T	Length of Train
MAPE	Mean Absolute Percentage Error
MOVES	Motor Vehicle Emission Simulator
mph	Mile Per Hour
MSBV	Mode Shift Benefit Values
MW	Mega Watt
MWh	Mega Watt Hour
N	Number of Lane
NCHRP	National Cooperative Highway Research Program
NEPA	National Environmental Policy Act
NO_2	Nitrous Oxide
NOx	Nitrous Oxide
NPV	Net Present Value
NTNM	National Transportation Noise Map
OTAQ	Office of Transportation Air Quality
P	Power
PAHs	Polycyclic Aromatic Hydrocarbons
PCP	Pneumatic Capsule Pipeline
PEST	Political Economical Social Technology
PHF	Peak Hour Factor
P_i	Emitted Pollution
PM	Particulate Matter
ppm	Parts Per Million
PTR	Portable Traffic Recorder
PV	Passenger Vehicle
R	Ratio
R^2	Correlation of Coefficient
ROW	Right-Of-Way
S	Sulfur
S	Speed
S_{Ave}	Average Speed
sec	Second
SECEF	Social and Environmental Cost Estimation Framework
S_i	Average Speed at Time Interval i

S_{i+1}	Average Speed at Time Interval i+1
SIA	Social Impact Assessment
S_{max}	Maximum Speed
S_{min}	Minimum Speed
SO_2	Sulfur Dioxide
SP	Slurry Pipeline
S_{RF}	Reduction Factor Speed
S_T	Speed of Train
SVM	Support Vector Machine
SWOT	Strength Weakness Opportunity Threat
t	Length of Time Interval
T	Tonnage
TBM	Tunnel Boring Machine
T_{Delay}	Delay Time
TFSPM	Traffic Flow Speed Prediction Model
TIFIA	Transportation Infrastructure Finance and Innovation Act
TOFC	Trailer on Flat Car
T_{Pass}	Total Duration of Single Passing a Train
TRD	Total Ramp Density
$T_{total\text{-}Delay}$	Total Annual Delay Time
$T_{total\text{-}Delay\text{-}HDT}$	Total Annual Delay Time of Heavy Duty Trucks
$T_{total\text{-}Delay\text{-}PV}$	Total Annual Delay Time of Passenger Vehicle
TVDM	Traffic Volume Distribution Model
TxDOT	Texas Department of Transportation
UFT	Underground Freight Transportation
UK	United Kingdome
USDOT	United States Department of Transportation
V	Number of Vehicle at each Time Interval and Segment
V	Demand Volume Under Prevailing Conditions
V/C	Volume to Capacity
Vi	Total Volume of Vehicle at each Time Interval
VOC	Volatile Organic Compounds
V_p	Demand Flow Rate Under Equivalent Base Conditions
V_{PV}	Volume of Passenger Vehicles
V_T	Volume of Truck
$V_{T\text{-}i}$	Number of Truck at Specific Road Closure
VTM	Vehicle-Mile-Traveled
WHO	World Health Organization
WIM	Weight-In-Motion
W_R	Width of Road

Definitions

Benefit-Cost Analysis (BCA)	A systematic method of comparing benefits and costs of a project.
Box Car	Box car railroad cars that is enclosed and general used to carry freight.
Breakpoint	The point separating the linear-speed portion of the curve from the rest of it.
Capacity	The capacity of a UFT system in terms of containers flow per day should be sufficiently high to justify the construction and operation of the system.
Covered Hopper	Covered hopper railroad car is for carrying dry bulk material, such as grain, sand, and clay. It can be loaded from top and unloaded from the bottom of the car
Cut-and-cover	Open trenching and installing a pipeline on a suitable bedding material and then embedding and backfilling
Discount Rate	A rate that is used to discount future costs or benefits to the present value
Emissions	Pollution (including noise, heat, and radiation) discharged into the atmosphere by residential, commercial, and industrial facilities.
Environmental Impact Assessment (EIA)	EIA is the required process to predict the positive and negative environmental consequences prior to the decision to move forward with the proposed action.
Environmental Impact Statement (EIS)	An environmental impact statement (EIS), under United States environmental law, is a document required by the National Environmental Policy Act (NEPA) for certain actions significantly affecting the quality of the human environment. An EIS is a tool for decision making. It describes the positive and negative environmental effects of a proposed action, and it usually also lists one or more alternative actions that may be chosen instead of the action described in the EIS.
Free-Flow Speed	The average speed of vehicles on a given facility, measured under low-volume conditions, when drivers tend to drive at their desired speed and are not constrained by control delay.

Flow	The equivalent hourly rate at which a maximum number of vehicles pass over a given point or section of a lane or roadway during a given time interval of less than one hour.
Gondola	Gondola railroad cars in an open-topped rail car to carry loose bulk materials. It is loaded and unloaded from top.
Greenhouse Gases	Greenhouse gases are components of the atmosphere that contribute to the greenhouse effect. Some greenhouse gases occur naturally in the atmosphere, while others result from human activities such as burning of fossil fuels such as coal. Greenhouse gases include water vapor, carbon dioxide, methane, nitrous oxide, and ozone.
Linear Induction Motors (LIM)	A linear induction motor (LIM) is an alternating current (AC), asynchronous linear motor that works by the same general principles as other induction motors but is typically designed to directly produce motion in a straight line.
Net Present Value (NPV)	The difference between the present value of benefits (cash inflows) and the present value of actual costs (cash outflows).
Peak Hour Factor	The hourly volume during the maximum volume hour of the day divided by the peak 15-minute rate of flow within that peak hour.
Social Benefits	The increase in the welfare of the society that is derived from a particular course of action.
Social Costs	The expense to an entire society resulting from particular course of action.
Traffic Congestion	Traffic congestion is a condition on transport networks that occurs as use increases, and is characterized by slower speeds, longer trip times, and increased vehicular queueing. The most common example is the physical use of roads by vehicles.
Traffic Flow	The number of vehicle passing per period of time from a particular recording station of a highway.
Trenchless Technology	Trenchless technology consists of a variety of methods, materials, and equipment for inspection, stabilization, rehabilitation, and replacement of existing culverts and

	installation of new culverts with a minimum of excavation from the ground surface.
TOFC	Trailer on the Flat Car
Tunneling	Tunneling techniques can be used for installation of pipelines and conduits with minimum amount of surface and subsurface excavation.
Twin Track	A UFT system tunnel with two lines in opposite directions
Underground Freight Transportation (UFT)	An unmanned, automated, and intermodal form of freight transportation utilizing pipelines and tunnels to transport container, crate and pallet freight between terminals. An automated technology to carry individual freight capsules through underground pipelines with minimum impact on the surface. This system can be built on available right-of-way (row) or under the highways.
Vehicle Mile Traveled	Vehicle miles of travel or vehicle miles traveled (VMT) is defined by the U.S. government as a measurement of miles traveled by vehicles within a specified region for a specified time period. The United States Federal Highway Administration (FHWA) compiles monthly and yearly VMT statistics nationally and by state.
Volatile Organic Compounds (VOC)	VOCs are organic chemicals that have a high vapor pressure at ordinary room temperature. Their high vapor pressure results from a low boiling point, which causes large numbers of molecules to evaporate or sublimate from the liquid or solid form of the compound and enter the surrounding air, a trait known as volatility.

Chapter 1 INTRODUCTION

1.1 Background

1.1.1 The U.S. Economy and Freight Transportation

The Nation's 125.8 million households, nearly 7.7 million business establishments, and 90,000 governmental units are all part of an economy that demands the efficient movement of freight. The U.S. economy was affected by an economic recession from December 2007 to June 2009, but it has been returned to prerecession levels. Freight transportation has grown over time with the expansion of population and economic activity within the United States and with the increasing interdependence of economies across the globe (FAF, 2017).

The U.S. population has grown by 5.5 percent between 2010 and 2017, reached to 325.7 million in 2017. Meanwhile, the Texas population has grown by 12.5 percent between 2010 and 2017, reached to 28.3 million in 2017 (USCB, 2018). The U.S. economy, measured by inflation adjusted gross domestic product (GDP), increased by 32.7 percent in real terms over the same period (National Economic Accounts, 2018). Median household income, another indicator of economic growth, declined by 5.5 percent between 2000 and 2015 (USCB, 2018).

Although freight moves throughout the United States, the demand for freight transportation is driven primarily by the geographic distribution of population and economic activity. Both population and economic activity have grown faster in the South and West than in the Northeast and Midwest, but the Northeast has the highest economic activity per capita. In 2015, the U.S. transportation system moved a daily average of about 49.3 million tons of freight valued at more than $52.5 billion (FAF, 2017). The Freight Analysis Framework (FAF) estimates show that the tonnage of goods moved in 2015 fully rebounded from the declines experienced during the December 2007–June 2009 economic recession. Tonnage is projected to increase at about 1.4 percent per year between 2015 and 2045. Figure 1-1 illustrates weight of exports and imports shipments by mode of transportation in 2012, 2015, and projected 2045 (FAF, 2017).

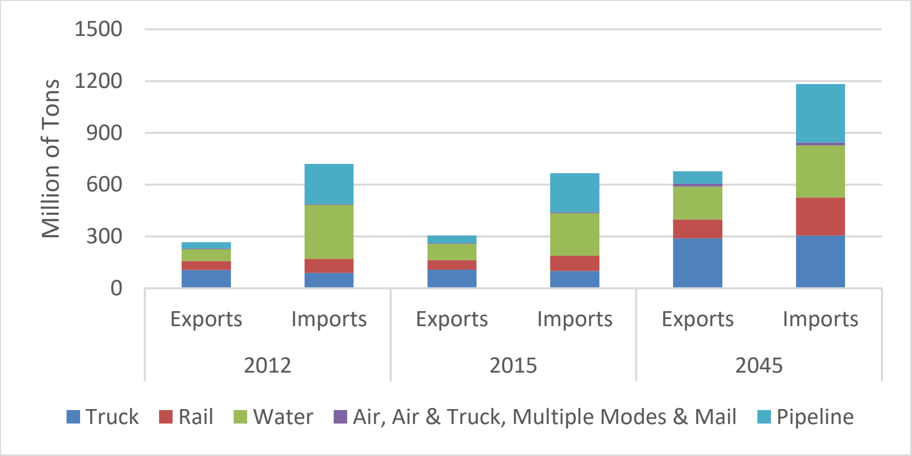


Figure 1-1 Weight of Imports and Exports Shipment by Mode of Transportation

Data Adapted from Freight Analysis Framework (2017)

Additionally, Figure 1-2 illustrates weight of domestic shipments by mode of transportation in 2012, 2015, and projected 2045 (FAF, 2017).

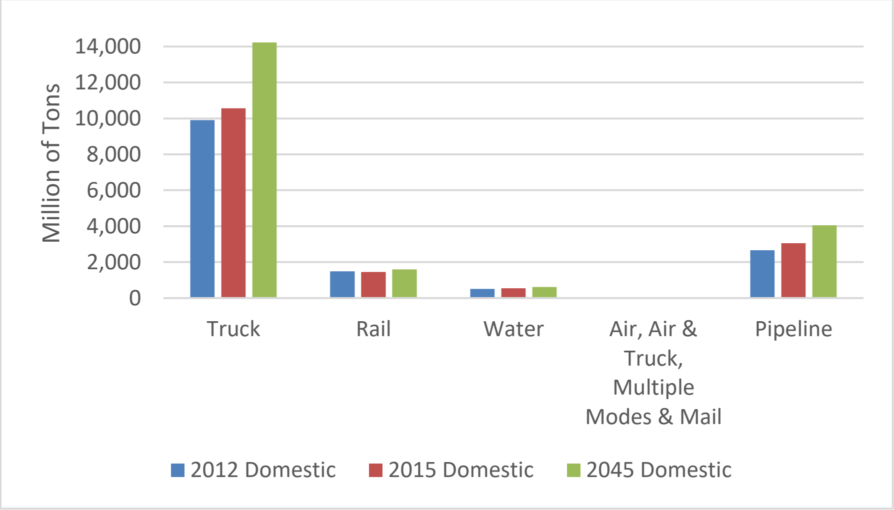


Figure 1-2 Weight of Domestic Shipments by Mode of Transportation

Data Adapted from Freight Analysis Framework (2017)

From 2000 to 2015, road infrastructure including bridges and roads have been increased for 5.2 percent while traffic volume increased 14.0 percent from 2,747 billion to 3,131 billion vehicle-miles traveled. During that time the total miles of pipeline mileage increased 15.9 percent, while Class 1 rail miles declined by 22.4 percent (FAF, 2017). Table 1-1 shows the total miles of transportation infrastructure by modes from 2000 to 2015.

Table 1-1 Miles of Transportation Infrastructure by Mode
(BTS, 2018)

Mode of Transportation	2000	2010	2013	2014	2015
Public Roads	3,951,101	4,033,282	4,115,462	4,177,074	4,154,727
Railroads (Class 1)[1]	120,597	95,573	95,134	94,268	93,527
Pipelines	1,554,316	1,731,696	1,762,758	1,780,095	1,790,637

The U.S. railroad system includes 138,000 rail miles, which 93,500 miles owned and operated by Class I railroad and the rest of them owned and operated by regional and local railroads (USDOT 2015). While the miles of railroad are decreasing due to the poor condition of rail road and lower structural capacity of bridges, it is projected the annual tonnage of freight transportation by railroad increase by 24% (USDOT, 2018). Additionally, according to Texas Freight Mobility Plan (2017), freight movement by rail is expected to increase from 441 million tons in 2016 to 668 million tons by 2045 in Texas, while highway tonnage is expected to double from 1.2 billion tons to 2.5 billion tons at same period of time.

On the other hand, a huge number of vehicles and rail cars move freight over the transportation network. The number of highway vehicles has remained relatively stable in recent years, while the number of rail cars has continued to decline due to improved

---

[1] Railroad Class I includes Amtrak, BNSF Railway, Canadian National Railway, Canadian Pacific Railway, CSX Transportation, Kansas City Southern Railway, and Union Pacific Railroad.

utilization and using larger cars. Table 1-2 shows the number of trucks, locomotives, and rail cars from 2000 to 2015 (BTS, 2018).

Table 1-2 Number of Trucks, Locomotives, and Rail Cars

Type	2000	2010	2013	2014	2015
All Highway Vehicles	N/A	250,070,048	255,876,822	260,350,938	263,610,219
Trucks	N/A	10,770,054	10,597,356	10,905,956	11,203,184
Locomotives (Class 1)	20,028	23,893	25,033	25,916	26,574
Rail Freight Cars (Class 1)	560,154	397,730	373,838	N/A	N/A
Total Rail Cars	1,380,796	1,309,029	1,335,639	N/A	N/A

Expanded U.S. oil production and changes in the location of oil production have increased the use of rail and barges to move oil from the wellhead to refineries and terminals for distribution to the final consumer. Although pipelines continue to be the major mode transportation for moving oil, use of railroad has been increased substantially in recent years. Regional oil shipments by rail increased from less than 1 percent in the beginning of 2010 to 22.6 percent in 2015. Tankers and barges move crude oil on U.S. inland waterways, from port to port along the coast. The use of tankers and barges for oil transport has risen as well, from 2.1 percent 2010 to 3.2 percent in 2015 (USDOT 2015). Figure 1-3 illustrates the freight flows by trucks, railroad, and waterway in 2012 (FAF, 2017).

The American economy stretches across a continent with links to the world, drawing on natural resources and manufactured products from many locations to serve markets at home and abroad. More freight is moving greater distances as part of far-flung supply chains among distant trading partners. Transportation facilities that move international trade into and out of the United States demonstrate the importance of all modes and intermodal combinations to global connectivity.

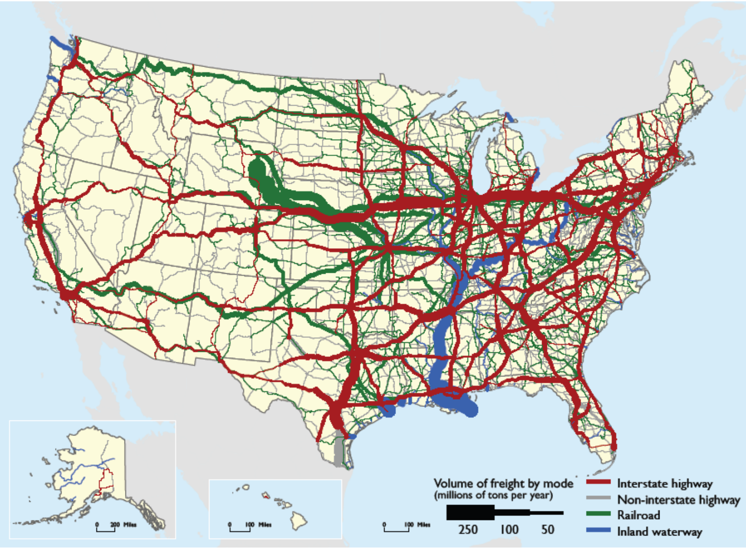


Figure 1-3 Freight Flows by Truck, Railroad, and Inland Waterway in 2012

Moreover, Figure 1-4 illustrates the projected average daily freight transportation by heavy duty trucks on the national highways in 2045 (FAF, 2017).

Figure 1-4 Projected Average Daily Freight Transportation by Heavy Duty Truck

The top 25 foreign-trade gateways measured by value of shipments in 2015 consist of 10 water ports, 6 land-border crossings, and 9 air gateways. Port of New York with $202.6 billion, was the highest international trade freight water gateway by value of shipment, and the Port of Houston with 153 million tons, was the highest international trade freight water gateway by weight of shipment. The top 25 gateways accounted for 61.5 percent of total U.S.-international trades. Figure 1-5 illustrates the top 25 U.S. international trade freight gateways by value of shipment (FAF, 2017; Transportation, 2017).

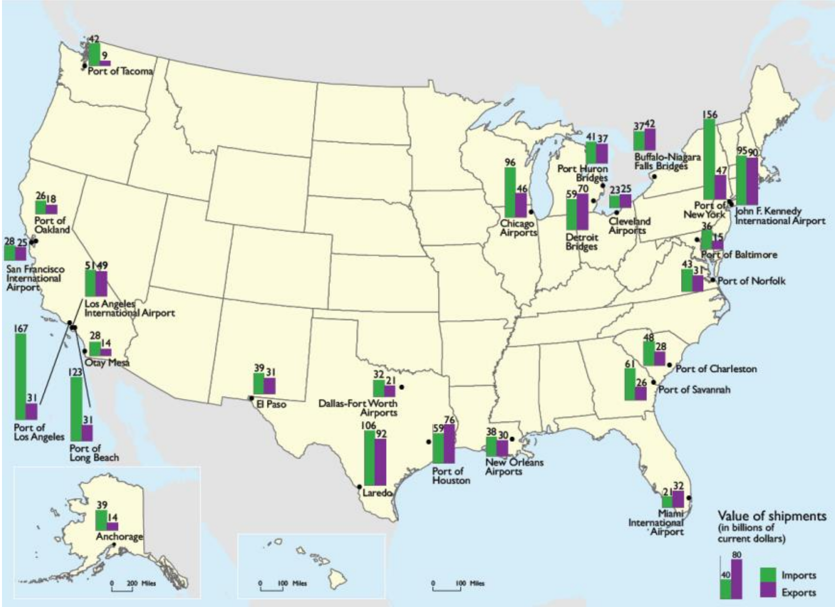


Figure 1-5 Top 25 U.S. International Trade Freight Gateway by Value of Shipment (FAF, 2017)

Today, freight patterns are changing at a global and local scale. International trade is increasing, global manufacturing centers are shifting, and trade routes are changing. Firms are driving down logistics costs through just-in-time shipping. Online shopping is increasing demand for home delivery of consumer products. Ports worldwide are becoming increasingly automated. Intermodal freight shipped in containers by ships, trains, and trucks is increasingly rapidly. Surging domestic energy production is straining infrastructure in oil production regions. Hence, foreign trade has had a major impact on all U.S. borders and coasts.

For example, an increase in trade with China has resulted in a large share of trade moving through Pacific coast ports. The newly expanded Panama Canal allows larger vessels to transit between the Atlantic and Pacific Oceans and it significantly impacts the Port of Houston (Najafi et al. 2016; Rezaei et al. 2016). Since 1990 the value of merchandise trade has increased by 153 percent in inflation-adjusted terms. Ports and airports on the Atlantic coast continued to account for the largest share in terms of trade value. In 2016 they accounted for 29 percent of the total $3.3 trillion in trade (FAF, 2017).

On the other hand, many trucks and trains carry goods into and out of the United States from Mexico and Canada. In 2016 more than 5.8 million trucks hauled 4.1 million loaded containers into the United States from Mexico, an increase of 28.2 and 73.0 percent, respectively, over 2000 levels. This traffic reflects an increase of 85.3 percent imports in trade values. In contrast, the number of incoming trucks and loaded containers from Canada declined by 16.6 and 9.9 percent, respectively, while incoming loaded rail containers increased by 28.8 percent between 2000 and 2016.

1.2 Problem Statement

Freight travels over an extensive network of highways, railroads, waterways, pipelines, and airways. Existing and anticipated increases in the number of freight vehicles, vessels, and other conveyances on both public and private infrastructure are stressing the system as more segments of the network approach or reach capacity, increasing maintenance requirements and affecting performance. As it illustrates at Figure 1-6, road infrastructure increased 34.3 percent while traffic volume 64 times increased from 47 billion to 3109 billion vehicle-mile traveled (VTM), over the 1920 to 2015 (Office of Highway Policy Information , 2017).

Freight transportation tonnage will be increased by 1.4% annually by 2045, while there is no plan to increase public roads and infrastructure by this time. Additionally, Trucks moved 11.5 billion tons of goods, or 63.8 percent of total freight shipments, in 2015 and it is projected to grow to 16.6 billion tons by 2045. It is predicted truck travel may increase from 282 million miles per day in 2012 to 488 million miles per day by 2045 (FAF, 2017).

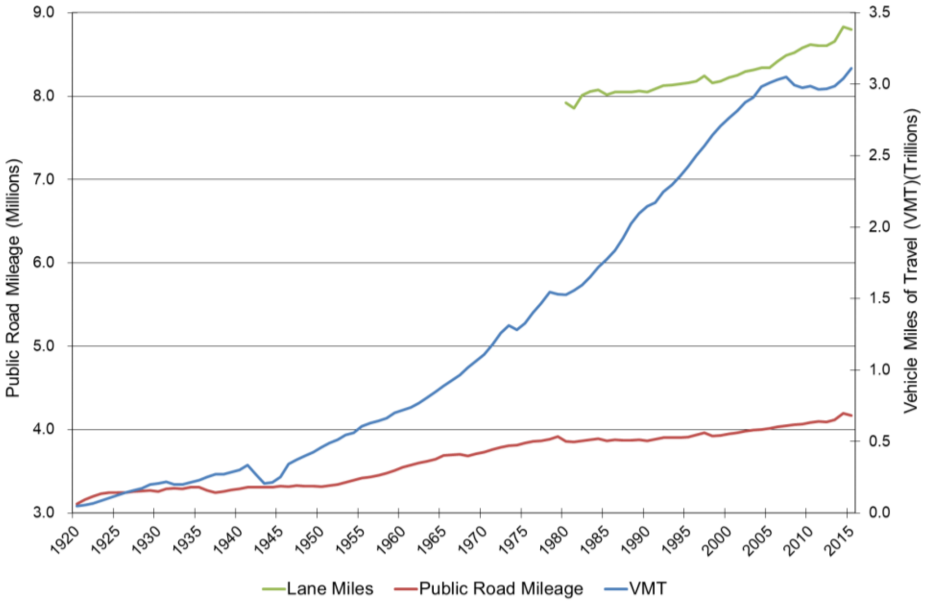


Figure 1-6 VMT Growth vs. Public Road Mileage Growth from 1920 to 2015

(Office of Highway Policy Information 2017)

Current demands for truck parking spaces exceed available spots, and projected increases in freight volume and increase in the number of trucks may worsen the problem. Besides, federal and state governments are concerned about truck weight because of the damage that heavy trucks can do to roads and bridges. To monitor truck weight, more than 208.3 million trucks were weighed in 2015, which less than 0.2 percent of commercial vehicle weighs resulted in violations (FHWA 2017).

The efficient and reliable movement of freight is important to the U.S. economy by increasing freight transportation performance. Travel time and speed are two indicator of system performance. Slower speed and higher travel time caused by traffic congestion, weather, accident, and other factors reduce productivity and operation efficiency, and increase fuel cost. These changes impact logistics, operational strategies, and load optimization.

Growing demand for freight transportation heightens concerns about its safety, energy consumption, and environmental impacts. Besides, Trucks accounted for 87.8 percent of all freight transportation fatalities and 11.6 percent of all highway fatalities in 2015. Most of fatalities involve passenger travel on highways.

The U.S. Environmental Protection Agency (EPA) estimates that trucks produced more than 2.3 million tons of NOx in 2016. However, substantial reductions in freight related NOx emissions have been made since the EPA required the use of ultra-low sulfur diesel fuel in heavy duty trucks and other diesel-powered highway vehicles beginning in 2006. Between 2000 and 2016, NOx emissions from gasoline and diesel powered single-unit and combination trucks decreased by 63.4 percent. Particulate Matter (PM_{10}) emissions declined by 59.3 percent over the same period.

In addition to carbon monoxide, nitrogen oxide, and particulate matter emissions, the transportation sector releases large quantities of greenhouse gases (GHGs), such as carbon dioxide, methane, nitrous oxide, and hydrofluorocarbons. After industrial sector, which produce the largest amount of GHG emissions with 29.3 percent, transportation was responsible for about 27.5 percent of all greenhouse gases emitted in the United States in 2015 (EPA, 2015).

In order to increase freight transportation performance system and address all projected problems, increasing freight transportation network capacity (FTNC) is must. If network capacity does not change, traffic congestion is forecasted to significantly increase by 2045 due to higher number of heavy duty trucks. These congestions will slow down traffic and close about 3,700 miles of highway system and create stop-and-go condition on an additional 13,000 miles of highway system (FAF, 2017). Indeed, to increase freight transportation capacity, following alternatives can be considered;

a) Increase railroad capacity by adding number of locomotive and railways
b) Increase freight transportation capacity by widening highway system
c) Implementation innovative technology such as Underground Freight Transportation (UFT)

1.3 Objectives

The main objective of this dissertation is to develop a framework to measure environmental and social benefits of following alternatives;

a) Increase railroad capacity by adding locomotives and railways
b) Increase highway capacity by widening highways and adding lanes
c) Implement Underground Freight Transportation (UFT)

Impacts of each alternative on air pollution, noise pollution, traffic congestion, accident cost, and energy consumption will be measured in terms of dollar value by use of a conceptual case study to see which alternative has the highest social and environmental benefits.

1.4 What is UFT?

1.4.1 Definition

Large urban and suburban area have increasingly suffered from heavy traffic congestion causing losing time of daily commuters, delay in delivery of products to retailers and consumers, increased risk of accidents caused by heavy duty trucks carrying out urban freight to distribution centers, increases in energy and fuel consumption and related emissions of Green House Gases (GHG) by all vehicles specially trucks, increased water and noise pollutions, and increased cost of infrastructures damages.

A prospective solution to reduce these impacts including prevention of their future escalation due to prospective growth in freight transportation volumes, can be partial replacement of the freight transportation by heavy duty trucks on the ground by Underground freight transportation (UFT) system (Teodorovic, 2017).

Underground Freight Transportation (UFT) is a class of automated transportation system in which vehicles carry freight through tunnels and pipelines between intermodal terminals (Najafi et al. 2016). Also, UFT includes all the methods of automated transport of general cargo by vehicles moving through a network of underground tunnels (Roop 2001). Figure 1-7 show schematic design of UFT system.

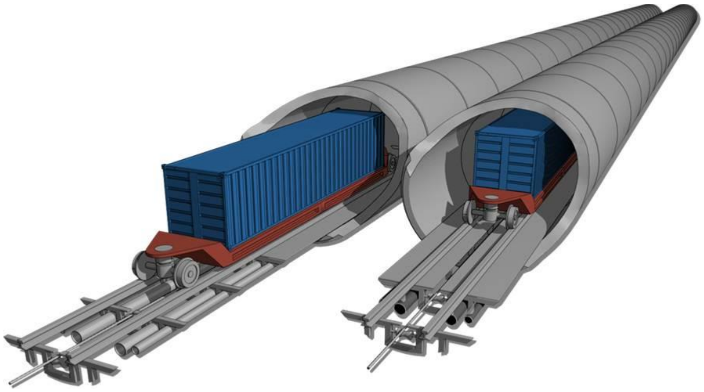


Figure 1-7 Schematic Design of UFT System

(Underground Container Mover, 2018)

Freight transportation is a technology to transport most cargoes, normally transported by trucks, including construction materials (i.e., sand, gravel, and cement), goods in pallets and crates, boxes, etc., and even full-size (i.e., 40-ft-length) shipping containers (Rezaei 2016).

UFT is not a new concept while this system has been in operation since 1927 by Royal Mail at Mail Rail System in London, UK, to move mail between different area of

London. At present, in Japan, UFT system have been successfully used to transport bulk materials for Nippon/Daifuku and Sumitomo Electric Industries.

Additionally, in Georgia, two UFT systems have been used to transport crushed rock, and in Russia to move garbage bags (Rijsenbrij, 2006). One of the key benefit of UFT is being able to build under available existing highway's right-of- way, which greatly reduce the construction costs.

There are different types of UFT system which are illustrated at Figure 1-8 (Mousavipour, 2015).

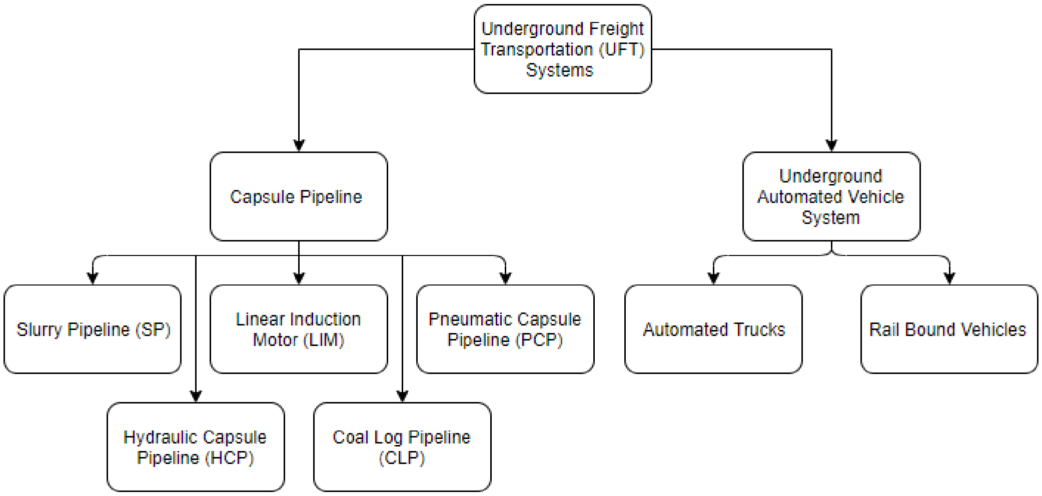


Figure 1-8 UFT System Types

(Mousavipour, 2015)

1.4.2 UFT Components and Sizes

The main components of an UFT system are the pipeline network (tunnels) with rails, terminals, vehicles or capsules, and their propulsion and guidance system. For design of UFT pipeline network and vehicles, three different size of freight which are pallet, crate, and container can be considered. For each size, the pipeline network can be designed as an "one twin-track tunnel" and "two single-track tunnels." In "one twin-track tunnel," two tracks are installed in one large diameter tunnel, and in “two single-track tunnels” two parallel tunnels are constructed with one track in each (Najafi et al. 2016). Table 1-3 shows each UFT size specifications (Najafi et al. 2016).

For this dissertation, Linear Induction Motor (LIM) for propulsion system of UFT is considered. The advantages of using LIM are cost effective, simplicity to assemble, ignition, and low maintenance (Rohter, 2007). The advantage of using LIM pump compare than Pneumatic Capsule Pipeline (PCP) is that the former is not interfering, therefore, the system can run continuously without having to make the vehicle bypass the pump.

Table 1-3 UFT Different Sizes Specifications

(Najafi et al. 2016)

Specifications		UFT Sizes		
		Pallet	Crate	Container
Freight Size	Width (ft)	3.3	5	8
	Height (ft)	3.3	5.3	9.5
	Length (ft)	4	10.4	40
Vehicle Dimensions	Width (ft)	4.2	5.6	9
	Height (ft)	4.5	6.8	10.5
	Length (ft)	10	22	49
Single-Track Tunnel	Internal Diameter (ft)	7	10	14
	External Diameter (ft)	8.4	11.8	16
	Wall Thickness (ft)	0.7	0.9	1
Twin-Track Tunnel	Internal Diameter (ft)	11	15	22
	External Diameter (ft)	13	17.4	25
	Wall Thickness (ft)	1	1.2	1.5
Speed	(mph)	45	45	45
Payload	(ton)	5.6	9.3	40
Volume	Total Shipment per day	8640	8640	5760

This not only simplifies the system but also enables the system to achieve much larger cargo throughput than that of PCPs using blowers and use of LIMs as booster pumps which enables the system to have any length or to be used for transporting cargoes over practically any distance (Liu and Lenau 2005).

A Linear Induction Motor is a mechanism that converts electrical energy directly into mechanical energy to provide linear motion without employing any intervening rotary components. The LIM system consists of a reaction plate and a 3 phase AC coil Assembly (Rohter, 2007). Figure 1-9 illustrate LIM components (Sinisterra, 2011).

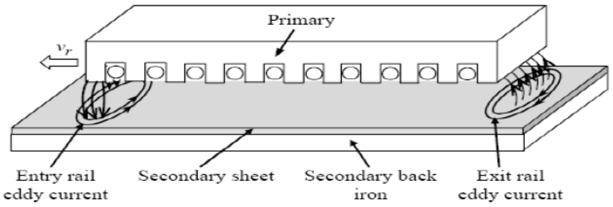


Figure 1-9 Side-view of LIM System

(Sinisterra 2011)

Figures 1-10 and 1-11 illustrate the cross section of single-track tunnel and twin-track tunnel for container size of UFT system (Najafi et al. 2016).

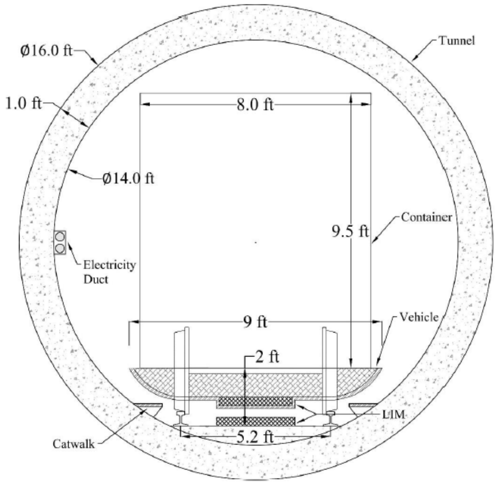


Figure 1-10 A Single-track System for Standard Shipping Container
(Najafi et al. 2016)

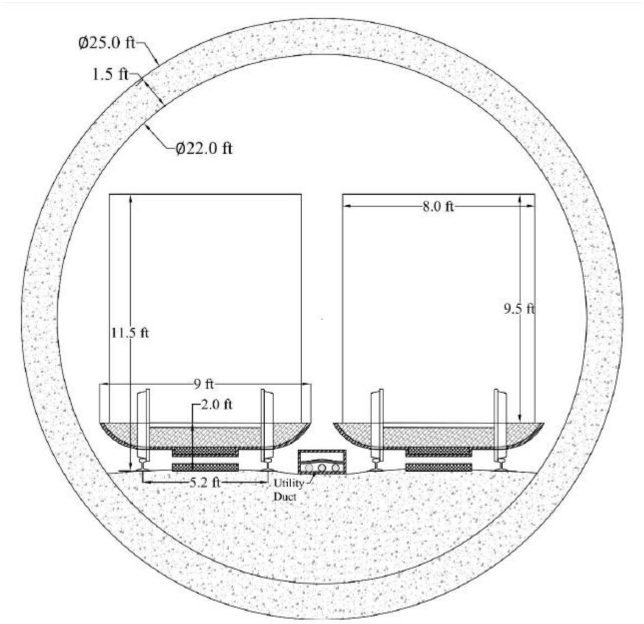


Figure 1-11 One Twin-track System for Standard Shipping Container

(Najafi et al. 2016)

The UFT terminals should be close to intermodal terminals or distribution centers to transfer freights between the UFT and other freight transportation modes. For example, these locations can the port, airport, and inland container terminals (Teodorovic, 2017). UFT system layout is shown in Figure 1-12.

