Dynamic Simulation Models for Road Safety and Its Sustainability Implications

SAFER SIM

SAFETY RESEARCH USING SIMULATION

UNIVERSITY TRANSPORTATION CENTER

Omer Tatari, PhD, PI
Associate Professor
Department of Civil, Environmental and Construction Engineering
University of Central Florida

Nuri Onat, PhD
Mehdi Alirezaei, PhD Student
M. Abdel-Aty, PhD, Professor
Department of Civil, Environmental and Construction Engineering
University of Central Florida

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Omer Tatari, PhD, PI

Associate Professor

Department of Civil, Environmental and Construction Engineering

University of Central Florida

Nuri Onat, PhD Candidate

Graduate Research Assistant

Department of Civil, Environmental and Construction Engineering

University of Central Florida

Mohamed Abdel-Aty, PhD, Co-PI

Pegasus Professor, Chair

Department of Civil, Environmental and Construction Engineering

University of Central Florida

Mehdi Alirezaei, PhD Student

Graduate Research Assistant

Department of Civil, Environmental and Construction Engineering

University of Central Florida

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Abstract

Road safety is one of the most complicated topics pertaining to the transportation sector and involves many interdependencies. Therefore, a sufficiently thorough analysis of road safety requires a novel system-based approach in which the associated feedback relationships and causal effects are given appropriate consideration. To this end, this project investigated common issues related to traffic accidents by considering the major causes and influences associated with such accidents and their complex relationships with climate change and with certain economic parameters. The factors affecting accident frequency and severity are highly dependent on economic parameters and weather conditions. The economic factors and/or impacts involved in roadway accidents and fatalities, including property damage costs and injury-related costs, have always been strongly affected by various road safety concerns and, conversely, by efforts to improve road safety and/or to reduce the likelihood of future traffic accidents. However, the environmental factors related to road safety, though not always accounted for as well as they should be, also interact very strongly with the transportation sector in terms of environmental causes and effects.

This project used a novel system dynamics (SD) modeling approach to model the climate change–road safety–economy nexus, thereby investigating the complex interactions among these important areas by tracking how they affect each other over time. For this purpose, five submodels were developed to model each aspect of the overall nexus and to interact with each other to simulate the overall system. As a result, this comprehensive model could provide a platform for policymakers to test the effectiveness and/or consequences of different policy scenarios with which to reduce the negative consequences of traffic accidents and/or improve road safety. In order to achieve the aforementioned goals, the following steps were taken in this study:

1. **Identification of parameters:** In order to create a causal loop diagram (CLD), different parameters typically involved in road safety and transportation were identified. It must also be determined which parameters may or may not be directly connected, while indirect connections typically will be revealed as separate series of one or more direct connections.

2. **System conceptualization:** In this section, a CLD was developed based on the previously defined parameters. A CLD is a feedback-loop-based diagram. Feedback loops are the most important characteristic of any SD model, as these connectors determine how the results or outputs of a sector within the system should be used as an input for another sector in the system.

3. **Model formulation:** In order to achieve the aforementioned goals of this study, the following models have been developed: an economic losses model for crashes with respect to fatalities, injuries and property damage only; a motor vehicle safety standards submodel; a highway system capacity submodel; an environmental impact model; and an economic impact submodel. Each of these models targets a specific area of this study, and the results of these models are used in the policy analysis section.

4. **Model validation:** In this step, the validity of the developed models was identified through a set of validation tests. These tests included structural validity tests, such as structure verification, parameter verification, extreme condition, boundary adequacy, and dimension consistency tests. In addition, model behavior verification tests were used to compare the output of the developed SD

model to real-world historical data to ensure that the data matched closely enough to conclude that the model's behavior accurately represented the behavior of the system in reality.

5. **Policy analysis:** The three main policy areas investigated are listed below. Any change in any of these policy areas could potentially affect other parts of the system, so the investigation into the proposed policies involved many interdependencies.

   - ***Worldwide CO_2 emissions reductions:*** This policy investigated whether worldwide greenhouse gas (GHG) emissions could affect road safety. The results showed that reducing CO_2 emissions by 25% and 50% could reduce the number of weather-related roadway fatalities to 6,560 and 6,480, respectively, by the year 2100. If no action is taken, this number could reach 6,640.
   - ***Travel demand reduction:*** This scenario attempted to investigate the effects of travel demand reduction on vehicle miles traveled (VMT), as well as its effects on the number of fatalities and on other parameters involved in this system. Based on this scenario, reducing VMT by 25% and 50% could reduce the number of roadway accident fatalities to 89,000 and 75,000, respectively, by 2100. If no action is taken, this number could reach 105,000.
   - ***Vehicular safety index increase:*** The increasing vehicle safety scenario focused on decreasing roadway accidents and the number of fatalities and injuries through increasing the safety index of vehicles. The modeling showed that increasing the vehicular safety index by 10% and 15% could increase the number of lives saved by vehicle safety technologies to 66,000 and 71,000, respectively, while if the current trend continues, this number could be 61,000 by the year 2100.

In this study, the climate change–road safety–economy nexus was investigated, and several related policies were analyzed to explore ways to reduce the accident rate in the U.S. Policies aiming to increase fuel efficiency reduced transportation-related emissions. However, reducing transportation-related emissions had a negligible impact on slowing the atmospheric temperature rise, which meant it could not eliminate or reduce the negative effects of climate change on road safety. Hence, as a second policy area, extreme worldwide emission-reduction policies were explored to show how climate change affects road safety. According to this policy area, reducing GHG emissions worldwide could significantly reduce roadway accident fatalities due to fewer extreme weather events, less infrastructure damage, and less distraction to drivers. A third policy area, reducing travel demand, was investigated. This resulted in a significant decrease in the rate of fatalities. This policy area was found to be a more effective way of reducing accidents than policies aiming to increase fuel efficiency. Lastly, the effects of improving the vehicle safety index on recurring fatalities were investigated. Improving the vehicle safety index could significantly reduce the number of fatalities and should be prioritized.

1 Future Projections of Road Safety Indicators in the United States

1.1 Introduction

Roadway accidents are among the major challenges of our century. According to the World Health Organization (WHO) (2011) more than 1.2 million people are killed annually by roadway accidents, while more than 20 to 50 million people annually suffer from non-fatal (but still potentially serious) injuries from roadway accidents. The economic cost of fatal crashes is also noticeable and has become a widely debated topic in recent years. Increases in population, and consequently in motor vehicle usage and traffic congestion, have worsened the situation. In light of these facts, employing new policies to reduce the number of fatalities has become crucial to road safety development. Reducing the number of crashes and mitigating injury severity in cases of crash are the ultimate goals of transportation safety engineers (Das & Abdel-Aty, 2011). To this end, several goals have been set by government and other transportation agencies. For instance, the United States National Highway Traffic Safety Administration (NHTSA) has set a goal of 5% annual reduction in roadway fatalities (Scott & Prasad, 2015). Moreover, roadway accidents and fatal crashes are the result of several parameters within the overall system. Thus, identifying and investigating these parameters and the interactions between them are vital steps in proposing effective long-term policies to reduce roadway accidents and fatalities.

There have been many different efforts to model the road safety problem. For instance, Kelly et al. (2013) investigated and discussed five common modeling approaches in road safety. Among their studied models, system dynamics (SD) was said to have several advantages, including providing useful learning tools to increase the general understanding of the system and system thinking, knowledge integration for modelers and end users, a distinction between true and perceived system conditions, a platform for policymakers, and more. The SD simulation approach provides a means to collectively analyze all of the factors involved in any given accident as well as the interactions between these factors (Goh et.al 2016).

System dynamics modeling was first introduced in the field of business management by Forrester in 1958 at MIT, Cambridge (Forrester 1958). At that time, it was a response to the traditional method of modeling, which relied more upon an independent, isolated sector of any system regardless of dependency on and interaction with other sectors (Akhtar et al., 2013). As its name implies, it concerns the systems and dynamic properties of the system. A system itself is defined by its individual components, which work together and have mutual interactions to determine the behavior of the system. The dynamic property of the system refers to the time dependency feature of the system. According to this feature, the behavior of the system depends upon time, and it can be changed by passing the time (Akhtar, 2011).

Several studies have applied SD modeling to investigate the issue of roadway accidents and fatalities associated with roadway accidents and to present accident-prediction models with a more holistic view. Most of these studies focused on detailed analyses of different specific parameters contributing to accidents, including those related to vehicle safety, road safety, and human factors (Miang & Love, 2012). Moreover, the development of different submodels with separate investigations into the roles of vehicle, infrastructure, and human factors were investigated (Kumar & Umadevi, 2011; Nachimuthu & Partheeban, 2013). There are many previously developed models that claim a holistic or system approach (Hughes et al., 2015). However, the discussion of whether these approaches have advantages over traditional one-by-one parameter models has been neglected. Traditional approaches do not have the ability to model interactions among parameters of the system, but in the SD approach this problem has been overcome. A comparison of traditional one-by-one and SD modeling approaches was not in the scope of this study, however, and can be a topic for future work. The aim of this study was to collectively investigate the most important factors involved in fatal crashes and the interactions between them without fragmenting the analysis of the overall system by dividing them into separate submodels. In order to achieve this goal, the SD simulation approach was utilized to investigate and discuss fatal crashes and roadway fatalities in the U.S.

This study distinguished itself from previous efforts in several ways. First, the problem of fatal crashes and fatalities in the U.S. was investigated from a broad-scale, holistic perspective. This approach not only investigated all parts of the problem individually, but also considered all parts of the overall system and their relationships. In this way, the interactions among different parameters could be investigated, and the parameters themselves could be investigated within the context of the overall system. Next, the main objective was to develop a comprehensive road safety model capable of capturing dynamic feedback relationships among the important parameters of road safety. The model aimed to enhance the current understanding of road safety issues by bringing different aspects of road safety together into a single comprehensive model. Finally, this model aimed to develop viable policy solutions to reduce the number of fatalities in roadway accidents. The model's capability to capture complex relationships among the system's parameters could help to reveal the side effects of different policies and pave the way for developing policies that are more effective.

This chapter begins with findings from an extensive literature review of previously developed models on the road safety problem. A causal loop diagram (CLD) is presented to identify each of the different parameters involved in roadway accidents and their interactions. A stock and flow diagram was created based on the CLD and the identified parameters to quantify these parameters and formulate the relationships between them. In addition, the model was validated using several qualitative and quantitative tests. Finally, several scenarios were applied to the developed SD model, and different policy implications were derived.

1.2 Literature Review

With demand for passenger vehicles continuing to grow (Noori et al., 2015), any delays in taking quick and effective action and employing new policies will inevitably result in an increase in fatalities and injuries from roadway accidents (Larsson et al., 2010). The WHO predicts that if the current situation continues, the number of fatalities and injuries from roadway accidents will become the third leading contributor to the global burden of diseases and injuries by 2020 (Breen & Seay, 2004; Miang & Love, 2012). One of the major concerns in the transportation industry is traffic safety. Crash occurrences caused immense human, social, and economic losses, especially in fatal crashes (Yu & Abdel-Aty, 2014). In developed countries such as the U.S., the implementation of different policies has proven successful in reducing the number of roadway fatalities. Despite efforts in the U.S. to reduce the number of roadway fatalities over the past few years, the number of fatalities has never dropped below 30,000 in the last 50 years (Egilmez & McAvoy, 2013).

There has been extensive effort to model roadway fatalities. For instance, in the Demand for Road use, Accidents and their Gravity (DRAG) family models (Guadry & Lassarre, 2000), accident frequency, severity, and exposure were regressed on a set of relevant explanatory variables. The goal of the DRAG family models was to evaluate the development of these variables over time (Sloboda, 2008). In addition, different policies and scenarios have been considered and examined over the past few years to reduce fatalities and/or injuries from roadway accidents. To this end, three categories were identified as the main sources of factors that may contribute, whether individually or collectively, to an accident on a typical roadway: road-related (or general infrastructure-related) factors, driver-related factors, and vehicle-related factors.

Most of the literature focused on these individual parameters. Conventional traffic safety analysis tried to establish a relationship among roadway condition, the driver, and environmental factors, rather than bringing all the parameters together (Abdel-Aty & Pande, 2005). For instance, the role of the driver(s) involved in a particular accident was evaluated in several studies, such as the WHO's report on road safety (Breen & Seay, 2004) where policies were proposed to minimize drivers' errors whether by imposing tougher regulations or by educating drivers more rigorously. Driver-related accidents are those that happen because of human error and account for more than 93% of accidents (National Highway Traffic Safety Administration, 2008). These studies have investigated the most common human-error contributors to accidents, such as falling asleep while driving (Pack et al., 1995; Sagberg, 1999; Stutts et al., 2003) or driver distraction due to eating, drinking, looking for an object, manipulating vehicle controls, using a cell phone, the driver's age, etc. (Lam, 2002; Stutts et al., 2005). Anderson et al. (1997) showed that reducing one's driving speed from 60 km/h to 50 km/h could reduce the number of fatalities by 25%. Dumbaugh and Rae (2009) discussed how enhanced community design could improve traffic safety. Community design is a way to facilitate the usage of alternative transportation modes such as walking or bicycling. Lastly, in order to reduce the number of fatal crashes due to human error, some studies have examined different policies and scenarios on how to control and reduce these types of accidents, including the identification of high-risk drivers and the use of stiffer punishments for driving under the influence (DUI) (Chandraratna et al., 2006; Gebers & Peck, 2003).

The effects of vehicle safety features on road safety have also been studied. The New Car Assessment Program (NCAP) set a rating system to show how safe a given vehicle is according to standard specifications. According to the literature, technological (anti-lock brakes, stability control, night vision, etc.) and structural (airbag, seat belts, energy absorbing steering columns, side door guide beam, etc.) vehicle safety features play a vital role in reducing roadway accidents and fatalities (Vrkljan & Anaby, 2011). In addition to the vehicle safety features, roadway infrastructure and road quality, such as pavement quality or the inclusion sobriety checkpoints along roadways, have impacted road safety.