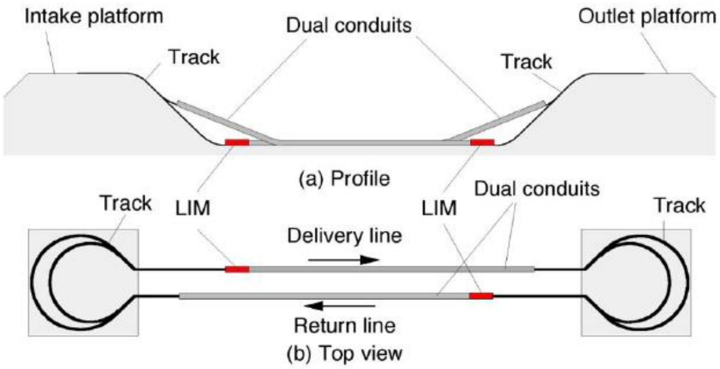


Figure 1-12 UFT System Layout

(Liu 2004)

1.5 Contributions to the Body of Knowledge

The contributions of this dissertation to the body of knowledge are followed;

- Developing a model to estimate distribution of daily traffic volume at different time interval based on average speed. According to literature search there are several models to estimate speed based on volume, but there is no available model to estimate daily traffic volume distribution based on speed and AADT.
- Developing a framework to quantify in dollar value, analyze and compare social and environmental impact of truck, railroad, and UFT. This framework can analyze social and environmental cost of air and noise pollution, traffic congestion, accident, and energy consumption of each mode of inland transportation. So far, several researchers have worked on social and environmental impact of truck and railroad, but few of them have addressed underground freight transportation. One the other hand, this dissertation is the first one, which compare all three modes of inland freight transportation and measure direct and indirect social costs.

According to literature review, this research has not been done and there is no available social and environmental impact framework for inland transportation sector.

1.6 Scope of Work

The scope of this research includes social and environmental impacts of trucks, railroad, and UFT during operation due to air and Noise pollution, traffic congestion, traffic accident, and excessive energy consumption. The operation consists only hauling the freight and does not include any social and environmental impact at terminals operation. Moreover, this dissertation does not cover economic, business and ecological impacts, job loss and creation, smart city developments, security, infrastructure damage, and social and environmental cost of construction, maintenance, and repairs.

1.7 Case Study Route

The potential route that considered for this research is a 42-mile route from Union Pacific Englewood Yard at Houston which is connected to the Port of Houston to suburban area of town of Brookshire, TX. This route covers congested freight corridor sections and can be constructed under the existing right-of-way (ROW) along highway IH-610 and IH-10 in Houston.

At this scenario, truck, railroad, and UFT can load and unload containers at Distribution Center at Brookshire, TX, instead of going into the City of Houston. Additionally, there is lack of railroad system from the City of Houston to Brookshire, TX. Therefore, it is assumed to build new rail road parallel to this route. Also, UFT can be an intermodal freight transportation system to connect Union Pacific railroad at the East side of Houston to Brookshire, TX. Figure 1.13 illustrate the proposed UFT route.

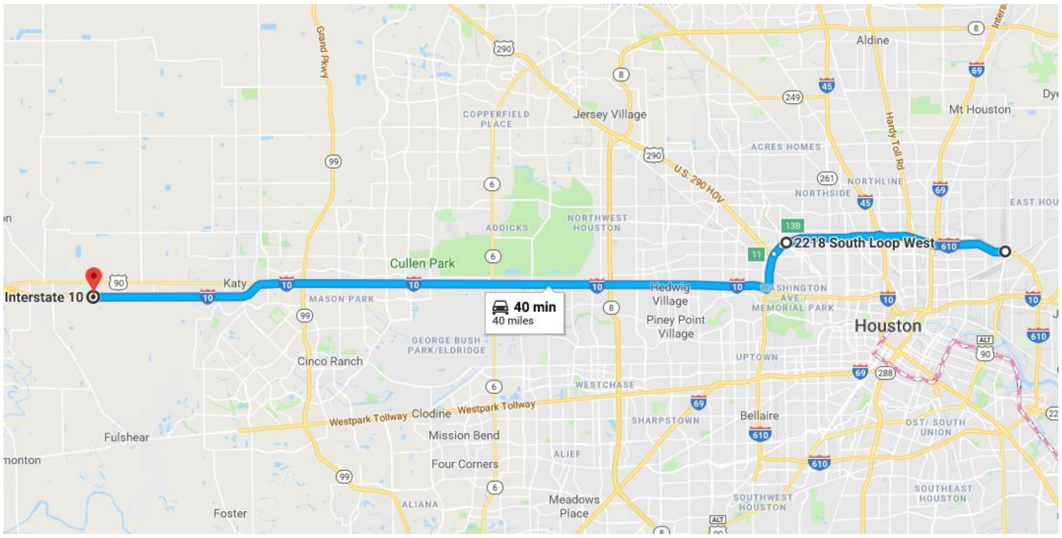


Figure 1-13 Location of Case Study UFT Route

According to USDOT, Houston is one of the most congested city in the nation since five of the most congested highways, out of 25 highways are located at the city of Houston (see Table 1-4) (FAF, 2017).

Table 1-4 Congested Freight Corridors at Houston, TX

(FAF, 2017; Texas Statewide Planing Map, 2018)

Location	Congestion Ranking	2015 AADTT	2035 AADTT	Growth %
IH-610 at US 290	5	12,755	25,510	100.00
IH-10 at IH-45	6	17,888	30,051	68.00
IH-45 at US 59	8	13,939	23,419	68.00
IH-10 at US 59	10	19,459	27,242	40.00
IH-45 at IH-610	21	14,771	24,815	68.00

On the other hand, the Port of Houston has predicted an increase in traffic in the long-term due to the Panama Canal expansion, expecting that the newly deepened Port will attract heavier or larger vessels to unload there (Prozzi & Overmyer, 2018). Thus, the City of Houston significantly impacted by highly congested highways due to heavy duty trucks heading or from the Port of Houston.

1.8 Methodology

The strategy of this research is to analyze combination of direct and indirect social and environmental impacts of three proposed alternatives at selected route. Figure 1-14 illustrates the overall methodology of this dissertation.

For first step of this dissertation, an extensive literature search about social and environmental impact of truck, locomotive, and UFT will be performed. Then, social and environmental cost of each impact will be calculated in 2018-dollar value. Moreover, all required data related to selected rout such as, average speed at pick hour, AADT, truck percentage, number of lane, ramp density, and intersections will be collected from FHWA, State's DOTs, and other reliable sources.

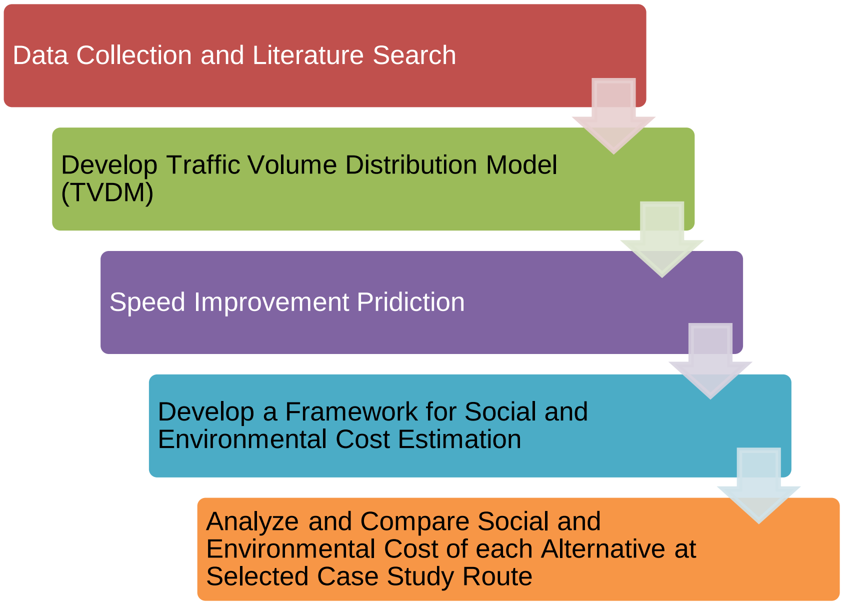


Figure 1-14 Methodology

At second step, Traffic Volume Distribution Model (TVDM) will be developed. The inputs of this model are average speed of traffic flow for both direction at specific time interval, such as, every 30 minutes, during peak hour from 5:00 am to 8:00 pm, AADT, and truck percentage. The outputs of this model are distribution of traffic volume for both direction at each time interval, and traffic distribution factor. This model will be validated with real data from another highway and compared with Highway Capacity Manual methodology. How about railroad?

The third step of this dissertation is speed improvement prediction at each segment of selected route due to implementing each alternative. Air and noise pollution, accident rate, traffic congestion, and energy consumption of heavy duty truck, locomotive, and UFT are speed dependent. Therefore, this is necessary to predict improved speed due to widening the highway (Alternative 1), reducing number of truck and shipping container by railroad (Alternative 2), or UFT (Alternative 3). This prediction is conducted with use of Highway Capacity Manual equations for basic freeways.

Forth step is developing a framework to estimate social and environmental cost of air and noise pollution, traffic congestion, accident rate, and energy consumption of each alternative. For Alternative 1, social and environmental cost of truck and benefit of widening the highway will be estimated. For Alternative 2, social and environmental cost of locomotive and benefit of removing 192[2] trucks per hour will be estimated. And finally, for Alternative 3, social and environmental cost of UFT and benefits of removing 96 trucks per hour will be estimated. All target impacts will be analyzed, and speed base regression will be generated to calculate social costs.

At final step, social and environmental costs of all alternatives will be analyzed and compared to select the best alternative with lowest social and environmental impact. This analysis can help decision makers to consider not only direct social and environmental cost of each alternative, but also indirect impact of each alternative.

1.9 Hypothesis

It is estimated utilizing UFT can help government agencies and people to save approximately 10% in air, and 30% noise pollution, 25% in traffic congestion, and 30% in accident. Also, implementing UFT has highest benefit compared with other alternatives.

1.10 Dissertation Organization

Chapter 1 presents a brief background on the U.S. freight transportation, future demand and growth, lack of freight transportation capacity, Underground Freight Transportation (UFT), and environmental impacts of freight transportation. Moreover, this chapter includes problem statement, objectives, methodology, contribution to the body of knowledge, and hypothesis.

---

[2] In average UFT can substitute 192 containers per hour from 5:00 am to 8:00 pm. Therefore, it is assumed 192 trucks per hour will be reduced. On the other hand, railroad tonnage and UFT tonnage considered to be equal.

Chapter 2 summarize all available literature related to Underground Freight Transportation and its limitations and recommendations. Chapter 3 explains traffic volume distribution model and provide supportive equations to predict speed improvement. Chapter 4 present the framework to estimate social and environmental cost of heavy duty truck, railroad, and UFT. Chapter 5 presents the result of framework and comparison of different alternatives. Finally, in Chapter 6, summary and conclusions are presented followed by limitations of this dissertation and recommendation for future research.

1.11 Chapter Summary

Increasing freight transportation capacity is the most important factor to keep US economy viable. Trucks moved 11.5 billion tons of goods, or 63.8 percent of total freight shipments, in 2015 and it is projected to grow to 16.6 billion tons by 2045. It is predicted truck travel may increase from 282 million miles per day in 2012 to 488 million miles per day by 2045. The U.S. railroad system includes 138,000 rail miles, which 93,500 miles owned and operated by Class I railroad and the rest of them owned and operated by regional and local railroads. While the miles of railroad are decreasing due to the poor condition of rail road and lower structural capacity of bridges, it is projected the annual tonnage of freight transportation by railroad increase by 24%. Existing and anticipated increases in the number of freight vehicles, vessels, and other conveyances on both public and private infrastructure are stressing the system as more segments of the network approach or reach capacity, increasing maintenance requirements and affecting performance. Increase freight transportation capacity by increasing railroad capacity, expanding highway system, and using innovative technology such as Underground Freight Transportation can be feasible options. The main focus of this research is estimating social and environmental impact of Truck, locomotive, and UFT.

Chapter 2 LITERATURE REVIEW

2.1 Comprehensive Study on UFT

Najafi et al. (2016) investigated the feasibility of underground freight transportation which allows for optimized use of existing transportation capacity. Objectives of this project are to evaluate using three sizes of pallet, crate, and container size of UFT in three proposed routes in Texas: specifically, the Port of Houston to City of Lancaster (near Dallas) for 250 miles, the Port of Houston to a distribution center within 15 miles of the Port's point of origin (Baytown), and the border crossing with Mexico in Laredo for four miles.

Najafi divided the whole project into six tasks of planning and design, construction method, cost estimating, environmental impacts, financial aspects, and stakeholder committee and investigate each task extensively (Najafi et al. 2016). In Task 1, planning and design, potential routes, sizes, preliminary design of tunnel, vehicles, propulsion system including LIM, headway, maximum speed, required power, required energy, and required equipment investigated.

The purpose of the Task 2, construction method, was to consider options for the conduit system and its components, such as shafts. Cut-and-cover and tunneling using TBM can be used for two single-track tunnels and one twin-track tunnel respectively. Cut-and-cover construction is potentially possible and less expensive as an alternate for pipeline installations at rural areas where there is surface availability with minimal disturbances to the traffic, public and the existing roads. While cut-and-cover method is discussed in this report, its use may not be possible along the select routes due to existence of frontage and crossing roads, bridges and foundations. Additionally, the cut-and-cover method has high social and environmental impacts.

In task 3, cost estimating, the capital and operation/maintenance costs for the tunnel, vehicles, the LIM system, controls, and terminals are provided. The tunneling cost is estimated for building one twin-track tunnel, and for comparison, cut-and-cover costs are estimated for two single track tunnels.

In task 4, environmental impact statement, the total annual benefits of UFT during its operation are calculated by quantifying each benefit in dollar value per ton-mile. The benefits that considered for this research project are air, noise, and water pollution reduction, traffic congestion and accident rate reduction, road and bridge maintenance cost reduction, energy efficiency, and increased safety and security. Also, impact of UFT system on rail road and trucking industry and tax revenue reduction due to selling less amount of fuel and part are investigated. Finally, three alternatives of no action, widening highways, and building UFT system are compared to bright impact of each alternative in point of environmental impact statement (EIS) view.

Social costs of air, water, and noise pollution, and traffic congestion, which are caused by heavy trucks, would be reduced by using UFT; therefore, social benefits of UFT was calculated based on reducing number of trucks on the road. Government agencies will lose some revenue, which will be the social costs of UFTs. The total benefit of UFT system is estimated to be $0.023 per ton-mile and total cost of this system is approximately $0.0014 per ton-mile. Therefore, annual benefit of 250-mile container size UFT from port of Houston to city of Lancaster is approximately $467,594, 784. Also, annual benefit of container size UFT from port of Houston to an inland satellite distribution center in Baytown, TX and border at Laredo, TX are estimated to be $28,055,687 and $8,446,938, respectively. This dissertation is continuation of this research project.

In Task 5, they evaluate the financial aspects of UFT project. Major funding sources, including federal, state, TIFIA and senior bank loans, revenue bonds and equity participation are identified. The project delivery methods considered are design-bid-build (DBB), design-build (DB), and design-build-finance-operate-maintain (DBFOM), among other options. Benefit-cost analysis of UFT for the standard shipping containers shows that the net present value (NPV) of UFT is $60 billion (in 2016 dollars) and benefit-cost ratio of the system is estimated to be 3.77.

The internal rate of return (IRR) is 12.44%, which indicates that UFT is certainly economically viable. Similar results are obtained for crate and pallet freight transportation. And in Task 6, a stakeholder committee was formed to guide the researchers in all aspects of this project. The stakeholder committee is in support of the project and has recognized the necessity of UFT as an intermodal freight transportation in Texas. Finally, Najafi conclude that Underground Freight Transportation is financially viable, feasible, greener, cost effective, and an important part of intermodal freight mobility in Texas.

2.2 UFT Application

Zandi and Gimm (1976) investigated the application of freight pipeline for the movement of solid goods, as a new option in the field of transportation. This report has five volumes of Volume I: Cost and Level of Service Comparison; Volume II: Freight Pipeline Technology; Volume III: Cost Estimating Methodology; Volume IV: Demand Analysis Methodology; and Volume V: Impact Assessment. At impact assessment study, they only identified the areas where truck and/or rail substitution by underground freight transportation may impacts.

According to Zandi and Gimm (1976), “it only can be said that pipeline, if it can substitute for surface traffic without correspondingly increasing it at other location, is inherently a more environmentally compatible mode of transportation. Based on his finding, freight pipeline reduces the truck traffic, street congestion, noise, energy consumption, accidents, and air pollution. As he stated, accident and noise reduction are certain, but the impact on energy consumption and air pollution depends on local conditions. At this report he just identified each impact but recommended to investigate quantitative analysis of impacts (Zandi & Gimm, 1976).

Vance and Milles (1994) claimed that UFT is technically feasible and has many advantages compare with trucks. Also, they conclude that cost-benefit analysis must be determined on a case-by case basis taking site-specific information into account such as freight volumes and construction costs. The authors also reported that using highway right-of-way (ROW), in unused underground areas along highways, can greatly enhance the economic feasibility of any pipeline freight project (Vance & Mills, 1994).

Golf and Shih (1998) studied the feasibility of 300-mile UFT structure between San Antonio and Dallas, with the diameter of 6.6 ft. Proposed terminals for this system located at San Antonio, Waco, Temple, Austin, and San Marcos, and Dallas. The propulsion of this system was LIM and capsules would travel at 55 mph. Based on this research, it was estimated that the mean years to failure for the propulsion and control systems are 80 years which is approximately eight times more effective (indicating more years of use) than the average of 10 years estimated for truck engine failure. The total life time of the tube system itself was estimated to 60 years until failure, which is approximately three times greater than highway and finally, the track or guide way would last approximately 55 years until failure (Goff & Shih, 1998).

Miles and Loose (2008) cunducted a UFT feasibility study for use on highway M25, London, UK, for Mole Inc. in this research, Miles and Loose studied how the new technology affect direct cost and capital cost as well as the potential social and environmental benefits. Based on the Miles and Loose (2008) study, by using UFT, travel time would be reduced by up to 5% which is equal to an estimated $4 billion in cost savings. In addition, based on estimated costs in the UK, the truck road building cost million dollars per miles however, the cost of one mile of UFT depends on the amount of earthwork and boring which is approximately $3 million per mile.

Based on 2005 statistics in the UK, Heavy Goods Vehicle (HGV) caused 486 accidents and 3200 serious injuries while carrying 63% of UK`s freight; however; oil pipelines carried 4% of the freight with no injuries. Finally, UFT works with electricity, which can be fed from a renewable source. Therefore, the amount of emitted air pollution is much less than trucks. Additionally, trucks have high visual impact and produce noise pollutants. Nevertheless, Miles and Loose (2008) predicted that all these negative impacts would be reduced by UFT system (Miles & Loose, 2008).

Miles et al. (2016) were awarded a grant in 2015 to investigate feasibility study on the application of urban freight pipeline solution at Northampton, UK. This conference paper derived from this study. The objectives of this study were to investigate the role of freight pipeline in the supply chains of Northampton and provide comprehensive methodology to examine freight pipeline any city in the world. They accomplished their objectives in three phases of data gathering, analysis, and examination of UFT design specifications. The important results of this research are followed (Miles et al. 2016);

- The key evaluation viability is financial aspect of the project and Internal Rate of Return (IRR) of the investment in required.
- Much of the socio-environmental benefits can be estimated by “Mode Shift Benefit Values (MSBVs) that are used by Department of Transportation to encourage users of road freight to transfer goods from road to more sustainable modes. In addition to this method, some benefits due to being environmental benefits of the system are considered.
- Based on 2013 Sustainability Assessment Manual, authors concluded that UFT has high positive impact on social and environment.

- Beside of cost effectiveness of the system, there are socio-environmental benefits, which are indirect benefits and can be achieved by implementation of UFT system.
- Direct cost saving of this system is approximately 15% of truck operating cost.
- Social can save from reduction in the level of air pollution, congestion, accident, road works, infrastructure damage, petroleum consumption, and have safer roads.
- The operation costs will not increase as fast as road systems as there is no driver costs and the power can come from renewable source.
- The level of socio-environmental benefits is proportional to the population and therefore it will be increased as the level of urbanization increases.

2.3 UFT Application in Texas

Roop et al. (2011) investigated freight transportation problems in the ports-of-entry (POE) along the border of Mexico from El Paso, TX to Ciudad Juarez. This region faces a heavy traffic congestion due to truck traffic. It is estimated in average each truck spends about one hour in traffic peak (most conducive to congestion). The other issues which leads to this problem was establishing manufactures in this area since the U.S is the closest market for Mexico. These problems contribute to more freight traffic which causes significant amount of air pollution, increasing fuel consumption, and more delay in freight delivery. In addition, a considerably high amount of drug traffic threatens the security of freight transportation. In order to solve these problems, an alternative freight transportation system, the Freight Shuttle System (FSS), has been suggested.

To analyze the feasibility of FSS via truck at highways, a 24-years statistical study conducted. One of the focus area of this study was the air pollution reduction. Since FSS is operated by electricity, and green electricity generator such as solar and wind turbine can be used, in a 24-year period, 87,000 tons of air pollution including 696 tons on NOx could be reduced. In addition to air pollution, FSS plays a significant role on petroleum consumption by reducing 47.9 million vehicle miles traveled (VMT), which leads reducing fuel consumption up to 7.5 million gallons. By calculating truck delay times, FSS can save approximately 3.1 million hours of delay, which costs $102 million dollars. Finally, by utilizing inspect-in-motion technology on FSS, Customs and Border Protection patrols can inspect 100 percent of cargos in less time (Roop, et al., 2011).

Mousavipour (2015) analyzed feasibility of underground freight transportation in Texas and identified features and benefits of UFT as well as its limitation compared than other mode of transportation. She supported her research by providing literature search about current and future of the U.S and Texas economy, population, freight transportation, and future needs in freight transportation capacity.

Then she discussed previous studies related to UFT, its component and construction method. Then as a case study she discussed the research that had been done by Dr. Liu in New York in 2004, and finally conduct a survey in Texas to obtain expertise ideas and comments about UFT. Based on her survey, UFT benefits are traffic congestion reduction, enhance highway safety, increase transportation reliability, reducing damage to the pavement, reducing fuel consumption, improving security, improving freight capacity, higher design life, and reducing noise and dust pollution, respectively.

Overall, according to the respondents, cost effectiveness is one of the most important factors that limits the UFT competitiveness with other freight transportation methods such as truck or rail (Mousavipour, 2015).

Rezaie et al. (2016) discussed the application of UFT in Texas and compared different routes and construction methods through establishing a stakeholder committee from government agencies, companies, universities, port and airports, freight industry and consultants. This paper presents results of the stakeholder committee meetings, conducted survey, and small group discussions for this project. At first meeting, a survey regarding UFT implementation was conducted. The top 10 issues that were discussed are followed in order from most important to least important (Rezaie et al. 2016);

- Need the UFT system in 25 years
- Short haul distance is preferred over long distance
- Safety and security
- Potential to connect the port of Houston to nearby satellite locations
- Two single-track tunnels are preferred than one twin-track tunnel.
- Private contribution funding for financing the project
- Educating the public
- Consider cost of terminals
- Freight movement inside DFW airport
- Automated use of UFT

At second meeting, a survey regarding UFT benefits were conducted. The participants scored and ranked UFT benefits from 100, which are followed in order;

- Reducing traffic congestion (score=94)
- Improving freight transportation capacity (score=82)
- Enhancing highway systems (score=81)
- Increasing reliability (score=64)
- Reducing fuel consumption (score=62)
- Improving safety (score=62)
- Better design life (score=41)
- Reducing damage to pavement (score=39)

Finally, a survey regarding UFT construction obstacle were conducted. The participants scored and ranked possible obstacle as followed;

- Tunnel construction (score=77)
- Underground water control (score=73)
- Cut-and-cover construction (score=56)
- Existing utility relocation (score=55)
- Spoil removal (score=54)
- Excavation support (score=54)
- Soil condition (score=51)
- Easement availability (score=41)
- Access shaft construction during tunnel construction (score=33)

2.4 UFT Technology

Visser and Binsbergen (1997) focused on urban freight transport as an element in larger transportation and distribution systems for the daily delivery of goods. This research included freight transportation systems with a linear motor (LIM) with pneumatically or electrically driven self-propelled transporting units for the city of Leiden in The Netherlands. This study mostly focused on receiving the goods, transporting the goods, delivering the goods, and the control system. Due to technical limitations in pneumatic systems like loss of compressed air and steering issues, Visser and Binsbergen stated that UFT is not feasible (Visser & Binsbergen, 1997).

Liu et al. (1998) compared different type of pipeline transportation system, including slurry pipeline, pneumatic pipeline, and capsule pipeline, and investigate advantages and limitations of each methods. According to this paper, in many situations, freight pipelines are not only the most economical and practical method of solid transportation, but also the most reliable, safest, and most environmental friendly transportation mode. Also, it helps to reduce future traffic congestion at highways. Additionally, the obstacles hindering the development and use of the most advanced freight pipeline system, such as lack of investment on research and development, initial cost of construction, and underground utilities and crossing private lands and other roads, are discussed (Liu et al. 1998).

Dr. Liu (2004) investigated the feasibility of using pneumatic capsule methods of Underground Freight Transportation, which has been operated successfully in Japan, in New York City. At this report, different applications of UFT, availability of construction technology and operation technology discussed. In conclude, he proved that new technology of PCP is both technically and environmentally feasible for various application in New York City, and using UFT can drastically cut the number of trucks needed to enter the City, resulting in reduced traffic jam, accident and air pollution, enhanced transportation safety and security, and economic development. Also, due to using electricity instead of petroleum fuel, the use of UFT also reduces the consumption of imported oil (Liu H. , 2004).

In another research, Dr. Liu (2005) investigated the technical and economic feasibility of advanced pneumatic capsule (vehicle) pipeline (PCP) system for transporting minerals and mine wastes. This advance system uses linear induction motors (LIM) instead of blowers at the inlet of the pipeline as a propulsion system, and steel wheels over rails. At this report, he compared LIMs with PCPs and provide advantages and limitations of each propulsion system.

Also, Dr. Liu analyzed energy intensiveness (EI) of LIM and PCP and compared with truck. Based on his finding, UFT system uses less than one-tenth of the energy used by trucks and less than one-fourth of the energy used by trains, to transport the same cargoes over the same distance. Finally, UFT will reduce the need of using trucks for minerals and solid wastes transportation, thereby reducing air pollution and global warming caused by trucks. The system is the most environmentally-friendly, safe and secure method for transporting minerals and mine wastes (Liu and Lenau 2005).

2.5 UFT Construction Technology

According to Luo et al. (2004), most of large cities in the world such as New York and Tokyo have severe traffic congestion problems on the streets and highways. Such cities can benefit greatly from an underground network of pneumatic capsule pipelines (PCPs) to transport freight. The purpose of this project is to gain an understanding of the approximate cost of constructing such underground PCP under different conditions.

The cost study is focused on a PCP system for transporting entire containers such as those carried by trucks. In urban areas, the study assumes that the tunneling is through underground bedrock approximately 10 m deep. The condition is similar to that in New York City and many other major cities around the world. Deep underground tunnels require the use of a 15-ft diameter tunnel bored by modern TBM. A lining with shotcrete is to be provided for the tunnel case. Besides, the tunnel cost includes a flat floor for the rail base of 9 ft width. For rural areas, the PCP system for such a purpose can be built most economically by using a reinforced concrete rectangular conduit of 9-ft width and 11-ft height, with a standard railroad track on its bottom, which are inner dimensions; a minimum of 1 ft of reinforced concrete for walls, ceiling and floor need to be included.

According to this study, in order to shorten the construction duration of rural PCP construction, prestressed concrete cylinder pipe (PCCP) is considered as an alternative to concrete conduit, which should significantly lower the labor and equipment cost, but increase the material cost. As results, cost of tunneling is about 6 times is higher than open-cut with $9,200 per foot and $1,425 per foot respectively. With PCCP the cost of open-cut increased to $5,000, but still more cost effective than tunneling method. These costs vary depend on structural type, construction method, construction materials, soil and rock conditions, groundwater level, location, cost of labor and electricity (Luo et al. 2004).

Rezaei (2016) identified construction technologies for building a large diameter tunnels and showed several important parameters to decide proper construction method for building UFT. To accomplish this research, first, she discussed all different types of tunneling as well as open-cut with their advantages and limitations for large diameter pipe to build UFT. Then, based on previous case studies, design and construction of different UFT concepts such as GRID Logistics concept, CargCap, and UFT concept at CUIRE are compared.

Finally, Rezaei conducted a survey and several interviews to gather valuable technical information on key elements of UFT. The results showed that, either there is a lack of knowledge in open-cut method for building a large diameter tunnels or it is preferable to build the tunnels by TBM method. The details of this survey mentioned at future chapter of this research (Rezaei 2016).

Tabesh et al. (2016) presented major parameters that need to be considered when comparing cut-and-cover with trenchless methods to select the most appropriate method. As a case study, authors present feasibility of using cut-and-cover and tunneling for building an Underground Freight Transportation (UFT) from Port of Houston to Dallas by providing an analysis of applicability, constructability, and cost to select appropriate method.

Authors divided whole 250 miles route into nine sections to analyze each section individually based on construction time, ROW restrictions, soil conditions, land use, social impacts, existing buildings and bridges, existing underground utilities, watertable, road and rail road crossing, river and creek crossing, and construction permits. Also, they compared cost of construction equipment, mobilization and demobilization, spoil removal, backfill and compaction, reinstatement of surface, shoring and sloping trench and shaft wall, dewatering, indirect, social, labor, and material for each construction method.

As a result, cut-and-cover method can be applicable to 50% of route mainly in rural areas due to availability of surface space. Tunneling should be utilize at urban area, where surface area is limited, and social and environmental aspects are important (Tabesh et al. 2016).

2.6 UFT Social and Environmental Benefits

In 1998, American Society of Civil Engineers (ASCE) Task Committee on Freight Pipelines, investigate the future potential of various types of freight pipelines. The final report, concluded that “Freight pipelines are economical in many situations, reliable, automatic, environmentally friendly, energy efficient, and safe to people and the ecosystem. Advancements in pipeline technology and computer control systems have greatly facilitated the development and use of freight pipelines” (ASCE- Pipeline Devision 1998).

Dietrich and Schoesser (2003) stated that cities are threatened by traffic congestion and accident, and due to the fact, the number of motor vehicles and trucks increase much faster than the capacity of the street network. Also, just-in-time delivery of the products to processing industry becomes more important and available freight network system is not enough for future need.

They introduced CargoCap as a fifth mode of transportation to transport good through underground pipeline to constitute a great problem in the future development of Germany. At this paper, they just mentioned that UFT is pollution free method of freight transportation and can be a key solution to remove traffic congestion and reduce traffic accident due to heavy duty trucks. This paper comes from 5-years study at the Ruher University of Buchum (Dietrich & Schoesser, 2003).

According to Hodson (2008), in food industry, about 92% of the energy used to transport raw material and other supermarket goods, while it can be reduced to 8% by

Underground Freight Transportation system. He proposed a scientific research on UFT to replace heavy duty trucks with lightweight cargo-capsules running in pipelines, directly to and from loading bays in shops, distribution centers, and processing and food production manufactures. By implementation of UFT in food industry at UK, annually 4 billion metric tons of Carbon Dioxide would be saved.

Hodson designed an UFT with 3.3 feet pipe diameter, 6.5 feet capsule long which carries 35 lbs. cargo with the speed of 94 MPH by utilizing LIM motors, and with annual capacity of 56,500,000 metric tons. He investigated pipe material, routing, and renewable energy sources to build UFT. As he claimed, UFT benefits are reduction at petroleum production due to less truck transportation and less asphalt road construction, reduction at air pollution, reduction at energy consumption, reduction at operation cost, increased at freight transportation reliability, reduction at number of trucks at roadways, and profitability for business due to less cost of transportation. Finally, he simulated cost-benefit ratio by STONER SOFTWARE and came up with 70% annual profit (Hodson, 2008).

Cotana et al. (2008) presented “Pie§net”, which is an Italian innovation to transport freight for payloads up to 50 Kg, constituted by a network of vacuum-sealed pipes, where goods-carrying capsules are moved by electric linear motors (LIM) in very low friction conditions and at variable speed. In this paper the main characteristics of the system like high transport capacity, low energy consumption, low environmental impact, high speed in goods delivery, integration with railways and road infrastructures, and door-to-door and spreading potential are discussed.

Based on this study, through a comparison with road and railways transport systems, economic, environmental and social advantages are investigated. According to this paper, this system can reduce 40% energy consumption, 33% air pollution, 7% accident rate, 5.5% injury due to accident, and 10% fatality incident due to accident in

Italian highway compare than truck in freight transportation. In recommendation part, (Cotana et al. 2008) recommend to research on cost and environmental impact of UFT since “cost and environmental impact of innovative infrastructures struggle to be accepted by public and private investors and decision-makers.” This research was funded from Italian Ministry of Environment and Fondazione Cassa di Risparmio di Perugia and done by the University of Perugia, Italy (Cotana et al. 2008).

Yu et al. (2010) presented a paper about the necessity of developing underground domestic waste transfer logistic system in Shanghai. This system is a kind of environment friendly method to improve traffic congestion, reduce energy consumption, and increase transfer efficiency. Also, the capital cost of this system is very high, but in a long term, it is cost effective, and has environmental and social impact (Yu & Fan, 2017).

GRID (2015) is another UFT study, which is based on Southern California geography and logistics, and is exportable and scalable to meet local geographic, geologic, environmental, and logistic needs. The objectives of this study were to reduce the amount off truck traffic, which delivers the cargoes between terminals in Southern California Harbor to the distribution centers. The freight pipeline is 137 miles long and is designed to follow current logistics routes 60 feet below that can coincide with the surface transportation routes.

This system powered by electric rail and transported by drone train technologies, it will operate out of sight and out of mind to deliver cargo to our inland feeder distribution terminals. This pipeline system is specifically designed to replace a large portion of truck drayage coming to and from port complexes. This system will significantly reduce time and increase the productivity of delivering the cargoes up to 90%. This includes servicing inter-state deliveries as well as the electric drone trains feeding into our freight pipeline (GRID, 2015).

Milinkovic and Patelic (2015) presented underground logistics system, as a solution to the problems of urban environments logistics. The concept combines social benefits by displacing traffic underground and the application of electric propulsion with the advantages of the unobstructed automatic transport through dedicated infrastructure which is separated from the passenger traffic. The idea was to, through various forms of underground transport, present basic characteristics, advantages and disadvantages as well as the results of their application.

The economic advantages of this system include almost direct delivery, 24-hour service, low operating costs and short feedback time. Social benefits include reduction of noise, visual pollution, physical interferences, gas emissions, reducing congestion and traffic jams, more intensive use of available space, relieving the street network and the increase of overall traffic safety.

Investment costs are high and technology which is used is new, which leads to lack of experience in automated mass transport systems. The application of these systems requires building the entire infrastructure which means that its realization requires a long period of time (Milinkovic & Patelic, 2015).

Chen et al. (2017) considered underground logistics system as an alternative to solve urban traffic problems. They used Macro-environment and situation analysis (PEST-SWOT) model, which is strategic analysis method to combines PEST and SWOT to effectively identify advantages, disadvantages, opportunities and threats. They reviewed all available literature related to UFT and summarized, which some of key points are followed;

- Large cities urgently need to increase freight transportation capacity by UFT.

- A Comprehensive analysis of the political, economic, social, environmental, and research for opportunities to meet challenge are needed to guarantee for success in the pilot project.
- UFT helps sustainable development of the city. Therefore, engineering practice needs the support and guidance of policy.
- In addition to economic benefits, more attention should be paid to benefit for traffic, environment, and society.
- UFT is complex system, and it necessities its own technology integration and collaboration with urban economy, transport, environment, and high degree of information and automation.

In next steps, they identify all strength and weaknesses (internal condition) and opportunities and threats (external environment) in four categories of politics, economy, society, and technology. Then they investigated the advantages and disadvantages of each category based on internal conditions and external environments (Chen et al. 2017).

According to Tavakoli (2017), carbon dioxide (CO2) is the primary greenhouse gas emitted through human activities. The construction industry is a major producer of such emission due in part to the magnitude of operations and the vast array of equipment. This paper presents a comparison of carbon footprint for conventional open-cut and trenchless technology methods, particularly tunneling in rural area.

The paper considers building a freight pipeline in a proposed route from Huntsville to Madisonville, Texas, under existing right-of-way and with a pipe diameter of 8 to 13 ft. The objective of this paper is to quantify carbon emissions produced by construction equipment for hauling excavated soils during pipeline construction for UFT. The methodology of this research was identifying equipment for each construction activity, calculate productivity per hour of each equipment, calculate amount of CO_2 per hour of each equipment, calculate amount of produced CO_2 per unit of each activity, and finally calculate total amount of produced CO_2 for each construction method.

As a result, UFT tunnel construction by trenchless technology method produce carbon dioxide 6 times less than tunnel construction by open-cut (cut-and-cover) method. Trenchless technologies with minimum surface and subsurface disruptions offer a viable alternative and result in lesser carbon emissions compared to open-cut method (Tavakoli et al. 2017).

Tabesh et al. (2017) presented environmental impacts of pipeline construction for Underground Freight Transportation (UFT) as a part of an Environmental Impact Assessment (EIA) analyses for feasibility study of UFT from Port of Houston to Dallas, TX. The EIS describes and summarized the environmental and social impacts of pipeline construction to help designers, engineers, and decision makers to utilize the best method of construction with less unfavorable environmental impacts between trenchless technology and cut-and-cover methods.

As a case study, the authors considered one-mile UFT construction section at north side of President George Bush Airport at Houston and compared tunneling by TBM for one twin-track tunnel and cut-and-cover for two single-track tunnels. As a result, pipeline construction with tunneling method has less impact to social and environment and it is suitable method for project with workspace limitations.

According to this study, while tunneling with TBM have a higher design life and construction productivity compare than cut-and-cover, it is costlier due to expensive tunneling equipment and procedure. Additionally, cut-and-cover has negative impacts on environment, ecosystem, and quality of life of citizens due to higher rate of traffic disruptions and land usage, higher safety hazards, and higher energy consumption (Tabesh et al. 2017).