Effective management and proper policymaking for complex systems pertaining to roadway accidents requires a holistic understanding of the system and of the interactions among all of the different parameters associated with the system (Kelly et al., 2013). To this end, the SD method has been used in situations where the complexity of the system under investigation was high and the different sectors involved in the system were all directly and/or indirectly interrelated. The primary advantage of the SD method over other simulation methods is its ability to accurately reveal and represent the system's associated feedback processes with stock/flow structures, time delays, and nonlinearities in order to qualitatively and quantitatively reflect the dynamics of the system as a whole (Akhtar et al., 2013). The methodology used is explained in detail in the next section.

1.3 Model Development

1.3.1 Problem Identification

Identification of the problem and root causes is crucial to the development of effective policies related to reducing the number of injuries and fatalities in roadway accidents. The number of roadway fatalities between 1994 and 2008, presented in Figure 1.1, was used as the reference mode to validate the developed SD model. Due to an increasing number of vehicles and the subsequent increase in vehicle miles traveled (VMT), the number of fatal crashes increased for a period of time. Eventually, the use of various strategies to reduce the number of fatal crashes caused fatalities to decrease significantly, although the overall number of fatalities was still high (National Highway Traffic Safety Administration, 2014). This study investigated the main factors involved in a given roadway accident, including environmental parameters, driving behaviors, state regulations, driving speed, population, traffic congestion, road maintenance, and safety belt usage, as well as the current obstacles that hinder efforts to reach zero fatal crashes.

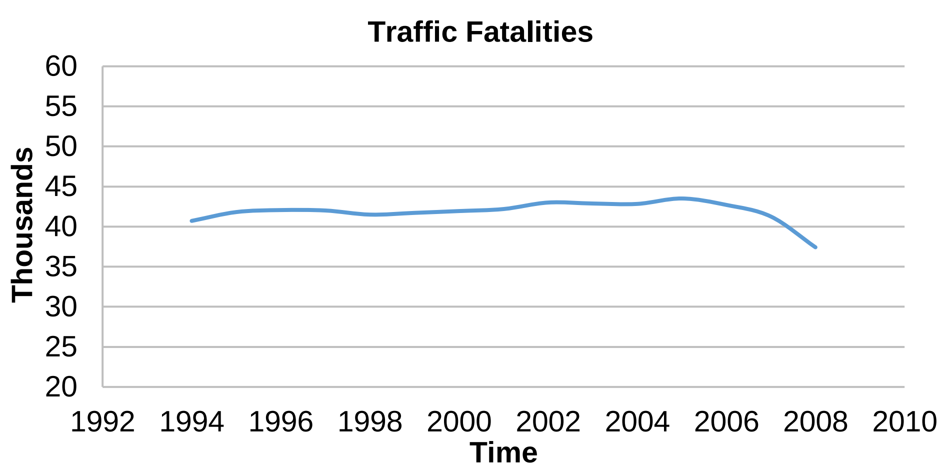

Figure 1.1 - Reference mode (NHTSA, 2014)

1.3.2 Identification of Parameters

In order to create the CLD, the parameters involved in roadway accidents had to be identified, and the parameters that may or may not be directly connected were determined. Indirect connections were revealed as one or more series of direct connections. For this purpose, the different parameters to be included in the CLD were introduced and organized by type (exogenous/"independent" versus endogenous/"dependent"). The parameters are described in Table 1.1 and are divided into five categories: driver factors, vehicle factors, environmental factors, infrastructure factors, and other factors. Endogenous variables were those obtained by means of mathematical formulations within the system and in relation to other parameters. Exogenous variables were those with specified values based on available data regardless of interaction with other parameters. Section 1.3.3 provides a description of how these parameters relate to road safety and validates the importance of their inclusion. It should be noted that these parameters are not the only ones used in the model, but rather the more aggregated form of the factors, which was used to explain fundamental relationships in the system.

Table 1.1 - Model parameters

Parameter	Description	Type	Units
Driver factors			
DUI	Driving under the influence	Endogenous	-
Experience	Practical contact with and observation of facts or events	Endogenous	-
Safety belt usage	The number of people using safety belts	Endogenous	-
Speed	The posted roadway speed limit	Endogenous	mph
Fatigue	Extreme tiredness resulting from mental or physical illness	Endogenous	-
Vehicle factors	Vehicle safety related factors (ANCAP rating)	Endogenous	-
Environmental factors	Rain, hurricane, snow, extreme heat/cold, etc.	Exogenous	-
Infrastructure factors	Road safety level and infrastructure equipment	Endogenous	-
Road capacity	The capacity of a road to support vehicles	Endogenous	-
Other factors			
Economy	Wealth and resources of a country or region	Endogenous	-
Population	The total number of people	Endogenous	-
Travel time	The total amount of time required to travel	Endogenous	hours
Traffic volume	The number of vehicles using the same road at a particular time	Endogenous	-
VMT	Vehicle miles traveled	Endogenous	miles
Congestion	An excessive or abnormal accumulation of vehicles on a road	Endogenous	-

1.3.3 System Conceptualization

System conceptualization is one of the most important stages of the model development, in which the CLD is developed and the feedback relationships are conceptualized (Onat et al., 2014). “Feedback” (sometimes referred to as “connector”) is the main feature of any SD simulation approach and can be defined as a process in which the results and outputs of each sector involved in a system are determined by the information obtained from a past or present sector. In other words, their duty is to set up a relationship between different variables within a system. In any process where a chain of cause and effect between different sectors has taken place, the “feedback” process and a loop have already formed. This should be a closed-loop system for relating the sectors in order to prevent any obstacles in information flow. The feedback effect can be positive or negative. A positive effect is when an increase or decrease in any sector results in an increase or decrease, respectively, in related sectors. In contrast, with a negative effect, an increase or decrease in any sector will cause a decrease or increase, respectively, in related sectors (Ahmad & Simonovic, 2000).

Within the area of systems, delay is a critical step to make the entire system dynamic. The dynamic property of each system refers to the time-dependency of that system (Akhtar, 2011). Stock and flow are terms that have different definitions but work very closely together. Their main difference is in units of measurement. A stock (also called “level”) variable is measured at a specific time and can show what the system owns at that specific time, i.e., it shows the system components accumulation. The flow variable (sometimes referred to as “rate”) is measured over an interval of time and can show the activities which add or deduct something from stocks (Ahmad & Simonovic, 2000).

In this section, a CLD was constructed to highlight the parameters considered in this study and their associated interactions (see Figure 1.2). In this diagram, there are five reinforcing and five balancing loops, which are briefly explained below. Balancing feedback loops, or negative feedback loops, are circles of cause and effect that counter a change with a push in the opposite direction. A negative causal loop refers to a situation where the two connected parameters change in opposite directions; if the parameter in which the loop starts increases, the other parameter decreases, and vice versa. A reinforcing loop (positive) is one in which an action produces a result that influences more of the same action, thus resulting in growth or decline (Hjorth & Bagheri, 2006).

Positive (+) signs on the arrows in the CLD indicate a reinforcing (increasing) effect (indicated as “R”) of one parameter on another parameter, whereas negative (-) signs indicate a balancing (decreasing) effect (indicated as “B”). The major feedback mechanism was defined through the CLD and could be negative (balancing) or positive (reinforcing) feedback (Vlachos et al., 2007). It is worth mentioning that in any level of investigation, different parameters can be added or removed from the system. The parameters in this study were chosen based on their importance in accidents. In fact, a boundary adequacy test was performed to ensure that the intended purpose of the study was achieved as a result of modeling (see Section 1.3.5.2.3). The major feedback loops in the developed model are described below.

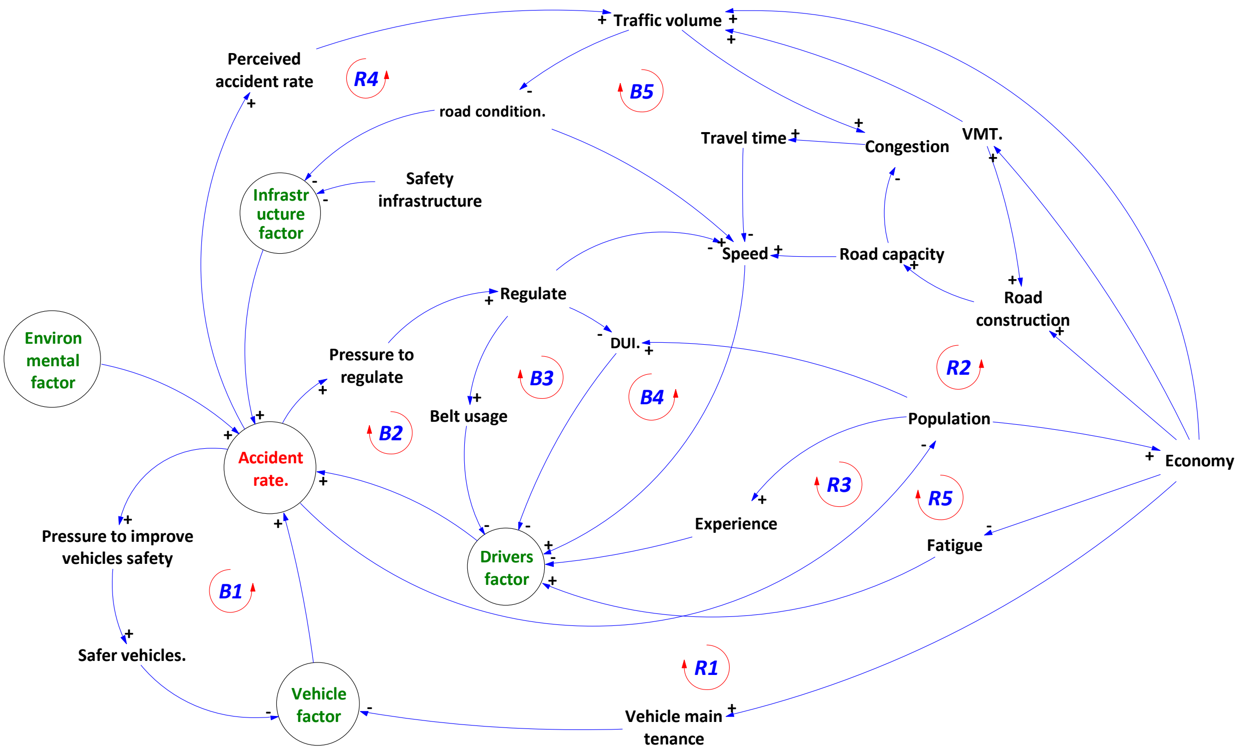

Figure 1.2 – Causal loop diagram

R1: Economy -> vehicle maintenance -> vehicle factor -> accident rate -> population->economy. This loop starts with the economic status of the area considered for the study (the United States). As the economy prospers, vehicle maintenance improves on average, decreasing the vehicle factor. By increasing or decreasing the vehicle factor, the accident rate will increase or decrease consequently (Connelly & Supangan, 2006; Elvik, 2000; Trawén et al., 2002). A decreased vehicle factor, in turn, increases the population, thereby helping to improve applicable economic indicators.

R2: Economy -> VMT -> traffic volume -> congestion -> travel time -> speed-> driver factor -> accident rate -> population -> economy. Improvements in economic indicators will increase total VMT, thereby increasing traffic volume and congestion, which will cause an increase in travel time. The increase in travel time means the average driving speed has been decreased. As a result of this decrease in driving speed, the driver-related contributions to the accident rate will decrease, which will lead to a decrease in the accident rate. In turn, decreasing the accident rate will result in a lower decrease in the total population, allowing economic indicators to improve (Dahl & Sterner, 1991; Law et al., 2009).

R3: Population -> experience -> driver factor -> accident rate -> population. As the total population (and thus the average age of the population) increases, the average driver's level of experience increases, reducing driver-related accidents and thus decreasing the total accident rate. Decreasing the accident rate results in fewer fatalities, which will result in lower population decreases and subsequently increase the average age of the available population (Deery, 1999; Mcknight & Mcknight, 2003; Sjogren, 1996).

R4: Traffic volume -> road condition -> infrastructure factor -> accident rate -> perceived accident rate -> traffic volume. Increasing the traffic volume deteriorates the existing road condition due to reductions in road maintenance quality, which will then increase infrastructure-related accidents. As a result, actual and perceived accident rates will both increase, thus increasing the traffic volume (Noland & Oh, 2004).

R5: Economy -> fatigue -> driver factor -> accident rate -> population -> economy. A deteriorating economic situation causes many drivers (including truck and taxi drivers) to work more and even suffer stress and other such pressures associated with the bad economic situation, which can lead to driver fatigue and increase driver-related accidents, thereby increasing the accident and fatality rates. As a result, the population will suffer larger decreases, and this reduction will further deteriorate the economy (Fell & Black, 1997; Lal & Craig, 2007; Ting et al., 2008).

B1: Accident rate -> pressure to improve vehicle safety -> safer vehicles -> vehicle factor -> accident rate. This loop starts with the total roadway accident rate. As the rate of accidents increases, the pressure to improve vehicle safety increases, resulting in higher demand for safer vehicles. This will reduce the vehicle factor in accidents. By increasing or decreasing the vehicles factor, the accident rate will increase or decrease, respectively. (Newstead et al., 2011).

B2: Accident rate -> pressure to regulate -> regulation -> belt usage -> driver's factor -> accident rate. As the accident rate increases, the pressure on legislators to enact more stringent regulations increases, thus leading to tougher regulations that will increase safety belt usage. Increasing safety belt usage will decrease driver-related factors in the overall accident rate, and the accident rate will decrease accordingly (Houston & Richardson, 2002, 2005; Rivara et al., 1999; Shults et al., 2004).

B3: Accident rate -> pressure to regulate -> regulation -> DUI -> driver factor -> accident rate. As the accident rate increases, public pressure to enact tougher regulations to deter driving under the influence will increase, resulting in tougher regulations that will reduce the number of annual DUI cases. This will decrease the contribution of driver-related factors to accidents and thus reduce the accident rate (Benson & Rasmussen, 1999; Ruhm, 1996; Young & Likens, 2000).