2.7 UFT Financing Means

Zahed et al. (2017) assessed investment opportunities of a container-size UFT system to transport freights from the Port of Houston to the City of Dallas. Based on this paper, planning for implementation of such large and innovative infrastructure projects, requires a rigorous investment valuation to explicitly show the advantages of the project for the public and private parties. Authors developed cash inflows and outflows of the UFT system for a 100-year life cycle of the system by considering onetime initial costs, such as cost of tunneling, cost of terminal land and development, and cost of the Linear Induction Motors (LIM).

Based on this study, other costs and benefits are assumed as recurring annual costs in the life cycle of the UFT system. Then, present values of the benefits and costs of the UFT are calculated. The Net Present Value (NPV), benefit-cost (B/C) ratio, and Internal Rate of Return (IRR) of the UFT system are obtained based on the present values. The NPV, B/C ratio, and IRR of the UFT system are $60 billion, 3.8, and 12.4%, respectively. The values of NPV and B/C ratio of the system along with the comparison of the system internal rate of return with the market discount rate clearly show the economic viability of the UFT system (Zahed et al. 2017).

At another research, Zahed et al. (2017) claimed that, construction of new intermodal transportation systems, such as underground freight transportation (UFT) systems by using underground tunnels can increase freight transportation capacity and mitigate the need for road widening or building new roads in areas bogged down by truck traffic. However, the gap between public service needs and the financial capabilities of the state governments has grown, and financing innovative infrastructure projects, such as UFT systems, has become increasingly challenging.

According to this research, successful implementation of a large UFT system demands availability of appropriate funding sources. The objective of this paper was to identify and evaluate viable funding sources and appraise the eligibility of these sources for constructing UFT systems in Texas. The authors conducted an extensive literature review, analysis of codes and legislation, and case study analyses to achieve the research objectives.

They identified a variety of public and private funding sources, such as federal, state, and local funds, Transportation Infrastructure Finance and Innovation Act (TIFIA) loans, funds provided under the Fixing America's Surface Transportation Act (FAST Act), revenue bonds, private activity bonds, and equity participation for financing UFT systems. The results highlight significant opportunities to qualify UFT projects with state or national significance for federal funding eligibility. It is also possible to identify UFT systems as projects that alleviate traffic congestion and improve safety to be eligible for Texas state funding programs (Zahed et al. 2017).

Zahed et al. (2018) conducted a comprehensive lifecycle benefit-cost analysis of linear induction motor-based UFT systems for five different scenarios. This methodology includes the following steps: (1) developing UFT scenarios with different sizes (small, medium, and large) and routes (short and long) in collaboration with a stakeholder committee; (2) determining lifecycle cash flows; (3) calculating net present values, benefit-cost ratios, and internal rates of returns; (4) conducting sensitivity analysis; and (5) performing breakeven analysis.

The results of this research show that the highest benefits of the UFT systems are revenue from shipment and reduction in air pollution. The internal rates of return, benefit-cost ratios, and net present values of the UFT scenarios indicate that the benefits offset the costs of the system. Results of sensitivity analysis show that the economic feasibility of the large and medium-size UFTs is more sensitive to tunnel construction cost and revenue from shipments. They also indicate that the economic feasibility of the UFT system with a short route and small size is more sensitive to higher discount rates and the policies concerning the shipment pricing. Results of breakeven analysis highlight a shorter payback period for the large and medium-size UFTs compared with small-size scenarios. The results show that the price of shipment for all the UFT scenarios is highly competitive compared with the current price of shipment by trucks (Zahed et al. 2018).

2.8 UFT Lifecyle Cost Analysis

Janbaz et al. (2017) estimated the capital and annual costs of a container size UFT system from port of Houston to Dallas via a 25-ft diameter tunnel. Life cycle cost analysis is an important step in feasibility study of infrastructure systems. Life cycle cost analysis of innovative infrastructure systems, such as Underground Freight Transportation (UFT) systems is often challenging since there is not much historical cost information about these systems.

The major capital cost UFT system is tunnel construction cost, linear induction motor cost, and vehicle cost. The annual cost components of the UFT system are maintenance cost, energy consumption cost, and administration cost. In order to accomplish this research, authors used historical tunneling costs to create a regression model to estimate costs of tunnels with various sizes, quotes from the industry, and RSMeans cost data to estimate costs of vehicles, propulsion system, UFT maintenance, energy consumption, and administration.

The preliminary capital cost estimate for the UFT system is approximately $53 million per mile, which including $47 million per mile for tunneling and $7 million per mile for the rest of infrastructure. The preliminary annual cost is approximately $150 million per year. These results inform transportation planners about estimated construction, maintenance, and operation costs of the UFT system (Janbaz et al. 2017).

2.9 Chapter Summary

Underground Freight Transportation has been investigated for more than 40 years. By today, several researchers have proven that UFT is applicable due to availability of LIM technology and control devices, constructible due to availability of TBMs and construction equipment, and feasible due to high benefit-cost ratio. A lot of literatures indicated that Underground Freight Transportation reduces the truck traffic, street congestion, noise, energy consumption, accidents, and air pollution. Moreover, UFT has higher design life compare with highway and railroad with lower life cycle cost. It was recommended to investigate quantitative analysis of UFT's benefits compare with other inland modes of transportation such as heavy-duty trucks and railroads.

Chapter 3 TRAFFIC MODELING

3.1 Traffic Volume Distribution Model (TVDM)

Traffic volume is critical data, which has a wide range of applications at transportation and urban planning. Traffic volume is a critical measurement that has a wide range of applications. Local transportation agencies need volume information to perform analysis on traffic (Zhan et al. 2017). Traffic volume can be an input data for analyzing traffic flow, measuring vehicle emission and traffic congestion. Estimating traffic volume and distribution are difficult task involving many challenges (Zhan et al. 2017;Gomati et al. 2018). The traditional way to estimate and predict the volume of traffic is using various road-based sensors, which are mainly applicable at major road segments including following categories (FHWA, Traffic Monitoring Guide , 2018);

- Automated Traffic Recorder (ATR), which is a traffic counter that is placed at specific locations to record the variation and distribution of the traffic flow by hour of the day, day of the week, and month of the year. This sensor can be used to collect data continuously at the permanent site or at any other location temporary.
- Continuous Count Station (CCS), which is a permanent counting site provides 27/7 service either for all days of the year or at least for a seasonal collection.
- Portable Traffic Recorder (PTR), which is traffic vehicle counter of classifier that is portable and not installed permanently.
- Weight-In-Motion (WIM), which is a device to measure the dynamic tire forces of a moving vehicle and estimating the corresponding tire loads of the static vehicle to classify the passing vehicles.

However, Installing and using road-based sensors such as loop detectors and cameras, are too expensive, therefore, it is difficult to collect direct information about the volume of vehicles (Gomati et al. 2018). There are several approaches that have been developed by researches to forecasted traffic volume, which can be divided into two categories of univariable and multivariable analysis. In univariate approach, model works based on traffic condition related variables such as average speed. In multivariable approach, model works based on combination of different variables as inputs (Clavon, 2017). Both approaches can be used for parametric techniques, such as, time-series model and historical average algorithms and non-parametric technique, such as nonparametric regression and artificial neural network (Ghosh et al. 2009). The objective of Traffic Volume Distribution Model (TVDM) is to estimate volume of vehicle at each time interval of the day. The volume and speed of vehicles helps to estimate social and environmental benefits of each alternative.

3.2 Current Practice

To estimate volume of traffic, transportation agencies usually utilize indirect traffic state measures, such as, traffic density or speed by using fundamental diagrams and equations of traffic flow from Highway Capacity Manual. This approach exploits the basic relationship between traffic volume, density, and speed to predict. The disadvantage of this approach is using too many variables with enough traffic data for each individual section that needs to be calibrated. Figure 3-1 illustrates the relationship between speed and flow rate (HCM, 2016) .

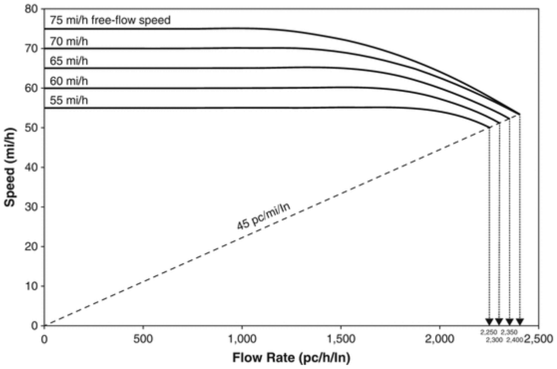


Figure 3-1 General Form for Speed-Flow Curves on Basic Freeway Segment

As stated at HCM (2016), in basic freeway segment, the capacity and Break Point (BP) values are directly related to the Free Flow Speed (FFS). Equation 3-1 shows the general analytic form of the speed-flow relationship (HCM, 2016);

$$\begin{cases} S = FFS_{adj} \ , \ v_p \leq BP \\ S = FFS_{adj} - \dfrac{\left(FFS_{adj} - \dfrac{C_{adj}}{D_c}\right)\left(v_p - BP\right)^a}{\left(C_{adj} - BP\right)^a} \ , \ BP < v_p \leq C \end{cases}$$

Equation 3-1

Where for basic Freeway Segment;

FFS_{adj}, Adjusted free flow speed (mph)

C, Base segment capacity (pc/h/ln)

C_{adj}, Adjusted segment capacity (pc/h/ln)

D_c, Density at capacity (pc/mile/ln)

BP, Breakpoint (pc/h/ln)

a, Exponent calibration parameter (decimal), and

v_p, Demand flow rate under equivalent base conditions (pc/h/ln)

Equation 3-2 calculates free flow speed at basic freeway segments (HCM, 2016);

$$FFS = BFFS - f_{LW} - f_{RLC} - 3.22 \times TRD^{0.84}$$

Equation 3-2

Where,

BFFS, Base FFS for the basic freeway segment, which is 75.4 (mph)

f_{LW}, Adjustment factor for lane width (mph)

f_{RLC}, Adjustment for right-side lateral clearance (mph), and

TRD, Total ramp density (ramps/mile)

Equation 3-3, calculates demand flow rate at basic freeway segments (HCM, 2016);

$$v_p = \frac{V}{PHF \times N \times f_{HV}}$$

Equation 3-3

Where,

V, Demand volume under prevailing conditions (veh/h)

PHF, Peak hour factor (decimal)

N, Number of lanes in analysis direction (Ea.), and

f_{HV}, Adjustment factor for presence of heavy vehicles (decimal)

Table 3-1 shows the value or equation of above parameters (HCM, 2016);

Table 3-1 Speed-Flow Equation Parameters

Parameter	Value or Equation
FFS_{adj}	$FFS_{adj} = FFS \times SAF$, where SAF=1.00 for base condition[3]
C	$C = 2{,}200 + 10(FFS - 50)$, where $C \leq 2{,}400$ and $55 \leq FFS \leq 75$
C_{adj}	$C_{adj} = C \times CAF$, where CAF=1.00 for base condition[4]
D_c	45
BP	$BP = [1{,}000 + 40 \times (75 - FFS_{adj}) \times CAF^2$
a	2.00
f_{LW}	$\begin{cases} 0.0\ when\ LW \geq 12\ ft \\ 1.9, when\ 12 > LW \geq 11 \\ 6.6, when\ 11 > LW \geq 10 \end{cases}$
f_{RLC}	See Table A-1, Appendix A
PHF	0.98
f_{HV}	$f_{HV} = \frac{1}{1+P_T(E_T-1)}$, where P_T is truck% and E_T=2.0 for base condition[5]

Equation 3-4 derived from Equation 3-1, when the average speed of traffic flow is known, and demands flow rate needs to be calculated. Also, Equation 3-5 shows how to calculate traffic volume from traffic demand.

---

[3] SAF is speed adjustment factor

[4] CAF is capacity adjustment factor

[5] ET is passenger car equivalent of one heavy vehicle in the traffic stream

$$v_p = \sqrt[a]{\frac{(FFS - S)(C_{adj} - BP)^a}{(FFS_{adj} - \frac{C_{adj}}{D_c})}} + BP$$

Equation 3-4

$$V = \frac{v_p \times PHF \times N}{1 + P_T(E_T - 1)}$$

Equation 3-5

As stated earlier, the current practice requires many variables that needs to be calibrated. Moreover, Equation 3-5 is reliable when the demand flow rate is higher than breakpoint and lower than the capacity of the segment. Therefore, the total demand volume under prevailing conditions per 24 hours, needs to be adjusted based on AADT.

Traffic Volume Distribution Model (TVDM) is mathematical univariable model, which using parametric technique to estimate distribution of the vehicle at specific time interval by using average speed. Not only this model helps to estimate distribution of the vehicle, but also, it helps to estimate directional distribution factor (D-Factor), which shows proportion of traffic traveling at each direction during peak hour of anytime of day.

This model is appropriate for highways and roadways without any intersections and interruptions. Since the inputs of this model are the average annual speed of each segment and Average Annual Daily Traffic (AADT), change in speed due to traffic accident or any other events do not impact the output.

3.3 Model Description

This model uses speed-time interval curve and AADT to estimate volume of vehicle at each time by considering the area above the curve up to limit line (L). This method is compared and validated by real data with the accuracy of 85%. Following steps is the procedure of TVDM to estimate traffic volume distribution.

a) By Equation 3-6, calculate limit line (L) for each direction.

$$L = 2S_{max} - S_{min}$$

Equation 3-6

Where,

L, Limit line (mph),

S_{max}, Maximum speed during peak hour (mph), and

S_{min}, Minimum speed during peak hour (mph),

b) By Equation 3-7, calculate Area (A) for each time interval at each direction.

$$A_i = \frac{(L - S_i) + (L - S_{i+1})}{2} \times t$$

Equation 3-7

Where,

A_i, Area at time interval i (mile)

S_i, Average speed at time interval i (mph),

S_{i+1}, Average speed at time interval i+1 (mph), and

t, Length of time interval (hour)

Figure 3-2 illustrates time intervals, areas (A), and limit line (L) and speed-time curve.

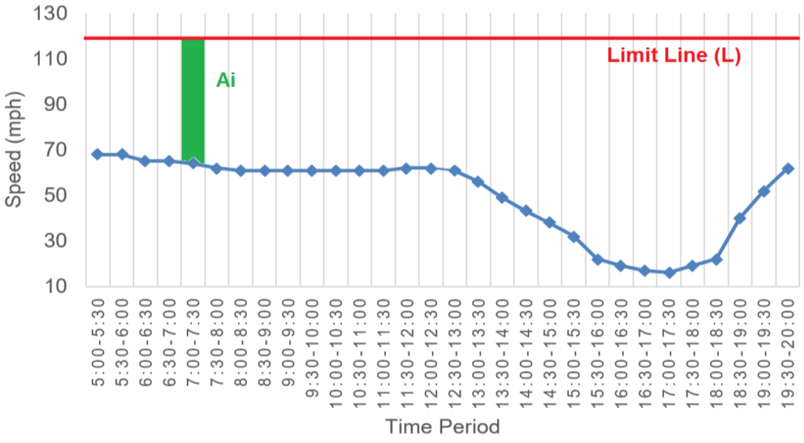


Figure 3-2 Traffic Volume Distribution Model Component

As it shows at Figure 3-2, average speed of vehicles gradually decreased from 70 mph to 62 mph from 5:00 am to 12:30 pm, then decreased sharply to reach 17 mph at 17:00, and finally increased up to 65 mph at 20:00. Therefore, at this segment, there is high congestion from 13:00 to 19:30 with higher number of vehicles.

c) According to WDOT (2010), 85% of vehicles travel from 5:00 am to 8:00 pm (WDOT, 2010). Equation 3-8 calculates $AADT_{peak}$.

$$AADT_{peak} = 85\% AADT$$

Equation 3-8

Where,

$AADT_{Peak}$, Average annual daily traffic from 5:00 am to 8:00 pm (Ea.), and

AADT, Average annual daily traffic (Ea.)

d) By Equation 3-9, calculate Ration (R).

$$R = \frac{AADT_{Peak}}{\sum_i^j A}$$

Equation 3-9

Where,

R, Ratio of vehicle per mile (Veh/mile),

$AADT_{Peak}$, Average annual daily traffic from 5:00 am to 8:00 pm (Ea.), and

A, Area at each time interval (mile) for both direction.

e) By Equation 3-10, estimate the number of vehicle at each time interval.

$$V_i = A_i \times R$$

Equation 3-10

Where,

V_i, Total volume of vehicle at time interval i (Veh),

A_i, Area at time interval i (mile), and

R, Ratio (Veh/mile)

Figure 3-3 illustrate the output of model and shows the volume of vehicle at each time interval. As it is obvious, this figure is almost symmetric with speed-time interval curve at Figure 3-2. The number of vehicles increase gradually from 5:30 to 12:30 pm from 3,100 vehicles to 3,500 vehicles per 30 minutes, then increase sharply to 6,200 vehicles per 30 minutes interval at 17:00.

f) By using AADTT or truck percentage, the volume of truck and passenger vehicle can be calculated.

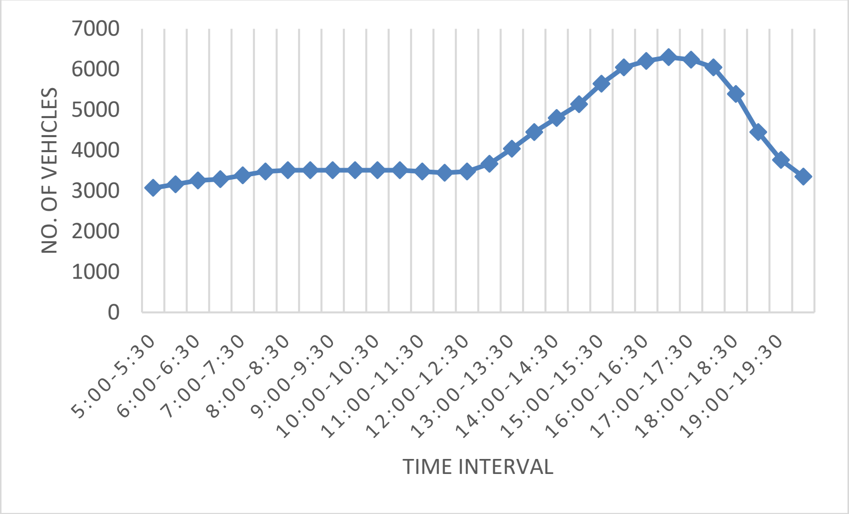


Figure 3-3 Traffic Volume Distribution Model Output

3.4 Model Validation with Case Study

This model compared with real data from three segments of “Leof Andrea Siggrou” Highway at Athens, Greece (Vlahogianni et al. 2015). Figure 3-4 illustrate the average speed of each segment for 24-hours.

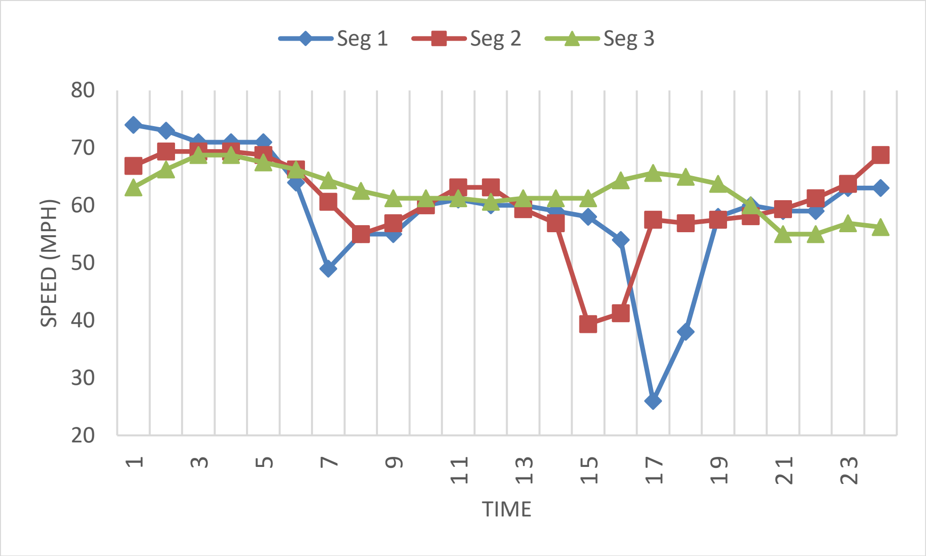


Figure 3-4 Average Speed of Vehicles

Data derived from (Vlahogianni et al. 2015)

According to Figure 3-4, average speed from 12:00 am to about 6:00 am is near speed limit of each segment. For this period, number of vehicles is varied and does not impact the average speed of segment. Figures 3-5 through 3-7 illustrate the differences between observed vehicle volume and estimated vehicle distribution by TVDM.

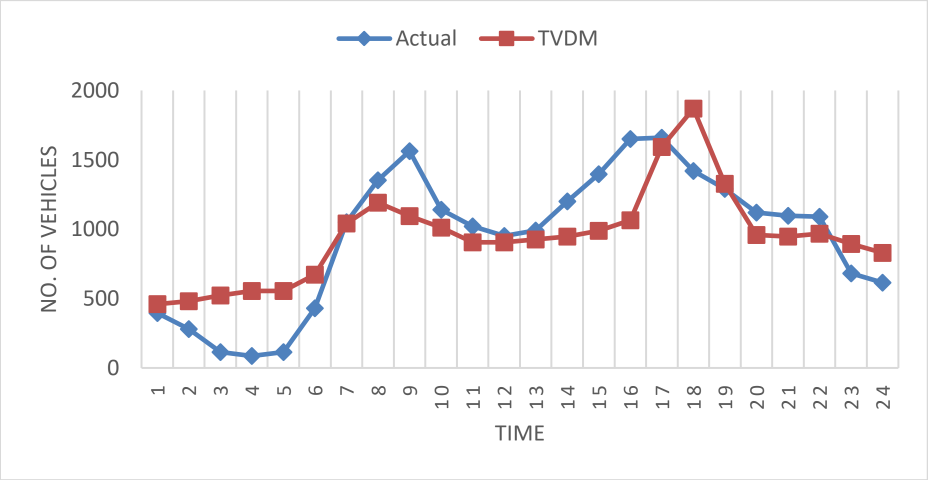


Figure 3-5 Actual Distribution vs. TVDM Result for Segment 1

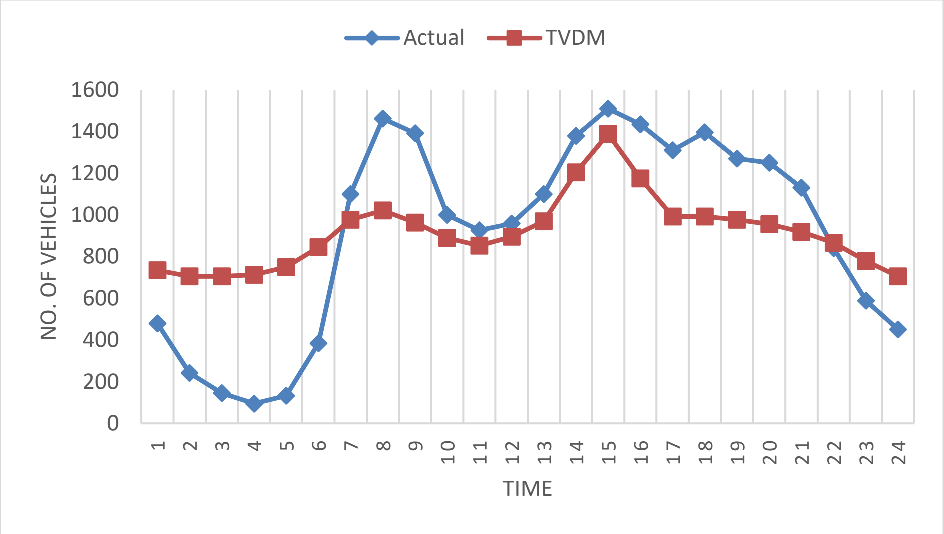


Figure 3-6 Actual Distribution vs. TVDM Result for Segment 2

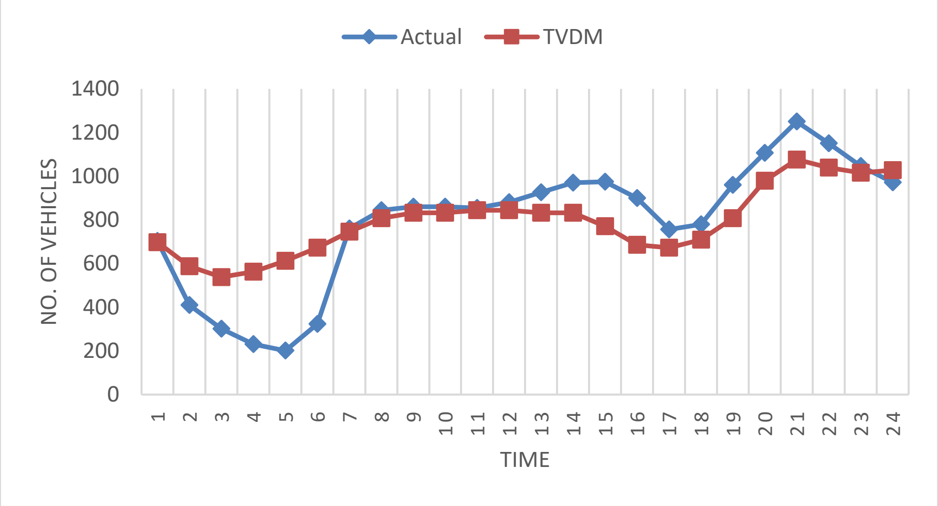


Figure 3-7 Actual Distribution vs. TVDM Result for Segment 3

In order to compare actual values with result of TVDM, Mean Absolute Percentage Error (MAPE) used. MAPE is a method to measure the accuracy of the prediction and shows the difference in percent. Equation 3-11 shows how to calculate the MAPE.

$$MAPE = \frac{\sum_{i=1}^{n} \left| \frac{A_i - F_i}{A_i} \right|}{n} \times 100$$

Equation 3-11

Where,

A_i, Actual value,

F_i, Forecast value,

And n, Number of data set

Table 3-2 shows MAPE of three segments, for whole day and for peak hours from 6:00 to 24:00.

Table 3-2 Mean Absolute Percentage Errors

Seg.	MAPE for all day (%) (24 hrs.)	MAPE for Peak Hour (%) (6:00-24:00)	MAPE for Non-Peak Hour (%) (24:00-6:00)
1	39.55%	17.01%	237.85%
2	92.82%	19.96%	311.40%
3	31.06%	9.28%	96.39%

3.5 Discussion and Results

Lewis (1982) Provided a framework to judge the accuracy of the model by MAPE. Table 3-3 shows his scale of judgement for any forecast model (Lewis, 1982; Clavon, 2017).

Table 3-3 Lewis's Scale of Judgement for MAPE

MAPE	Judgment of Accuracy
Less than 10%	Highly Accurate
11% to 20%	Good Forecast
21% to 50%	Reasonable Forecast
51% or more	Inaccurate Forecast

Based on Table 3-2, this model perfectly works during peak hours, when speed of vehicles depends on the volume of vehicle, while it does not work at non-peak hours periods due to high MAPE. The reason is, there is no congestion from 12:00 am to 6:00. Therefore, the average speeds are not depended on the volume of vehicle, while during peak hour, the average speed depends on the number of vehicle. This model estimates the maximum possible number of vehicle that can go by speed limit at non-peak hour period, while the reality can be much less than what model estimated.

For example, for segment 1, during non-peak hours, up to 700 vehicles can drive approximately 70 mph. If the number of vehicles reduced during this time, speed is still 70 mph. Unlike non-peak hour, at peak hour, by increasing or decreasing number of vehicle, speed would change.

This model works at peak-hour period at highways and freeways, without any intersection and interruption. Therefore, TVDM reran for the same segments from 7:00 to 24:00 and MAPE recalculated, which are 14.24%, 16.21%, and 8.73% for segment 1 through 3, respectively. Moreover, Figures 3-8 through 3-10 illustrate the new distribution of vehicles.

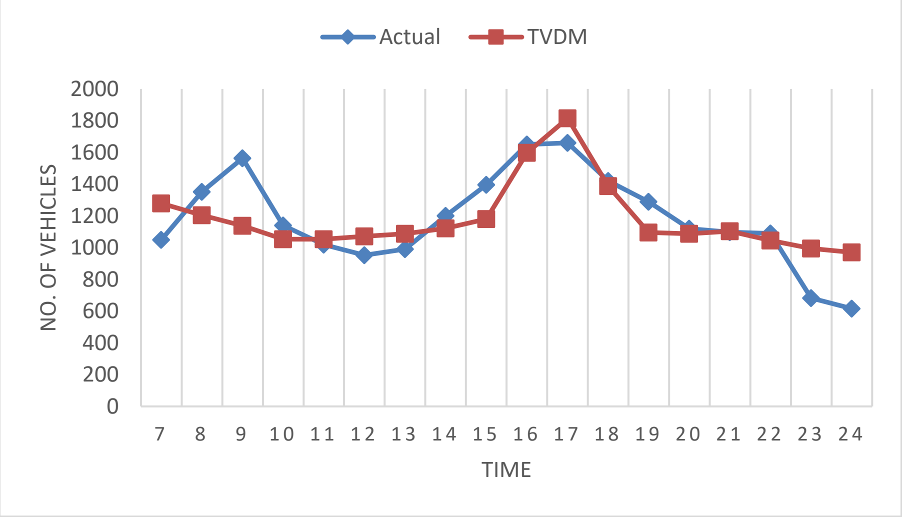


Figure 3-8 Actual Distribution vs. TVDM Result for

Segment 1 During Peak Hours

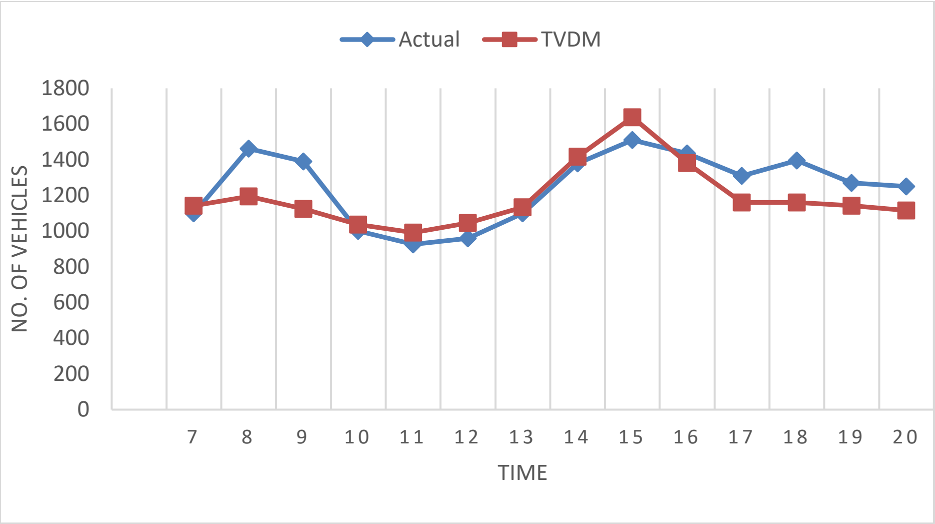


Figure 3-9 Actual Distribution vs. TVDM Result for

Segment 2 During Peak Hours

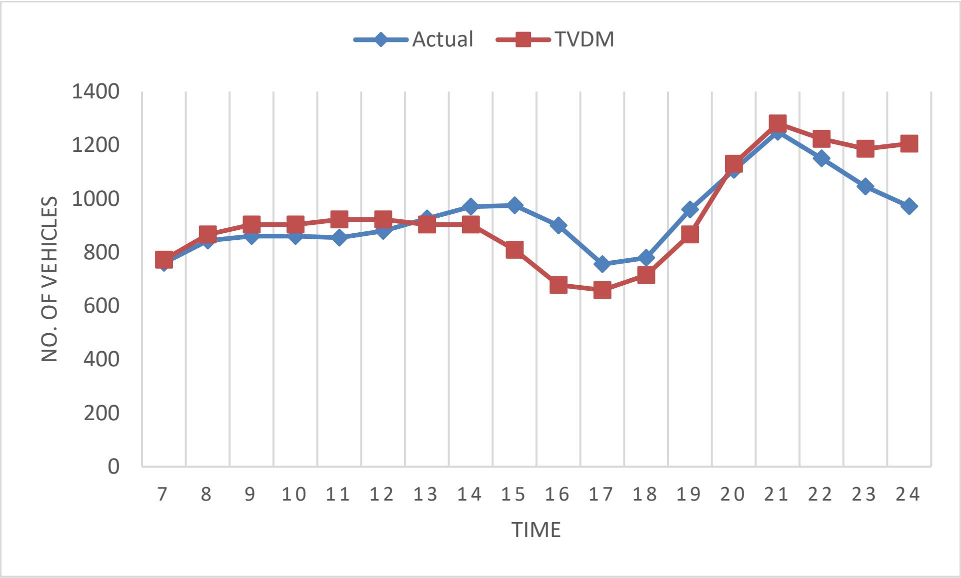


Figure 3-10 Actual Distribution vs. TVDM Result for

Segment 3 During Peak Hours

For this dissertation, from Houston TranStar Traffic Map, the average speed of 18 segments of selected route, at 30-minutes time intervals collected (TranStar, 2018).

Additionally, average annual daily traffic and truck percent information collected from TxDOT (TxDOT, Statewide Planing Map, 2018). Then, by the TVDM, the volume of vehicles at each time interval estimated. At next step, all required data related to the selected route such as segment's length, number of lanes, exit and entry ramps, and road and highway intersections collected and analyzed to use at Traffic Flow Speed Prediction Model (TFSPM).

3.6 Model Comparison with HCM

The average volume of traffic at every 30 minutes time interval from 5:00 am to 8:00 pm of 18 segments of selected case study route, with TVDM model estimated and compared with the result from Equations 3-4 and 3-5.

As a result, the overall mean absolute percentage error (MAPE) of TVDM results is 10%, which shows the model is highly accurate compare with HCM method. Figures 3-11 through 3-13 illustrate this comparison.

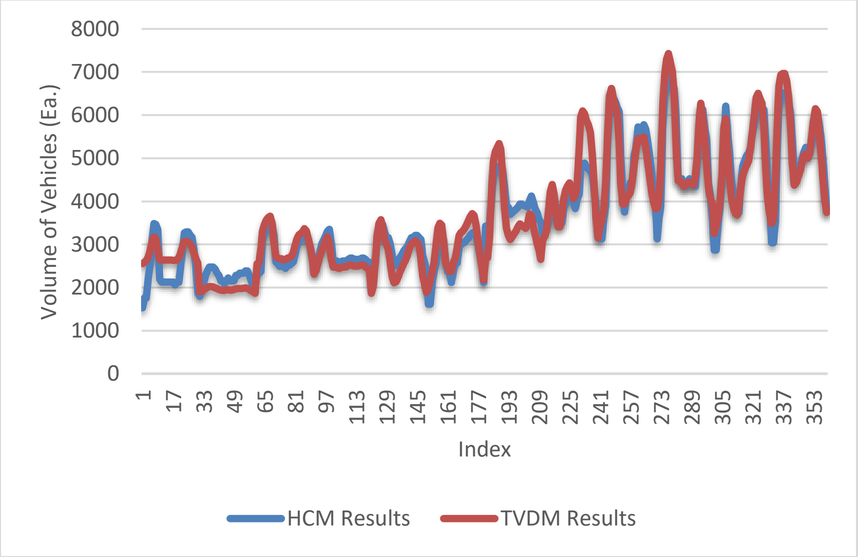


Figure 3-11 TVDM Comparison with HCM with 9% MAPE

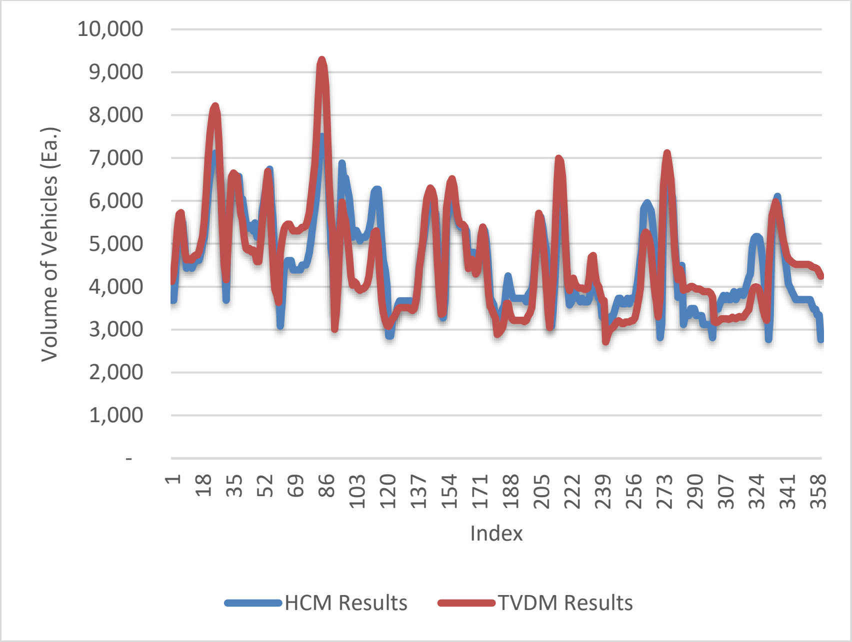


Figure 3-12 TVDM Comparison with HCM with 12.7% MAPE

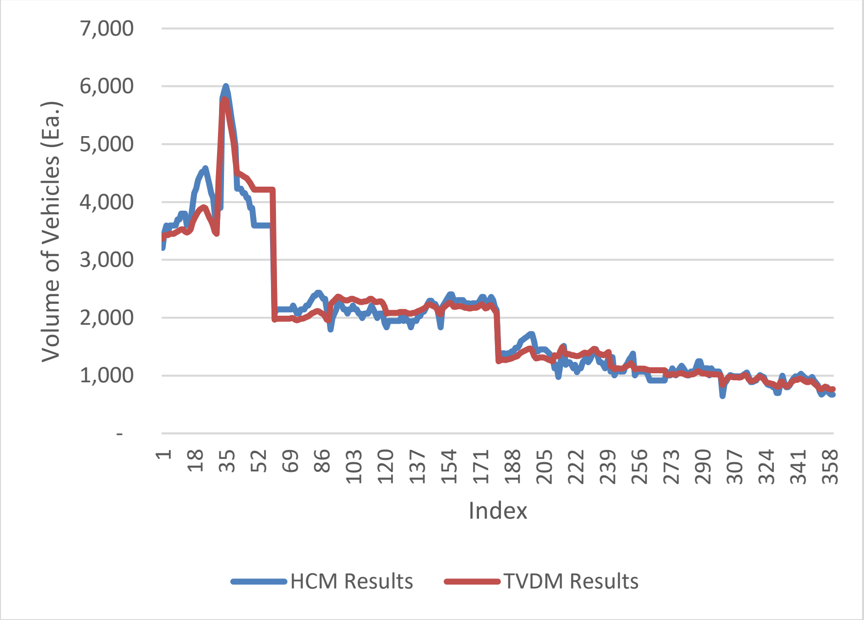


Figure 3-13 TVDM Comparison with HCM with 7.9% MAPE

3.7 Traffic Flow Speed Prediction

As stated earlier, air and noise pollution, accident rate, traffic congestion, and energy consumption of heavy duty truck, locomotive, and UFT are speed dependent. Therefore, this is necessary to predict improved speed due to widening the highway by adding lane at each direction (Alternative 1), reducing number of truck and shipping container by railroad (Alternative 2), or UFT (Alternative 3). The next step is predicting speed improvement at each segment of selected route due to implementing each alternative. This prediction is conducted with use of Highway Capacity Manual equations for basic freeways.