B4: Accident rate -> pressure to regulate -> regulation -> speed -> driver factor -> accident rate. By increasing the accident rate, legislators will face increased public pressure to pass tougher anti-speeding laws, and will therefore enact and enforce more stringent regulations that will, in turn, reduce instances of speeding. With fewer drivers exceeding the speed limit, the contribution of driver-related factors to accidents will also decrease, thereby reducing the accident rate (Aarts & van Schagen, 2006; Ossiander & Cummings, 2002; Retting & Cheung, 2008; Rock, 1995).

B5: Traffic volume -> congestion -> travel time -> speed -> driver factor -> accident rate -> perceived accident rate -> traffic volume. As traffic volume increases, traffic congestion will also increase, reducing the average driving speed of on-road vehicles and increasing travel times. This speed reduction will decrease driver-related contributors to accidents, reducing the actual and perceived accident rates and thus decreasing average traffic volumes (Aarts & van Schagen, 2006; Ossiander & Cummings, 2002; Retting & Cheung, 2008; Rock, 1995).

1.3.4 Model Formulation

In this section, a stock and flow diagram (see Figure 1.3) is presented based on the parameters defined in the CLD. This model contained the mathematical formulations of the relationships between different parameters. The data were obtained through NHTSA and the United States Department of Transportation (USDOT) (National Highway Traffic Safety Administration, 2014).

The stock and flow diagram included both endogenous variables and exogenous variables, and variables of both types are discussed below. Endogenous variables were as follows:

- *Total fatality rate per 100 million VMT.* This parameter was the summation of the fatality rates per 100 million VMT after all increases and decreases due to different parameters. There were seven main parameters that affected the number of fatal crashes and fatalities: aggressive driving, driving under the influence, speeding, driving distractions, seat belts, airbags, and "other factors."
- *Vehicle miles traveled (VMT).* The VMT was one of the most important parameters in this model. Increasing or decreasing this parameter affected all other fatality rates, which then increased or decreased the total fatality rate. The VMT was highly dependent on the number of vehicles, the gross domestic product (GDP), and the total population. To obtain the VMT, a regression analysis was performed for the VMT with respect to the total number of vehicles (thousands); the resulting equation is provided below.

$$VMT = -169(\text{total number of vehicles})^2 + 8.6(\text{total number of vehicles}) - 8E + 12 \quad (1.1)$$

- *Total number of fatalities.* This number was calculated by simply multiplying two parameters, as shown in Equation 1.2.

$$\text{Total number of fatalities} = (\text{Total fatality rate per 100M VMT}) * VMT \quad (1.2)$$

- *Number of vehicles.* This parameter was a function of the GDP, meaning that increasing the economic indices increased the total number of registered vehicles in the country.
- *Roadway congestion index.* The congestion index illustrated the congestion level of a specific road section with respect to its free-flow condition, and was a function of the number of vehicles and highway mileage. Equation 1.3, for the roadway congestion index with respect to highway mileage and VMT, was obtained via regression analysis:

$$\text{Roadway congestion index} = -2.25 + 2.7e\text{-}6*(\text{highway mileage}) - 1.64e\text{-}12*(VMT) - 4.55e\text{-}13*(\text{highway mileage})^2 + 4e\text{-}19*(\text{highway mileage})*(VMT) \quad (1.3)$$

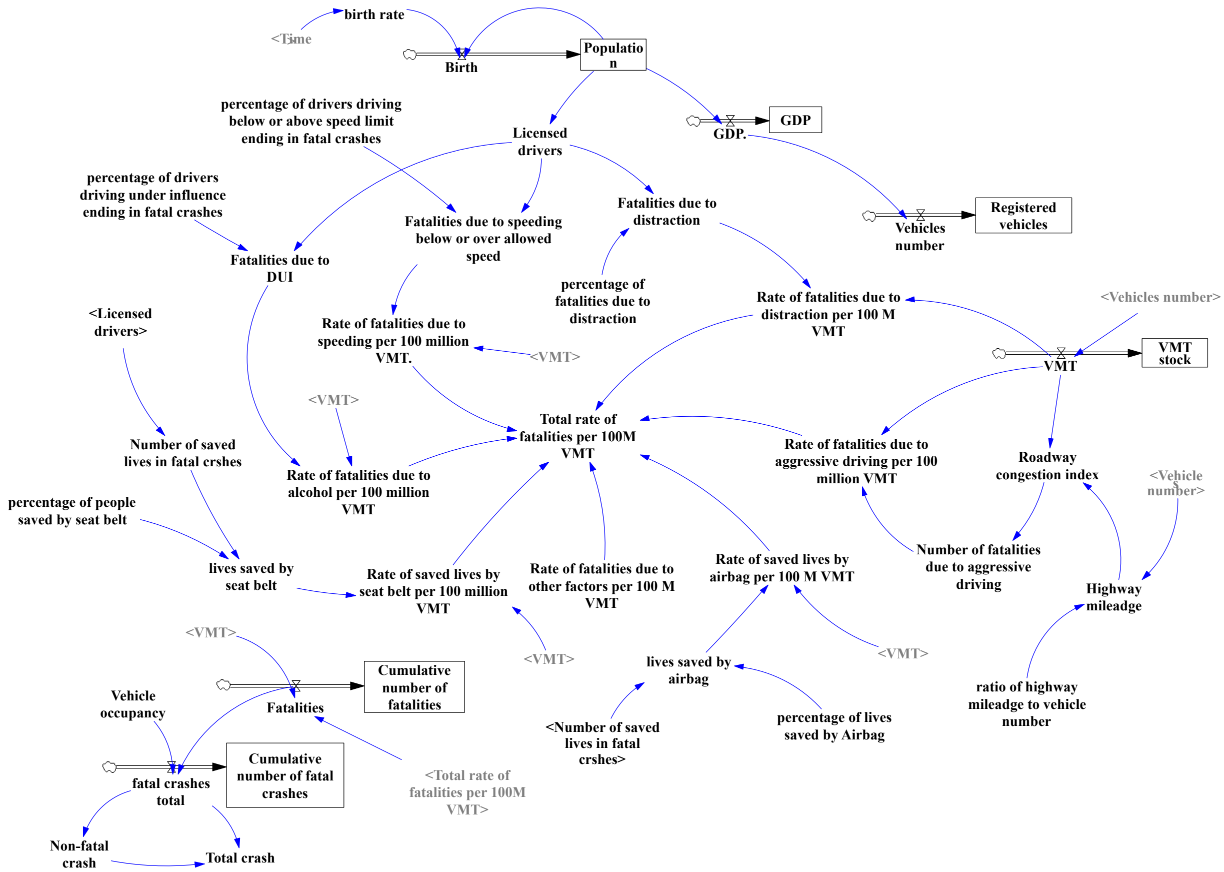

Figure 1.3 - Stock and flow diagram

- *Driving under the influence, speeding, aggressive driving, and distracted driving*. These parameters were the main contributors to fatal accidents. They included, respectively, fatal crashes due to driving under the influence, driving over the speed limit, aggressive driving, and driver distractions such as cell phone usage or usage of other distracting instruments while driving. The problem of aggressive driving has received a great deal of attention in recent years from the media and from police. According to NHTSA's official definition, aggressive driving occurs when "an individual commits a combination of moving traffic offenses so as to endanger other persons or property" and can include tailgating, signaling violations, speeding, frequent unnecessary lane changes, and so on. Several studies have investigated the effects of traffic congestion on aggressive driving (Shinar, 2004; Timo Lajunen, 1999). A formula for the number of fatalities due to aggressive driving with respect to the roadway congestion index was obtained by performing a regression analysis. It is summarized in Equation 1.4.

$$\text{Number of fatalities due to aggressive driving} = -21026.6*(\text{roadway congestion index})^2 + 49180.3*(\text{roadway congestion index}) - 13131.2 \quad (1.4)$$

Since the “speeding” parameter was already included within the parameters affecting the number of fatalities, fatalities due to speeding were excluded from the above equation.

These endogenous parameters were obtained by multiplying the number of people involved in fatal crashes by a multiplier that represented the contribution of these parameters to the total fatality rate.

- *Seat belts and airbags.* The inclusion of seat belts and airbags in more vehicle designs significantly reduced the number of roadway fatalities in recent years. This effect was represented by the estimated number of lives saved by occupant protection, motorcycle helmets, and drinking age laws between 1994 and 2008 (U.S. Department of Transportation, 2014).
- *Number of fatal accidents.* This parameter represented the total number of fatal accidents and was obtained by dividing the total number of roadway fatalities per year by average vehicle occupancy.

Exogenous variables were as follows:

Population. The first exogenous variable in this model was population, which was represented by a LOOKUP function based on available population data (National Highway Traffic Safety Administration, 2014).

- *Vehicle occupancy.* The vehicle occupancy was the average person per vehicle in the U.S., which is 1.63 according to the National Household Travel Survey (Federal Highway Administration, 2009).

The values of all other exogenous variables are presented in Table 1.2.

Table 1.2 - Values of other parameters (NHTSA, 2014)

Parameter	Value
Percentage of drivers (thousands) driving under the influence ending in fatal crashes	6.4%
Percentage of drivers (thousands) driving below or above the posted speed limit ending in fatal crashes	6.5%
Percentage of fatalities due to distracted driving	2.4%
Percentage of lives saved by airbags	3.4%
Percentage of lives saved by seat belts	22.75%
Ratio of highway mileage to number of vehicles	17.3

Rate of fatalities due to other factors per 100 million VMT	0.5
Vehicle occupancy	1.63

The scope of this study covered a limited number of main parameters involved in fatal crashes. Other parameters affecting the number of roadway accidents and fatalities not directly considered in this study include climate change factors, drivers' ages, vehicle ages, and so on. For improved accuracy, the parameter "rate of fatalities due to other factors per 100 M VMT" was added to this model in order to project the effect of the above-listed parameters on the total number of fatalities.

1.3.5 Model Validation

Model validation consisted of a series of tests designed to guarantee the structural and behavioral validity of the SD model. The model should reflect the real-world behavior of the modeled system as accurately as possible. To this end, the structure of the model and the behavior of its key results (roadway fatalities) were examined to see if the model's formulation and structure adequately reflected the actual system. The model validation step was as important as the development of the model. In fact, without proper model validation testing, one cannot guarantee the model accurately represents the real-world situations being analyzed, and any predictions based on the model regarding the future behavior of the system and/or tests of potential policy applications could be unreliable.

1.3.5.1 Model Structural Validity

For this part of the model validation step, five different tests were performed to confirm the structure of the model was working properly.

1.3.5.2 Structure Verification Test

In this test, the structure of the developed SD model was compared to currently available knowledge of the structure of the real system. To pass this test, every modeled parameter and formulation in the SD model should represent a part of the real system, and there should be no contradictions between the model and any current knowledge of the actual system. For this purpose, the model could be verified by reviewing it with highly knowledgeable experts on corresponding parts of the real system or by comparing the model assumptions to organizational relationships found in relevant literature. In most cases, the structure verification test is first conducted based on the model builder's knowledge and is then extended to include comments from experts with direct experience from the real system (Forrester & Senge, 1980). For this model, the structure of the system was verified by referencing all relationships among different parameters to other published studies on this subject; these references were discussed in Sections 1.2and 1.3. No contradictions were found in any of the aforementioned parameters or relationships with respect to any available knowledge about the structure of the real system.

1.3.5.2.1 Parameter verification test

This test was similar to the structure verification test. Both tests were qualitative rather than quantitative and had the same goal: to ensure that the SD model was an accurate representation of the actual system. More specifically, this test worked to ensure that any and all parameters used in the model were consistent with available knowledge of the actual system. For this model, all of the parameters presented in the CLD (see Figure 1.2) and listed in Table 1.1 were compared with the real situation to make sure they corresponded to the real world, and no contradictions were found.

1.3.5.2.2 Extreme conditions test

This test was one of the most important and powerful tests for the SD model validation. It ensured that the model was robust enough to handle extreme parameter values without encountering errors. Consequences of extreme conditions form much of our knowledge about a real system's behavior. As Forrester & Senge (1980) stated, "if knowledge about extreme condition is incorporated, the result is almost always an improved model in the normal operating region." If parameter C was defined as the result of A×B, and either A or B was set equal to zero, then parameter C must be equal to zero in order to pass the extreme condition test. In this study, extreme values were assigned to different parameters, and the resulting behavior of the system from these extreme values was analyzed accordingly. To pass this test, the behavior of the model had to be logically valid based on the assigned extreme values. Table 1.3 shows the parameters and extreme values used for this model, as well as their associated results. These values showed that the model and its formulations still worked properly under extreme conditions, and therefore the model successfully passed this test.

Table 1.3 - **Extreme values of the parameters**

Extreme values	**Value of the parameters**
Percentage of drivers driving below or above speed limit ending in fatal crashes = 0	Rate of fatalities due to speeding per 100 million VMT = 0
Percentage of drivers driving under influence ending in fatal crashes = 0	Rate of fatalities due to alcohol per 100 million VMT = 0
Total rate of fatalities per 100 million VMT = 0	Fatalities = 0

1.3.5.2.3 Boundary adequacy test

This test ensured that the established structural boundaries of the model adequately fit the intended purpose of the model. This test checked that the model aggregation was appropriate and that the model included all relevant structures. To pass this test, the model had to include all of the important factors affecting the behavior of interest. In most cases, an expanded version of a simple model with limited boundaries is used to address more complex systems (Shreckengost, 1985). In this study, the main purpose was to investigate the issue of road safety and the number of fatalities in roadway accidents.

From the structure of this model, it was observed that this goal was achieved and we could see the different parameters contributing to increases or decreases in the number of fatalities in roadway accidents.

1.3.5.2.4 Dimensional consistency test

This test was closely related to the parameter verification test and sought to verify the consistency of the units of all parameters within the model. This test was an additional structural test that could be ignored as trivial or obvious, but could reveal error in the results. From Table 1.1 and the stock and flow diagram presented in Figure 1.3, it can be seen that the units used in the model were all consistent with each other.

1.3.5.3 Behavior reproduction test

This test evaluated whether the output of the SD model (in this case, the number of roadway fatalities) adequately corresponded to available data for the same variable(s). For this purpose, the output results obtained from the model for roadway fatalities were compared to available historical data from NHTSA for the number of fatalities between 1994 and 2008, as shown in Figure 1.4.