For Alternative 1, by using Equation 3-3, demand flow rate under equivalent base condition (v_p) recalculated with increasing number of lane (N) and use the same demand volume (V). For this prediction, it is assumed that after implementing Alternative 1, which is widening the highway, average traffic volume will not increase. Then, Equation 3-1 used to calculate average speed at different segment and time interval. As a result, by widening the highway, it is predicted that the average speed of vehicles will be improved for 12 miles per hour, at selected route from 5:00 am to 8:00 pm.

For other alternatives, it is assumed that 192 trucks will be substitute with railroad (Alternative 2) or UFT (Alternative 3). Therefore, based on new heavy vehicle adjustment factor (f_{HV}) with updated percentage of trucks, demand flow rate under equivalent base condition (v_p) by Equation 3-3 recalculated. Then, Equation 3-1 used to calculate average speed at different segment and time interval. As a result, removing 192 heavy duty trucks from selected route per hour, it is predicted that the average speed of vehicles will be improved for 9 miles per hour from 5:00 am to 8:00 pm.

3.8 Chapter Summary

To estimate volume distribution of vehicle at each time interval, Traffic Volume Distribution Model (TVDM) was developed. This model was accurate to estimate volume of vehicle by using average speed of vehicles during peak hour. Then, by using equations from Highway Capacity Manual, average speed of vehicles due to implementing each alternative, predicted. Based on calculation, widening the highway has better impact on average speed improvement compare with removing heavy duty trucks.

Chapter 4 SOCIAL AND ENVIRONMENTAL COST ESTIMATION FRAMEWORK

4.1 Air Pollution

According to World Health Organization (WHO), approximately 6.5 million people are died due to the air pollution. This number is much greater the sum of number of death due to HIV/AISD, tuberculosis, and road accidents (IEA, 2016). Moreover, air pollution has high impact on economy, environment, and food security. Air pollution is effect to the surrounding air by concentrations of solid, liquids, or gases, which have a negative impact on the environment and people.

Two major source of air pollution is natural source such as dust, wildfire, and volcanoes, and human activity source with local, national, regional, or global range (IEA 2016). Greenhouse gases are the major part of global air pollution. Greenhouse gases are the one, which trap heat in the atmosphere, including Carbon Dioxide, Methane, Nitrous Oxide, and Fluorinated gasses (EPA 2018).

Climate change or global warming is caused by greenhouse gases that increase atmospheric solar heat gain (Litman, 2009). Anthropogenic greenhouse gas (GHG) emissions have been increased in last 100 years. In 2015, at Paris, over 100 countries agreed to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below two degrees Celsius to prevent additional and irreversible economic, ecological, and infrastructure damage (UNFCCC, 2018). The United States is the second-highest GHG-emitting nation in the world, after China in the first rank, and in recent years emits about 15% of global GHG emissions (Quiros et al. 2017).

According to the EPA, in 2013, total greenhouse gas emissions were 6,673 million metric tons of carbon dioxide equivalents and these emissions increased 2.0% from 2012 to 2013. Recent trends can be attributed to multiple factors, but the most important one is an increase in miles traveled by on-the-road vehicles, especially trucks (EPA 2015). Figure 4-1 provides an overview of greenhouse gas emissions in the United States based on information from the inventory.

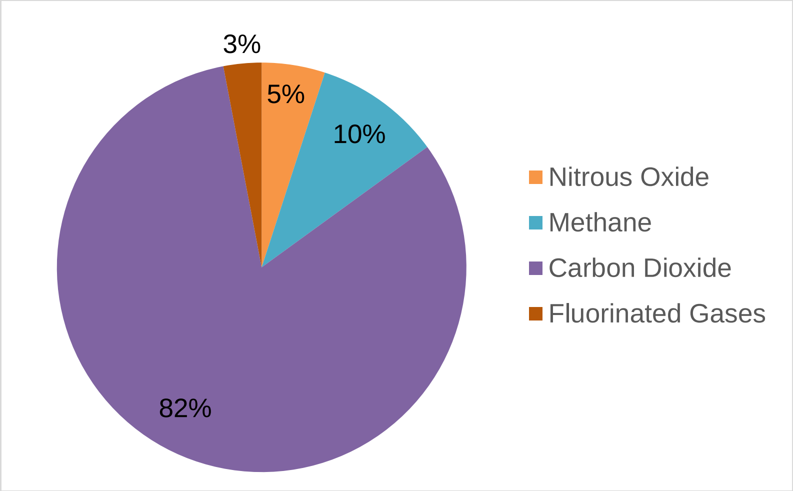


Figure 4-1 Overview of Greenhouse Gases

(EPA 2015)

Greenhouse gas concentrations in the atmosphere will increase unless the billion tons of our annual emissions decrease substantially. Increasing greenhouse gas concentrations is the primary cause of increasing earth average temperature, which is expected to increase by 2°F to 11.5°F by 2100.

This predicted temperature increase is the year 2100 is dependent on the level of future greenhouse gas emissions, reduction of ice and snow cover, rise in sea level, increase in ocean acidity, climate change, and the pattern and amount of precipitation such as unprecedented heavy rain in Texas on May 2015 (EPA 2015). Figure 4-2 provides an overview of greenhouse gas sources in the United States.

Burning fossil fuels for transportation sector such as diesel and gasoline produced carbon dioxide in the atmosphere. Climate scientists have observed that amount of carbon dioxide (CO_2) has been increased for 40% from 280 parts per million (ppm) at mid-1800s to 403 ppm by 2016. Also, they stated that there is an average growth of 2 ppm/year in the last ten years (IEA, 2017).

According to Environmental and Energy Study Institute (EESI, 2015), people and freight transportation accounts for 1.8 trillion tons, or 27 percent of the U.S. greenhouse gas (GHG) emissions. Also, approximately, 70 percent of produced oil use for people and freight transportation. Heavy and medium duty trucks are only 5 percent of total vehicles on the road, but they account for more than 20 percent of transportation emissions.

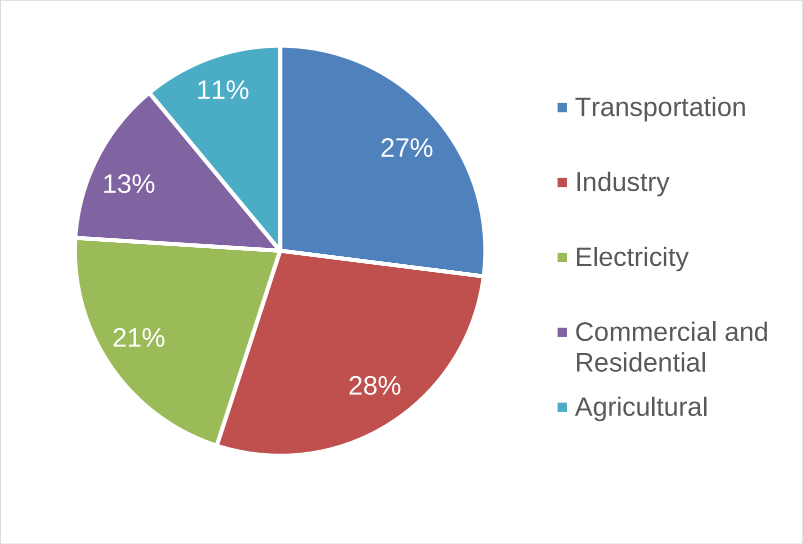


Figure 4-2 Overview of Greenhouse Gases Sources

(EPA, 2015)

4.1.1 Air Pollution Components

Usually air pollution is considered the most important environmental threat posed by transportation. Mobile sources of air pollution emit ozone, particle pollution, and air toxics. Millions of people’s health affect by mobile source air pollution, especially people who live near busy highways and roads, railroads, airports, and other ports. The environmental impacts include haze in many parts of the U.S., including many of our national parks and wilderness areas, and the acidification of lakes and streams. The six important criteria of air pollutions, which are regulated by EPA are followed (FHWA 2018);

Carbon Monoxide (CO): CO is an odorless and colorless gas, which is formed when the carbon in a fuel is not burnet completely in absence of oxygen. Passenger vehicles are responsible for approximately 54% of produced CO, while diesel engines for heavy duty trucks are not major emitters of CO, because diesel engines need high air-fuel ratio (air / fuel > 1.0) (Aslan Resitoglu et al. 2015; FHWA 2018). CO is mostly produced at the time of starting the engine and instantaneous acceleration, when the rich mixture of fuel and air required (Aslan Resitoglu et al. 2015).

Carbn Dioxide (CO_2): CO_2 produced from solid waste, tree and woods, and burning fossil fuels, such as, deisel, gasoline, natural gas, coal, and oil, and certain chemical reaction at manufactures, such as cement production. CO_2 cen be removed from the atmosphere when it is absorbed by plants and trees as part of the biological carbon cycle (EPA, Overview of Greenhouse Gases , 2018).

Nitrogen Dioxides (NO_2): NO_x is part of reactive gaseous compound family, which contribute to urban and rural air pollution. It is produced during combustion of fuel when temperature reach to 2900°F. Most of NOx is formed when the piston is near the top of stroke and the flame temperature is at the highest point. The amount of produced NOx can be treefold for every 200°F increase in combustion temperature (Aslan Resitoglu et al. 2015).

Transportation sectors produce approximately 59 percent of total NOx emissions. Freight transportation system via heavy duty truck, railroad, and air cargo accounted for approximately 57 percent of transportation emissions. NO_2 is the largest group of NOx family and has higher interest for the purpose of regulations. Nox is a precursor with other pollutants, since it reacts with VOCs in the persence of sunlight to form ozone. Also, it reacts with sulfur dioxide (SO_2) to fomr acid rain, which can increase the acidicity of the water bodies and make them unsuitable for many uses (FHWA 2018).

Ground-level Ozone (O_3): O_3 is not emitted but is forms from chemical reaction betwin NOx and VOCs. Sunlight breaks down NOx and VOC in a process called photolysis, then oxygen atoms combine to form ozone. As a result, ozone concentrations increased in the summer when there are more sunny days. Sources of the pollutants that create ozone include vehicle exhaust, industrial processes, gasoline vapors, chemical solvents, and even some elements of natural vegetation.

Ground-level ozone is the primary component of smog. Ozone formation can be severe by daytime operations at major freight facilities, such as ports. Wind currents can carry ozone and other pollutants for many miles, therefore, even areas with low freight volumes can be affected. There is no reliable method to estimate the proportion of ozone by freight sector, but diesel engines are a significant source of NOx, which is a precursor to ozone (FHWA 2018).

Particulate Matter (PM): PM emissions in the exhaust gas are resulted from combustion process. They are very small particles of partly burned fuel, lube oil, ash content of fuel oil, and cylinder lube oil or sulfates and water (Aslan Resitoglu et al. 2015). PMs are comosed of small solid particles and liquid droplets of a wide range of chemicals and other agents, such as organic chemicals, metals, acids, and dust particles.

Some PM is directly produced from exhaust as a byproduct of engine combustion,or produced from tire and brake wear. On the other hand, some PMs are produced in the exhaust plume outside of the vehicle, when finer PM molecules attach to other molecules or each other and makes bigger PM. Additionally, road dust is a major compond of PM.

Particulate matters from diesel engines are typically spheres about 15–40 nm in diameter, and approximately more than 90 % of PM is smaller than 1 μm in diameter. Particulate matter emissions from diesel engines are considerably six to ten times higher than from gasoline engines. For regulatory pourpose, PMs gropped into two sub categories of $PM_{2.5}$ and PM_{10}. $PM_{2.5}$ are the particles with less than 2.5 micrones in diameter.

This type of PMs are more hazardous to human health compare than PM_{10}. $PM_{2.5}$ is produced through secondray formation when diesel exhaust particles react with other compounds such as NOx in the atmosphere. PM_{10} are particles with less than 10 microns in diameter. The transportation sector is accounted for approximetely 54 percent of PM_{10} emissions, while freight transportation responsible for 51% of this portion (FHWA 2018).

Sulfure Dioxide (SO_2): SO_2 is formed when fuel sources containing sulfur are burned. These gases dissolve into water easily. SO2 combines with water vapor in the atmosphere to creat acid rain, which contaminate waterbody. All transportation sources combined accounted for 11 percent of the total produced SO_2 (FHWA 2018).

Volatile Organic Compounds (VOC): VOCs are organic chemicals with high vapor pressure at regular room temperature due to their low boiling point. It causes large numbers of molecules to evaporate or transfer from the liquid state or solid-state form of the compound and enter the surrounding air, which associate with a range of negative health effects (Najafi et al. 2016).

Methane (CH_4): CH_4 Methane is emitted during the production and transport of coal, natural gas, and oil. Additionally, CH_4 emissions is result of livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills (EPA, Overview of Greenhouse Gases , 2018).

In brief, Equation 4-1 shows emitted air pollution due to combustion by combination of fuel and air (Bozek, 1990);

$$\text{Fuel (HC)} + \text{Air } (O_2 \text{ and } N_2) = \text{Energy} + CO_2 + H_2O + N_2 + H_2 + HC + CO + NOx$$

Equation 4-1

4.1.2 Air Pollution Impacts

Based on (Kurer, 1991), Table 4-1 shows summary of major pollutants emitted by on-the-road (long-haul) vehicles, their sources, and impacts to humans, ecosystems, global climate, and quality of life. Several studies used different methodologies to show how air pollution due to the transportations contributes to various health issues such as cancer, respiratory and cardiovascular diseases, and perinatal mortality. Table 4.2 shows the human health effects by common air pollutants (HEI, 2010).

Table 4-1 Air Pollutions and Their Impacts

Pollutant	Source	Impact				Scale
		Humans	Vegetation	Global Climate	Properties	
Carbon Monoxide (CO)	Incomplete combustion	Inadequate oxygen supply, heart, circulatory, nervous system	N/A	Indirect through ozone formation	N/A	Local
Carbon Dioxide (CO_2)	Combustion	N/A	N/A	Major greenhouse gas	N/A	Global
Hydrocarbons (HC-includes methane, isopentenyl, pentane, toluene)	Incomplete combustion, carburetion	Some are carcinogenic ozone precursor	Build-up in soil, feed, food crops	Methane has high greenhouse potential, leads to ozone formation	N/A	Global
Nitrogen Oxides (NO_x)	Oxidation of N_2 and N-compounds in fuels	Respiratory irritation and other problems.	Acidification of soil and water, over fertilizing	NO_2 has high greenhouse potential, leads to ozone formation	Weathering, erosion	Local and Regional
Particulates	Incomplete combustion, road dust	Respiratory damage, various toxic content	Reduced assimilation	N/A	Dirt	Local and Regional
Soot (diesel)	Incomplete combustion	Carcinogenic	N/A	N/A	Dirt	Local
Ozone (formed by interaction of other pollutants)	Photochemical oxidation with NO_x and HC	Respiratory irritation, ageing of lungs	Risk of leaf and root damage, lower crop yields.	High greenhouse potential	Decomposition of polymers	Regional

Table 4-2 Human Health Effects of Common Air Pollutants

Pollutant	Quantified Health Effects	Unquantified Health Effects	Other Possible Effects
Ozone	• Mortality • Respiratory RAD • Minor RAD • Hospital Admissions • Asthma Attacks • Change in Pulmonary Function • Chronic Sinusitis and Hay Fever	• Increase Airway Responsiveness to Stimuli • Centro acinar Fibrosis • Inflammation in the Lung	• Immunologic Changes • Chronic Respiratory Diseases • Extrapulmonary Effects (Change in the Structure or Function of the Organs)
Particulate Matter	• Mortality • Chronic and Acute Bronchitis • Minor RAD • Chest Illness • Day of Work Loss • Moderate or Worse Asthma Status	• Change in Pulmonary Function	• Chronic Respiratory Diseases other than Chronic Bronchitis • Inflation of the Lung
Carbon Monoxide	• Mortality • Hospital Admissions • Congestive Heart Failure • Decrease Time to Onset of angina	• Behavioral Effects other than Hospital Admissions	• Other Cardiovascular Effects • Developmental Effects
Nitrogen Oxide	• Respiratory Illness	• Increased Airway Responsiveness	• Decreased Pulmonary Function • Inflammation of the Lung • Immunological Change
Sulfur Dioxide	• Morbidity in Exercising Asthmatics • Change in Pulmonary Function Respiratory Symptoms		• Respiratory Symptoms in Non-Asthmatics Hospital Admissions
Lead	• Mortality • Hypertension • Nonfatal Coronary Heart Disease • Nonfatal Strokes • Intelligence Quotient (IQ) Loss	• Neurobehavioral Function • Other Cardiovascular diseases • Reproductive Effects • Fetal Effects from Maternal Exposure • Delinquent and antisocial Behavior in Children	

4.1.3 Motor Vehicle Emission Simulator (MOVES)

The Motor Vehicle Emission Simulator (MOVES) have been developed by the EPA, Office of Transportation Air Quality (OTAQ). This is a science emission modeling system to estimate emissions for mobile sources at the national, county, and project level for criteria air pollutions, greenhouse gases, and air toxics. MOVES model database estimate emissions under single (base) scenario of conditions for temperature, air conditioning, local and fuel properties, and humidity.

But it designed to adjust these base emission rate depends on condition of the location (EPA 2015). These adjustments affect running exhust, start exhaust and extended idling emissions. For example, the crankcase emission are different at different conditions, such as start engine, runing engine, and extended idling engine, thus changing the temperature affected the amount of air pollution and fuel consumption.

There is no adjustment needed for temperature higher than 75°F (EPA 2015) but additive grames must be added when the temperature is below 75°F. Additionally, humidity impact on the rate of NO_x, since water in the air cools the peak conmustion temperature and reduce the amount of emitted NO_x. The MOVES based scenario is whne the humidity, in units of grains of water per pound of dry air, is between 21 and 124.

For this study, the current relase of MOVES databes, which is MOVES2014a, is used. Also, the affect of humidity, temperature, and use of air condition are not considered. The regulatory classes that used in MOVES 2014a are shown at Table 4-3. Class ID 0 is “doesn’t matter” regulatory class, which is used in the model if the emission rates for a given pollutant and process are independent of regulatory class (EPA 2015).

Table 4-3 Regulatory Classes in MOVES2014

Reg. Class ID	Regulatory Class Name	Description
10	MC	Motorcycles
20	LDV	Light-Duty Vehicles
30	LDT	Light-Duty Trucks
40	LHD≤10K	Class 2b Trucks with 2 Axles and 4 Tires (8,500 lbs<GVWR[6]≤10,000 lbs)
41	LHD≤14K	Class 2b Trucks with 2 Axles and at least 6 Tires or Class 3 Trucks (8,500 lbs<GVWR≤14,000 lbs)
42	LHD45	Class 4 and 5 Trucks (14,001 lbs < GVWR ≤ 19,500 lbs)
46	MHD	Class 6 and 7 Trucks (19,501 lbs < GVWR ≤ 33,000 lbs)
47	HHD	Class 8a and 8b Trucks (GVWR > 33,000 lbs)
48	Urban Bus	Urban Bus

The vehicle emission modeling software that EPA uses to estimate average emissions from highway vehicles is Motor Vehicle Emission Simulator (MOVES), which estimates emission factors for gasoline-fueled and diesel highway motor vehicles, and for certain specialize vehicles such as natural-gas-fueled or electric vehicles.

4.1.4 Social Cost of Air Pollution

According to literature search, there are several methodologies to estimate social cost of air pollution, but so far none of them has been proved. Due to different approach, there is a wide range of social cost, for each pollutant. The most common items that considered to estimate social cost of air pollution are:

a) Human life: For considering the value of human life, moral, ethical, and economic impact consideration are greatly involved (Quah & Boon, 2003).

b) Human health changes and issues: According to (Maddison et al. 1996), not only willingness to pay by affected people is good basis to estimate, but also, change in human morbidity and mortality must be considered based on what people are

---

[6] Gross Vehicle Weight Rating (GVWR)

willing to pay or accept as a compensation to be away from the change in health status.

c) Productivity reduction at different industries such as, agriculture and construction

d) Damage to buildings and structures: Due to acid rain and PMs.

e) Stress on ecosystem

Additionally, several researches estimated the future cost of emitted air pollution by considering future population, economic growth, pollutant growth, discount rate, and climate responsiveness measurement by increasing concentrations of pollutant and greenhouse gases in the atmosphere (GAO, 2014). Table 4-4 shows the summary of central values for the social cost of carbon dioxide estimated issued by the interagency working group on social cost of carbon dioxide in 2013 for the U.S. Government Accountability Office (GAO, 2014). Table 4-5 shows summary of social cost of carbon dioxide by different researchers based on different methodologies. Due to different sets of assumptions in each model, social cost of carbon dioxide is varied.

Table 4-4 Central Values for the Social Cost of Carbon Dioxide by GAO

Year	**2013 Central Values (2018 Dollar Value per metric ton)**
2010	$39.6
2020	$53.2
2030	$64.4
2040	$75.5
2050	$87.9

Table 4-5 Social Cost of Carbon Dioxide Based on Different Model

Model	**Study by**	**$/ton (2018 dollars)**
PAGE	(Hope, 2006)	$7.30
PAGE	(Stern, 2007)	$123.60
DICE	(Nordhause, 2008)	$8.75
FUND	(Anthoff et. al 2011)	$9.20
PAGE	(Hope, 2013)	$121.70

Table 4-6 shows estimated social cost of carbon dioxide by EPA for next 35 years.

Table 4-6 Social Cost of Carbon Dioxide Per Ton by EPA

Discount Rate				
Year	**5% Average**	**3% Average**	**2.5% Average**	**3% 95th Percentile**
2015	$12	$40	$62	$124
2020	$13	$47	$69	$148
2025	$16	$51	$76	$158
2030	$18	$56	$81	$180
2035	$20	$61	$87	$200
2040	$23	$67	$93	$212
2045	$26	$71	$99	$233
2050	$29	$77	$106	$254

Moreover, Table 4-7 shows social cost of other pollutant based on different sources.

Table 4-7 Social Cost of Other Pollutants

Pollutant	Social Cost ($/ton) (2018-dollars)	Source
NOx	$36,100	(EPA, 2011)
SOx	$432.00	(Najafi, 2016)
PM	$6,523.00	(Najafi, 2016)
HC	$3,465.00	(EPA, 2018)

Because of wide range of methodologies, there is wide range of social costs of air pollutions. For this dissertation, social cost of air pollutant at Table 4-7 and $124 for each tone of carbon dioxide from Table 4-6 considered. Moreover, according to (Forkenbrock, 1998; Matthews et al. 2001; Z. Farahani et al. 2011; Austin, 2015), I can conclude that the social cost of air pollution at urban area is approximately 25% higher and at rural area is approximately 25% lower than these costs. Therefore, depends on location, these cost must be adjusted.

4.1.5 Emitted Air Pollution by Heavy Duty Trucks

Air pollution, is caused by many different human activities, such as transportation by heavy duty trucks, which damages vegetation, ecosystem, effects on climate changes, and human and animal health. For example, truck diesel engines emit a complex mixture of air pollutants composed of gaseous and solid material. The visible emissions in diesel exhaust are known as particulate matter or PM. The majority of greenhouse gas emissions from transportation are CO_2 emissions resulting from the combustion of petroleum-based products, like diesel, in internal combustion engines.

The majority of emissions from this sector comes from freight trucks, passenger cars and light-duty trucks, pickup trucks, minivans, and trains. Also, small amounts of methane (CH_4) and nitrous oxide (N_2O) are emitted during fuel combustion. In addition, a small amount of hydro fluorocarbon (HFC) emissions are included, which is the result of using mobile air conditioners and refrigerated transport (EPA 2015). Exhaust emissions due to engine combustion and non-exhaust emission due to tire and break wear are two main source of heavy duty trucks emissions.

Exhaust Emissions

Heavy duty truck is a major source of producing GHG. The engines that power heavy duty trucks have standard set for three gases, which are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Methane is a short-lived climate pollutant with average lifetime of 12.4 years, with global warming potential (GWP) equal to 25 times higher than CO_2 over a 100-year time horizon.

N_2O is also a potent GHG with a longer lifetime of 121 years and a GWP of 298 over a 100-year time horizon. N_2O, as a heat-trapping pollutant, is the largest known remaining anthropogenic threat to the stratospheric ozone layer (Quiros et al. 2017). These pollutants are emitted through exhaust, crankcase, and evaporative processes of heavy duty trucks, operating on gasoline, diesel, and compressed natural gas (CNG) fuels.

There are several factors that affect the amount of air pollution trucks emits and the resulting stress on the environment, whether the vehicle is being driven or is at idle. Some of the most important are (EPA 2008; VTPI 2018):

- Truck type and truck size: larger and heavier trucks tend to produce more emissions.
- Truck age, accumulated mileage, and condition: older vehicle has less fuel consumption efficiency and effective emission control system, which produce more pollutant.
- Maintenance condition of the truck: better maintenance helps engine to work smoother with less pollutant
- Driving Cycle: when the engine is cold, the amount of missions is higher.
- Driving Style: faster accelerations tend to increase emission rate.
- Driving condition: emission per mile increase at traffic congestion when it is under highly stop-and-go conditions, and at low and high speed.

Vehicle emissions depend on the gross vehicle weight, quantity of goods, idle time, traveled distance, and most importantly speed. As it shown at Appendix B, by increasing heavy duty trucks and passenger vehicle (PV) speed, the amount of emitted air pollutions is decreased. Furthermore, MOVES project running emission rates of CO,HC, PM, NOx, VOC, and CO_2 versus the operating speeds (Yao et. al 2014).

All produced rate curve of pollutants (g/mile) vs. speed (mph) for passenger vehicle (PV) and heavy-duty trucks (HDT) can be found at Appendix B. In order to calculate social cost, the produced rate of each pollutant at different speed are analyzed. Table 4-8 shows the summary of curve fitting analysis with proper regression and highest possible correlation of coefficient (R^2) for passenger vehicles and Table 4-9 shows the same for heavy duty vehicles. “Y” represents the amount of emitted pollutant (g/mile) and “S” represents speed of vehicle (mph).

Table 4-8 Summary of Curve Fitting Regression for Passenger Vehicle

Pollutant	**Equation**	**R^2**
HC	$y = 0.25 \times S^{-0.524}$	0.92
NO_x	$y = (8S^2 \times 10^{-5}) - 0.007S + 0.32$	0.80
PM	$y = 0.017S^{-0.346}$	0.77
SO_2	$y = (2 \times 10^{-6}S^{1.9}) - (1.18 \times 10^{-4}S) + 0.0051$	0.97
CO_2	$y = 0.165S^2 - 15.25S + 633.32$	0.97

Table 4-9 Summary of Curve Fitting Regression for Heavy Duty Truck

Pollutant	**Equation**	**R^2**
HC	$y = 8.41S^{-0.794}$	0.98
NO_x	$y = 101.4S^{-1.023}$	0.96
PM	$y = 2.55S^{-0.59}$	0.96
SO_2	$y = 0.26S^{-0.24}$	0.89
CO_2	$y = 4906.4S^{-0.238}$	0.89

Total social cost of air pollution can be calculated by Equation 4-2;

$$C_{air} = \sum (P_i \times c_i)$$

Equation 4-2

Where

C_{air}, Total social cost of air pollution ($/mile)

P_i, Emitted pollution (g/mile)

And c_i, social cost of P_i ($/gr)

Figures 4-3 and 4-4 illustrate the social cost of exhaust emission by heavy duty trucks and passenger vehicle per mile depends on speed, respectively.

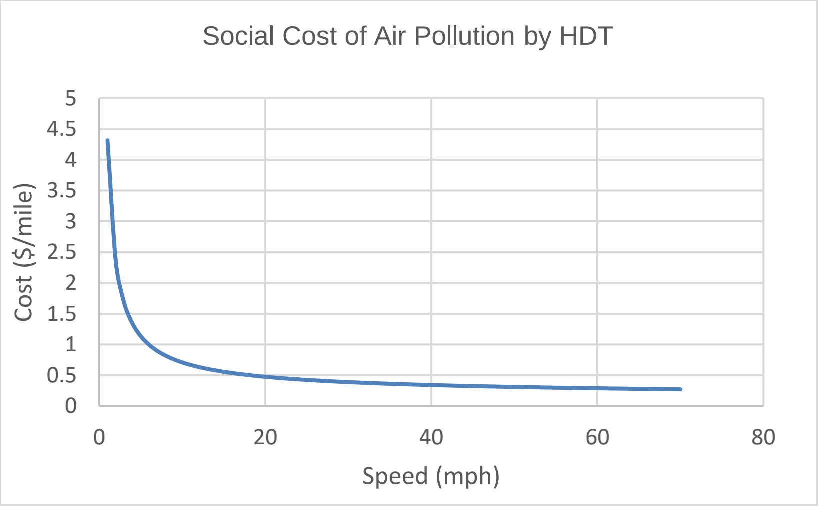


Figure 4-3 Total Social Cost of Exhaust Emission of HDT
(2018 Dollar Value)

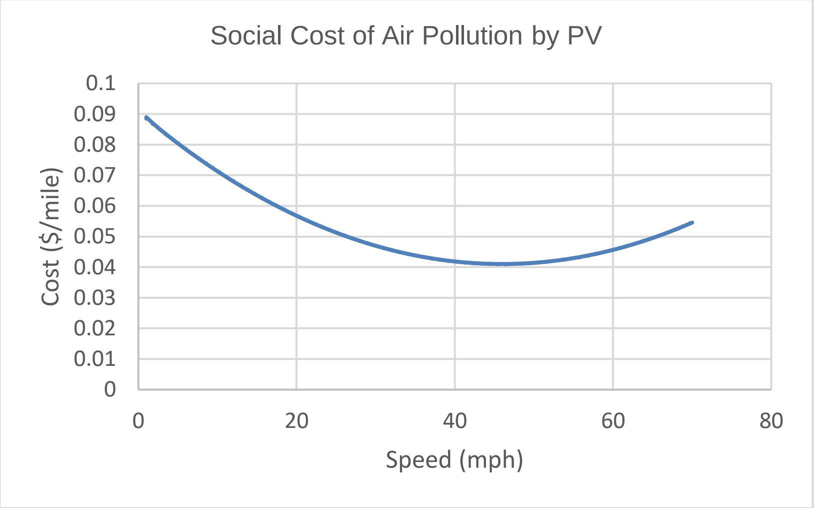


Figure 4-4 Social Cost of Exhaust Emission of PV
(2018 Dollar Value)

In other word, social cost emitted air pollution by heavy duty truck due to the combustion, at different speed per mile, can be calculate by Equation 4-3;

$$C_{Air-HDT} = 4S^{-0.6}$$

Equation 4-3

Where,

$C_{Air-HDT}$, Social cost of emitted air pollution by heavy duty truck due to the combustion ($/mile)

And S, speed of truck (mph)

Furthermore, social cost of emitted air pollution by passenger vehicle due to the combustion, at different speed per mile, can be calculated by Equation 4-4;

$$C_{Air-PV} = 0.00002S^2 - 0.002S + 0.1$$

Equation 4-4

Where,

C_{Air-PV}, Social cost of emitted air pollution by passenger vehicle due to the combustion ($/mile)

And S, speed of passenger vehicles (mph)

Furthermore, social cost of air pollution at idle condition for heavy duty truck is approximately $3 per hour and for passenger vehicle is $0.19 per hour.

Non-Exhaust Emissions

The source of particulate matter (PM) in transportation sector includes exhaust emissions due to engine related process such as fuel combustion, and burnt oil, and non-exhaust process such as brake and tire wear, and suspension or resuspension of road dust. Particulate matter from brake and tire can be created by corrosion, turbulence, and abrasion, then suspended into the atmosphere.

These types of PM are different than PM due to exhaust emission related in chemical composition and size (EPA 2015). According to literatures, following items affect the amount of PM emission due to brake wearing;

- Number, type, and composition of brake pad
- Front and rear braking

- Airborne fraction and rolling resistance
- Vehicle class (weight and size of vehicle)
- Drag coefficient

Table 4-10 shows the non-exhaust emission rate due to brake wear, which derived from the literature search.

Table 4-10 Non-Exhaust PM Emission due to Brake Wear

Authors	**Type of Vehicle**	**PM$_{2.5}$ (mg/mile)**	**PM$_{10}$ (mg/mile)**
Luhana et al. (2004)	Passenger Vehicle		0-126.5
	Heavy Duty Truck		0-976
Sanders et al. (2003)	Passenger Vehicle		2.4-11.2
Abu-Allaban et al. (2003)	Passenger Vehicle	0-8	0-128
	Heavy Duty Truck	0-24	0-976
Westurland (2001)	Passenger Vehicle		11
	Heavy Duty Truck		66
Garg et al. (2000)	Passenger Vehicle	5.4	7.4
	Medium Duty Truck	14.2	19.4
Rauterberg-Wulff (1999)	Passenger Vehicle		1.6
	Heavy Duty Truck		39.2
Carbotech (1999)	Passenger Vehicle		2.9-7.8
	Heavy Duty Truck		5.6
Cha et al. (1983)	Passenger		12.5
	Heavy Duty Truck		2.5

Table 4-11 shows the average brake wear PM$_{2.5}$ and PM$_{10}$ emission rate from MOVES2014a database in milligrams per vehicle-miles. For this dissertation, these data will be used to calculate social cost of air pollution by heavy duty trucks.

Table 4-11 Average PM2.5 and PM10 Emission due to Brake Wear

Source Type	**$PM_{2.5}$ (mg/mile)**	**PM_{10} (mg/mile)**
Motorcycle	1.81	14.50
Passenger Vehicle	3.06	24.44
Passenger Truck	3.41	27.32
Light Commercial Truck	3.44	27.53
Intercity Bus	19.99	159.96
Transit Bus	15.35	122.77
School Bus	13.18	105.42
Single Unit Short-Haul Truck	13.39	107.09
Single Unit Long-Haul Truck	14.49	115.91
Motor Home	11.93	95.45
Combination Short-Haul Truck	18.40	147.16
Combination Long-Haul Truck	19.28	154.26

Another essential part of any vehicle, which produce non-exhaust air pollution is Tire. Contact between tires and surface of the roads causes tires to be worn, but it depends on variety factors. The tire wear occurs through friction between tire and the road surface. This friction causes particles to wear from surface of the tire and released as airborne particulates.

Since the road surface is the cause of friction and abrasion, the roughness of the pavement is important factor of tire wear. Additionally, the amount of tire wear depends on following factors (EPA 2015; Carpenter et al. 1999):

- Style of driving: Heavy braking, high accelerating, speed, and fast turning
- Seasonal influences: Temperature, humidity, and water contact
- Road grade and Highway geometry
- Vehicle characteristics: Weight, suspension, steering geometry, and axle geometry

- Tire characteristics: Stiffness, shape of tire, rubber volume, tread pattern, and rubber type

According to literature search, the easiest method to determine the amount of tire wear is the periodic measurement of the tire weight. Table 4-12 is tire wear rate which is found through literature search;

Table 4-12 Non-Exhaust PM Emission due to Tire Wear

Source	**Type of Vehicle**	**Rate (mg/mile)**
(Kupiainen et al. 2005)	Unknown	14.5
(Luhana et al. 2004)	Unknown	118.5
(Councell et al. 2004)	Unknown	320
(Warner et al. 2004)	Average for all vehicles	155
(Kolioussis & Pouftis 2000)	Average for all vehicles	64
(EMPA 2000)	Passenger Vehicle	84.5
	Heavy Duty Truck	1277
(SENCO 2000)	Passenger Vehicle	84.5
	Trucks	2245
(UBA 1998)	Passenger Vehicle	128
	Heavy Duty Truck	302.5
	Articulated Truck	374.5
	Bus	307

Luhana et al. (2004) measured the amount of tire wear at different speed. According to this research, an exponential regression curve was fitted by correlation of coefficient of 0.41, which is very low. Therefore, for this dissertation, the fix amount of tire wear (mg/mile), without considering speed, from MOVES2014a database is considered. Table 4-13 shows average $PM_{2.5}$ and PM_{10} emission due to tire wear for each vehicle type.