A one-way analysis of variance (ANOVA) test was performed to compare the number of fatalities obtained from the model with the historical number of fatalities. Prior to performing the ANOVA test, however, the two assumptions of the ANOVA test (normality and equal variances) had to be investigated with respect to both data sets to determine if any data transformations were first necessary (Egilmez & Tatari, 2012). The results of the normality test (Table 1.4) showed that both the model output data and the historical data were normally distributed (sigma > 0.05). Then, the equal variances test was performed in the SPSS software and yielded a sigma value greater than 0.05, which indicated that the data sets had equal variances. Finally, the results of the ANOVA test (Table 1.5) indicated a p-value of 0.0591. This was not less than the selected α-value of 0.05, which meant that there was no significant difference between the mean number of real fatalities obtained from historical data and the mean number of simulated fatalities obtained from the SD model output.

Table 1.4 - Normality test results

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Model	0.131	15	0.2*	0.925	15	0.229
Data	0.209	15	0.078	0.783	15	0.002

[a].Lilliefors Significance Correction.

*This is a lower bound of the true significance.

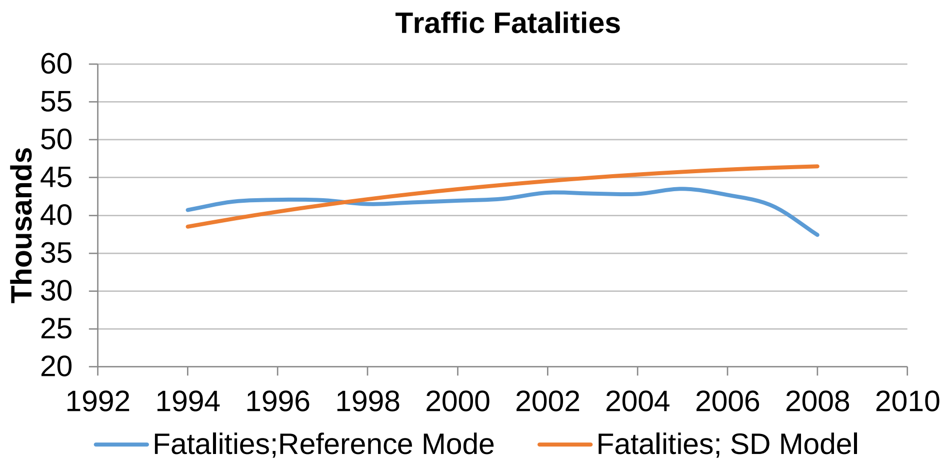

Figure 1.4 - Result of validation model

Table 1.5 - One-way ANOVA test results

Source of Variation	SS	df	MS	F	p-value	F crit
Between Groups	8,101,938	1	8,101,938	3.9250	0.0591	4.2596
Within Groups	49,540,050	24	2,064,169			
Total	57,641,988	25				

Because the outcome of the model and the reference case data points were matched pairs, a two-tailed small sample statistical test (t-test) was applied. The results revealed that the p-value of the two-tailed test equaled 0.0776, which was greater than the significance level of 0.05. Moreover, the t-value of the test equaled -2.0872, which had an absolute value lower than the critical t-value of 2.16. From the above tests and comparisons between the NHTSA historical data and the output data from the model, it was concluded that there was no statistically significant difference between the historical data and the model output, and the behavior of the SD model was therefore a valid representation of the behavior of the system in the real world.

1.4 Policy Analysis

The aim of this study was to show the importance of reducing the number of fatal crashes and roadway accidents in order to save more lives. For this goal to be achieved, different policies have been discussed in the literature. There have been several studies to address the need to reduce the number of fatalities caused by roadway accidents in the U.S., but there is still no singular strategy to encompass all of the suggestions made by these studies. In light of the importance of having a national strategy on road safety, several different organizations involved in highway safety have agreed on a national strategy on highway safety known as “Toward Zero Deaths” which, as the name suggests, aims to reduce the number of roadway fatalities to zero. Some suggested scenarios to achieve this goal have included (but are not limited to) vehicle ownership reduction, fuel price increases, traffic speed reductions, increased safety belt usage, increased safety of younger drivers, improved mode shifting, and improved vehicle safety (Sorel & Costales, 2012).

In the U.S., the federal government has set several objectives that cover different areas of road safety, and these objectives must be met according to the plan defined by NHTSA. NHTSA has set 14 minimum performance goals that must be considered in any plan developed for any given state (Scott & Prasad, 2015).

1.5 Discussion and Results

As the main purpose of this modeling effort was to examine different policies towards reducing roadway accidents, four performance goals are discussed. Different policies to achieve these goals were studied individually.

1.5.1 *Reducing the Number of Speed-Related Fatalities by 5% Annually*

According to the Federal Highway Administration (2014), speed has always been among the top five primary collision factors for fatal and injury crashes and is the reason for almost one-third of all traffic fatalities in the U.S. Different scenarios have been tested to reduce the number of speed-related fatalities throughout the world, from increasing the safety culture of drivers to restricting the engine capacity for beginner drivers. Speed limit is also a very common tool for managing speed, and the most common approach for setting an appropriate speed limit is based on engineering studies that take into account different parameters affecting the safety of drivers. Automated speed enforcement tools such as speed cameras have also shown to be effective in reducing the number of speed-related fatalities and injuries. By combining these factors, reducing the speed-related fatalities seems to be an achievable goal. To make the progress measurable, the goal of reducing the number of speed-related fatalities by 5% annually has been set (Scott & Prasad, 2015). The number of speed-related fatalities in 2008 was 13,369, and according to the model, this number was expected to increase to 15,022 by 2020 if the trend continued. However, reducing the number of speed-related fatalities by 5% annually would bring this number down to 7,295 by 2020. Figure 1.5 compares the number of speed-related fatalities from 2008 to 2020 if no action is taken (blue line) to the number of speed-related fatalities if an annual reduction of 5% is achieved (red line). The percentage of drivers below or above the posted speed limit and thereby causing fatal crashes could be reduced from 6.51% to 3.16%, which can be achieved by employing the methods mentioned above.

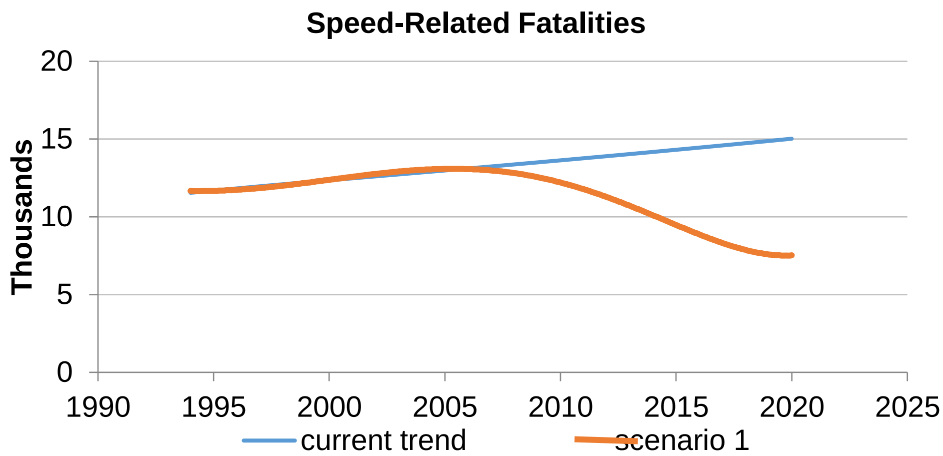

Figure 1.5 - The expected impact of scenario 1 on number of speed-related fatalities

1.5.2 Reducing the Number of DUI-Related Fatalities by 5% Annually

According to the Centers for Disease Control and Prevention (2014), almost 30 people die every day in the U.S. as a result of motor vehicle crashes that involve alcohol, and these accidents cost $59 billion annually. Despite serious action in past years, there is a long way to go to control the problem of alcohol-impaired drivers. Different approaches have been presented to reduce the number of alcohol-impaired drivers. Among the policies, confiscating the driver's licenses of intoxicated drivers, increasing sobriety checkpoints, raising the price of alcohol, increasing the minimum legal drinking age, and actively enforcing the 0.08% blood alcohol concentration (BAC) law have proven to be the most effective approaches to reduce the number of alcohol-related fatalities (National Transportation Safety Board, 2013). The goal of reducing the number of alcohol-related fatalities by 5% annually was set (Scott & Prasad, 2015), and plans are in development to accelerate the decreasing trend of alcohol-related fatal crashes in the U.S.

According to our model (see Figure 1.6), this goal could reduce the total number of DUI-related fatalities to 7,216 by 2020, as opposed to 14,860 by the same year. To achieve this goal, the percentage of drivers (thousands) driving under the influence and thus causing fatal crashes must decrease from 6.43% in 2008 to 3.12% by 2020, which could be achieved with stiffer DUI penalties and/or more effective public education on driving under the influence.

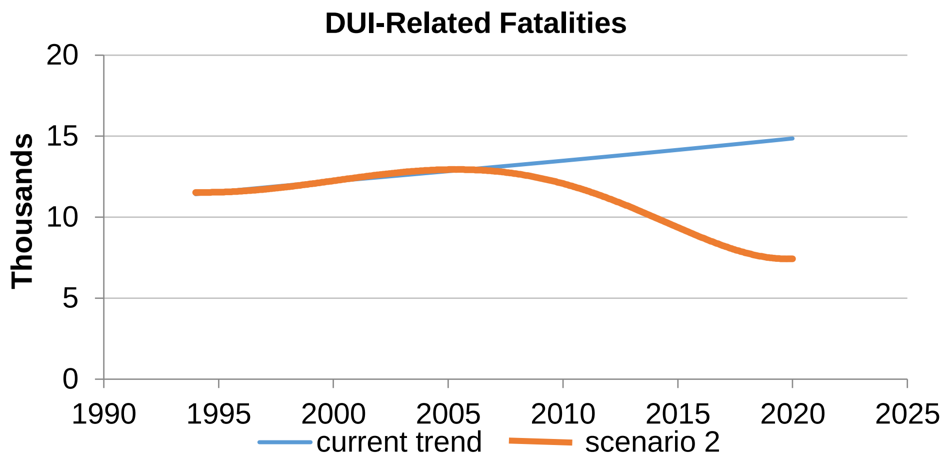

Figure 1.6 - The expected impact of scenario 2 on number of DUI-related fatalities

1.5.3 Increasing the Number of Lives Saved by the Use of Seat Belts by 5% Annually

Safety belt usage is one of the main factors affecting the total number of roadway fatalities. Published reports by NHTSA and studies done in this regard mention the seat belt as the most effective tool to reduce the number of fatalities in roadway accidents. An increase in the rate of seat belt use from 17% in 1983 to 75% in 2002 showed significant progress had been achieved during this 20-year period. Since state laws are critical in increasing seat belt use, the federal government has asked states to take necessary actions to increase the seat belt use rate through secondary law enforcement along with primary law enforcement and increasing the fine for violating the law (Houston & Richardson, 2005). Predictive estimates from the SD model (Figure 1.7) show that, if current seat belt usage trends continue, the number of lives saved by seat belts will only increase to 15,402 by 2020. This number could be increased by 5% annually to reach 24,858 lives saved by 2020. For this goal to be achieved, the percentage of lives saved by seat belt use must increase from 22.75% to 36.7%. This can be achieved by enacting tougher seat belt usage laws and policies (such as the “Click It or Ticket” campaign in the state of Florida (Florida Department of Highway Safety and Motor Vehicles, 2008)) and expanding primary seat belt laws and other such laws in other states.

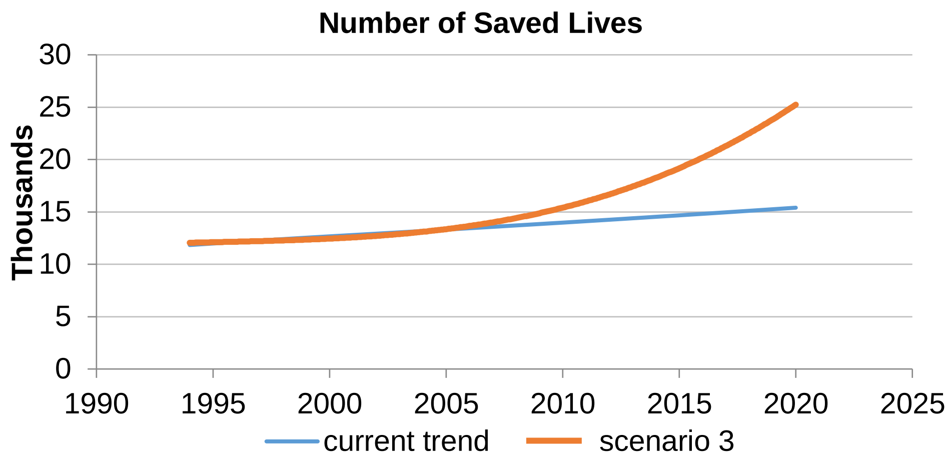

Figure 1.7 - The expected impact of scenario 3 on number of saved lives

1.5.4 Decreasing the Number of Fatalities due to Aggressive Driving

Increasing traffic congestion levels will increase aggressive driving behavior and thereby increase the number of fatalities due to aggressive driving (see Section 1.3.4). On the other hand, a closer look at the historical data showed that the increasing trend of VMT stopped as of 2007. The SD model output predicted that it would continue on a decreasing trend until 2020, and that this decreasing trend would have a direct impact on the number of fatalities due to aggressive driving. In the meantime, increasing road mileage per vehicle (which can manifest as a reduction in the roadway congestion index) would also help to reduce the number of fatalities due to aggressive driving. Overall, this scenario (Figure 1.8) demonstrated how increasing the ratio of highway and/or street mileage to number of vehicles by 0.8% would increase the slope of the current decreasing trend, allowing the number of aggressive driving fatalities under current conditions in 2020 to drop from 5,584 to 4,248, for a total reduction of as much as 24%.

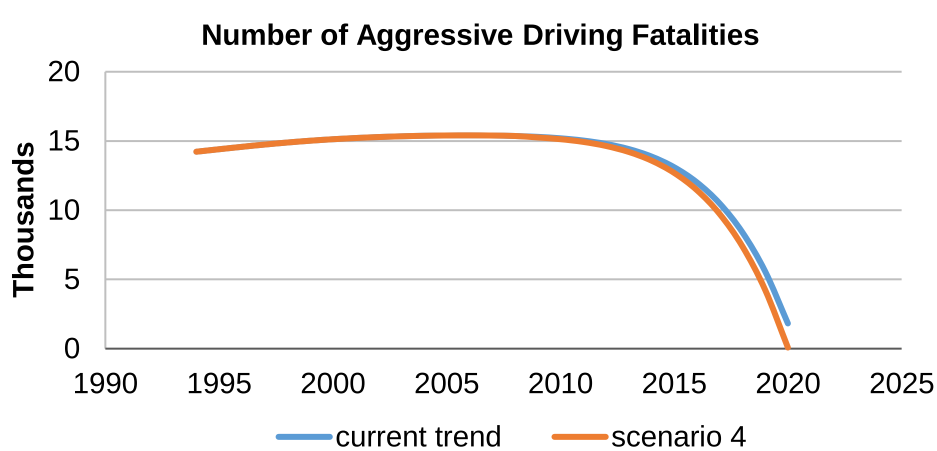

Figure 1.8 - The expected impact of scenario 4 on number of aggressive driving fatalities

1.6 Conclusion

This study highlighted the benefits of SD modeling, advancing the state of practice in road safety research. An important contribution of this study was the consideration of dynamic interactions among the parameters within the system of road safety. Because previous research studied road safety factors separately with an isolated approach, this work filled the research gap by integrating these different subsystems using SD. The aim of this study was to demonstrate how the SD approach could relate different parameters involved in any accident to each other. The reason was to show how SD can help policymakers define plans and policies to meet the preset goals in road safety. Some of the important findings of this study are summarized below.

Fatalities due to speeding can be reduced by 5% annually if the percentage of drivers driving below or above the posted speed limit can be reduced from 6.51% in 2008 to 3.16% by 2020. DUI-related fatalities can be reduced by 5% annually if the percentage of drivers driving under the influence and thus causing fatal crashes can be dropped from 6.43% in 2008 to 3.12% by 2020. Increasing the number of lives saved by the use of seat belts by 5% annually should increase lives saved from 22.75% to 36.7% by 2020 and can be achieved by increasing seat belt efficiency. Reducing traffic congestion is a key factor in reducing fatalities due to aggressive driving. Increasing the ratio of highway and/or street mileage to number of vehicles by 0.8% can reduce the number of fatalities up to 24% by 2020.

Although the model gave important insights about the factors contributing to fatalities due to roadway accidents, it did not analyze specific policy implications, such as the effect of stiffer DUI penalties and/or more effective public education on driving under the influence to reduce related fatalities. Moreover, while it gave flexibility to policymakers to select a specific policy, the model did not provide information about which policy action is more effective. Future work will include more detailed policy actions by unfolding some of the submodels and integrating the specific policy actions. It is worth mentioning that future improvements would require additional efforts to identify the most promising measures. From the current study, it is obvious that a single deterrence action will not produce dramatic decreases in roadway fatalities.

It is important to note that SD is not the only approach for modeling the road safety problem. One downside of SD modeling is the nature of the software to facilitate the process of adding a variable to the model, meaning that different variables can be easily added to the environment of the system dynamic in each step of the modeling process. Although the process of adding different variables to the model can be helpful in achieving the goals of the model but at the same time it could result in having a super-complex model paying less attention to key variables that are playing a more important role in the system than other variables. Another potential disadvantage of SD modeling is the lack of enough evidence to verify the behavior of the model (compared to the behavior of the system in the real world) due to considering unnecessary feedback loops and uncertainties, which could result in a super-complex model (Kelly et al., 2013).

Studying and modeling population and the parameters affecting population and birth rate were beyond the scope of this study. Traffic-related fatalities could have direct and indirect effects on population. For instance, traffic fatalities have huge impacts on GDP, and GDP along with other parameters affects the birth rate. Based on available data and future projections, the population will continue to increase until 2050, although an increase in the number of traffic-related fatalities could lower the population increase rate. In fact, population is still increasing but at a relatively lower rate. Studying the impact of other parameters (such as GDP, birth rate, etc.) would be in the scope of future studies.

2 The Climate Change–Road Safety–Economy Nexus: A System Dynamics Approach to Understanding Complex Interdependencies

2.1 Introduction

Roadway accidents are responsible for more than 1.2 million deaths and more than 50 million injuries annually, so the need to take very quick and effective actions to reduce roadway accidents and accident-related fatalities and injuries is inevitable (Hughes et al., 2015). Based on current trends, it has been predicted that the number of fatalities and injuries from roadway accidents will become the third leading contributor to the global burden of disease and injuries by 2020 (Breen & Seay, 2004; Miang & Love, 2012). Furthermore, surface transportation (e.g., cars, trucks) is still the most important subsector of transportation for people and commerce in the United States (Pisano et al., 2001). Due to the immense losses in different aspects with respect to the transportation sector (e.g., human, social, environmental, and economic aspects), traffic safety has become a major area of concern in the transportation industry (Yu & Abdel-Aty, 2014). This makes it all the more critical for policymakers to provide a good infrastructure system to make surface transportation as safe and efficient as possible. The currently increasing trends in accident-related fatalities and injuries show that, despite policymakers' efforts thus far to reduce these fatalities and injuries, society still has a long way to go to accomplish the goals currently established. In the U.S., despite all efforts to reduce the number of roadway accidents and accident-related fatalities, the number of annual roadway fatalities has never dropped below 30,000 in last 50 years (Egilmez & McAvoy, 2013). The ultimate goals of transportation safety engineers are to reduce the number of crashes and to mitigate the severity of crash-related injuries (Das & Abdel-Aty, 2011). One of the main problems with the complex issue of road safety is the sheer number and variety of the parameters simultaneously playing different roles in traffic accident rates. These parameters tend to affect each other on a short-term or long-term basis, potentially making a bad situation even worse.

There are different ways to categorize traffic accidents. Some past studies and reports attempted to put more emphasis on the number of vehicles involved in a particular crash, i.e., 1 vehicle crashes, 2 vehicle crashes, and 3+ vehicle crashes (Guarino & Champaneri, 2010). Other studies and reports place the main reasons for any crashes under three main categories: driver-related factors, or whether the accident in question was the fault of any or all of the drivers involved; vehicle-related factors, or whether the accident may have been caused by any safety issue(s) with respect to any or all of the vehicles in question; and infrastructure/road-related factors, or whether improper or damaged infrastructure may have caused the accident.

The main purpose of conventional traffic safety analysis is to find a relationship among the different parameters involved in any given accident, such as driver-related factors, roadway conditions, environmental factors, and other such parameters (Abdel-Aty & Pande, 2005). This project sought to develop submodels capable of investigating each of these three main factors, with the main focus on driver-related factors, which is the primary category of factors involved in accident rates.

Climate change is another key factor that plays a very important role in accidents, and it should be seriously investigated and considered in long-term road safety planning. Environmental factors connected to climate change have become a major obstacle to road transportation safety, especially now that climate change has become one of the most important issues of the 21st century due to recent tremendous environmental changes. These environmental changes have a strong impact on road safety; according to the USDOT, weather-related accidents account for nearly 23% of the almost six million accidents per year. By definition, weather-related crashes are traffic accidents that occur under adverse weather conditions (rain, snow, fog, etc.), or accidents that occur on slick (e.g., wet or slushy) pavement. The negative effects of climate change can be projected as increasing the frequency of extreme weather events such as heat waves, rising sea levels, storms, hurricanes, floods, etc. (U.S. EPA, 2016). Road transportation safety is compromised under any of these conditions or possible combinations thereof due to vehicle safety measures becoming less effective than they might be under normal weather conditions or due to the destructive effects of extreme weather conditions on roads and infrastructures.

For example, extremely hot weather conditions can cause cars to overheat and can accelerate tire deterioration. Extremely hot weather conditions may also soften asphalt, which can lead to asphalt deformation, thermal expansion of bridge joints, and other potential hazards (National Research Council, 2008). As another example, rising sea levels may lead to floods that can cause skidding and even drowning of vehicles (especially for transportation in coastal areas, which are more vulnerable to sea-level rise) and may also cause infrastructure erosion. Ultimately, the main concern with these sudden unpredictable weather changes is that today's infrastructure has generally been designed to last for a certain amount of time based on predicted weather conditions that can no longer be considered valid due to rapid climate change. As a result, the original infrastructure designs must be changed or even discarded altogether in favor of newly designed models based on changing weather patterns (Transportation Research Board, 2011).

Numerous studies have investigated the effects of adverse weather conditions on roadway accidents. In order to classify these effects and their associated consequences, the USDOT has released a report about its road weather management program in which different weather variables are classified into different groups, including air temperature/humidity, wind, precipitation, fog, pavement temperature, water level, and so on. The effects of these phenomena on road safety have been a widely debated topic, but can generally be categorized into three areas: roadway impacts, which can include parameters such as visibility, distance, infrastructure damage, pavement friction, and lane obstruction; traffic flow impacts, which can include traffic speed, travel time delay, speed variance, and roadway capacity; and operational impacts, which can include vehicle performance, driver behavior, speed limit control, and traffic signal timing.

Among all of these possible weather events and associated impacts, precipitation has proven to pose the greatest threat to road safety. Statistical data has shown that 74% of all crashes happen on wet pavement and 46% of crashes occur during rainfall (Federal Highway Administration, 2011), while no other type of adverse weather condition can even compare with these percentages.

It is also worth noting that the greater frequency of these extreme weather conditions in recent years is primarily due to increasing atmospheric temperature changes, which are highly dependent on the emissions of greenhouse gases (GHGs) such as CO_2. According to the United States Environmental Protection Agency (EPA), the transportation sector is directly responsible for almost 30% of CO_2 emissions in the United States, and also contributes significantly to the remaining 70% (U.S. EPA, 2016). It can be seen that the above-listed factors are part of a closed-loop system, meaning that they have mutual effects on each other.

The economy is another important area to consider with respect to accidents and road safety in general. On the one hand, economic factors can have a positive impact on road safety through increases in highway system capacity that will reduce roadway congestion, through improvements in vehicle safety, or through various other road safety initiatives. On the other hand, however, roadway accidents and their associated injuries and fatalities can do significant damage to the economy. In 2010, there were almost 33,000 fatalities, 3.9 million injuries, and damages to 24 million vehicles in the U.S. as a result of motor vehicle crashes (Blincoe et al., 2010). According to NHTSA, the total economic cost of all of these negative impacts was estimated to be around $277 billion, or almost 1.9% of the total U.S. GDP; if quality of life valuations are added to this amount, the total cost increases to $871 billion. Climate change, extreme weather conditions, and traffic congestion can also have a similarly tremendous effect on the economy, which (as shown in later sections) interacts directly and/or indirectly with other sectors.

Effective management and proper policymaking for complex systems requires a holistic understanding of the system so that one can correctly interpret the interactions involved among different parameters in the system (Kelly et al., 2013). To achieve such an understanding and interpretation, it is necessary to integrate different branches of science to cover all or most of the parameters in the system (or, at the very least, the most important thereof) in such a way that one can analyze each parameter individually and/or as part of the system given its interactions with other parameters. Integrated assessment modeling is a very useful tool for modeling complex systems like those pertaining to environmental concerns, as well as related issues such as climate change and predicting associated future weather patterns, because such systems usually contain many subcomponents that each play their own major or minor roles within the system. Therefore, analyzing the actions and interactions among these components will be crucial to determining the behavior of the overall system. This is also why analyzing such systems by focusing solely on single components is misleading and results in wrong and/or incomplete solutions. The main focus of integrated assessment modeling is on analyzing the feedback processes through which the actions and interactions within the system take place (Davies & Simonovic, 2011). Integrated assessment modeling can integrate different branches of science for this purpose and can investigate the behavior of each component within the system as well as each parameter's individual behavior. Finally, once a sufficiently accurate model has been developed with this methodology, the model is then used to inform policymaking (Davies & Simonovic, 2011). The most recently developed integrated assessment modeling procedure is based on SD modeling; the word "system" refers to the parameters interacting with each other and how these interactions will determine the behavior of the system, while the word "dynamics" refers to the time-dependency feature of the system (Akhtar, 2011), which will make time a particularly important parameter in the SD modeling approach.

As mentioned earlier, one of the difficulties of investigating complex systems like road safety is that the interactions among different parameters playing any role within the system are often neglected. This oversight becomes even more serious when the system and its parameters are dynamic in nature and when parameters are time-dependent. Therefore, a comprehensive SD model to help policymakers find ways to reduce roadway fatalities and injuries should be capable of identifying all of the parameters related to road safety, and should also take into account the relationships and interactions between all of these parameters. The SD modeling approach is evolving as an answer to these difficulties.

In previous studies, these systems were investigated individually, regardless of their interactions with other parameters and submodels. In contrast, this study aimed to develop different submodels to investigate each of these systems individually and/or in interaction with other systems. The results were used to predict the behavior of these different systems up to the year 2100, after which they were used to test different scenarios to improve the behavior of the system and reduce the negative consequences of roadway accidents.

2.2 Model Development

2.2.1 Problem Identification

The main purpose of this study was to provide a platform from which different scenarios could be tested to find the most efficient way(s) to increase road safety and to reduce the negative consequences of traffic accidents. For this purpose, a CLD (Figure 2.2) was developed and presented to identify the parameters of different submodels, after which a stock and flow diagram (Figure 2.3, Figure 2.5, Figure 2.6, Figure 2.7, Figure 2.8, and Figure 2.9) was constructed for each submodel for quantification. In order to validate the constructed model, the reference modes for VMT, number of crash fatalities, CO_2 emission, and U.S. GDP are presented in Figure 2.1. These parameters were chosen because they play key roles in determining the other parameters.