Table 4-13 Average PM Emission due to Tire Wear
(EPA 2015)

Source Type	**$PM_{2.5}$ (mg/mile)**	**PM_{10} (mg/mile)**
Motorcycle	0.7	4.9
Passenger Vehicle	1.5	9.8
Passenger Truck	1.5	10.0
Light Commercial Truck	1.5	10.2
Intercity Bus	4.4	29.3
Transit Bus	2.9	19.7
School Bus	2.7	17.8
Single Unit Short-Haul Truck	2.7	17.7
Single Unit Long-Haul Truck	3.1	20.6
Motor Home	2.4	15.8
Combination Short-Haul Truck	4.7	31.6
Combination Long-Haul Truck	5.2	34.9

Based on provided data at Tables 4-10 and 4-12, the social cost of PM pollution due to brake and tire wear for heavy duty truck and passenger vehicle are $0.00123 and $0.00022 per mile, which are already added to the Equation 4-3.

4.1.6 Emitted Air Pollution by Railroad

The U.S. Environmental Protection Agency (EPA) has estimated the average rate of locomotive emission for two different types of operation, which are followed (EPA 2009);

a) Lowe power cycle which is operation in a switch yard: Idle time to load, unload, or switch the cars
b) High power cycle which is general long-haul operation: Pulling freight from one terminal to another terminal

The amount of emitted pollutants, for each ton of freight, depends on following criteria (e-CFR, 2018);

- Number of brake horsepower per hour and number of locomotives for each haul

- Age and maintenance of engine
- Temperature, humidity, and rail Slope
- Cycle Time between terminals
- Fuel type: Alcohol, gaseous, or diesel type engine
- Engine characteristics: Combustion cycle, cooling system, nominal bore and stroke dimensions, intake and exhaust event timing, location of the intake and exhaust valve, the size of the intake and exhaust valve, overall injection or ignition timing, the combustion chamber configuration, method of air aspiration, turbocharge or supercharge, type of air inlet cooler, injector's type and pressure, smoke control system, and type of catalyst.

Tables 4-14 and 4-15 shows rate of emitted pollutant by locomotive at each tier for each operation type (Standards, 2018);

Table 4-14 Line-Haul Emission Factors (g/bhp-hr.)

Tier	**Model Year**	**PM**	**HC**	**NOx**
0	1973-2001	0.22	1.00	8.00
1	2002-2004	0.22	0.55	7.4
2	2005-2010	0.10	0.30	5.5
3	2011-2014	0.10	0.30	5.5
4	2015 or later	0.03	0.14	1.3

Table 4-15 Switch Emission Factors (g/bhp-hr.)

Tier	**Model Year**	**PM**	**HC**	**NOx**
0	1973-2001	0.26	2.10	11.8
1	2002-2004	0.26	1.2	11.0
2	2005-2010	0.13	0.60	8.1
3	2011-2014	0.10	0.60	5.0
4	2015 or later	0.03	0.14	1.3

According to Primus (2005), the average life expectancy of diesel locomotives is 15 to years (Primus, 2005). Therefore, in order to simplify calculation of social cost of emitted air pollution by railroad, the average amount of pollutant for last three tiers, is considered. Table 4-16 shows the required brake horsepower for four different scenario depends on total cargo weight. For these scenarios, following assumptions considered;

- The location of case study is Houston, TX. Therefore, the average gradient is zero.
- The initial speed is zero.

Table 4-16 Required BHP for four Scenario

Railroad Scenario	Speed (mph)	Cargo (tons)	Required Locomotives	Required BHP for each Locomotive
Heavy Unit	30	10,500	2	3,000
Mixed Freight	30	6,500	2	2,000
Intermodal	35	3,500	1	3,000
Double-Stack	20	8,000	2	2,000

For hauling freight by railroad, Table 4-17 shows the average amount of emitted air pollution and its cost per hour for four scenarios.

Table 4-17 Social Cost of Air Pollution for Different Scenarios (2018-Dollar)

Railroad Scenario	PM (g/hr.)	HC (g/hr.)	NOx (g/hr.)	Cost ($/hr.)	Cost ($/mile)
Heavy Unit	460	1,500	24,600	$896.26	$29.88
Mixed Freight	307	1,000	16,400	$597.51	$19.92
Intermodal	230	750	12,300	$448.13	$12.80
Double-Stack	307	1,000	16,400	$597.51	$29.88

Additionally, the amount of SO_2 and CO_2 is greatly depending on fuel properties rather than engine parameters and should be calculated based on fuel properties. Amount of SO_2 in grams per gallon can be estimated by Equation 4-5, which is followed (EPA 2009);

$$Amount\ of\ SO_2\left(\frac{gr}{gal}\right) = \gamma \times c \times S \times R$$

Equation 4-5

Where,

ɣ, Fuel density, which is equal to 3200 g/gal (EPA 2009)

c, Fraction of fuel sulfur converted to SO_2, and it is equal 97.8 percent (EPA 2009)

S, Sulfur content of fuel, which is equal to 300 ppm (EPA 2009)

And R, Weight ratio of SO_2 over S which is equal to:

$$R = \frac{64.0638\ gr\ SO_2}{32.065\ gr\ S} = 1.998\ \approx 2$$

Therefore, the amount of emitted SO_2 would be:

$$= 3200\frac{gr}{gal}\ \times 0.978\ \times 300 \times 10^{-6} \times 2 = 1.88\ \frac{gr}{gal}$$

Additionally, amount of CO_2 in grams per gallon can be estimated by Equation 4-6 (EPA 2009).

$$Amount\ of\ CO_2\left(\frac{gr}{gal}\right) = \ \gamma \times C \times R$$

Equation 4-6

Where,

ɣ, Fuel density, which is equal to 3200 g/gal (EPA 2009)

C, Carbon content of fuel, which is equal to 87% (EPA 2009)

And R, Weight ratio of CO_2 over C which is equal to:

$$R = \frac{44.0095\ gr\ CO_2}{12.0107\ gr\ C} = 3.664$$

Therefore, the amount of emitted CO_2 would be:

$$= 3200\frac{gr}{gal}\ \times 0.87 \times 3.664 = 10200.57\ \frac{gr}{gal}$$

Unlike SO_2 and CO_2, N_2O, methane, and other air toxics are depended on engine parameters. N_2O is considered as a proportional of total NOx and methane and other air toxics are considered as a proportional of total hydrocarbons.

Thus, to calculate amount of emitted CO_2 and NO_2, required amount of fuel needs to be calculated. Table 4-18 shows range of railroad fuel efficiency based on different rail car type (ICF, 2009).

Table 4-18 Range of Rail Fuel Efficiency

(Data derived from (ICF, 2009)

Rail Car Type	Min (ton-mile/Gall)	Max (ton-mile/Gall)	Average (ton-mile/Gall)
Double-Stack	220	520	370
Covered Hopper	480	490	485
Box Car	410	470	440
Gondola	280	450	365
Tank Car	370	380	375
TOFC	270	280	275
Auto Rack	160	170	165

Equation 4-7 describe how to calculate required amount of fuel;

$$Required\ Fuel = \frac{T\ \times D}{E}$$

Equation 4-7

Where,

T, Tonnage (ton)

D, Distance (mile)

And E, Efficiency which is equal to average range of rail fuel efficiency, per Table 4-18.

Table 4-19 shows the amount of emitted CO_2 and SO_2 for four scenarios.

Table 4-19 Amount of Emitted CO_2 and SO_2 for Four Scenarios

Railroad Scenario	Cargo (ton)	Dist. (mile)	Fuel Eff. (ton-mile/gal)	Req. Fuel (gal)	Emitted CO_2 (ton)	Emitted SO_2 (ton)
Heavy Unit	10,500	1,000	370	28,380	289.5	0.0533
Mixed Freight	6,500	500	350[7]	9,285	94.7	0.017
Intermodal	3,500	2,000	440	15,910	162.3	0.03
Double-Stack	8,000	2,000	370	43,245	441.1	0.08

Finally, Table 4-20 shows total cost of air pollution for all four scenarios per mile and per ton-mile.

Table 4-20 Social Cost of Emitted Air Pollution by Railroad (2018-Dollar)

Railroad Scenario	Weight (ton)	Total ($/mile)	Total ($/ton-mile)
Heavy Unit	10,500	$65.80	$0.006
Mixed Freight	6,300	$43.40	$0.006
Intermodal	3,360	$22.90	$0.006
Double-Stack	6,720	$57.25	$0.007

For this dissertation, the average social cost of four scenarios, which is $0.006 per ton-mile, is considered.

4.1.7 Emitted Air Pollution by Underground Freight Transportation

As stated in Chapter 1, for this research, Linear Induction Motor (LIM) for propulsion system of UFT is considered. The advantages of using LIM are cost effective, simplicity to assemble, ignition, and low maintenance (Rohter, 2007). The advantage of using LIM pump compare than Pneumatic Capsule Pipeline (PCP) is that the former is not interfering, therefore, the system can run continuously without having vehicle bypass pump.

This not only simplifies the system, but also enables the system to achieve much larger cargo compare than PCPs by using blowers. Also, use of LIMs as booster pumps, enables the system to have any length or to be used for transporting cargoes over

---

[7] The average of all fuel efficiency is considered.

practically any distance (Liu and Lenau 2005). A Linear Induction Motor is a mechanism that converts electrical energy directly into mechanical energy to provide linear motion without employing any intervening rotary components. The LIM system consists of a reaction plate and a 3 phase AC coil Assembly (Rohter, 2007).

The energy consumption in LIM systems has a direct relation to the operating speeds and acceleration rates. Keeping the operating speed of the UFT system low, will lead to lower power requirements and operating costs. A lower speed also has benefits regarding the wear and tear on rail tracks, vehicles, the overall tunnel system and therefore, system depreciation.

Based on the above, an operating speed of 45 mph is considered, while this speed is high enough to be comparable to the overall speeds of trucks and freight trains but low enough to minimize energy consumption. Table 4-21, shows the summary of design requirements, parameters, and required electricity for LIM system of all three size of UFT (Najafi et al. 2016).

Table 4-21 LIM Design Parameters and Electricity Consumption

Parameters	Container Size	Crate Size	Pallet Size
Total Payload (ton)	40	9.3	5.6
Payload Cross Section Area (ft^2)	88	38	19
Friction Force (lbf)	78	18.6	11.2
Air Resistance Force (lbf)	220	91	45
Total Frictional Force (lbf)	298	109.6	56.2
Required Power (HP)	36	13.5	7.5
Required Electricity (kW)	27	10	5.5

Although people think that electricity is clean and safe source of energy, generation and transmission, and distribution of electricity impact the environment. Almost, all types of power plant have a negative impact on environment. All the power plants have a physical footprint, while they require land clearing to build, road and railroad access, transmission lines, cooling water system and pipeline to deliver required fuel (eia, Electricity and the Environment , 2018). Figure 4-5 illustrate different type of power plant and its proportion to produce electricity in the U.S (eia 2018).

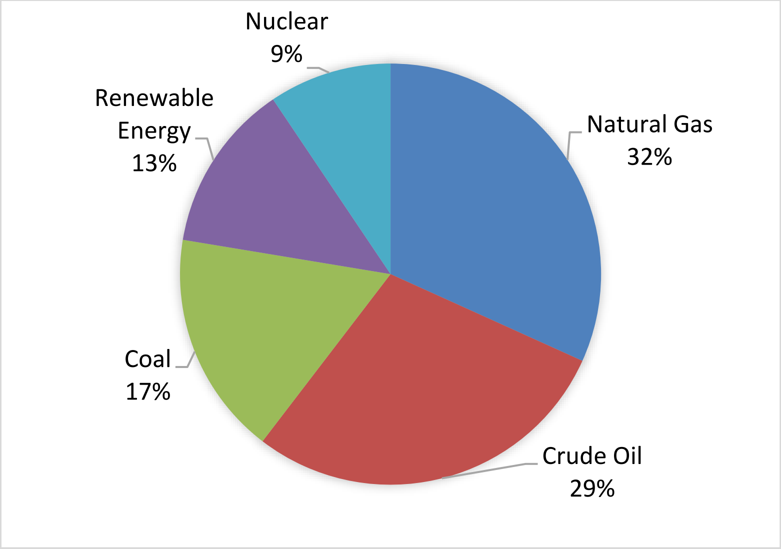


Figure 4-5 Power Plant Proportion in the U.S.

Emissions that are results from combustion of fossil fuels at power plants are carbon dioxide (CO_2), Hydrocarbon (HC), sulfur dioxide (SO_2), nitrogen oxides (NOx), particulate matter (PM), and heavy metals such as mercury (EIA 2018).

Additionally, nuclear power plants produce two different type of waste which are;

a) Low-level waste, which are contaminated tools and stuff such as, covers, clothing, wiping rage, filters, reactor water treatment residuals, and need to store at power plant till the radioactivity in the waste decays to safe level, then store at low-level radioactive waste disposal site (EIA 2018).

b) High-level waste, which are highly radioactive and shall be stored at designed storage containers and facilities (EIA 2018).

Since every type of power plant generator produce different type and amount of air pollution, for this dissertation, the average amount of emitted pollutant per megawatt hour (MWh) of power generation in Texas, are considered. Figure 4-6 illustrate the average emitted pollutant for the nation and Figure 4-7 illustrate the average emitted pollutant for the state of Texas (EIA, 2013, 2014, 2015, & 2016). Data for these Figures derived from several reports from the U.S. Energy Information Administration. According to these reports, CO_2, SO_2, and NOx are the most critical pollutants.

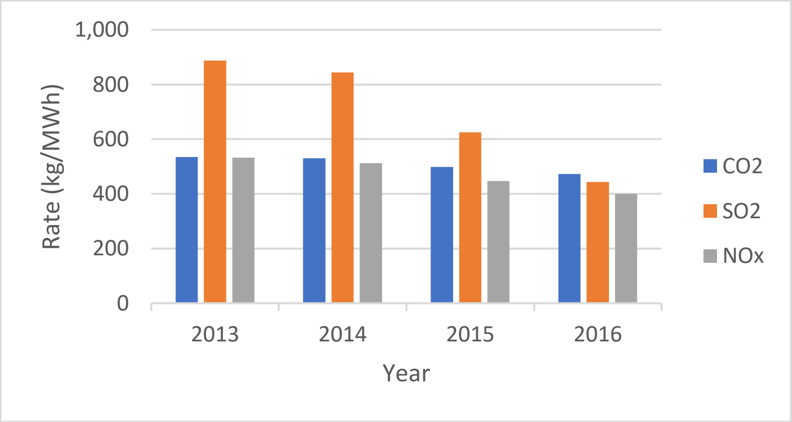


Figure 4-6 Emitted Air Pollution per MWh of Electricity Generation for the U.S.A

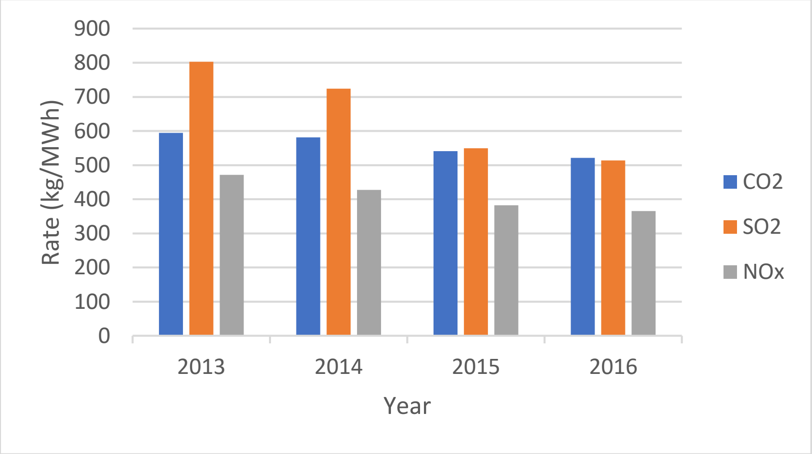


Figure 4-7 Emitted Air Pollution per MWh of Electricity Generation in Texas

In the U.S., only 1,182 of the 2,728 plants reported particulate matter (PM). These plants accounted for 75% of the total electricity generated by all 2,728 power plants and produced 92% of total PM emissions (CEC, 2018). The average emitted CO_2, NO_X, and SO_X, to produce one Megawatt hour electricity at each state calculated and can be found at Appendix B.

Additionally, according to Commission for Environmental Cooperation (2018), the average PM emission to produce one Mega-Watt-hour energy is 0.077 kg in Texas (CEC 2018). Moreover, the average amount of produced hydrocarbon (HC) in Texas is 0.04 kg per Mega-Watt-hour (eGRID, 2018).

According to Table B-1, the average social cost of air pollution for producing one Mega-Watt-hour energy in Texas is \$78.64. Therefore, to calculate social cost of emitted air pollution by UFT per mile, Equation 4-8 can be used:

$$C_{UFT-AP} = \frac{C_{En} \times P}{1000 \times S}$$

Equation 4-8

Where,

C_{UFT-AP}, Social cost of air pollution by UFT per mile (\$/mile)

C_{En}, Social cost of air pollution by generating 1MWh electricity (\$/MWh)

P, Power required (kW)

And, S, Speed (mph)

Table 4-22 shows the social cost of air pollution per mile for different size of UFT.

Table 4-22 Air Pollution Social Cost of UFT

UFT Size	Req. Power (kW)	Speed (mph)	Social Cost ($/MWh)	Social Cost ($/mile)
Container	27	45	$78.64	$0.047
Crate	10	45	$78.64	$0.017
Pallet	5.5	45	$78.64	$0.010

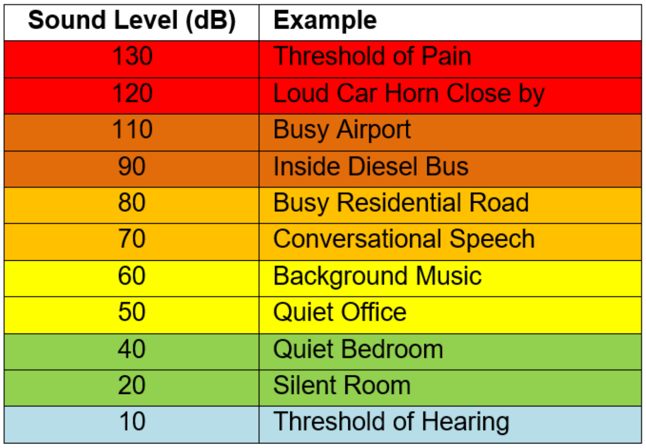
4.2 Noise Pollution

Noise pollution is unwanted or disturbing sound and can be harmful to human health due to its quality and characteristic. Because noise is invisible, its impact on the surrounding environment is often more difficult to recognize than is the case with chemical pollutants found in the air or water. However, the effects of noise on our lives are very real. One of the most important noise sources is transportation via roads which is a concern to resident.

Sound becomes unwanted when it either interferes with normal activities such as sleeping, conversation, or disrupts or diminishes one’s quality of life. The persistent and escalating sources of sound can often be considered an annoyance. This “annoyance” can have major consequences, primarily to one’s overall health (EPA, 2015). Sound is measured logarithmically in decibels (dB), which is amplitude or magnitude of the pressure wave, and a range of 0–140 dB can be received by the human ear.

Figure 4-8 illustrate the level of sound by example. Noise levels above 55 to 65 dB may result in nervous stress reactions, such as change of heart beat frequency, increase of blood pressure, and hormonal changes. In addition, noise exposure increases as a co-factor the risk of cardiovascular diseases and decreases subjective sleep quality.

The negative impacts of noise on human health results in various types of costs, such as medical costs, costs of productivity loss, and the costs of increased mortality. Noise level greater than 100 dB is extremely loud and will cause annoyance while 130 dB is threshold of physical pain (Becker & Gerlach, 2012)



Sound Level (dB)	Example
130	Threshold of Pain
120	Loud Car Horn Close by
110	Busy Airport
90	Inside Diesel Bus
80	Busy Residential Road
70	Conversational Speech
60	Background Music
50	Quiet Office
40	Quiet Bedroom
20	Silent Room
10	Threshold of Hearing

Figure 4-8 Level of Sound by Example

Moreover, Figure 4-9 illustrate three major effects of noise pollution (Hammer et al. 2014).

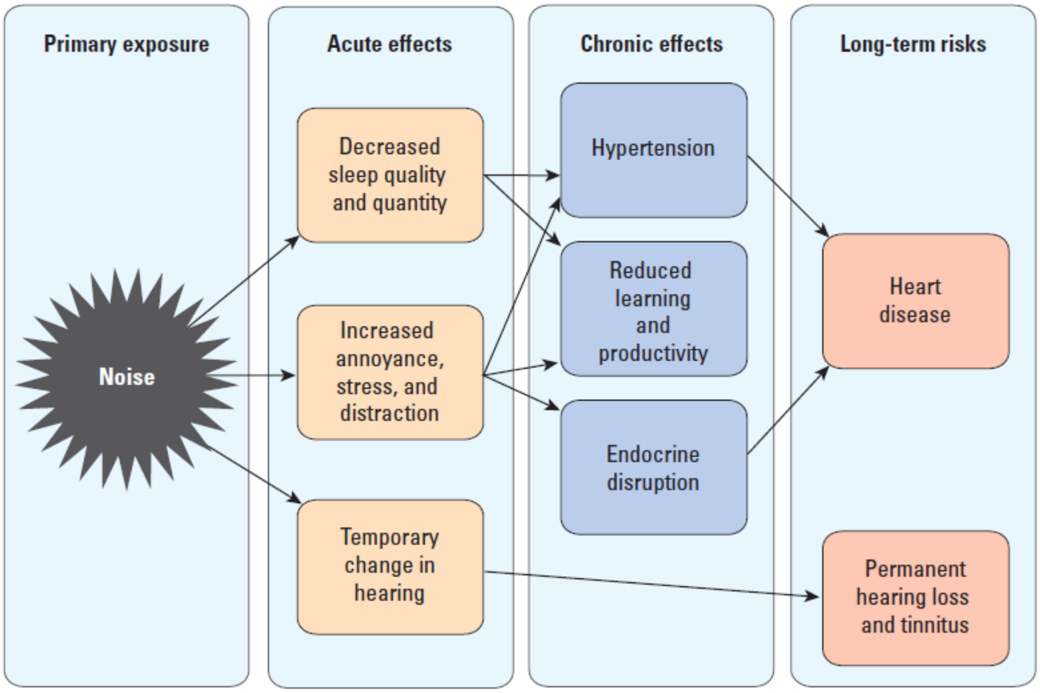


Figure 4-9 Noise Pollution Effects

(Hammer et al. 2014)

In general, three different sources of surface transportation noise are engine noise, rolling noise, and aerodynamic noise (EUP, 2012).

4.2.1 Noise Pollution by Heavy Duty Truck

Trucks, especially heavy-duty trucks are major source of road noise. Motor vehicles, especially heavy-duty trucks, buses, and motorcycles cause various type of noise (MacKenzie et al. 1992). At lower speeds, most noise comes from vehicle engine, but at higher speed it dominates from aerodynamic and tire rolling over pavement surface (Homberger et al. 1992). There is several factors that affect the amount of noise pollutation by road traffic, which are followed;

a) Traffic Speed: There is direct relation between traffic noise and speed. Higher speed brings louder engine. For examples, in urban area with the speed of 20 to 35 mph, the level of noise would be reduced by 40%, if speed reduced by 6 mph (UK Noise Association, 2009). Figure 4-10 illustrates the contribution of the various sub-sources of vehicle at different speed.

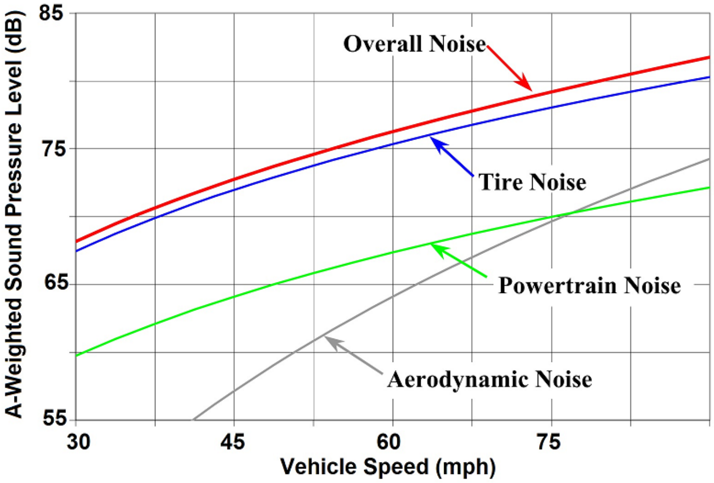


Figure 4-10 Contribution of the Various Sub-sources of Vehicle depends on Speed

Figure modified from (Bernhard & Wayson, 2005)

b) Traffic Volume: Traffic volume significantly impact the level of noise. Reducing traffic level, even by a small amount, could reduce noise level by reducing the overall noise source (UK Noise Association, 2009). Table 4-23 shows the relation between traffic volume and noise level distance.

Table 4-23 Decibel Levels Based on Traffic Volume and Distance from the Road (Forkenbrock, 1998)

AADT	55 dBA[8] (ft)	65 dBA (ft)
Up to 7,999	404	57
8,000 to 27,999	736	159
28,000 to 47,999	970	209
Greater than 48,000	1,339	289

For example, Figure 4-11 illustrate the level of noise at west of the City of Houston. As it is shown, along IH-10 after Hunters Creek Village, the noise imission level from the center line of the highway to 1250 ft of each side of the highway is 45 to 50 dBA.

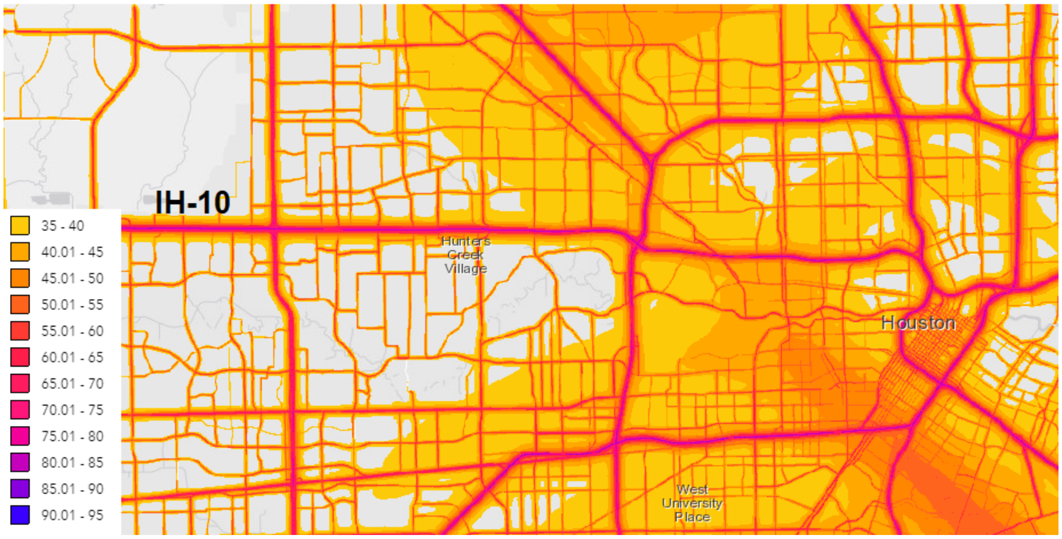


Figure 4-11 Noise Emission and Emission at the West of Houston, TX

---

[8] dBA is the unit of noise imission. Noise imission is the level of sound that emitted by source, but noise emission is the level of sound that can be heard by observer and it depends on distance (NAE, 2010).

Figure generated from National Transportation Noise Map (NTNM, 2018)

c) Accelerating and decelerating: They have a high influence on traffic noise. Acceleration has higher impact and its importance is greater at lower speed. Acceleration accounted to 10% of traffic noise (UK Noise Association, 2009). Engine noise is getting louder when a vehicle is accelerating. Also, aggressive driving, with faster acceleration and harder deceleration, increase the noise (VTPI, 2018).
d) Type of vehicle: Motorcycles, heavy duty trucks, buses, and vehicles with faulty exhaust system tend to produce higher noise level (VTPI, 2018)
e) Engine type: Along all different type of engines, diesel engines tend to produce higher noise compare that gasoline, natural gas, hybrid, and electric engines (VTPI, 2018).
f) Tire design and tread
g) Type of pavement: Smoother pavement surface emit less noise (VTPI, 2018)
h) Horns and vehicle theft alarms
i) Distance and barriers: Noise reduced with distance, structures, walls, trees, hills, and sound resistant features (VTPI, 2018).

4.2.2 Noise Pollution by Railroad

Railroad is one of the source of surface transportation noise. Most of emitted noise pollution by railroad comes from locomotive engine or by the interaction of the wheels with the track (Lotz & Kurzweil, 1979). Rolling noise, which is results of interaction of the wheels ant trach, is higher for poorly maintained rail vehicles and infrastructure (EUP, 2012).

When the train speed is less than 20 mph, engine noise is higher than rolling noise, but by increasing the speed above 20 mph, rolling noise is getting louder. For high speed train with the speed of 120 mph, aerodynamic noise source is higher than other two.

4.2.3 Noise Pollution by Underground Freight Transportation

As stated in Chapter 1, at underground freight transportation system (UFT), vehicles run through the underground pipeline, and they are not only invisible to the populace above, but also do not produce noise. Loading and unloading operation for all three alternatives are not part of the scope of research, therefore, we can state that UFT does not have any impact to environment in terms of noise pollution.

4.2.4 Social Cost of Noise Pollution

To calculate the social cost of noise pollution, two costs of annoyance and health should be considered (Ricardo, 2014):

a) Cost of Annoyance: Cost of annoyance is economically based on preferences of individuals. Transport noise imposes undesired social disturbance, which results in social and economic costs like reducing productivity, any restriction on enjoyment of desired leisure activities, discomfort or inconvenience.

b) Health Cost: Transport noise can be caused of physical health damages. Hearing damage can be caused by noise levels above 85 dB while lower levels (above 60 dB) may result in nervous stress reactions, such as change of heart beat frequency, increase of blood pressure and hormonal changes. In addition, noise exposure increases the risk of cardiovascular diseases. Finally, transport noise can result in a decrease of subjective sleep quality.

Social cost estimation of noise pollution is very complex; therefore, the cost of noise pollution is varying due to different methodology. Table 4-24 shows the summary of noise pollution cost per vehicle mile traveled from literature review.

Table 4-24 Summary of Social Cost of Noise Pollution

Study by	**Source**	**Cost ($/mile) (02018-Dollar)**
(FHWA, 1997)	Passenger Vehicle (Urban)	$0.0012
	Pickup & vans (Urban)	$0.0012
	Buses (Urban)	$0.027
	Combination Trucks (Urban)	$0.060
	All Vehicles (Urban)	$0.0037
(Delucchi & Hsu, 1998)	Passenger Cars (Urban)	$0.0025
	Medium Trucks (Urban)	$0.0136
	Heavy Truck (Urban)	$0.0384
	Buses (Urban)	$0.0136
	Motorcycle (Urban)	$0.016
(Forkenbrock, 1998)	Large Intercity Trucks	$0.016
(Safirova et al. 2007)	Heavy Duty Truck	$0.0065
(Maibach, 2008)	Passenger Car (Urban-Daytime)	$0.017
	Passenger Car (Urban-Nighttime)	$0.031
	Motorcycle (Urban-Daytime)	$0.033
	Motorcycle (Urban-Nighttime)	$0.062
	Buses (Urban-Daytime)	$0.84
	Buses (Urban-Nighttime)	$0.153
	Heavy Duty Truck (Urban-	$0.154
	Heavy Duty Truck (Urban-	$0.282
(GAO, 2011)	Truck (Urban – Per ton-mile)	$0.0006
	Railroad (Urban – Per ton-mile)	$0.0006
(Evans, 2014)	Passenger Car (Urban)	$0.002
	Buses (Urban)	$0.002
	Train (Urban)	$0.002
(Najafi et al. 2016)	Truck (Cost per ton-mile)	$0.00028

Based on knowledge of author, (GAO, 2011) is the latest study on social cost of noise pollution in the U.S., at the time of writing this dissertation, therefore, for this dissertation, (GAO, 2011)'s results are used. Additionally, according to (Maibach ,2008) and (VTPI, 2018), social cost of noise pollution in suburban and rural area are approximately 50% and 85% less than urban area, respectively.

4.3 Traffic Accidents

Transportation safety is a top priority of USDOT due to criticality. Traffic accident is the leading cause of death for one to 34-year-old people, in the US. According to (USDOT, 2016), American people spend approximately one million days in the hospital each year due to traffic accident and pay approximately $18 billion in medical cost and lose approximately $33 billion in work lost costs.

Just in 2015, 35,092 people got killed in motor vehicle crashes, and 2.44 million people were injured (NHTSA, 2017). Texas with 3,516, California with 3,176, and Florida with 2,939 fata, have the highest rank of fatal crashes in the US in 2015 (NHTSA, 2017). Figure 4-12 illustrate the number of fatality of each state in 2015 and percent change from 2014.

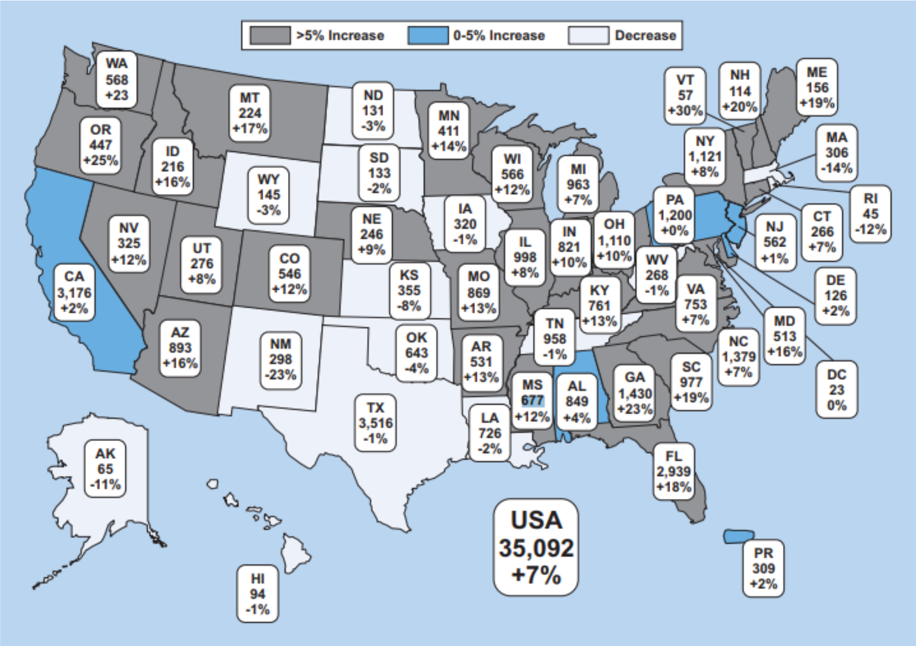


Figure 4-12 Traffic Fatalities by State in 2015 and Percent Change from 2014 (NHTSA, 2017)

Fortunately, the rate of highway fatality accident has been decreased significantly in recent decades. Innovation technologies, new policies, and new vehicle and roadway designs help to improve further reduction in the rate of accident (USDOT, 2016). Figure 4-13 illustrate the fatality rate reduction from 2005 to 2017 (NHTSA, 2018).

The rate of freight transportation at large urban area is increasing, therefore, there is a higher possibility of conflict between passenger vehicles and freight. Freight transportation accounted for approximately 13% of all transportation fatalities.

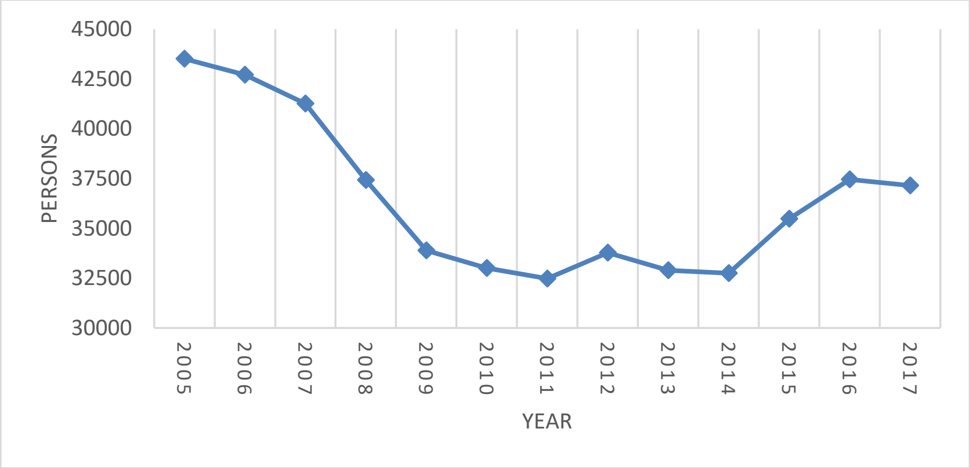


Figure 4-13 Total Fatalities by Traffic Accidents from 2005 to 2017

Data Derived from (NHTSA, 2018)

4.3.1 Traffic Accident by Heavy Duty Trucks

Heavy duty trucks are responsible for approximately 8% of fatal crashes, approximately 3% of injury crashes, and approximately 4% of property-damage-only crashes, in 2016 (NHTSA, 2018). Figure 4-14 illustrate the rate of fatality crashes, when heavy duty truck involved, from 1975 to 2015.