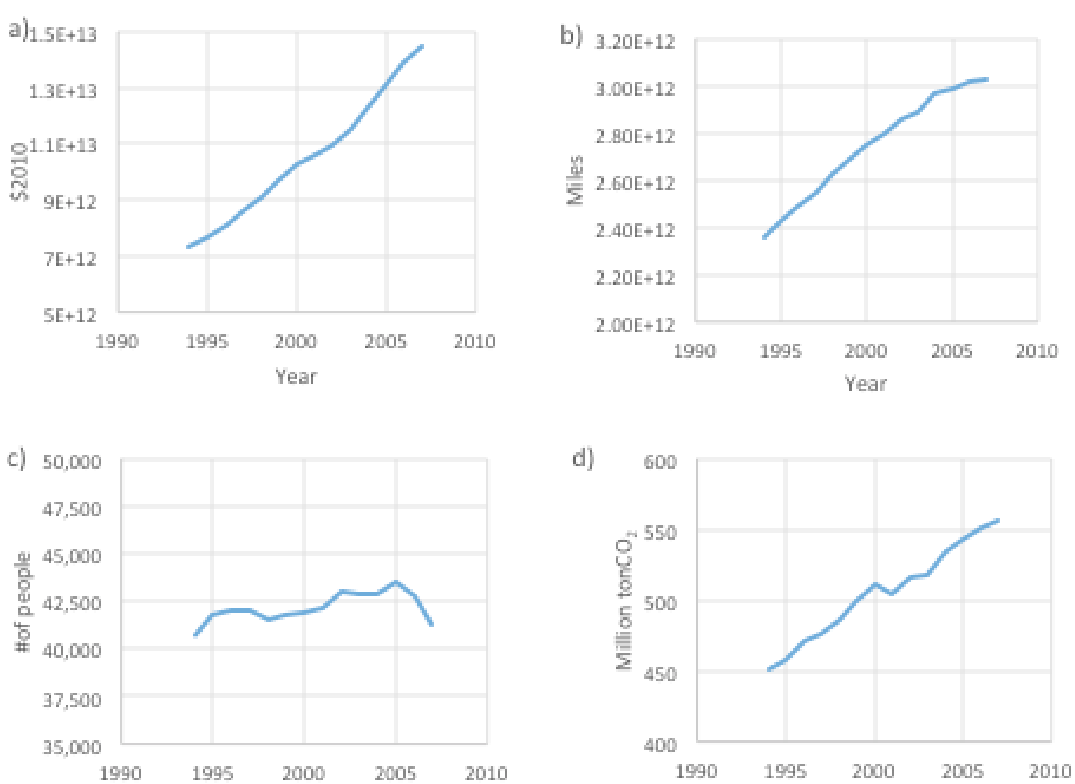

Figure 2.1 - Reference mode (NHTSA, 2014):

a) U.S. GDP, b) VMT, c) number of fatalities, and d) CO_2 emissions

2.2.2 Identification of Parameters

To create the CLD, the different parameters typically involved in road safety and transportation were identified, the parameters that may or may not be directly connected were determined, and indirect connections were revealed as separate series of one or more direct connections. The different parameters to be included in this CLD were introduced and organized by type (exogenous/"independent" versus endogenous/"dependent"); they are briefly described in Table 2.1. The validation for the inclusion of these parameters is described in the next section.

Table 2.1 - Key model parameters

Parameter	Description	Type	Units
Vehicle condition	Vehicle-safety-related factors (ANCAP rating)	Endogenous	-
Climate change	Extreme weather conditions (rain, hurricane, snow, extreme heat/cold, etc.)	Endogenous	-
Infrastructure condition	Road safety level and infrastructure equipment	Endogenous	-
Economy	Wealth and resources of a country or region	Endogenous	-
Population	The total number of people	Endogenous	-
Driver contribution	The accidents in which the driver's fault will be the primary factor	Endogenous	-
VMT	Vehicle miles traveled	Endogenous	Miles
Accident	The total number of accidents that happen in a certain period of time	Endogenous	-

2.2.3 System Conceptualization

In this section, a CLD was developed based on the parameters defined in Table 2.1. As discussed previously, one of the main advantages of the SD modeling approach compared to other modeling procedures was that it allowed for a more in-depth investigation of the relationships and interactions between different parameters within the system through their associated feedback loops, which were used to develop the CLD. Feedback loops are the most important characteristic of any SD model, as these connectors determine how the results or outputs of a sector within the system should be used as an input for another sector in the system. These feedback loops can be positive or negative, depending on their overall effect after one full rotation within the loop. A positive ("reinforcing") loop means the related parameters or sectors have the same overall increasing or decreasing trend, such that increasing or decreasing one parameter will result in a corresponding increase or decrease in that same parameter after a full rotation within the loop. Conversely, a negative ("balancing") loop means that an increase or decrease in any parameter will have a decreasing or increasing effect, respectively, on that same parameter after a full rotation. A CLD (Figure 2.2) was constructed based on the parameters within the scope of this study, and a brief explanation of how these parameters affected each other is provided in the next section.

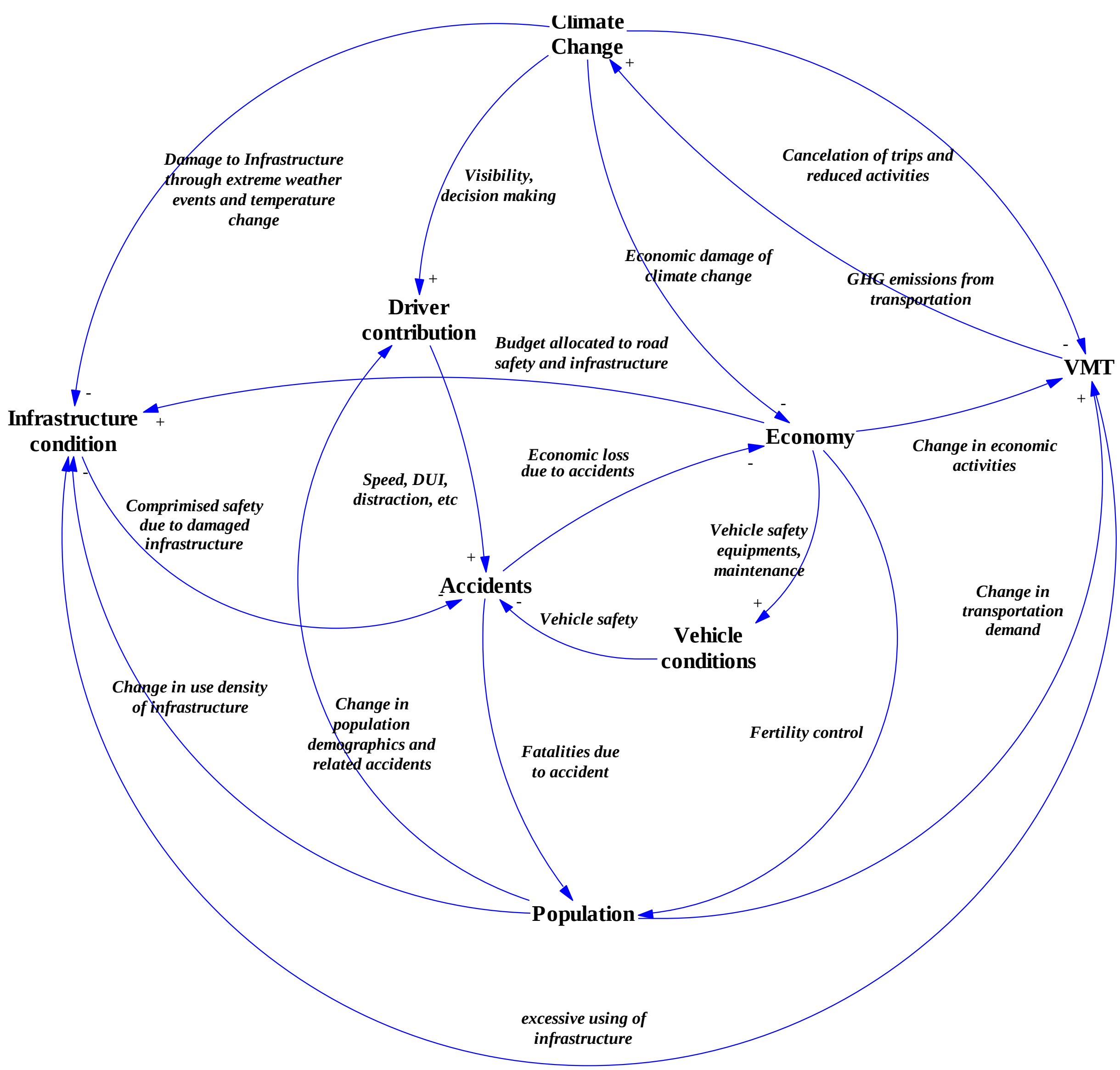

Figure 2.2 - Causal loop diagram

2.2.4 Causal Loop Diagram Explanation

Climate change- infrastructure condition- accidents - economy- VMT- climate change. An increase in extreme weather events will cause infrastructure to deteriorate, and this deterioration will increase accident rates. The increased number of accidents and accident-related fatalities and injuries will have a negative impact on the economy and decrease the VMT, reducing GHG emissions and thereby leading to less atmospheric temperature change, contributing less to extreme weather events in the long run (U.S. EPA, 2013; Koetse & Rietveld, 2009; Blincoe et al., 2000; Blincoe et al., 2010; Zimmerman, 2003).

Climate change- driver contribution- accident rate- economy- VMT- climate change. Increasing the frequency of extreme weather conditions (rainfall, fog, snow, etc.) will increase the driver's contribution to traffic accidents due to negative impacts on factors such as visibility and decision-making. This will increase the accident rate, which will have a negative impact on the economy and lower the VMT. Decreasing VMT rates will reduce GHG emissions and, consequently, result in less atmospheric temperature change and a reduced likelihood of extreme weather conditions in the future (Kilpeläinen & Summala, 2007; Blincoe et al., 2000; Blincoe et al., 2010; Mills & Andrey, 2003).

Population- VMT- climate change- infrastructure condition- accident rate- economy- population. Increasing the population will increase travel demand, which will result in an increase in VMT and subsequent increases in GHG emissions, in turn increasing the atmospheric temperature. This atmospheric temperature change will then change the relevant precipitation models and increase the frequency and severity of extreme weather conditions, resulting in long-term infrastructure degradation. Subsequently, this infrastructure deterioration will increase the accident rate and thereby incur the economic losses associated with traffic accidents. Finally, although the relationship between economic prosperity and fertility rates and/or populations is still debatable, it is generally accepted that more economic prosperity will increase the fertility rate to some extent (U.S. EPA, 2013; Flahaut, 2004; Blincoe et al., 2000; Blincoe et al., 2010; Noland, 2003).

Infrastructure condition- accident rate- economy- VMT- infrastructure condition. Improving the condition of available infrastructure will result in fewer accidents, and will thereby decrease the total economic burden of accidents. This increase in economic prosperity will result in an increase in travel demand and vehicle manufacturing, which will lead to an increase in VMT. However, the excessive use of infrastructure from this increased VMT will lead to greater infrastructure deterioration (Flahaut, 2004; Blincoe et al., 2000; Blincoe et al., 2010; Noland, 2003).

Accident rate- economy- vehicle safety- accident rate. Increasing the accident rate and/or the number of fatalities and injuries will have a negative impact on the economy. Based on a report published by NHTSA, the economic loss of roadway accidents sometimes reaches up to 2% of the GDP of the country. This reduction in economic prosperity will leave less money available for vehicle safety improvements. According to NHTSA's evaluation of the cost of the Federal Motor Vehicle Safety Standard (FMVSS) since 1975, when the GDP increases (i.e., when the economy grows stronger), the vehicular safety index will increase at the same time. Conversely, the resulting reductions in vehicle safety will increase the number and/or severity of future accidents (Tarbet, 2004; Blincoe et al., 2000; Blincoe et al., 2010).

Economy- infrastructure condition- accident rate- economy. A better economic situation will allow for better infrastructure conditioning due to the increased transportation sector share from the GDP. This can also help to increase highway mileage and capacity, reducing traffic congestion while increasing infrastructure quality. These improvements in infrastructure will also reduce accident rates, making the economy less likely to suffer from the typical economic consequences associated with traffic accidents (Blincoe et al., 2000; Blincoe et al., 2010; Noland, 2003).

Population- VMT- climate change- infrastructure condition- accident- population. As the population increases, travel demand and the number of vehicles will also increase, increasing the VMT. This increase in VMT will result in increasing GHG emissions and consequently increase atmospheric temperatures, resulting in increasing extreme weather events, which will negatively affect infrastructure condition. This combination of extreme weather conditions and poor infrastructure conditions will increase the accident rate and/or its associated fatalities and injuries, directly decreasing the population (U.S. EPA, 2013; Flahaut, 2004; Mills & Andrey, 2003; Noland, 2003).

2.2.5 Model Formulation

In the next step of the SD modeling process, the developed CLD helped to construct a stock and flow diagram for different systems. The following submodels each contained the mathematical formulations of the relationships between different parameters. Each submodel focused on a specific area related to road safety, which included submodels to represent motor vehicle safety, highway systems, and the environment, as well as two submodels that mainly focused on economic losses due to transportation-related issues.

2.2.5.1 Economic Losses Submodel for Crashes with Respect to Fatalities, Injuries, and Property Damage Only

The total rate of fatalities per 100 M of VMT and number of crashes with injury and property damage were used only to estimate the total economic cost of all types of crashes. This model can be seen in Figure 2.3.

In this model, the number of crashes with respect to fatalities, injuries, and property damage only was obtained, and the economic losses were then calculated based on the information provided by NHTSA.

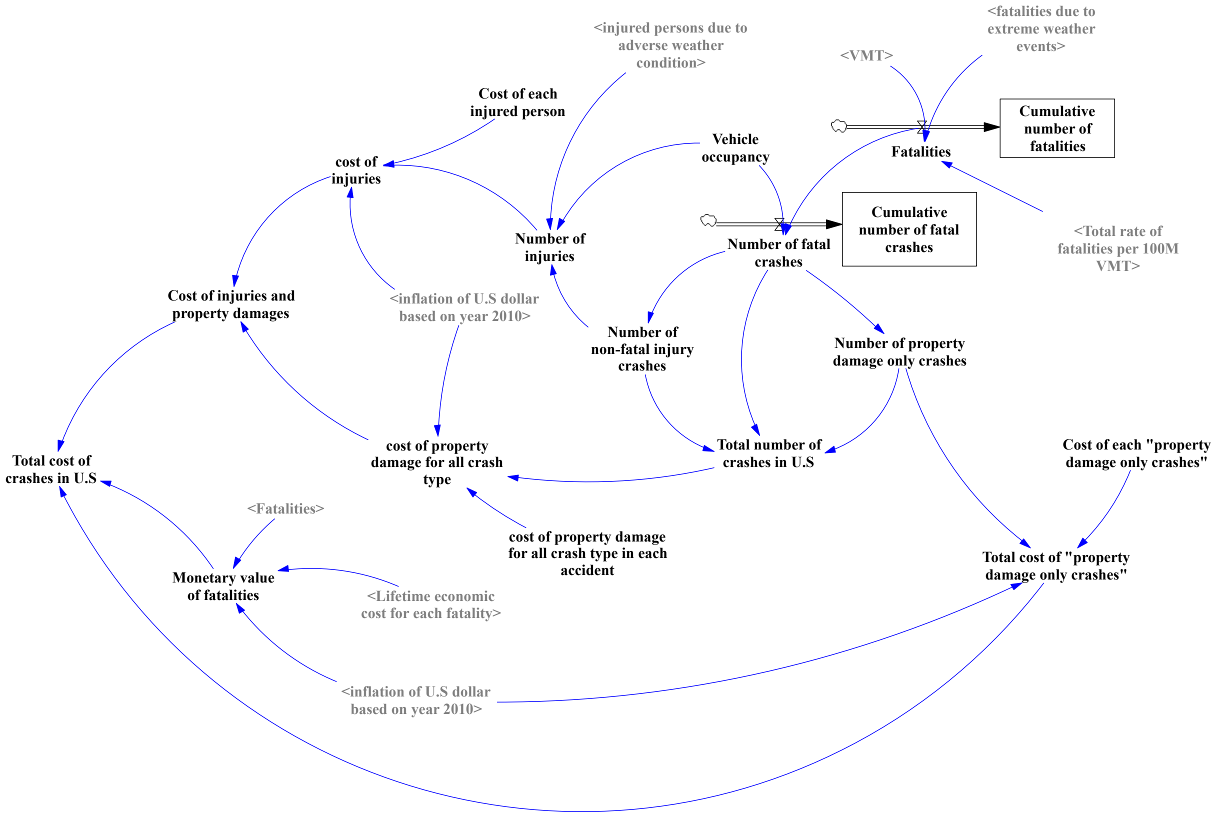

Figure 2.3 - Economic losses submodel

Table 2.2 - Values of other parameters (NHTSA, 2014).

Parameter	Value
Cost of each injured person	$37,524
Cost of property damage for all crash types in each accident	$13,836
Cost of each "property damage only crashes"	$17,875
Lifetime economic cost for each fatality	$1,400,000
Average added cost by FMVSS per vehicle	$940
Vehicle occupancy	1.63

Different costs related to different crash types were obtained from NHTSA reports. For more accuracy, the value of the U.S. dollar for different years was calculated and multiplied by different costs so that all costs were presented in the value of the 2010 U.S. dollar (see Figure 2.4).

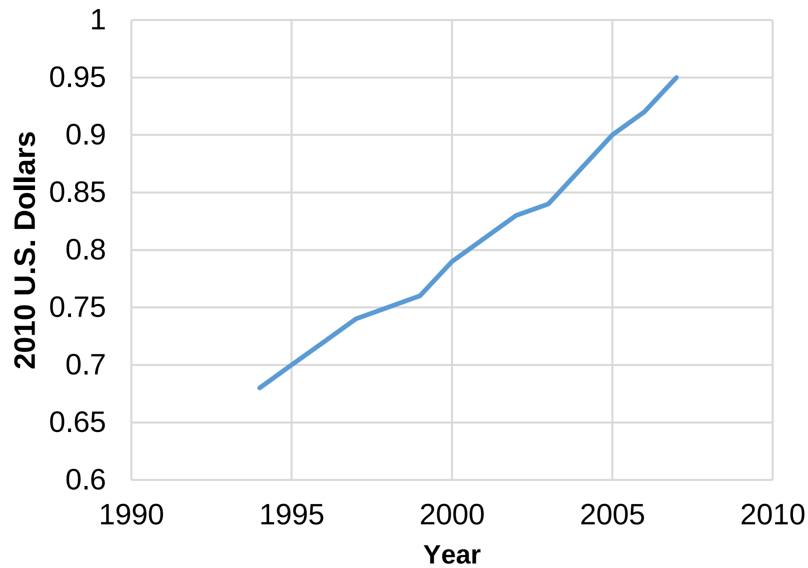

Figure 2.4 - U.S. dollar values adjusted to 2010 U.S. dollars

2.2.5.2 Motor Vehicle Safety Standards Submodel

This submodel was used to model the role of vehicle safety standards in preventing roadway fatalities. NHTSA began to require the manufacturers of motor vehicles and equipment to apply certain safety standards in their products as indicated by National Traffic and Motor Vehicle Safety Act of 1966, and those were accounted for in this model.

The FMVSS aim is to provide minimum safety performance requirements for motor vehicles and/or motor vehicle equipment. According to NHTSA, these requirements are specified such “that the public is protected against unreasonable risk of crashes occurring as a result of the design, construction, or performance of motor vehicles and is also protected against unreasonable risk of death or injury in the event crashes do occur" (National Highway Traffic Safety Administration, 1999).

As shown in Figure 2.5, this model sought to estimate the number of lives saved through the implementation of the FMVSS based on the information provided in a report published by NHTSA (Kahane, 2004). According to this information, more than 328,000 lives were saved between 1960 and 2002 by applying the FMVSS. With this in mind, a statistical model was used to estimate the number of lives saved by the implementation of the FMVSS based on the vehicular safety index. Utilizing the model developed by NHTSA, one can understand how many people would have died if the vehicles had not been equipped with these safety technologies.

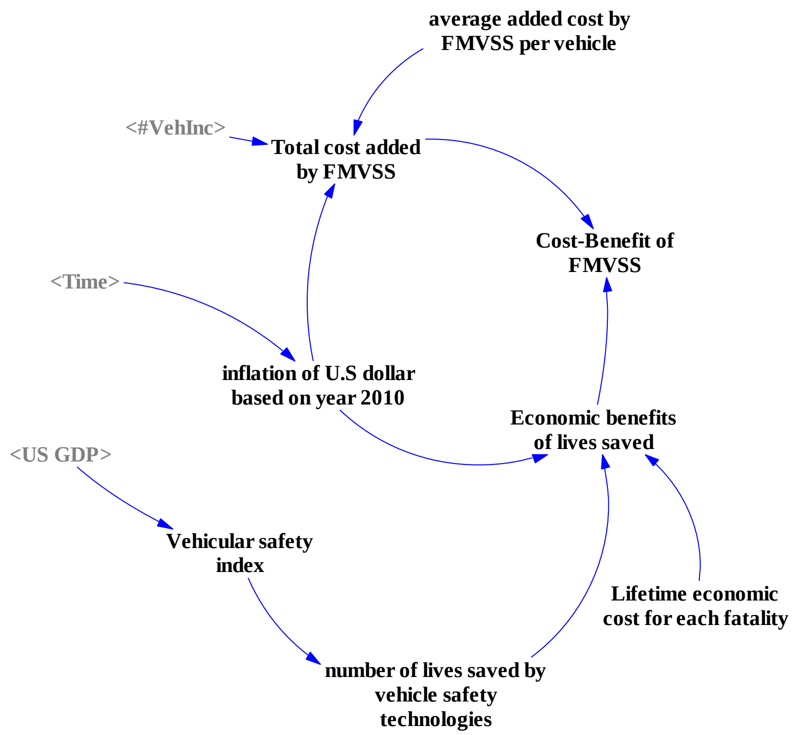

Figure 2.5 - Motor vehicle safety submodel

The number of lives saved by vehicle safety technologies was obtained by a polynomial regression analysis based on data provided by NHTSA and using Equation 2.1.

$$\textit{Number of lives saved by vehicle safety technologies} = -0.18786*(\textit{Vehicular safety index})^2 + 708.375*(\textit{Vehicular safety index}) - 1{,}240 \quad (2.1)$$

2.2.5.3 Highway System Capacity Submodel

This submodel presented a more holistic view of the problem by concentrating on parameters such as population, VMT, vehicle fuel usage, and traffic congestion.

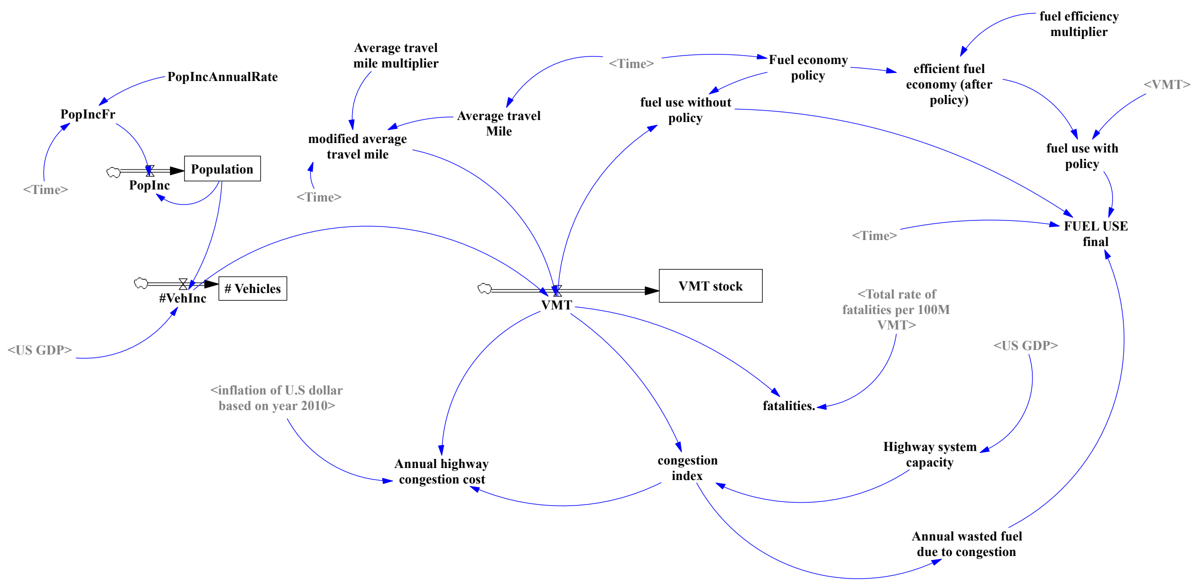

Figure 2.6 - Transportation system submodel

In this model, the total number of vehicles was a function of the U.S. population and GDP and was obtained using Equations 2.2, 2.3, 2.4, and 2.5.

*Total number of vehicles = (1.79197e+007) + 0.449554*Population + U.S. GDP*(6.52e-006)* (2.2)

*Congestion index = -2.25 + (2.69e-006)*Highway system capacity – (1.64e-012)*VMT*(4.55e-013)*(Highway system capacity)^2 + (3.94e-019)*Highway system capacity*VMT* (2.3)

Annual wasted fuel due to congestion = (1.93025e+008)(congestion index)^2 - (3.20771e+008)*(congestion index) + (1.4234e+008)* (2.4)

$$\text{Fuel use} = 1.39311*\left(\frac{VMT}{\text{Fuel economy policy}}\right) + (3.71441e{+}009) \quad (2.5)$$

The fuel economy and average travel miles per vehicle were each entered as exogenous variables defined in the software VENSIM as a lookup table for different years. The total rate of fatalities per 100 M of VMT had already been calculated for different years. In this model, these fatality rates were simply multiplied by the VMT to obtain the total number of fatalities.

2.2.5.4 Environmental Impact Model

This model tracked the environmental impacts of the transportation sector. Using this model, the amount of CO_2 emitted from the transportation sector was calculated for different years, after which the atmospheric temperature changes from the calculated CO_2 emissions were obtained accordingly. Next, based on these atmospheric temperature changes, the changes in the applicable precipitation models were investigated, specifically to see how increasing the atmospheric temperature changed the precipitation models based on the average precipitation patterns over the last 30 years. Data from the USDOT FHWA in the road weather management program was used to construct this model.

As shown in Figure 2.7, this model simulated the atmospheric temperature change over time and was also capable of calculating economic losses due to climate changes by using the Dynamic Integrated Climate-Economy (DICE) model, as well as the economic damage function already calculated by Pindyck (2010).