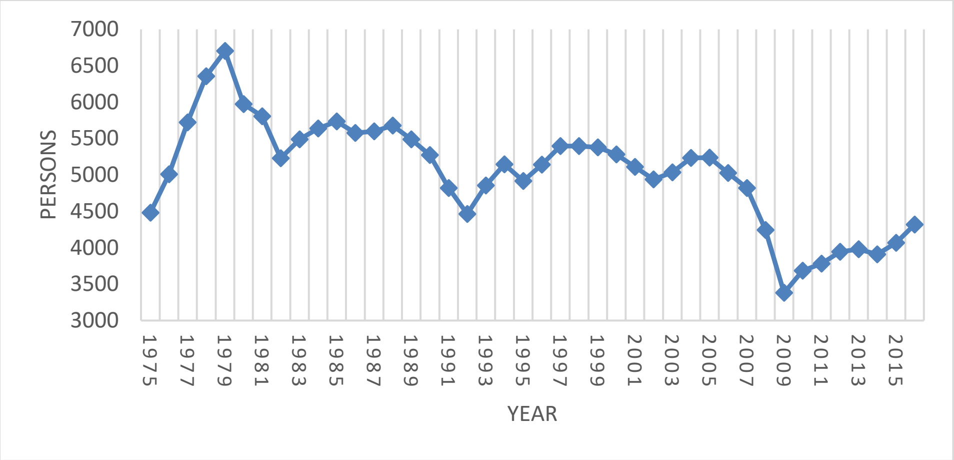


Figure 4-14 Persons Killed in Crashes Involving a Heavy-Duty Truck

Data derived from (NHTSA, 2017)

Moreover, Figure 4-15 illustrate the number of injured persons in crashes, when heavy duty trucks involved from 1988 to 2015 (NHTSA, 2017).

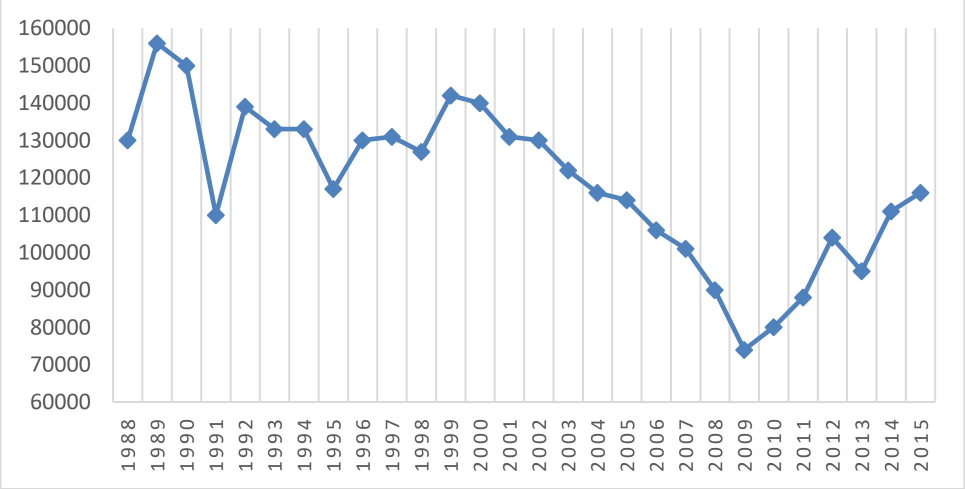


Figure 4-15 Persons Injured in Crashes Involving a Heavy-Duty Truck

Data derived from (NHTSA, 2017)

As it is obvious, by improving economy after recent recession, the rate of crashed, involving heavy duty trucks, increased.

According to FMCSA (2017), 50 to 55 mph is the most critical speed for trucks, since approximately 35% of total truck crashes happened at this speed. Figure 4-16 illustrates the rate of truck accident at different speeds (FMCSA, 2017).

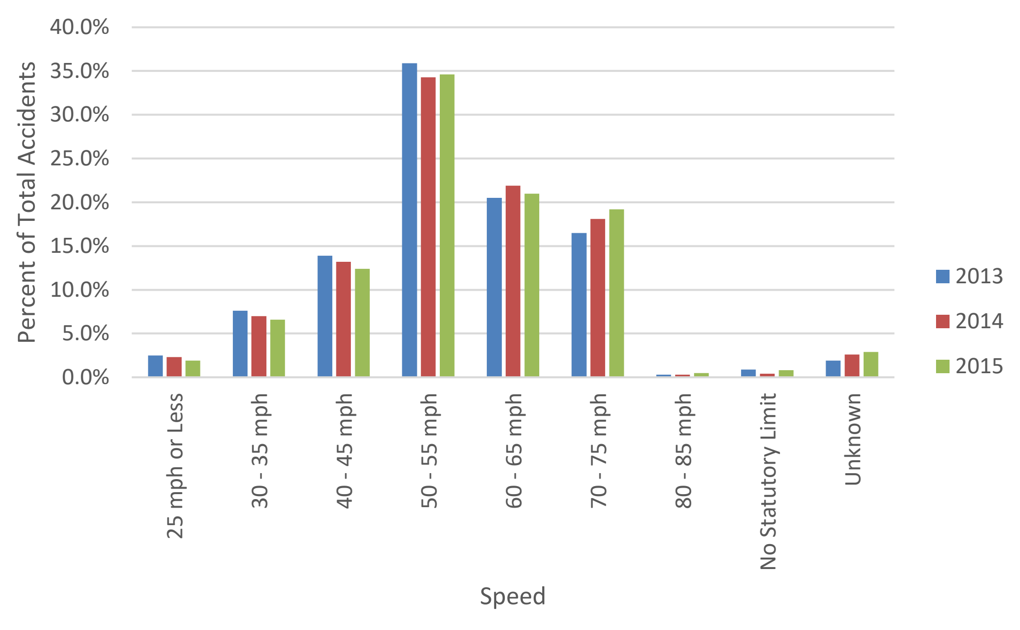


Figure 4-16 Fatal Crashes Involving Heavy Duty Trucks by Speed

Data derived from (FMCSA, 2017)

4.3.2 Traffic Accident by Railroad

The greatest Railroad network in the world is belonged to the United States with approximately 140,000 miles track and transporting over 40% of intercity ton-mile of freight (FRA , 2010). Reducing the risk of train accident is top priority of the U.S. Department of Transportation (USDOT) and railroad companies. Traffic accident with railroad fall into three categories, which are followed (Forkenbrock, 1998);

a) Collisions at highway-rail grade crossing
b) Persons stuck by a train at other location
c) Accident involving the train alone

Table 4-25 shows the number of train accidents and fatalities from 2015 to 2018 (FRA, 2018).

Table 4-25 Accident and Incident by Train

Data derived from (FRA, 2018)

Year	2015	2016	2017	2018
Train Fatalities Accident	1	1	1	3
Train Nonfatalities Accident	54	89	135	132
Train Collisions	35	29	18	17
Highway-Train Fatalities Accident	57	65	63	57
Highway-Train Nonfatalities Accident	338	208	211	197
Employee Fatalities	4	3	5	5
Trespasser Fatalities	96	97	103	135
Fatalities due to related Incidents	116	105	111	144
Total Accident/Incident	3,055	2,729	2,800	2,717

4.3.3 Traffic Accident by Underground Freight Transportation

As stated earlier, Underground Freight Transportation (UFT) is a class of automated transportation system in which vehicles carry freight through tunnels and pipelines between intermodal terminals (Najafi et al. 2016). Since all freight carries through tunnel, the probability of accident is zero. Some accident may happen during loading and unloading, which is not considered for all type of transportation mode at this dissertation.

4.3.4 Social Cost of Traffic Accident

Blauwens et al. (2016) define the marginal road accident costs as the product of number of affected vehicles with accident risk for other transport users. On the other hand, (Korzhenevych et al. 2014) explain external accident cost as “those social costs of traffic accidents, which are not covered by risk-oriented insurance premiums”. Accident leads to damage material, properties, infrastructures, and injury and death people (Janic, 2007).

According to literature search, there are several methodologies to estimate social cost of traffic accident, but so far none of them has been proven. Due to different approach, there is a wide range of social cost. Social cost of traffic accident can be divided into three categories;

a) Direct economic cost: it is observable as an expenditure, including medical and rehabilitation cost, legal cost, emergency service cost, and property damage cost.

b) Indirect economic cost: It is hard to observed and including cost of productivity reduction to the economy that results from death or reduced working capability due to the accident.

c) Value of Safety: It is equal to the amount of money that people are willing to pay to reduce the risk of accident and death due to the accident.

Since there is a lot of uncertainty to estimate social cost of accident, such as cost of human life, or different cost of productivity reduction, accurate estimation is not possible yet. Table 4-26 shows the costs of traffic accident from different studies.

Table 4-26 Social Cost of Accident based on Literature Search

Study By	Accident Cost by Trucks ($/ton-mile) (2018 Dollar Value)	Accident Cost by Railroad ($/ton-mile) (2018 Dollar Value)
(Forkenbrock, 1998)	$1.01	$0.29
(GAO, 2011)	$0.00125 - $0.0025	$0.0027
(Austin, 2015)	$0.009 - $0.024	$0.0012-$0.0027
(Najafi et al. 2016)	$0.0029	N/A

According to NHTSA (2017), American people drove approximately 3,095,373,000,000 miles in 2015. At the same year, the total number of fatal were 35,485 persons, the total number of injured were 1,715,000 persons, and the total number of damaged property were 4,548,000. It is estimated the economic cost of traffic crashes in 2015 were $280 billion (2018-dollar value) (NHTSA, 2017).

Therefore, the average cost of crashes per vehicle-mile-traveled (VMT) without considering the type of vehicle, accident, and cause, would be $0.0904. Furthermore, based on (TxDOT 2003; TxDOT 2016; TxDOT 2017), Texans drove approximately 261,994,000,000 miles, in 2016. At the same year, the total number of fatal due to traffic accident were 3,773 persons and the estimated economic loss of all motor vehicle due to crash was $41,400,000,000. Therefore, the average social cost of crashed per vehicle-mile-traveled (VTM) was approximately $0.16, which is equal $0.004 per ton-mile for heavy duty trucks.

Providing accurate estimate of social cost of accident by truck and rail is not possible. This inaccuracy comes from variety of situations and case of accidents. There is no systematic way to measure the percentage of involvement of freight truck or train in accidents. If the main cause of accident is another vehicle, the involvement of truck or train may not have precipitated the incident (Forkenbrock, 1998).

Since Texas has the highest rate of traffic accident and fatality in the nation, and the location of case study for this dissertation is Houston, TX, the social cost of traffic accident for heavy duty truck, $0.004 per ton-mile, and for railroad $0.0012 per ton-mile, are considered.

4.4 Fuel Consumption and Energy Efficiency

According to the U.S. Energy Information Administration (EIA), transportation is accounted for 29% of total air pollution and greenhouse gases in the U.S. (EIA, 2018). Petroleum products, such as, gasoline and diesel, accounted for approximately 92% of the total transportation sector energy use in the U.S. After petroleum, biodiesel with less than 5%, natural gas with about 3%, and electricity with less than 1% are other sectors of energy for transportation industry (EIA, 2018).

Figure 4-17 illustrates the share of total transportation energy use by type of transportation in 2016.

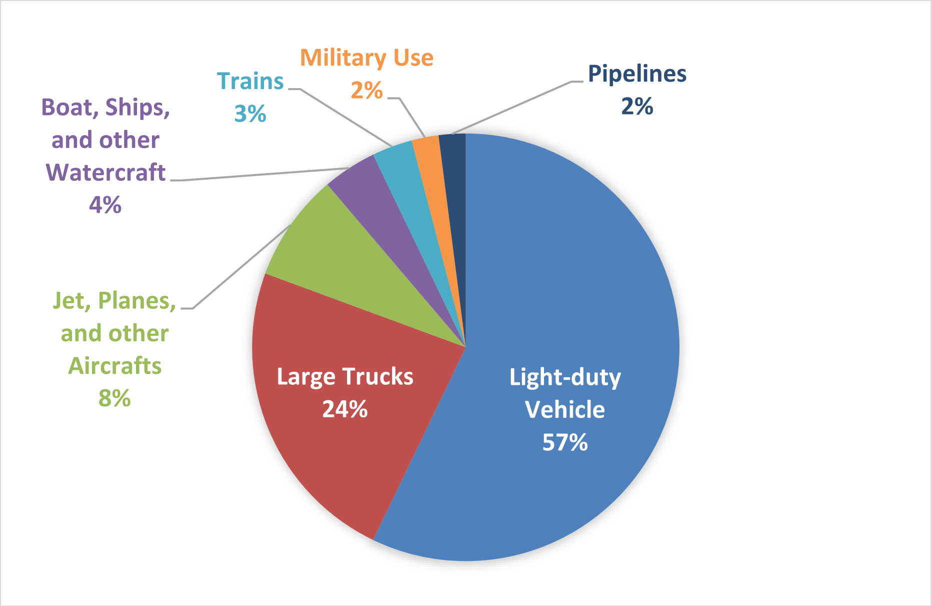


Figure 4-17 Shares of Total U.S. Transportation Energy Use in Transportation Sector

Data derived from (EIA, 2018)

Air pollution emissions increase with higher fuel consumption; therefore, energy efficiency is necessary and key for better environmental quality (Tolliver et al. 2014).

4.4.1 Fuel Consumption by Heavy Duty Trucks

According to (Davis et al. 2017), the average fuel consumption of heavy duty truck is approximately 5.5 to 6.0 mpg[9]. Figure 4-18 illustrates the average fuel consumption of heavy duty truck at different speeds (Davis at al. 2017).

---

[9] Mile Per Gallon

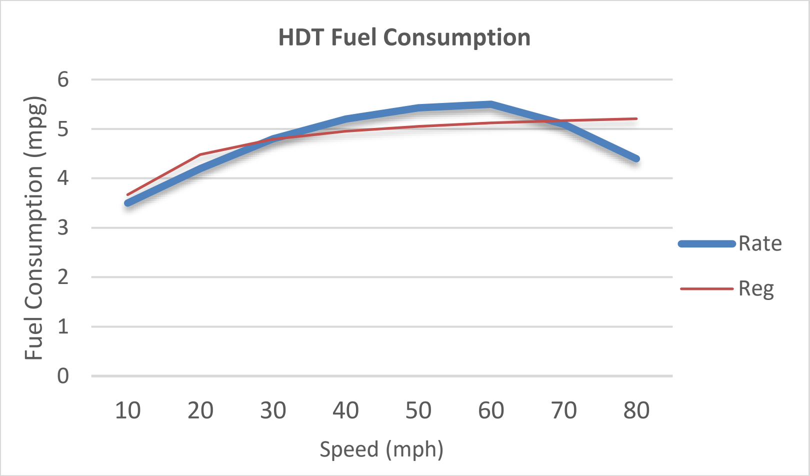


Figure 4-18 HDT Fuel Consumption (mpg)

Data derived from (Davis et al. 2017)

Equation 4-9 comes from curve estimation regression of above figure, which can be used to estimate average fuel consumption at different speed.

$$F_{HDT} = e^{\left(1.7-\frac{4}{S}\right)}$$

Equation 4-9

Where,

F_{HDT}, Average fuel consumption of heavy duty truck (mpg)

And S, speed (mph)

Additionally, Figure 4-19 illustrates the average fuel consumption of passenger vehicles at different speeds (Davis et al. 2017). By Equation 4-10 from this regression, average fuel consumption of passenger vehicle in mile per gallon can be estimated.

$$F_{PV} = 6 + S - 0.01S^2$$

Equation 4-10

Where,

F_{PV}, Average fuel consumption of passenger vehicle (mpg)

And S, speed

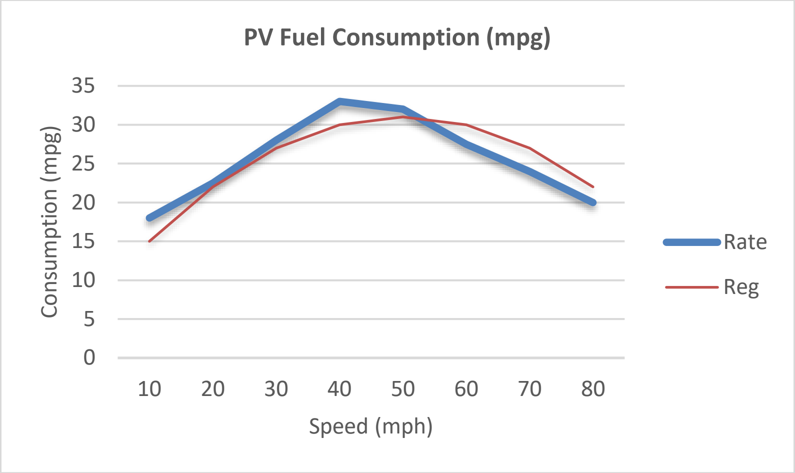


Figure 4-19 PV Fuel Consumption (mpg)

Data derived from (Davis et al. 2017)

Since the fuel source of HDT, railroad, and UFT are different, and one of the objectives of this dissertation is comparison of energy efficiency, the required amount of fuel needs to convert in British Thermal Unit (BTU). According to (EIA, 2018), a BTU is “a measure of the heat content of fuels or energy sources.

It is the quantity of heat required to raise the temperature of one pound of liquid water by 1 degree Fahrenheit at the temperature that water has its greatest density (approximately 39 degrees Fahrenheit).” Every gallon of diesel fuel is equal to 137,452 BTU (EIA, 2018), therefore, required amount of energy in BTU per mile can be calculated by Equation 4-11.

$$E_{HDT} = \frac{137{,}452}{F_{HDT}}$$

Equation 4-11

Where,

E_{HDT}, Average energy consumption of heavy duty truck (BTU/mile)

F_{HDT}, Average fuel consumption of heavy duty truck (mpg)

By assuming transportation of 40-ton cargo by each truck, the required amount of energy in BTU per ton-mile is calculated by Equation 4-12;

$$E_{HDT} = \frac{3436.3}{F_{HDT}}$$

Equation 4-12

Where,

E_{HDT}, Average energy consumption of heavy duty truck (BTU/ton-mile)

F_{HDT}, Average fuel consumption of heavy duty truck (mpg)

By assuming 55 mph average speed of truck and 40 tons weight of freight, the average energy consumption of truck is 669.50 BTU/ton-mile.

4.4.2 Fuel Consumption by Railroad

As stated earlier in section 4.1.6, four different scenarios are discussed. The average fuel consumption of railroad depends on tonnage, distance, and fuel efficiency. Table 4-27 shows the summary of fuel consumption for four scenarios. Also, Table 4-28 shows the required amount of energy in BTU for different scenarios.

Table 4-27 Railroad Fuel Consumption

Railroad Scenario	Fuel Eff. (ton-mile/gal)	Fuel Eff. (gal/ton-mile)	Req. Fuel (gal)	Req. Fuel (gal/mile)
Heavy Unit	370	0.00270	28,380	28.38
Mixed Freight	350	0.00286	9,285	18.57
Intermodal	440	0.00227	15,910	7.95
Double-Stack	370	0.00270	43,245	21.62

Table 4-28 Railroad Energy Consumption in BTU

Railroad Scenario	Fuel Eff. (gal/ton-mile)	Energy (BTU/ton-mile)	Req. Fuel (gal/mile)	Energy (BTU/mile)
Heavy Unit	0.00270	371.120	28.38	3,900,888
Mixed Freight	0.00286	393.113	18.57	2,52,484
Intermodal	0.00227	312.016	7.95	1,092,743
Double-Stack	0.00270	371.120	21.62	2,971,713

For the purpose of this dissertation, the average energy consumption of four scenarios, which is 362 BTU/ton-mile is considered.

4.4.3 Fuel Consumption by Underground Freight Transportation

According to (EIA, 2018), every kilowatt hour of electricity is equal to 3,412 BTU. Table 4-29 shows the summary of different size UFT energy consumption in BTU.

Table 4-29 UFT Energy Consumption in BTU

UFT Size	Payload (ton)	Req. Energy (kWh)	Req. Energy (BTU/mile)	Req. Energy (BTU/ton-mile)
Container	40	27	2047.2	51.20
Crate	9.3	10	758.22	81.50
Pallet	5.6	5.5	417.02	74.50

4.5 Traffic Congestion

According to NCHRP (2001), traffic congestion is defined as “A condition of traffic delay, when the flow of the traffic is slowed below reasonable speeds, because the number of vehicles trying to use the road exceeds the traffic network capacity to handle them (NCHRP, 2001).”

Traffic congestion is one of the major issues in large cities and metroplexes. Traffic congestion has been increased substantially over the past three decades (TTI, 2015).Traffic congestion has wide range of negative impacts including, excessive air pollution, reduce in quality of life, and economic impact due to additional cost and less service from workforce, supplier, and costumer (NCHRP, 2001). Immediate and long-term solution are needed to reduce the amount of undesirable traffic congestion.

There are several different ways to measure the level of traffic congestion on the roadway. The summary of these techniques is shown at Table 4-30.

Table 4-30 Summary of Traffic Congestion Methodologies

Techniques	**Variation**	**Summary**
Time-related Measures	• Average travel speed • Average travel time • Average travel rate • Travel time contours • Origin-destination travel time • Percent travel time under delay conditions • Percent of time average speed is below threshold value	• Widely use measure, applicable to a distinct starting and ending point • Estimate necessary time to travel • Estimate travel time from single point to multiple destinations • Set threshold speed to estimate percent time on congestion • Google Map and other navigation system use this method
Volume Measures	• Vehicle miles traveled/lane mile • Traffic volume	• Estimate V/C ratio by using AADT data • Model distribution of traffic flow
Congestion Indices	• Congestion index • Roadway congestion index • TTI's suggested congestion index • Excess delay	• Comparison level of congestion among U.S. cities • Estimate overall level of congestion
Delay Measures	• Delay/trip • Delay/vehicle miles traveled • Minute miles of delay • Delay due to construction or incident	• Very close to time-related method • Results use for performance measurement
LOS Measures	• Lane miles at LOSx • Vehicle hour traveled/ vehicle miles traveled at LOSx • Predominant intersection LOS • Number of congested intersections	• Quantitative measurement of congestion • Describe operational condition of roadway • Not applied to person movement • Designated with a letter, A to F ○ A: best operation condition ○ F means the worst

Although there are a several methods to measure traffic congestion, time-related measure method offers the best way to estimate the economic impacts of the traffic congestions, for many reasons such as (NCHRP, 2001);

- Travel time is corresponding travelers experience directly

- It efforts to estimate the direct user costs of congestions based on considering value of travel time
- It produces estimates of speed and time for individual roadway segments.

4.5.1 Traffic Congestion by Heavy-Duty Trucks

According to (TTI, 2015), heavy duty trucks are responsible for 18% pf the traffic congestion, although trucks are approximately 7% of the total traffic. According to the American Transportation Research Institute (ATRI), economic cost of traffic congestion on the U.S. national highway systems is approximately $63.4 billion in 2015 (ATRI, 2018). This cost includes 996 million hours delay and excessive fuel consumption. In 2015, states of Florida, Texas, and California had the highest cost of congestion in the U.S. with approximately 23% of share of total cost of congestion (ATRI, 2018).

In order to calculate social cost of highway traffic congestion, following steps must be taken;

- Step 1: Data collection, such as, AADT, AADTT, Average speed and volume of vehicle per time interval at each segment, and free-flow speed.

This data can be found at the states DOT's websites such as Statewide Planning Maps for TxDOT[10].

- Step 2: Consider following constants at Table 4-31;

Table 4-31 National Congestion Constant for Cost of Traffic Congestion

Data derived from (TTI, 2015)

Constant	Value
Vehicle Occupancy	1.25 Persons per Vehicle
Average Cost of Time (2018 Dollar)	$18.93 per person hour
Heavy Duty Truck Operating Cost (2018 Dollar)	$100.73 per vehicle hour
Total Travel Days	364 Days

---

[10] http://www.dot.state.tx.us/apps/statewide_mapping/StatewidePlanningMap.html

Nation Average Cost of Gasoline[11]	\$2.95 per gallon
Nation Average Cost of Diesel[9]	\$3.21 per gallon

- Step 3: By Equation 4-13, calculate speed reduction factor to evaluate the level of congestion (TTI, 2015):

$$S_{RF} = \frac{S_{Ave.}}{S_{FF}} \times 100$$

Equation 4-13

If,

$$\begin{cases} 100\% \geq S_{RF} \geq 80\%, No\ to\ Low\ Congestion \\ 80\% > S_{RF} \geq 65\%, Moderate\ Congestion \\ 65\% > S_{RF}, Severe\ Congestion \end{cases}$$

Where,

S_{RF}, Reduction factor speed (unitless)

$S_{Ave.}$, Average speed (mph)

S_{FF}, Free flow speed (mph)

- Step 4: By Equation 4-14, calculate delay time for each vehicle at each segment and time interval;

$$T_{Delay} = D \times \left(\frac{1}{S_{Ave.}} - \frac{1}{S_{Limit}}\right)$$

Equation 4-14

Where,

T_{Delay}, Delay Time (hour)

D, Distance (mile)

S_{Ave}, Average Speed at congestion situation (mph)

---

[11] Data collected from www.gasprices.aaa.com in 06/03/2018.

S_{Limit}, Speed Limit (mph)

- Step 5: By Equation 4-15, calculate Total Delay time per year;

$$T_{Total-Delay} = [\sum_{i}^{j}(T_{Delay} \times V \times 1.25)] \times 364$$

Equation 4-15

Where,

$T_{Total-Delay}$, Total annual delay time (hour)

T_{Delay}, Summation of delay time for all time interval (hour)

V, Number of vehicle at each time interval and segment (Ea.)

1.25, Average number of person per vehicle (from Table 4-31)

364, Number of days per year (from Table 4-31)

- Step 6: By Equation 4-16, calculate annual time value loss;

$$C_{TL} = (T_{total-Dekay-PV} \times \$18.93) + (T_{total-Delay-HDT} \times \$100.73)$$

Equation 4-16

Where,

C_{TL}, Cost of time value loss (\$)

$T_{total-Delay-PV}$, Total annual delay time of passenger vehicle (hour)

$T_{total-Delay-HDT}$, Total annual delay time of heavy duty trucks (hour)

- Step 7: By Equations 4-17 and 4-18, calculate social cost of excessive emitted air pollution due to the traffic congestion;

$$C_{AP-T} = (\sum_{i}^{j}[\int_{S_{Ave.}}^{S_{Limit}} -\frac{2.4}{S^{1.6}} dS] \times V_T) \times D \times 364$$

Equation 4-17

Where,

C_{AP-T}, Annual cost of emitted air pollution by heavy duty truck ($)

$C_{Air-HDT}$, Social cost of emitted air pollution by HDT ($) (from Equation 4-3)

S_{Limit}, Speed Limit (mph)

S_{Ave}, Average speed (mph)

V_T, Volume of truck (Ea.)

D, Distance (mph)

$$C_{AP-PV} = \sum_{i}^{j} ([\int_{S_{Ave.}}^{S_{Limit}} 0.00004S - 0.002\, dS] + 0.1) \times V_{PV} \times D \times 364$$

Equation 4-18

Where,

C_{AP-PV}, Annual cost of emitted air pollution by passenger vehicle ($)

C_{Air-PV}, Social cost of emitted air pollution by PV ($) (from Equation 4-4)

S_{Limit}, Speed Limit (mph)

S_{Ave}, Average speed (mph)

D, Distance (mile)

V_{PV}, Volume of passenger vehicles (Ea.)

- Step 8: By Equations 4-19 for HDTs and 4-20 PVs, calculate social cost of excessive amount of fuel consumption;

$$C_{Fuel-HDT} = \sum_{i}^{j} \int_{S_{Ave}}^{S_{Limit}} 4e^{(-1.7+\frac{4.}{S})} S^{-2}\, dS \times V_T \times D \times \$3.21 \times 364$$

Equation 4-19

Where,

$C_{Fuel-HDT}$, Cost of excessive fuel consumption for HDT ($)

S_{Limit}, Speed Limit (mph)

S_{Ave}, Average speed (mph)

F_{HDT}, Fuel consumption of HDT (mpg) (from Equation 4-9)

V_T, Volume of truck (Ea.)

And D, Distance (mile)

$$C_{Fuel-PV} = \sum_{i}^{j}(\left[\int_{S_{Ave}}^{S_{Limit}} -0.02S + 1\, dS\right] + 6) \times V_{PV} \times D \times \$2.95 \times 364$$

Equation 4-20

Where,

$C_{Fuel-PV}$, Cost of excessive fuel consumption for PV ($)

S_{Limit}, Speed Limit (mph)

S_{Ave}, Average speed (mph)

F_{PV}, Fuel consumption of PV (mpg) (from Equation 4-12)

V_{PV}, Volume of PV (Ea.)

And D, Distance (mile)

4.5.2 Traffic Congestion by Railroad

America's freight railroad system has over 140,000 route miles connecting consumers to manufacturing, agricultural, economic, and population centers. An essential aspect of US freight infrastructure, railroads move approximately 39 percent of all intercity freight in America each year. Rail is the major mode of transportation for heavy bulk commodities like coal, grain and minerals and for high valued cargo, such as intermodal traffic, traveling between 750 and 2000 miles.

Freight rail is a $70 billion industry comprising over 560 regional and short-line freight railroads, including seven "Class 1" railroads that represent the bulk of the industry's rail mileage, revenues and workforce. Highway and road traffic congestion does not impact railroad system. However, railroad system has a significant impact on highway and road traffic especially in urban area, when there is intersection between road and railroad.

Social cost of road traffic congestion due to the railroad crossing depends on number of intersections, crossing road width, traffic volume at each cross road, time of crossing, speed of train, and number of train car or length of train.

To calculate social cost of traffic congestion, following steps must be taken;

- Step 1: Data collection such as identifying intersections, AADT and AADTT at each crossing road, and crossing road width.
- Step 2: By Equation 4-21, calculate closing time at each intersection.

$$T_{pass} = \frac{L_T + W_R}{S_T \times 1.467} + 20$$

Equation 4-21

Where,

T_{Pass}, Total duration of time that the road is closed due to single passing a train (sec)

L_T, Length of train (ft)

W_R, Width of road (ft)

S_T, Speed of train (mph)

1.467, Conversion factor to convert speed from mile per hour to foot per second

And 20, Advance warning actuation time (Long, 2002).

- Step 3: Estimate the number of HDT and PV passing at the time of road closing.
- Step 4: By Equation 4-22, calculate total annual delay time of passenger vehicle and heavy-duty truck separately.

$$T_{total-Delay} = [\sum_{i}^{j}(\frac{T_{pass-i} \times V_i \times 1.25}{3600})] \times 364$$

Equation 4-22

Where,

$T_{total\text{-}Delay}$, Total annual delay time

$T_{Pass\text{-}i}$, Total duration of time that the road is closed due to passing a train (sec),

V_i, Number of vehicle at each road closure (Ea.),

1.25, Average number of person per vehicle (Ea.) (from Table 4-31)

- Step 5: By Equation 4-23, calculate total value of time loss.

$$C_{TL} = \left(T_{total-Delay-PV} \times \$18.93\right) + \left(DT_{total-Delay-HDT} \times \$100.73\right)$$

Equation 4-23

Where,

C_{TL}, Cost of time value loss ($)

$T_{total\text{-}Delay\text{-}PV}$, Total annual delay time of passenger vehicle (hour)

$T_{total\text{-}Delay\text{-}HDT}$, Total annual delay time of heavy duty trucks (hour)

- Step 6: By Equations 4-24 and 4-25, calculate annual social cost of excessive air pollution due to idling vehicles at road closing.

$$C_{AP-T} = [\sum_{i}^{j} (\frac{T_{pass-i} \times V_{T-i} \times \$0.26}{3600})] \times 364$$

Equation 4-24

Where,

$T_{Pass\text{-}i}$, Total duration of time that the road is closed due to passing a train (sec),

$V_{T\text{-}i}$, Number of truck at specific road closure (Ea.),

And \$0.26, social cost of air pollution by HDT at idle condition ($/hr.)

$$C_{AP-PV} = [\sum_{i}^{j} (\frac{T_{pass-i} \times V_{PV-i} \times \$0.19}{3600})] \times 364$$

Equation 4-25

Where,

T_{Pass-i}, Total duration of time that the road is closed due to passing a train (sec),

V_{PV-i}, Number of passenger vehicle at specific road closure (Ea.),

And \$0.19, social cost of air pollution by PV at idle condition (\$/hr.)

- Step 7: Consider cost of excessive fuel consumption at idle time due to road closing.

  According to the U.S. Department of Energy (2015), in average, heavy duty trucks consume approximately 0.8 gallons of diesel per hour at idling condition. Therefore, the cost of excessive fuel for HDT is \$2.57 per hour (DOE, 2015). Also, passenger vehicles consume approximately 0.16 gallons of gasoline per hour per liter of engine displacement (Ecomobile, 2018). By assuming 2.4-liter engine displacement, in average passenger vehicles burn \$1.13 per hour.

4.5.3 Traffic Congestion by Underground Freight Transportation

As stated earlier, Underground Freight Transportation (UFT) is a class of automated transportation system in which vehicles carry freight through tunnels and pipelines between intermodal terminals (Najafi et al. 2016). Since all freight carries through tunnel, UFT does not affect traffic congestion. Traffic congestion may happen around terminals by other modes of transportations, but it is not considered at this research.

4.5.4 Social Cost of Traffic Congestion

Table 4-32 shows social cost of traffic congestions based on several studies. For this dissertation, social cost of traffic congestion will be calculated based on value of delay time, excessive amount of air pollution, and fuel, then will be compared with other literatures.

Table 4-32 Social Cost of Traffic Congestions

Study By	Congestion Cost of HDT ($/ton-mile) (2018 Dollar Value)	Congestion Cost of Railroad ($/ton-mile) (2018 Dollar Value)
(Safirova et al. 2007)	$0.37[12]	N/A
(GAO, 2011)	$0.0027-$0.0066	$0.00035
(Austin, 2015)	$0.0045-$0.001	$0.00033
(ATRI, 2018)	$0.25[13]	N/A
(Najafi et. Al 2016)	$0.0023	N/A

4.6 Chapter Summary

This chapter provided a framework to estimate social and environmental cost of air pollution, noise pollution, accident, energy consumption, and traffic congestion for heavy duty truck, railroad, and underground freight transportation. Air pollution, energy consumption, and traffic congestion are speed dependent and the amount of their social and environmental costs are different at different speeds. Additionally, noise pollution and accident rate are speed dependent, but the social cost of these items considered to be constant. According to several researches, the social cost of air pollution and noise pollution are varying depends on location (rural or urban). Therefore, depends on location these costs are different.

---

[12] Cost per mile

[13] Cost per mile

Chapter 5 FRAMEWORK RESULTS, DISCUSSIONS, AND VERIFICATION

5.1 Framework Results

In order to measure social and environmental benefits of each alternative, social and environmental cost of air pollution, noise pollution, traffic accident, and traffic congestion at current state of selected route calculated and considered as a “Do Nothing.”

For Alternative 1, the improved speed due to adding one lane from TFSP model used to calculate new social and environmental cost. The difference between this cost and “Do Nothing” cost is the benefits of Alternative 1.

For Alternative 2, the improved speed due to removing 192 trucks per hour from TFSP model used to recalculate all social and environmental costs. Then social and environmental cost of railroad added to. The difference between the total cost of Alternative 2 and “Do Nothing” is the benefit of Alternative 2.

For Alternative 3, same as Alternative 2, the improved speed due to removing truck from traffic considered and all social and environmental cost of traffic recalculated and social and environmental cost of UFT added. The difference between total cost of Alternative 3 and “Do Nothing” is the benefit of Alternative 3. Table 5-1 shows the annual social and environmental cost of selected route by implementing each alternative, and Table 5-2 shows the annual benefit of each alternative.

Table 5-1 Annual Social and Environmental Cost (2018-Dollar)

Alternatives	Air Pollution ($/Year)	Noise Pollution ($/Year)	Traffic Accident ($/Year)	Traffic Congestion ($/Year)	Excessive Fuel ($/Year)
Do Nothing	$286,576,926	$7,339,043	$48,926,953	$1,230,393,026	$2,643,788
Alternative 1	$253,622,337	$7,339,043	$48,926,953	$175,245,000	$10,068,393
Alternative 2	$253,694,366	$7,339,043	$39,030,812	$552,664,715	$11,003,467
Alternative 3	$236,699,000	$5,220,598	$34,803,986	$513,506,836	$9,416,750

Table 5-2 Annual Social and Environmental Benefits (2018-Dollar)

Alternatives and Benefits	Alternative 1 (Adding Lane)	Alternative 2 (Adding Railroad)	Alternative 3 (UFT)
Air Pollution	$32,954,589	$32,882,560	$49,877,926
Noise Pollution	$0	$0	$2,118,445
Traffic Accident	$0	$9,894,141	$14,122,967
Traffic Congestion	$1,055,148,026	$677,728,311	$716,886,190
Excessive Fuel	($7,424,605)	($8,359,679)	($6,772,962)
Total Annual Benefits	**$1,080,678,010**	**$712,147,333**	**$776,232,566**

5.2 Discussion

Based on Tables 5-1 and 5-2, the biggest portion of social cost of freight transportation at selected route is traffic congestion. At these measurement, social and environmental cost of air pollution due to the traffic congestion is considered as a part of the cost of air pollution. Therefore, the cost of traffic congestion includes cost of time loss value.

In reality, by raising vehicles' speed, social cost of noise pollution and traffic accident would increase due to higher engine noise and probability of accident. For this dissertation, due to lack of available data at the time of writing, the social cost of both items considered to be constant at any speed. Additionally, by increasing speed, the average fuel consumption will increase as well. Table 5-3 shows the percentage of improvement by implementing each alternative.

Table 5-3 Social and Environmental Cost Reduction (%)

Alternatives and Benefits	Alternative 1 (Adding Lane)	Alternative 2 (Adding Railroad)	Alternative 3 (UFT)
Air Pollution	11.50%	11.47%	17.40%
Noise Pollution	0.0%	0.0%	28.87%
Traffic Accident	0.0%	20.23%	28.87%
Traffic Congestion	85.76%	55.08%	58.26%
Excessive Fuel	(280.83%)	(316.20%)	($256.18%)

As it shown, UFT has the highest reduction in social cost of air pollution, noise pollution, and traffic accident, while widening highway by adding lane has higher social cost reduction at traffic congestion. The reason is more than 90% of traffic at selected route is passenger vehicles, therefore, widening the highway improves the flow and increase average speed of overall traffic. On the other hand, by widening the highway or removing truck, the average speed of vehicles will increase, therefore, the average fuel consumption of all the vehicles would increase which is costly to the drivers.

In order to clarify social and environmental cost of each mode of inland freight transportation, Figure 5-1 through 5-4 illustrate social cost of each modes.

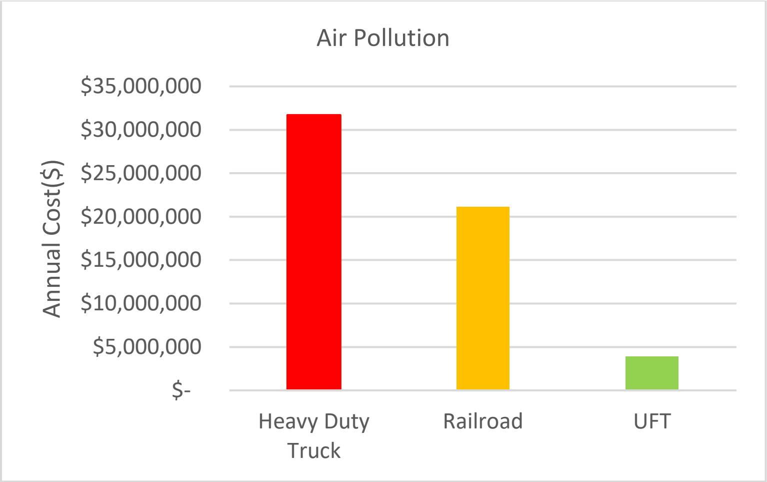


Figure 5-1 Comparison of Social Cost of Air Pollution

(2018-Dollar Value)

As it is illustrated at Figure 5-1, social cost of emitted air pollution by heavy duty truck (with average 55 mph) is one and half times higher than railroad and more than eight times higher than UFT.

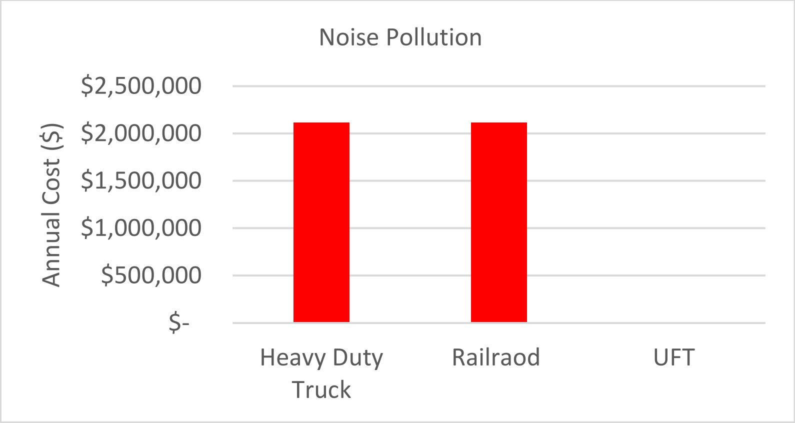


Figure 5-2 Comparison of Social Cost of Noise Pollution

(2018-Dollar Value)

Since UFT carries cargos through tunnel and works with LIM motor, it does not emit any noise pollution, while social cost of noise pollution for heavy duty trucks and railroad is more than two million dollars per year.

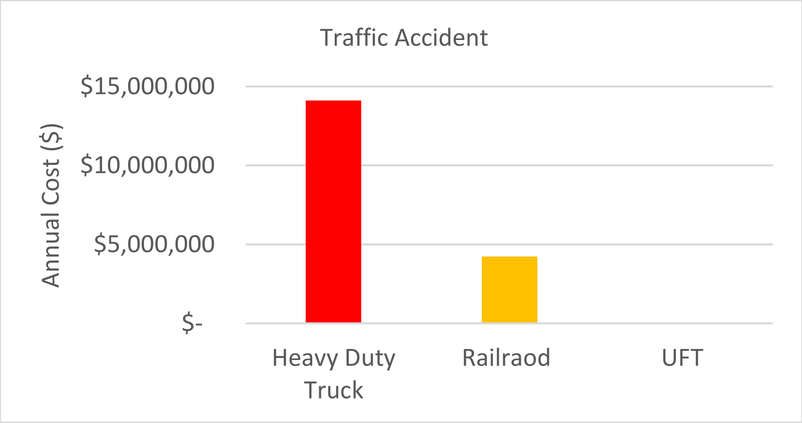


Figure 5-3 Comparison of Social Cost of Traffic Accident

(2018-Dollar Value)

Another benefit of UFT is its safety. Social cost of traffic congestion by heavy duty truck is 3.5 times higher than railroad, while UFT is not cause of any accident and does not have traffic accident cost.

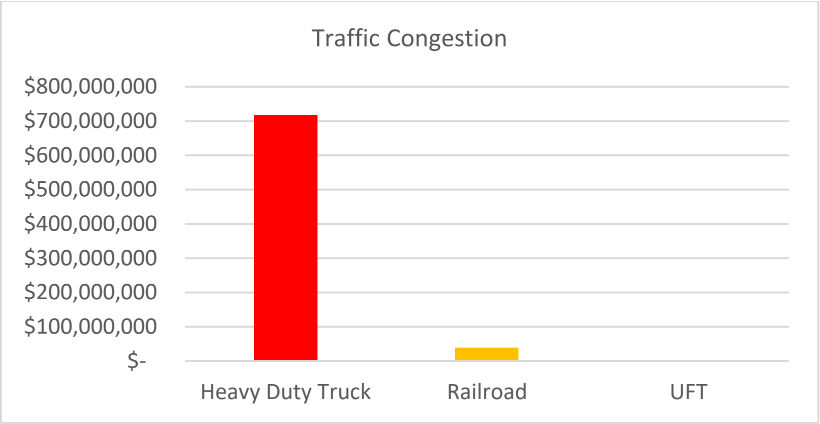


Figure 5-4 Comparison of Social Cost of Traffic Congestion

(2018-Dollar Value)

The highest portion of inland freight transportation social cost is traffic congestion. The social cost of traffic congestion by heavy duty truck at selected route is approximately $700,000,000, which is almost eighteen times higher than railroad. Furthermore, since cargo travels through pipe at UFT, it does not have any impact on surface traffic flow. Lastly, Figure 5-5 illustrate a comparison between UFT with railroad and truck.

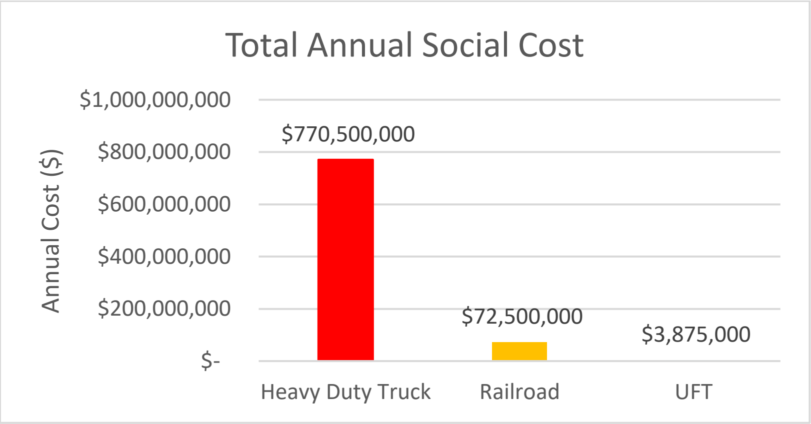


Figure 5-5 Comparison of Total Annual Social Cost

(2018-Dollar Value)

Moreover, Figure 5-6 illustrates a comparison of UFT with heavy duty truck and railroad, in term of energy consumption.

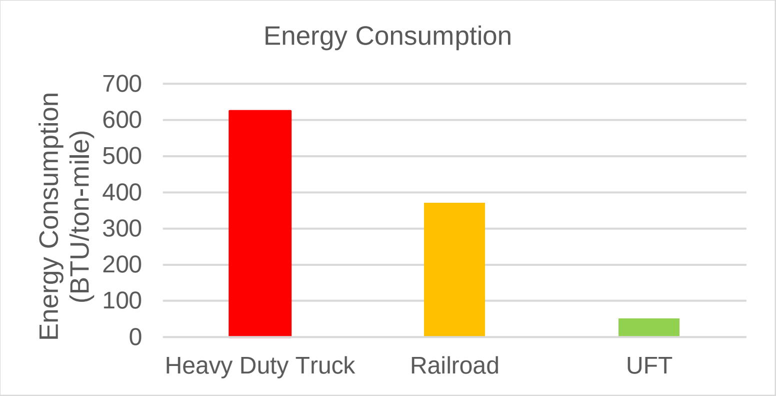


Figure 5-6 Comparison of Energy Consumption

5.3 Verification

As noted before, social and environmental cost air pollution, noise pollution, and traffic congestion of heavy duty trucks and railroads are location dependent. Also, social and environmental cost of air pollution and traffic congestion is speed dependent as well. Tables 5-4 through 5-6 show the comparison of social cost of heavy duty truck, railroad, and UFT with other sources, per discussion at Chapter 4.

Table 5-4 Heavy Duty Truck Social and Environmental Costs Verification

Impact	Calculated Social Cost ($/ton-mile)	Verified By	Comment
Air Pollution	$0.009	(EPA 2017) (Najafi 2016) (Fronkenbrock 1998)	• Location Adjusted • Vehicle Speed Adjusted • Dollar Value Adjusted • Air Pollution Due to Traffic Congestion is Included.
Noise Pollution	$0.0006	(GAO 2011)	• Dollar Value Adjusted
Traffic Accident	$0.004	(TxDOT 2017)	• Same as TxDOT Costs
Traffic Congestion	$0.20		• Cost is Location Based • New Methodology Based on Vehicles and Trucks' Speed • All Trucks and Passenger Vehicles are Considered

Table 5-5 Railroad Social and Environmental Costs Verifications

Impact	Calculated Social Cost ($/ton-mile)	Verified By	Comment
Air Pollution	$0.006	(EPA 2017) (Fronkenbrock 1998)	• Location Adjusted • Vehicle Speed Adjusted • Dollar Value Adjusted • Air Pollution Due to Traffic Congestion is Included.
Noise Pollution	$0.0006	(GAO 2011)	• Dollar Value Adjusted
Traffic Accident	$0.0012	(Austin 2015)	• Dollar Value Adjusted
Traffic Congestion	$0.011		• Cost is Location Based • New Methodology Used • All Trucks and Passenger Vehicles are Considered

As discussed at Section 4.5, at this dissertation, the social cost of traffic congestion includes cost of time loss and excessive fuel consumption. The social cost of excessive air pollution due to traffic congestion, considered as a part of social cost of air pollution. Furthermore, the cost of traffic congestion is location based and cannot be compared with other location due to different number of truck and passenger vehicle with different speed along the selected route. On the other hand, unlike other researches, at this study, excessive amount of traffic congestion by heavy duty trucks for other passenger vehicles is calculated and considered.

Table 5-6 UFT Social and Environmental Costs Verification

Impact	Calculated Social Cost ($/ton-mile)	Verified By	Comment
Air Pollution	$0.0012		• Location Adjusted • Depends on UFT Configuration
Noise Pollution	$0.00	(Najafi et al 2016)	---
Traffic Accident	$0.00	(Najafi et al 2016)	---
Traffic Congestion	$0.00	(Najafi et al 2016)	---

This study for the first time the social and environmental cost of air pollution by UFT calculated. This cost is location based and depends on the amount of emitted air pollutant by power plant and UFT propulsion configuration.

5.4 Chapter Summery

At this chapter social and environmental benefits of each alternative calculated and compared. Also, social and environmental cost of UFT with heavy duty trucks and railroad compared. Based on results, UFT is the most environmental friendly mode of inland freight transportation due to lower amount of emitted air pollution and no impact on traffic accident, congestion, and noise pollution. On the other hand, Alternative 1, which is widening the highway by adding lane at each direction has the highest benefit to social due to removing traffic congestion.

Chapter 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Increasing freight transportation capacity is the most important factor to keep US economy viable. Trucks moved 11.5 billion tons of goods, or 63.8 percent of total freight shipments, in 2015 and it is projected to grow to 16.6 billion tons by 2045. It is predicted truck travel may increase from 282 million miles per day in 2012 to 488 million miles per day by 2045. Existing and anticipated increases in the number of freight vehicles and other conveyances on both public and private infrastructure are stressing the system as more segments of the network approach or reach capacity. Increase freight transportation capacity by increasing railroad capacity, expanding highway system, and using innovative technology such as Underground Freight Transportation can be feasible options.

As stated in chapter 1, the main objective of this dissertation was to measure and compare social and environmental benefits of three alternatives, which are widening the highway (Alternative 1), add railroad (Alternative 2), and building underground freight transportation (UFT) (Alternative 3), in dollar value to find which one has the highest benefits in terms of social and environmental cost. Also, as a case study, 42-mile route from Union Pacific Englewood Yard at Houston to suburban area of town of Brookshire, TX, was selected.

Chapter 2 summarized and discussed available literatures about UFT. According to this chapter, UFT is applicable due to availability of LIM technology and control devices, constructible due to availability of TBMs and construction equipment, and feasible due to high benefit-cost ratio. A lot of literatures indicated that Underground Freight Transportation reduces the truck traffic, street congestion, noise, energy consumption, accidents, and air pollution. Moreover, UFT has higher design life compare with highway and railroad with lower life cycle cost. It was recommended to investigate quantitative analysis of UFT's benefits compare with other inland modes of transportation such as heavy-duty trucks and railroads.

Chapter 3 presented Traffic Volume Distribution Model. TVDM, as a mathematical model, helped to estimate volume of vehicle at each time interval based on speed, during peak hour. This model compared with current practice with Highway Capacity Manual (HCM) and validate by 10% mean absolute percentage error (MAPE). Also, this model validated by a real case study with average 13% MAPE. The contribution of this model was to estimate volume of vehicle at each time interval based on average speed, to help whoever is not familiar with Highway Capacity Manual Equations.

At second step at this chapter, by HCM equations average improved speed of traffic flow, by adding one lane at each direction of the selected route (Alternative 1) and removing 192 trucks per hour to consider Alternatives 2 and 3 are predicted. As a result, in average, widening the highway by adding lane helps to improve speed of overall traffic by approximately 38 %. Moreover, by removing 192 trucks per hour, the average speed would be improved by approximately 24.8%.

Chapter 4 presented the developed Social and Environmental Cost Estimation Framework, to measure social and environmental cost of air pollution, noise pollution, traffic accident, and traffic congestion for heavy duty-truck, railroad, and UFT. As discussed, the cost of traffic congestion and amount of emitted air pollution are depended on vehicles’ speed. By increasing the speed of the vehicle up to 70 mph, the amount of emitted air pollution may be decreased. For social and environmental cost of air pollution, new sets of regression for each content of emitted air pollution, developed. Then, the social cost of each content investigated, and finally another equation to calculate social cost of air pollution based on vehicle speed, developed. The contribution of this model was to estimate social and environmental cost of each inland freight transportation based on speed and provide a methodology to calculate excessive amount of air pollution by passenger vehicle due to heavy duty truck congestion and road closer by railroad. Also, for first time, the social and environmental benefit of UFT compared with heavy duty truck and railroad in detail.

In Chapter 5, the social and environmental benefits of each alternative for selected route measured and compared. As a result, UFT was the most environmental friendly mode of transportation with lowest environmental cost compared with truck and railroad. By using UFT, the amount of air pollution, noise pollution, and traffic accident would decrease significantly. But, widening the highway by adding one lane at each direction, would improve traffic flow and decrease traffic congestion cost. Therefore, in overall, Alternative 1, which is widening the highway, was more beneficial to the public, for selected route. This is important to say that, widening the highway is not feasible at congested urban area, when there is no available land.

6.2 Research Limitations

Limitations of this dissertation are listed below:

- Social cost of noise pollution considered to be independent from speed.
- Social cost of traffic accident considered to be independent from speed.
- Social cost of Carbon Monoxide is not considered at this study.
- Social cost of produced Mercury at power plant is not considered.
- Social cost of electricity wastage at transition and distribution facilities, is not considered.
- Social cost of diesel and gasoline production at refinery and distribution to gas stations is not considered.
- Due to limitation data, in order to calculate social cost of traffic congestion by railroad, for some intersection, the number of vehicles assumed.

- Only the unit cost of each impact considered.
- Social and environmental cost of terminal operation, and maintenance of facilities such as tunnel, road, and railroad are not considered.

6.3 Recommendations for Future Research

Based on the conclusions and finding of this dissertation, the following recommendations for future studies on environmental and social cost of inland freight transportation, are provided;

- Measure social and environmental cost of following alternative during construction based on their design life;
    - Widening the highway by adding lane at each direction
    - Building new route of railroad
    - Building underground freight transportation
- Consider social and environmental cost of electric heavy-duty trucks and electric locomotives.
- Provide a methodology to measure social and environmental cost of noise pollution depends on speed.
- Provide a methodology to measure social and environmental cost of traffic accident depends on speed.
- Consider passenger transportation together with use of UFT.
- Research on applicability of UFT for freight distribution to consumers in urban environment compared with transportation between terminals.
- Prepare a plan to generate public interest to advocate UFT infrastructure.

Chapter 7 REFERENCES

(2018, Feb 23). Retrieved from United States Census Bureau: https://www.census.gov/data/tables/time-series/demo/income-poverty/historical-income-households.html

Administration, U. E. (2013-2014-2015-2016). *Power Plant Operation Report, EIA-923.* U.S. Energy Information Administration.

Aslan Resitoglu, I., Altinsik, K., & Keskin, A. (2015). The pollutant emissions from diesel-engine vehicles and exhaust aftertreatment systems. *Clean Technologies and Environmental Policy, Vol 17*, 15-27.

Association, U. N. (2009). *Speed and Road Traffic Noise .* UK Noise Association.

ATRI. (2018, June 02). *Trucking Industry Congestion Cost* . Retrieved from American Transportation Research Institute: http://atri-online.org/2017/05/16/trucking-industry-congestion-costs-top-63-4-billion/

Austin, D. (2015). *Pricing Freight Transport to Account for External Costs .* Washington, DC: Working Paper Series, Congressional Budget Office.

Becker, T., & Gerlach, J. (2012). *The True Cost of Automobility: External Costs of Cars, Overview an existing estimates in EU-27.* Dresden, Germany : Technische Universitat.

Bernhard, R., & Wayson, R. (2005). *An Introduction to Tire/Pavement Noise of Asphalt Pavement .* Purdue University .

Blauwens, G., Baere, P., & Van de Voorde, E. (2016). *Transport Economics, 6th Eddition* . De Boeck.

Bozek, J. (1990). *Formation and Control of Combustion Pollutants from Gasoline-Fueled Otto Cycle Motor Vehicle Engines .* Offic of Mobile Source Air Pollution Control, EPA.

BTS. (2018, July 26). *Freight Facts & Figures*. Retrieved from Bureau of Transportation Statistics : https://www.bts.gov/bts-publications/freight-facts-and-figures/freight-facts-figures-2017-chapter-3-freight

CEC. (2018, July 29). *Particulate Matter Emissions*. Retrieved from North American Power Plant : http://www2.cec.org/site/PPE/content/particulate-matter-emissions-0

CEC. (2018, July 29). *Particulate Matter Emissions - Less than 10 microns*. Retrieved from North American Power Plan: http://www2.cec.org/site/PPE/pm10emissions?page=26&order=field_plant_state_value&sort=asc

Chen, Z., Dong, J., & Ren, R. (2017). Urban underground logistics system in China: Opportunities or Challenges? *Elsevier - Underground Space*, 195-208.

Clavon, D. (2017). *Applying Computational Intelligence Techniques To Forecast Traffic Flow Using Traffic Sensor Data & Weather Data.* George Washington University.

Cotana, F., Rossi, F., Marri, A., & Amantini, M. (2008). Pipe§net: innovation in the transport through high rate small volume payloads. *5th International Symposium on Underground Freight Transportation (ISUFT).* Arlington, TX: CUIRE.

Councell, T., Duckenfield, K., Landa, E., & Callender, E. (2004). Tire-wear particles as a source of zinc to the environment. *Environmental Science & Technology, Vol 38*, 4206-4214.

Davis, S., Williams, S., & Boundy, R. (2017). *Transportation Energy Data Book, Edition 36.1.* U.S. Department of Energy.

Delucchi, M., & Hsu, S.-L. (1998). External Damage Cost of Noise Emitted from Motor Vehicles. *Journal of Transportation Economics and Policy, Vol 34*, 135-168.

Devision, A. T. (1998). Freight Pipeline: Current Status and Anticipated Future Use. *Journal of Transportation Engineering*, 300-310.

Dietrich, S., & Schoesser, B. (2003). CargoCap - Transportation of Goods Through Underground Pipelines: Research Project in Germany . *ASCE Pipeline* (pp. 1625-1634). Baltimore, Maryland : ASCE .

DOE. (2015). *Long-Haul Truck Idling Burns Up Profit.* U.S. Department of Energy, Energy Efficiency & Renewable Energy.

e-CFR. (2018, 05 25). *Control of Emissions from Locomotives* . Retrieved from Electronic Code of Federal Regulations: https://www.ecfr.gov/cgi-bin/text-idx?SID=159ba6f126272ea1995c71a43b7af309&mc=true&node=pt40.36.1033&rgn=div5

Ecomobile. (2018, 06 13). *Don't let your engine idle*. Retrieved from Ecomobile: https://ecomobile.gouv.qc.ca/en/ecomobilite/tips/idling_engine.php

EESI. (2015). *Fact Sheet: Vehicle Efficiency and Emissions Standards.* Washington, DC: Environmental and Energy Study Institute.

eia. (2018, 05 26). *Electricity and the Environment* . Retrieved from The U.S. Energy Information Administration: https://www.eia.gov/energyexplained/?page=electricity_environment

EIA. (2018, 06 03). *Energy Units and Calculations*. Retrieved from U.S. Energy Information Administration: https://www.eia.gov/energyexplained/index.php?page=about_btu

EIA. (2018, 06 03). *Energy Use for Transportation*. Retrieved from U.S. Energy Information Administration: https://www.eia.gov/energyexplained/?page=us_energy_transportation

eia. (2018). *May 2018, Monthly Energy Review.* Washington, DC: U.S. Energy Information Administration.

EMPA. (2000). *Anteil des Strassenverkehrs an den PM10 und PM2.5 Imissionen.* Dubendorf, Switzerland: NFP41, Verkehr und Umwelt.

EPA. (2009). *Emission Factors for Locomotives .* the U.S. Environmental Protection Agency .

EPA. (2015). *Brake and Tire Wear Emission From On-road Vehicles in MOVES2014.*

EPA. (2015). *Emission Adjustment for Temperature, Humidity, Air Conditioning, and Inspection and Maintenance for On-road Vehicles in MOVES2014.* United States Environmental Protection Agency .

EPA. (2015). *Inventory of U.S. Greenhouse Gas Emissions and Sinks .* United States Environmental Protection Agency .

EPA. (2015, June 05). *Noise Pollution*. Retrieved from U.S. Environmental Protection Agency: www.epq.gov/air/noise.html

EPA. (2015). *Population and Activity of On-Road Vehicles in MOVES2014.* United State Environmental Protection Agency .

EPA. (2015). *United States Environmental Protection Agency*. Retrieved from https://www.epa.gov/ghgemissions/overview-greenhouse-gases

EPA. (2016). *Air Toxic Emissions from On-road Vehicles in MOVES2014.* EPA.

EPA. (2018, July 29). *eGRID*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/sites/production/files/2018-02/documents/egrid2016_summarytables.pdf

EPA. (2018, 05 26). *Overview of Greenhouse Gases* . Retrieved from U.S. Environmental Protection Agency: https://www.epa.gov/ghgemissions/overview-greenhouse-gases

EPA. (2018, June 01). *The Social Cost of Carbons*. Retrieved from United States Environmental Protection Agency : https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

EUP. (2012). *Reducing Railway Noise Pollution Study.* European Parliament .

Evans, C. (2014). *Updating Environmental Externalities Unit Values .* Austroads Publications Online. Retrieved from Austroads Publications Online.

FHWA. (1987). *Environmental Impact and Related Procedures.* Federal Highway Administration.

FHWA. (1997). *1997 Federal Highway Cost Allocation Study.* USDOT.

FHWA. (2017). *Annual State Certifications of Size and Weight Enforcement on Federal-aid Highways.* FHWA.

FHWA. (2018, 05 06). *FHWA*. Retrieved from https://ops.fhwa.dot.gov/publications/fhwahop10024/sect2.htm

FHWA. (2018, June 08). *Traffic Monitoring Guide* . Retrieved from U.S. Department of Transportation, Federal Highway Administration: https://www.fhwa.dot.gov/policyinformation/tmguide/tmg_2013/traffic-monitoring-theory.cfm

FMCSA. (2017). *Large Trucl and Bus Crash Facts 2015 - FMCSA-RRA-16-021.* Analysis Division, Federal Motor Carrier Safety Administration.

Follin, J. N. (1998). *Environmental Risk, Decision Making, and Public Perception.* Pittsburgh, Pennsylvania : Carnegie Mellon University.

Forkenbrock, D. (1998). *External Costs of Truck and Rail Freight Transportation.* The Univesrity of Iwoa's Institutional Repository.

FRA. (2010). *National Rail Plan Progress Report .* Washington, DC: Federal Railroad Administration.

FRA. (2018, May 31). *Total Accident/Incident Report Software*. Retrieved from Federal Railroad Administration, Officeof Safety Analysis: https://safetydata.fra.dot.gov/officeofsafety/publicsite/summary.aspx

(2017). *Freight Analysis Framework.* U.S. Department of Transportation, Bureau of Transportation Statistics and Federal Highway Administration.

Fulari, S., Vanajakshi, L., & Subramanian, S. (2015). Artificial Neural Network-Based Traffic State Estimation Using Erroneous Automated Sensor Data . *Journal of Transportation Engineering, Part A: Systems*.

GAO. (2011). *Surface Freight Transportation.* The U.S. Government Accountability Office .

GAO. (2014). *Regulatory Impact Analysis - GA 14-663.* United States Government Accountability Office.

Ghosh, B., Basu, B., & Mahony, M. (2009). Multivariate Short-Term Traffic Flow Forecasting Using Time-Series Analysis. *IEEE Transactions on Intelligent Transportation Systems, Vol 10*, 246-254.

Goff, A., & Shih, C. (1998). *Feasibility of Freight Pipelines to Relieve Highway Congestion.* Texas: Texas Departement of Transportation.

Gomati, T., Krishna, K., & Lahari, V. (2018). Traffic Volume Estimation Using Trajectory Data. *International Journal of Engineering Development and Research*, 873-874.

Google. (2018, Jan 15). *Google Map*. Retrieved from Google: https://www.google.com/maps/@29.7857258,-95.5349362,12.17z

GRID. (2015). *GRID Logistics*. Retrieved March 23, 2018, from http://www.gridinc.biz/thegridproject

Hammer, M., Swinburn, T., & Neitzel, R. (2014). Environmental Noise Pollution in the United States: Developing an Effective Public Health Response. *Environmental Health Perspectives, Vol 122*, 115-119.

HCM. (2016). *Highway Capacity Manual .* TRB.

HEI. (2010). *Traffic-related Air Pollution: A Critical Review of the Liturature on Emissions, Exposure, and Health Effects.* HEI.

Hodson, N. (2008). Energy Saving Pipeline Capsule Goods Transport Foodtubes. *5th International Syposium on Underground Freight Transportation.* Arlington,TX: CUIRE.

Homberger, Kell, & Perkins. (1992). *Fundamental of Traffic Engineering.* Institute of Transportation Studies.

IAIA. (2015). *International Association for Impact Assessment*. Retrieved March 23, 2018, from http://www.iaia.org/wiki-details.php?ID=23

ICF. (2009). *Comparative Evaluation of Rail and Truck Fuel Efficiency on Competitive Corridors.* Washington, DC: U.S. Department of Transportation, Federal Railroad Administration, Office of Policy and Communications.

iea. (2016). *Energy and Air Pollution .* International Energy Agency .

IEA. (2017). *CO2 Emissions from Fuel Combustion.* International Energy Agency .

Janbaz, S., Shahandashti, M., & Najafi, M. (2017). Life Cycle Cost Analysis of an Underground Freight Transportation (UFT) System in Texas. *ASCE Pipeline .* Phoenix, AZ: ASCE .

Janic, M. (2007). Modelling the full costs of an intermodal and road freight transport network. *Transportation Research Part D: Transport and Environment, Vol 12*, 33-44.

K., K., H., T., & M., R. (2005). Size and composition of airborne particles from pavement wear, tyres, and traction sanding. *Environmental Science & Technology, Vol 39*, 699-706.

Kadali, B., Rathi, N., & Perumal, V. (2014). Evaluation of Pedestrian Mid-block Road Crossing Behavior Using Artificial Neural Network. *Safe, Smart, and Sustainable Multimodal Transportation System* (pp. 1911-1922). Changsha, China: ASCE.

Kolioussis, M., & Pouftis, C. (2000). *Calculation of tyre mass loss and total waste material from road transport.* Thessaloniki, Greece: Laboratory of Applied Thermodynamics, Report No. 0010.

Korzhenevych, A., Dehnen, N., Brocker, J., Holtkamp, M., Meier, H., Gibson, G., & Cox, V. (2014). *Update of the handbook on external costs of transport.* DIW.

Kurer, R. (1991). International Symposium on Theory and Practice in Transport Economics. Berlin, Germany.

Lewis, C. (1982). Industrial and business forecasting methods: A Radical guide to exponential smoothing and curve fitting.

Litman, T. (2009). *Climate Change Emission Valuation for Transportation Economic Analysis.* VTPI.

Liu, H. (2004). *Feasibility of Underground Pneumatic Freight Transport in New York City.* Albany, NY: The New York State Energy Research and Development Authority.

Liu, H., & Lenau, C. (2005). *An Electromagnetic Pneumo Capsule System for Conveying Minerals and Mine Wastes.* Columbia, Missouri: U. S. Department of Energy.

Liu, H., Gandhi, R., Carstens, R., & Klinzing, G. (1998). Freight Pipeline: Current Status and Anticipated Future Use. *Journal of Transportation Engineering*, 300-310.

Long, G. (2002). *Clearance Time Requirements at Railroad-Preempted Traffic Signals.* Gainesville, FL: University of Florida.

Long-Haul Truck Idling Burns Up Profit . (2018, May). Retrieved from U.S. Department of Energy : http://www.afdc.energy.gov/uploads/publication/hdv_idling_2015.pdf

Luhana, L., Sokhi, R., Warner, L., Mao, H., Boulter, P., & McCrae, I. (2004). *Measurement of Non-exhaust Particulate Matter.* European Commission, DG TrEn, 5th Framework Programme.

Luo, Y., Najafi, M., & Liu, H. (2008). Evaluation of Construction Cost of Underground Tunnel for Large Diameter Pneumatic Capsule Pipeline . *4th International Symposium on Underground Freight Transportation (ISUFT).* Bochum, Germany : ISUFT .

MacKenzie, Dower, & Chen. (1992). *The Going Rate.* World Resources Institute.

Maddison, D., Pearce, D., Johansson, O., Clathrop, E., Litman, T., & Veroef , E. (1996). *True costs of road Transport, Blueprint 5.* London, UK: Earthscan Publications Ltd.

Maibach, M. (2008). *Handbook on Estimation of External Cost in the Transport Sector.* CE Delft.

Matthews, S., Hendrickson, C., & Horvath, A. (2001). External Costs of Air Emissions from Transportation. *Journal of Infrastructure System, Vol 7*, 13-17.

Miles, R., & Loose, B. (2008). Sizing the Prize - Presenting the Case for Freight Pipelines . *ISUFT.* Arlington, TX: ISUFT .

Miles, R., Gough, A., & Silverthorne, B. (2016). The Northampton Mole Project - A case study of the application of freight pipeline in an urban environment . *ISUFT .* Arlington, TX.

Milinkovic, L., & Patelic, J. (2015). Underground System in Service of City Logistics. *2nd Logistics International Confernce* (pp. 315-320). Belgrade, Serbia: LOGIC.

Mousavipour, H. (2015). *Feasibility of Underground Freight Transportation (UFT) in Texas .* Arlington, TX: The University of Texas at Arlington .

NAE. (2010). *TEchnology for a Quieter America.* Washington, DC: National Academy of Engineering.

Najafi, M. (2013). *Trenchless Technology, Planning, Equipment, and Methods.* New York, NY: McGraw-Hill.

Najafi, M., & Gokhale, S. (2005). *Trenchless Technology, Pipeline and Utility Design,Construction, and Renewal.* New York, NY: McGraw-Hill.

Najafi, M., Ardekani, S., & Shahandashti, S. (2016). *Integrating Underground Freight Transportation into Existing Intermodal System.* Autin, TX: TXDOT.

National Economic Accounts. (2018, Feb 23). Retrieved from Bureau of Economic Analysis, U.S. Department of Commerce: https://www.bea.gov/national/index.htm

NCHRP. (2001). *Economic Implications of Gongestion, Report 463.* National Cooperative Hghway Research Program.

NHTSA. (2017). *Traffic Safety Facts 2015.* U.S. Department of Transportation, National Highway Traffic Safety Administration.

NHTSA. (2018). *Early Estimate of Motor Vahicle Traffic Fatalities in 2017.* U.S. Department of Transportation, National Highway Traffic Safety Administration .

NHTSA. (2018). *Traffic Safety Facts, Large Trucks.* Washington, DC: US Department of Transportation, National Highway Traffic Safety Administration.

NTNM. (2018, June 02). *National Transportation Noise Map*. Retrieved from U.S. Department of Transportation: https://maps.bts.dot.gov/arcgis/apps/webappviewer/index.html?id=a303ff5924c9474790464cc0e9d5c9fb

Office of Highway Policy Information . (2017, Feb 25). Retrieved from FHWA: https://www.fhwa.dot.gov/policyinformation/statistics/2015/

P., C., & P, C. (1999). Tyre Wear Modeling for HDM$. *Opus International Consultants.* New Zealand .

Perry, E. (2003). *Integration, Status and Potential of Environmental Justice and the Social Impact Assessment Process in Transportation Development in Missouri.* The University of Missouri - Columbia.

Primus, R. (2005). Design Challenges of Locomotive Diesel Engines. *11th Diesel Engine Emissions Reduction Conference.* Chicago, Illinois: DEER Conference, .

Prozzi, J., & Overmyer, S. (2018). *The Potential Impacts of the Panama Canal Expansion on Texas Ports .* College Station, TX: Texas A&M Transportation Institute.

Quah, E., & Boon, T. (2003). The economic cost of particulate air pollution on health in Singapore. *Journal of Asian Economics, Vol 14*, 73-90.

Quiros, D., Smith, J., Thiruvengadam, A., Huai, T., & Hu, S. (2017). Greenhouse gas emissions from heavy-duty natural gas, hybrid, and conventional diesel on-road trucks during freight transport. *Atmospheric Environment* , 36-45.

Rezaei, N. (2016). *Comparison of Construction Methods for Building an Underground Freight Transportation in Texas.* Arlington, TX: The University of Texas at Arlington.

Rezaei, N. T. (2016). Evaluation of Applications and the Comparison of Routes for Underground Freight Transportation in Texas. *ASCE Pipelines* (pp. 847-856). Baltimore: ASCE.

Rezaie, N., Tabesh, A., Najafi, M., Ma, B., & Mousavipour, S. (2016). Evaluation of Application and the Comparison of Routes for Underground Freight Transportation in Texas. *ASCE Pipeline* (pp. 847-856). Kansas City,MO: ASCE.

Rijsenbrij, J. P. (2006). *Sate-of-the art on automated (underground) freight transport system for the EU-TREND project.* Delft University of Technology.

Rohter, L. J. (2007). *AUTOMATED SHIPPING CONTAINER TRANSPORTATION SYSTEM DESIGN FOR CHICAGO.* Illinois, Chicago: Illinois Institute of Technology's (IIT).

Roop, S. O. (2001). *The Technical and Economic Feasibility of A Freight Pipeline System in Texas.* College Station, TX : Texas Transportation Institute.

Roop, S., Aldrete, R., Bujanda, A., Fierro, K., Warner, J., & Williams, J. (2011). *Freight Shuttle System: Crossing - Border Movement of Goods.* Texas Department of Transportation Research and Technology Implementation.

Safirova, E., Houde, S., & Harrington, W. (2007). *Marginal Social COst Pricing on a Transportation Network.* Washington, DC: Resources for the Future.

SENCO. (2000). *Collation of information on particulate pollution from tyres, brakes, and road surfaces.* Colchester, Essex, UK: Sustainable Environment Consultants Ltd.

Sharma, V., Rai, S., & Dev, A. (2012). A comprehensive study of artificial neural networks. *International Journal of Advance Research, Computer Science Software Engineering, Vol 10*, 278-284.

Sinisterra, A. (2011). *Modeling of Linear Induction Machines For Analysis and Control .* Boca Raton, FL: Florida Atlantic University .

Standards, E. (2018, 05 10). *United States: Locomotives*. Retrieved from DieselNet : www.dieselnet.com/standards/us/loco.php

Tabesh, A. N. (2016). Comparison of Construction Methods for Underground Freight Transportation in Texas . *ASCE Pipeline* (pp. 817-826). Kansas City: ASCE .

Tabesh, A., Najafi, M., Ashoori, T., Tavakoli, R., & Shahandashti, S. (2017). Environmental Impact of Pipeline Construction for Underground Freight Transportation. *ASCE Pipeline* (pp. 181-191). Phoenix,AZ: ASCE.

Tabesh, A., Najafi, M., Ashoori, T., Tavakoli, R., & Shahandashti, S. (2017). Environmental Impacts of Pipeline Construction for Underground Freight Transportation. *ASCE Pipeline* (pp. 181-191). Phonix, AZ: ASCE.

Tam, C., Tong, K., & Zhang, H. (2007). *Decision Making and Operation Research Techniques for Construction Management .* Hong Kong: City University of Hong Kong.

Tavakoli, R., Najafi, M., Tabesh , A., & Ashoori, T. (2017). Comparison of Carbon Footprint of Trenchless and Open-cut Methods for Underground Freight Transportation. *ASCE Pipeline* (pp. 45-55). Phoenix, AZ: ASCE.

Teodorovic, D. a. (2017). *Transportation Engineering, Theory, Practice and Modeling .* Elsevier .

Texas Statewide Planing Map. (2018, March 17). Retrieved from Texas Department of Transportation : http://www.txdot.gov/apps/statewide_mapping/StatewidePlanningMap.html

Tolliver, D., Lu, P., & Benson, D. (2014). Railroad Energy Efficiency in the United States: Analytical and Statistical Analysis . *Journal of Transportation Engineering, Vol 140*, 23-30.

Transportation, U. D. (2017, Feb 13). *North American Transborder Freight Data*. Retrieved from Bureau of Transportation Statistics: http://www.bts.gov/programs/international/transborder/

TranStar, H. (2018, Jan 21). *Houston TranStar Traffic Map*. Retrieved from Houston TranStar : http://traffic.houstontranstar.org/layers/

TTI. (2015). *2015 Urban Mobility Scorecard.* Texas A&M Transportation Institute .

TTI. (2015). *Methodology for the 2015 Urban Mobility Scorecard.* Texas A&M Transportation Institute.

TxDOT. (2017). *Comparison of Motor Vehicle Traffic Death, Vehicle Miles, Death Rates, and Economic Loss 2003-2016.* Austin, TX: Texas Department of Transportation .

TXDOT. (2018). *Houston Transtar Map*. Retrieved April 04, 2018, from http://traffic.houstontranstar.org/layers/

TxDOT. (2018, Jan 13). *Statewide Planing Map*. Retrieved from Texas Department of Transportation: http://www.dot.state.tx.us/apps/statewide_mapping/StatewidePlanningMap.html

Tylor, F. (2012). Principles and guidelines for social impact assessment in the USA: The interorganizational committee on principles and guidelines for social impact assessment. *Impact Assessment and Project Appraisal*, 231-250.

UBA. (1998). *Exemplarische Erfassung der Umweltexposition Ausgewaehlter Kauschukderivate bei der bestimmungsdemaessen Verwendung in Reifen uind deren Entsirgung.* UBA-FB 98-003.

Underground Container Mover. (2018, March 16). Retrieved from DENYS: http://www.denys.be/nl/projecten/index/1/Underground-Container-Mover/1/dream-works

UNFCCC. (2018, April 11). *The Paris Agreement* . Retrieved from United Nations Climate Change: https://unfccc.int/process/the-paris-agreement/what-is-the-paris-agreement

United States Census Bureau. (2018, Feb 23). Retrieved from CENSUS: https://www.census.gov/data/tables/2017/demo/popest/nation-total.html

USDOT. (2015). *Freight Facts and Figures.* Washington, DC: USDOT.

USDOT. (2016). *2045 Beyond Traffic, Trends and Choices .* U.S. Department of Transportation.

USDOT. (2018, July 26). *DOT Relases 30-Years Freight Projections*. Retrieved from USDOT: https://www.transportation.gov/briefing-room/dot-releases-30-year-freight-projections

Vance, L., & Mills, M. (1994). *Tube Freight Transportation.* FHWA.

Vanek, F. (1998). *Three Papers on Reducing the Environmental Impact of Freight Transportation and Logistics .* University of Pennsylvania.

Visser, J., & Binsbergen, A. (1997). • *Underground Networks for Freight Transport: A Dedicated Infrastructure for Intermodal Short – Distance Freight.* Netherland: University of Delf.

Vlahogianni, E., Karlaftis, M., & Golias, J. (2015). Recurrence Analysis Applications to Short-Term Macroscopic and Microscopic Road Traffic . *Springer International Publishing Switzerland*, 375-397.

VTPI. (2018). *Transportation Cost and Benefit analysis II - Air Pollution Costs .* Victoria Transport Policy Institute.

VTPI. (2018). *Transportation Cost and Benefits Analysis II - Noise Costs.* Victoria Transportation Policy Institute.

Warner, L., Sokhi, L., Luhana, L., Boulter, I., & McCrae, I. (2004). Non-exhaust particle emissions from road transport. *11th International Conference "Transport and air pollution".* Dept. of Environmental Sciences Univ. of Hertfordshire,UK.

WDOT. (2010). *Guide for Interpreting Short Duration Traffic Count Reports.* Washington Department of Transportation .

Yao, Z., Wei, H., Perugu, H., Liu, H., & Li, Z. (2014). Sensitivity Analysis of Project Level MOVES Running Emission Rates for Light and Heavy Duty Vehicles . *Journal of Traffic and Transportation Engineering*, 81-96.

Yu, M.-j., & Fan, Y.-q. (2017). Plan and Conceptual Design of Urban Underground Domestic Waste Transfer Logistics System. *1th Academic Forum for China Society Underground Freight Transportation*, (pp. 334-343).

Z. Farahani, R., Rezapour, S., & Kardar, L. (2011). *Logistics Operations And Management .* Waltham, MA: Elsevier.

Zahed, E., Shahandashti, S. M., & Najafi, M. (2017). Financing Underground Freight Transportation System in Texas: Identification of Funding Sources and Assessment of Enabling Legislation. *Journal of Pipeline System Engineering and Practice* .

Zahed, E., Shahandashti, S., & Najafi, M. (2017). Investment Valuation of an Underground Freight Transportation (UFT) System in Texas . *ASCE Pipeline* (pp. 192-201). Phoenix,AZ: ASCE.

Zahed, E., Shahandashti, S., & Najafi, M. (2018). Lifecycle Benefit-Cost Analysis of Underground Freight Transportation Systems . *Journal of Pipeline Systems Engineerings and Practice* .

Zandi, I., & Gimm, K. (1976). *Transport of Solid Commodities via Freight Pipeline .* Washington, DC: U.S. Departement of Transportation.

Zelenakova, M. a. (2016). Risk Analysis within Environmental Impact Assessment of Proposed Construction Activity. *Environmental Impact Assessment* , 76-89.

Zhan, X., Zheng, Y., Yi, X., & Ukkusuri, S. (2017). Citywide Traffic Volume Estimation Using Trajectory Data. *IEEE Transaction on Knoeledge and Data Engineering, Vol 29, No.2*, 272-286.

APPENDIX A

Table A-1 Adjustment to FFS for Right-Side Lateral Clearance

Right-Side Lateral Clearance (ft)	Number of Lanes in			
	2	3	4	≥5
≥6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

APPENDIX B

Heavy Duty Trucks Emission Rate

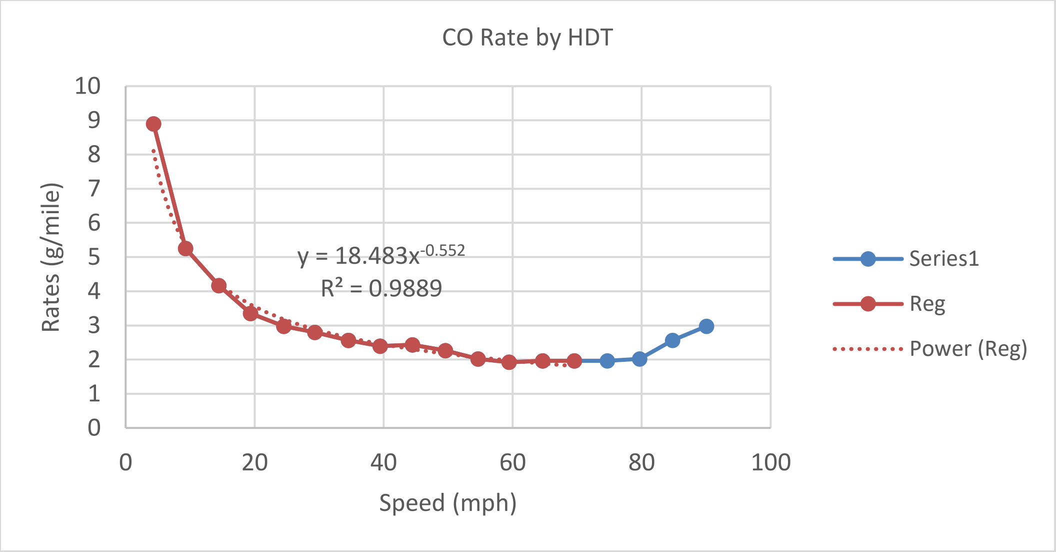


Figure B-1 CO Emission Rate by Heavy Duty Truck

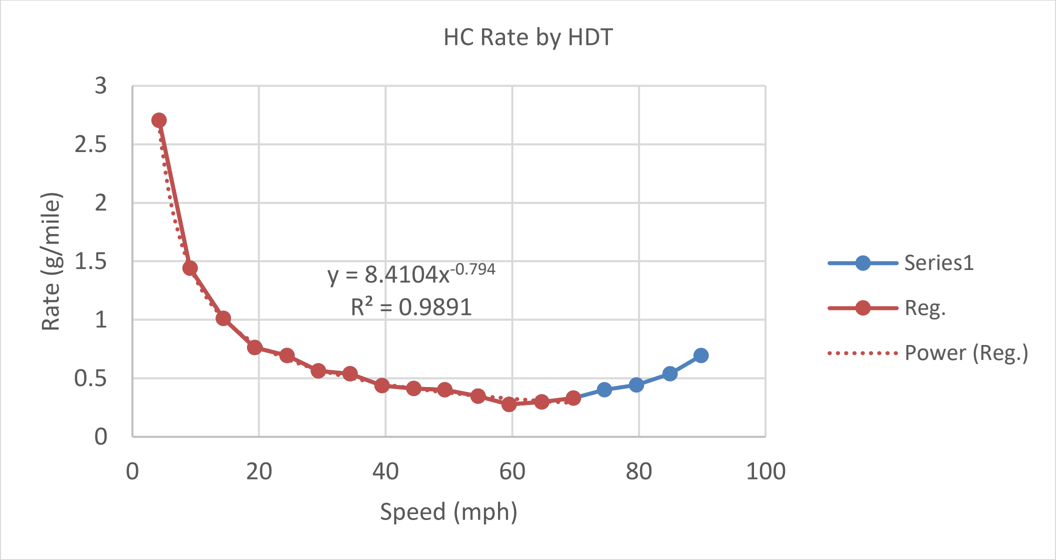


Figure B-2 HC Emission Rate by Heavy Duty Truck

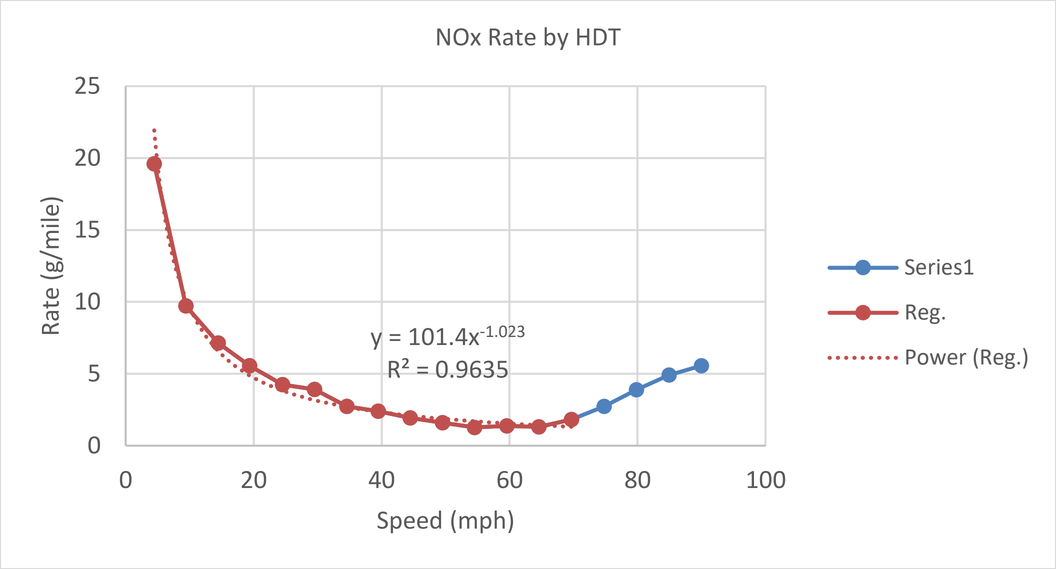


Figure B-3 NO_x Emission Rate by Heavy Duty Truck

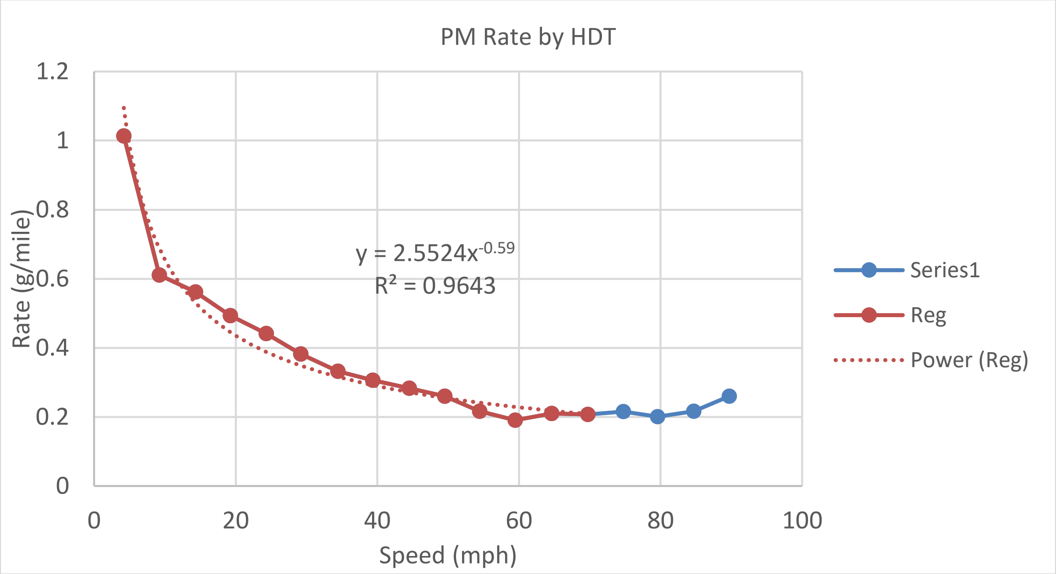


Figure B-4 PM Emission Rate by Heavy Duty Truck

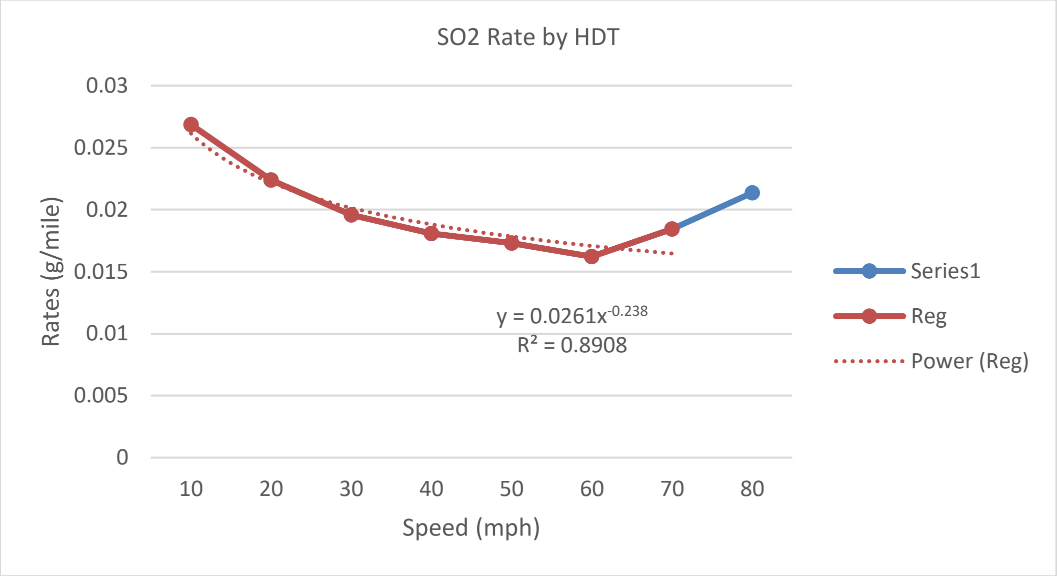


Figure B-5 SO_2 Emission Rate by Heavy Duty Truck

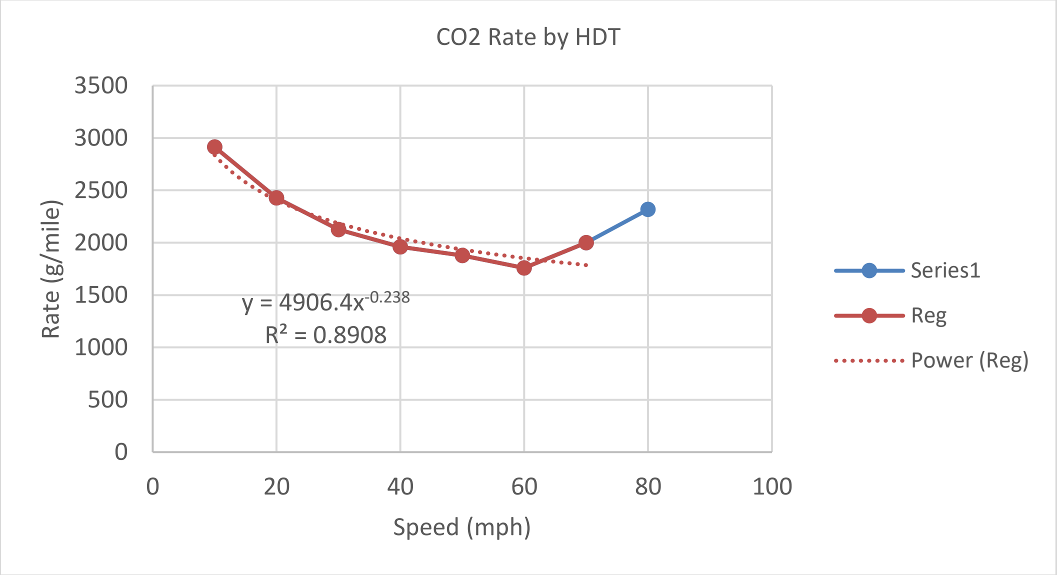


Figure B-6 CO_2 Emission Rate by Heavy Duty Truck

Passenger Vehicles Emission Rate

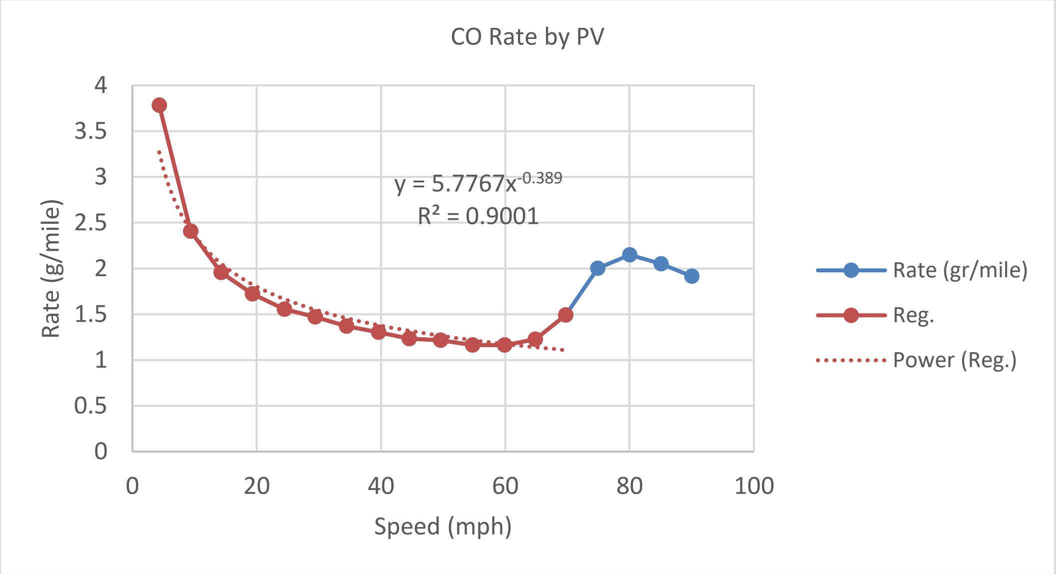


Figure B-7 CO Emission Rate by Passenger Vehicle

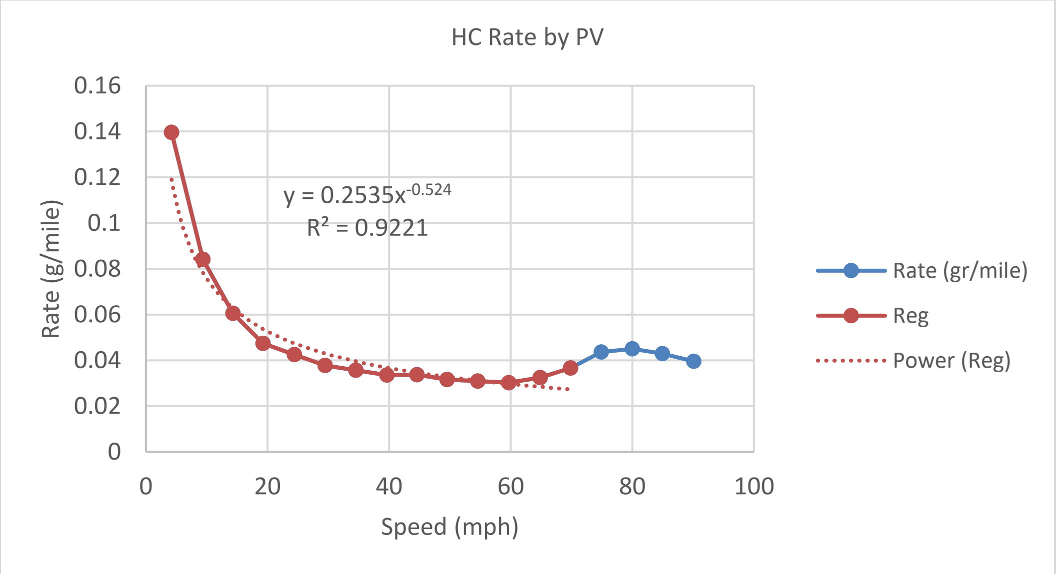


Figure B-8 HC Emission Rate by Passenger Vehicle

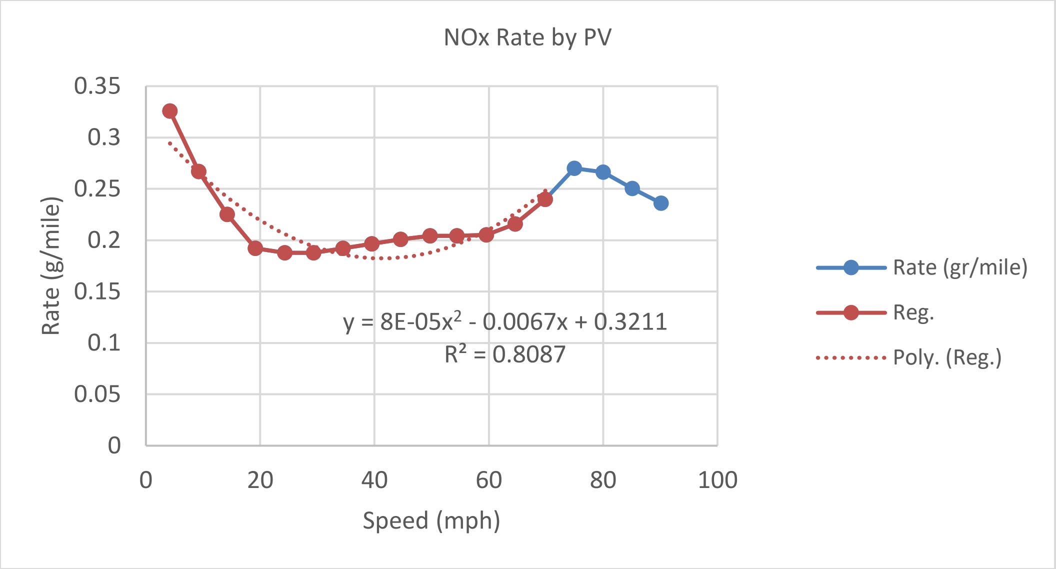


Figure B-9 NOx Emission Rate by Passenger Vehicle

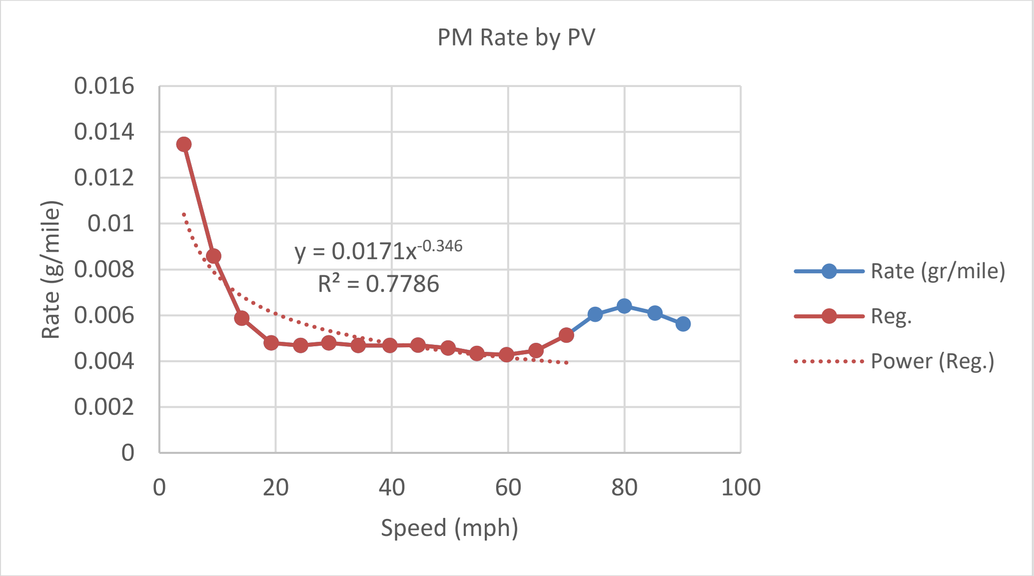


Figure B-10 PM Emission Rate by Passenger Vehicle

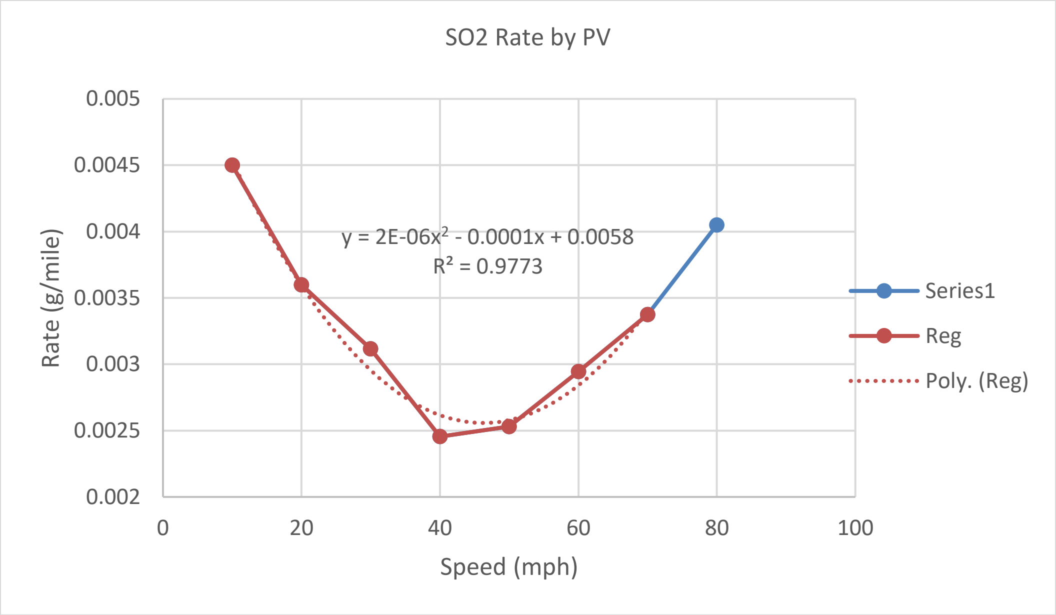


Figure B-11 SO_2 Emission Rate Passenger Vehicle

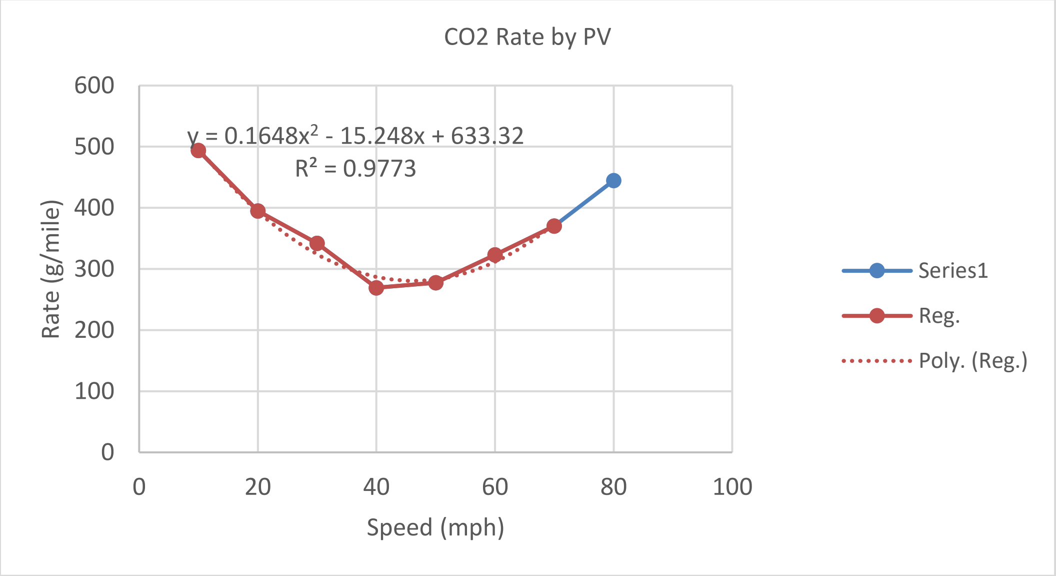


Figure B-12 CO_2 Emission Rate by Passenger Vehicle

Table B-1 Social Cost of Emitted Air Pollution by Power Planet

Census Division and State	CO2 (Kg/MWh)	SO2 (g/MWh)	NOX (g/MWh)	Social Cost of PM and HC ($/MWh) (2018-Dollar Value)	Social Cost of Air Pollution ($/MWh) (2018-Dollar Value)
New England	270	111	242	$ 0.65	$ 42.89
Connecticut	235	16	165	$ 0.65	$ 35.75
Maine	222	608	527	$ 0.65	$ 47.49
Massachusetts	398	105	323	$ 0.65	$ 61.71
New Hampshire	131	46	113	$ 0.65	$ 21.01
Rhode Island	407	13	139	$ 0.65	$ 56.10
Vermont	6	27	304	$ 0.65	$ 12.38
Middle Atlantic	322	283	307	$ 0.65	$ 51.74
New Jersey	272	36	151	$ 0.65	$ 39.83
New York	233	137	239	$ 0.65	$ 38.22
Pennsylvania	395	463	405	$ 0.65	$ 64.50
East North Central	579	738	462	$ 0.65	$ 89.45
Illinois	385	521	191	$ 0.65	$ 55.54
Indiana	839	817	878	$ 0.65	$ 136.74
Michigan	523	825	468	$ 0.65	$ 82.75
Ohio	686	1,100	546	$ 0.65	$ 105.94
Wisconsin	630	431	434	$ 0.65	$ 94.59
West North Central	626	756	550	$ 0.65	$ 98.42
Iowa	556	577	485	$ 0.65	$ 87.30
Kansas	541	136	362	$ 0.65	$ 80.91

Census Division and State	CO2 (Kg/MWh)	SO2 (g/MWh)	NOX (g/MWh)	Social Cost of PM and HC ($/MWh) (2018-Dollar Value)	Social Cost of Air Pollution ($/MWh) (2018-Dollar Value)
Minnesota	498	407	426	$ 0.65	$ 78.02
Missouri	798	1,185	683	$ 0.65	$ 124.76
Nebraska	630	1,293	549	$ 0.65	$ 99.18
North Dakota	790	1,140	940	$ 0.65	$ 133.05
South Dakota	232	66	93	$ 0.65	$ 32.84
South Atlantic	466	338	333	$ 0.65	$ 70.58
Delaware	500	53	224	$ 0.65	$ 70.72
District of Columbia	622	69	4,457	$ 0.65	$ 238.70
Florida	463	247	296	$ 0.65	$ 68.88
Georgia	451	395	321	$ 0.65	$ 68.34
Maryland	500	664	353	$ 0.65	$ 75.65
North Carolina	401	361	366	$ 0.65	$ 63.78
South Carolina	289	238	159	$ 0.65	$ 42.28
Virginia	395	288	342	$ 0.65	$ 62.11
West Virginia	902	547	626	$ 0.65	$ 135.27
East South Central	538	499	347	$ 0.65	$ 80.13
Alabama	406	346	247	$ 0.65	$ 60.04
Kentucky	902	901	680	$ 0.65	$ 137.49
Mississippi	418	193	237	$ 0.65	$ 61.09
Tennessee	503	611	274	$ 0.65	$ 73.21
West South Central	512	564	414	$ 0.65	$ 79.30
Arkansas	525	898	507	$ 0.65	$ 84.41

Census Division and State	CO2 (Kg/MWh)	SO2 (g/MWh)	NOX (g/MWh)	Social Cost of PM and HC ($/MWh) (2018-Dollar Value)	Social Cost of Air Pollution ($/MWh) (2018-Dollar Value)
Louisiana	496	538	619	$ 0.65	$ 84.68
Oklahoma	472	633	343	$ 0.65	$ 71.80
Texas	521	514	365	$ 0.65	$ 78.64
Mountain	574	277	559	$ 0.65	$ 92.16
Arizona	409	108	334	$ 0.65	$ 63.54
Colorado	663	327	531	$ 0.65	$ 102.17
Idaho	117	240	301	$ 0.65	$ 26.09
Montana	593	407	580	$ 0.65	$ 95.26
Nevada	365	61	250	$ 0.65	$ 55.04
New Mexico	705	228	1,079	$ 0.65	$ 127.07
Utah	741	294	867	$ 0.65	$ 123.92
Wyoming	947	754	837	$ 0.65	$ 148.60
Pacific Contiguous	176	58	255	$ 0.65	$ 31.74
California	239	13	351	$ 0.65	$ 42.92
Oregon	136	133	201	$ 0.65	$ 24.88
Washington	90	96	118	$ 0.65	$ 16.05
Pacific Noncontiguous	659	1,287	2,294	$ 0.65	$ 165.67
Alaska	547	500	3,325	$ 0.65	$ 188.75
Hawaii	729	1,788	1,637	$ 0.65	$ 150.98
U.S. Total	473	443	400	$ 0.65	$ 73.93