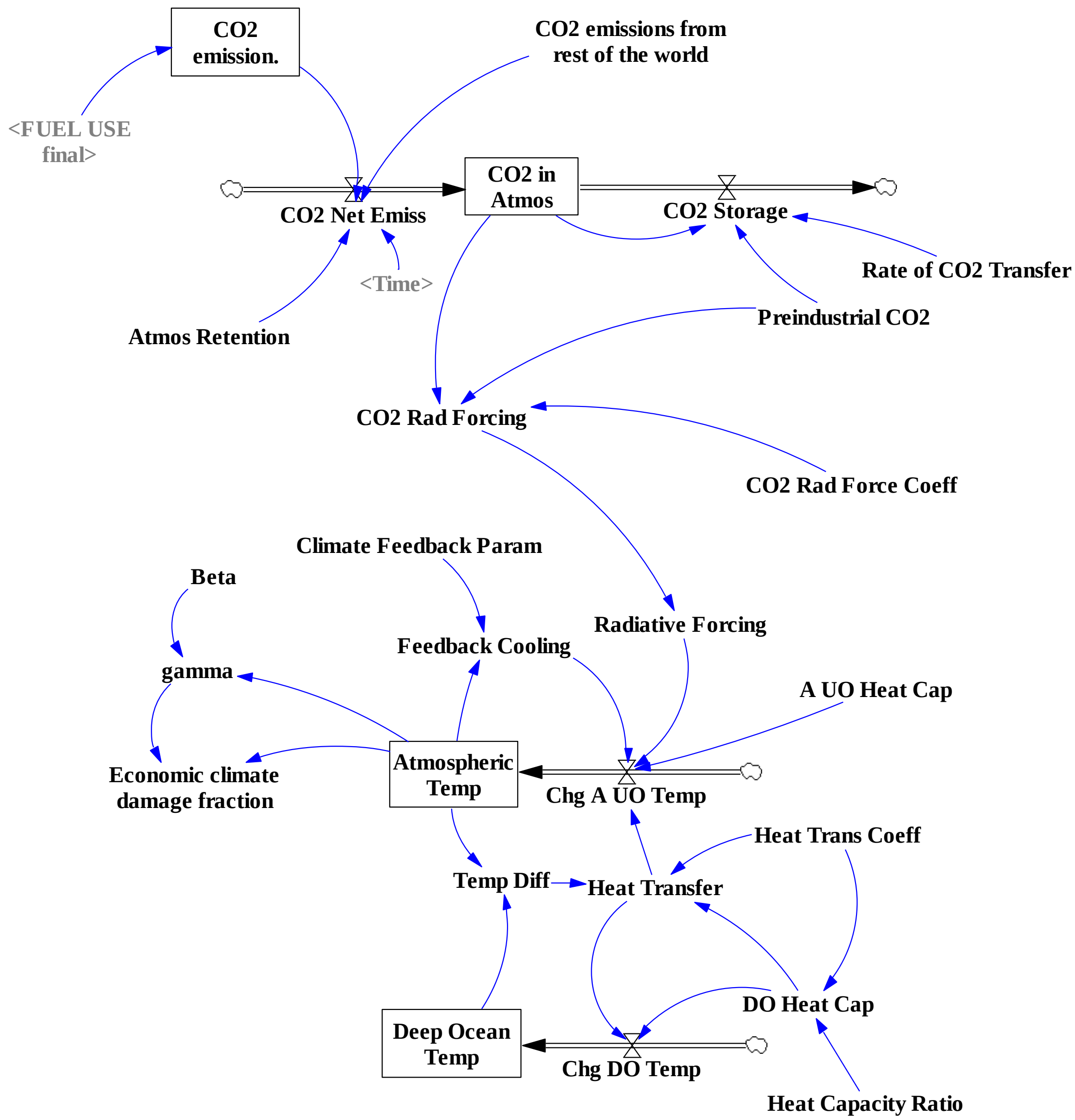

Figure 2.7 - Environmental impact submodel (GHG emissions)

The DICE model was developed by William Nordhaus which investigates the dynamic nature of the relation between economics, carbon cycle and climate science (Newbold, 2010). The economic damage function parameter was used later in the second economic submodel (see Figure 2.8) to calculate the economic damages to the GDP from atmospheric temperature change. Economic losses due to climate change were represented as damages to the GDP, which were usually related to damages associated with agricultural productivity, dislocations resulting from higher sea levels, and dollar-equivalent costs such as increases in mortality, morbidity, and social disruption (Pindyck, 2011).

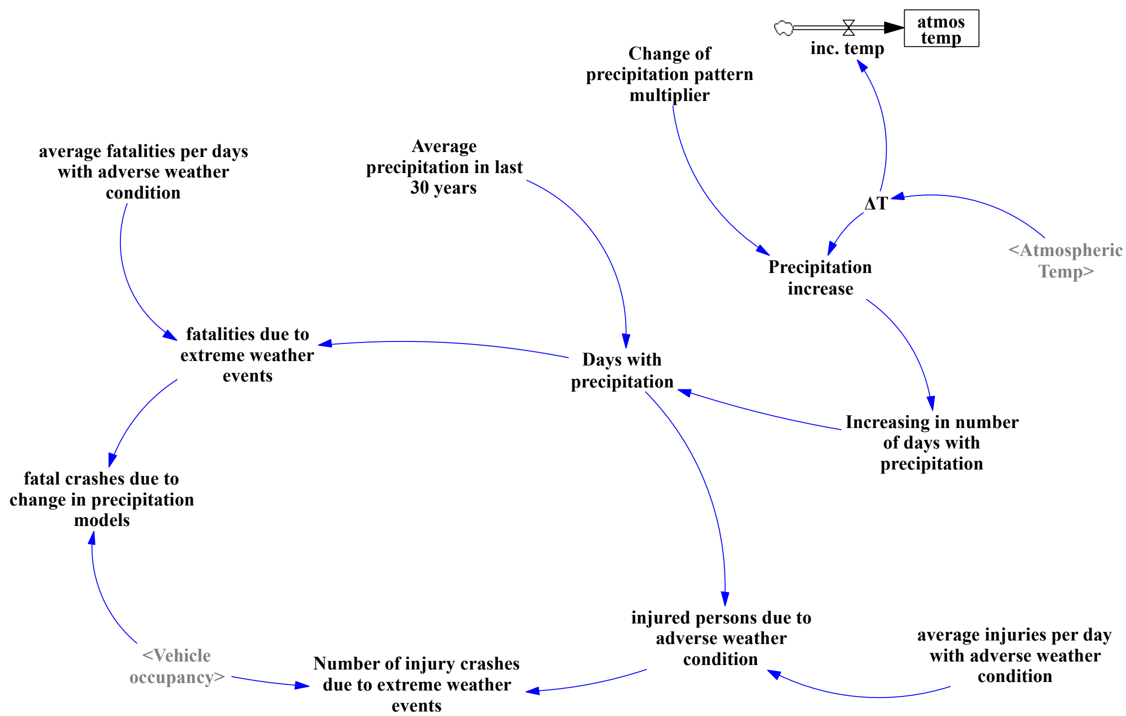

Figure 2.8 - Environmental impact submodel (precipitation and weather)

The next step was to investigate the consequences of this temperature change and its effect on road safety. For this purpose, another model was developed and is presented in Figure 2.8.

This study attempted to develop a model that was capable of estimating the number of days with extreme weather events up to the year 2100 based on climate change models of the past 30 years. In terms of the effects of weather conditions on road safety, several variables seem to be more important than others. For instance, there were several studies in this area to investigate the effects of weather conditions on road safety, and it was proven by this and other such methods that precipitation is the most important variable in this regard. Empirical data showed that rain and snow affect the frequency and severity of roadway accidents (Koetse & Rietveld, 2009). Therefore, in terms of extreme weather events, this model focused primarily on precipitation model changes, such that the average increases in precipitation over time can be predicted based on estimations of the number of roadway accidents.

2.2.5.5 Economic Impact Submodel

One of the most important parameters considered in all four of the above-mentioned submodels was the economy. Each of the economic parameters discussed in the previous submodels had an increasing or decreasing effect on the GDP, and these effects were combined in the final submodel (Figure 2.9) to obtain the overall impact on the GDP.

As shown in Figure 2.9, four parameters from the previous models determine the overall negative impacts of road transportation on U.S. GDP: the cost of crashes in the U.S., including the cost of crashes with respect to fatality, injury, and/or property damages only; the cost-benefit analysis of increasing the safety performance of motor vehicles by implementing the FMVSS; the economic benefits of decreasing the frequency and severity of roadway accidents due to increasing the safety level of motor vehicles; and the annual highway congestion cost as a result of increasing the roadway congestion index.

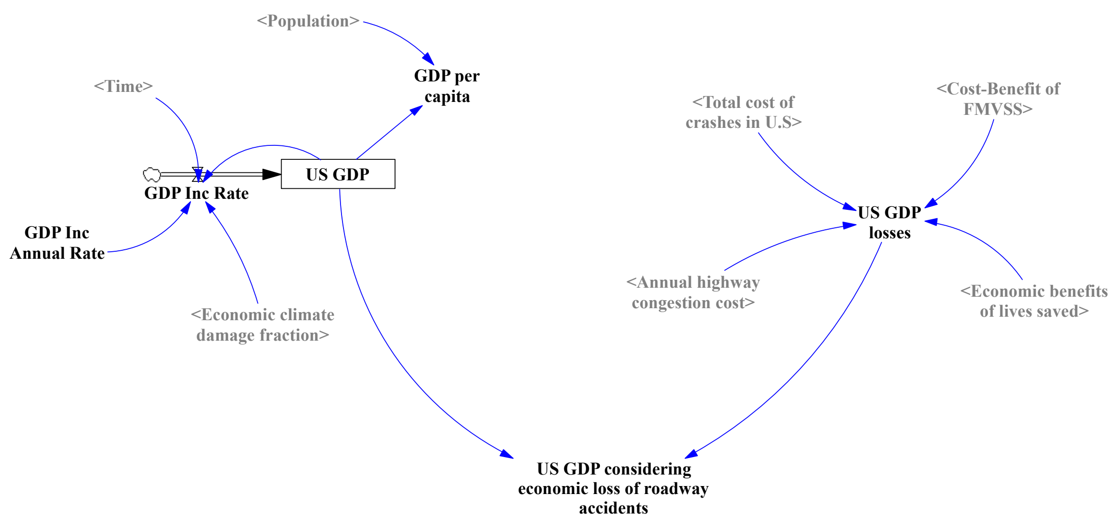

Figure 2.9 - Economic impact submodel

2.3 Model Validation

Model validation was a very important part of the SD modeling process, as it used a series of tests to guarantee the structural and behavioral accuracy of the developed model. Because the purpose of an SD model is to reflect the real-world behavior of the modeled system, six key aspects of the model as a whole were tested to determine if the model's structure and behavior reflected the corresponding structure and behavior of the actual system. For this purpose, the results of the model were compared with historical data (the reference modes from Figure 2.1); the comparison is shown in Figure 2.10. Without performing these validation tests, one could not guarantee that the SD model represented the modeled system in reality, meaning that the model's predictions and the proposed policies based on these predictions could not be trusted to be reliable.

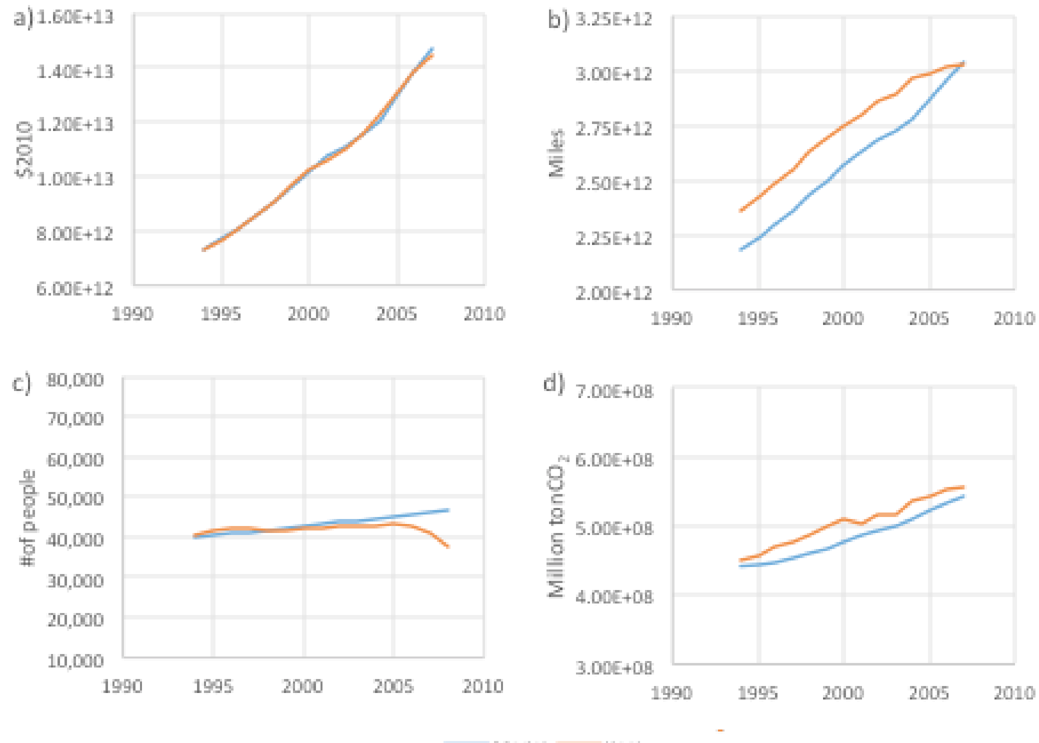

Figure 2.10 - Behavioral validation results

=a) U.S. GDP, b) VMT, c) number of fatalities, and d) CO_2 emissions

2.3.1 Model Structure Validity

In order to ensure that the structure of the developed SD model was adequate, five tests were performed: a structure verification test, a parameter verification test, an extreme condition test, a boundary adequacy test, and a dimensional consistency test.

2.3.1.1 Structure Verification Test

The first test ensured that the parameters in the model and the simulated relationships among them did not contradict any currently available knowledge of the system. This study used other published studies as references to model all of the parameters in the SD model as well as their simulated relationships. These references were discussed in Section 2.2.4.

2.3.1.2 Parameter Verification Test

The second test was similar to the first test in that they were both qualitative rather than quantitative and in that they both had the same ultimate goal. However, this test more specifically sought to determine whether the developed SD model was an adequate representation of the real system. For this purpose, all of the parameters mentioned in the explanation of the CLD and stock and flow diagrams (Sections 2.2.4 and 2.2.5) were checked to ensure that the modeled system did not in any way contradict currently available knowledge of the real-world system.

2.3.1.3 Extreme Condition Test

The third test investigated the accuracy of the system's structure by assigning extreme values to different parameters to determine if the model demonstrated logically valid behavior based on the assigned extreme values. It was qualitatively observed that the model passed the extreme condition test by showing logical behavior.

2.3.1.4 Boundary Adequacy Test

The fourth test ensured that the boundaries of the developed model were defined in such a way that the model was well suited for the purposes of the study. In this study, the purpose of the model was to investigate the different parameters that affect road safety (motor vehicle safety, climate change, congestion, etc.), and from the different submodels (Section 2.2.5) it was observed that the goal of the system was achieved by taking into account all of the aforementioned parameters.

2.3.1.5 Dimension Consistency Test

The fifth test sought to verify the consistency of the units of the parameters used in the stock and flow diagrams (Section 2.2.5). From the different stock and flow diagrams and their relevant equations, it can be seen that the units of the parameters were all consistent with each other.

2.3.2 Model Behavior Verification

The final test compared the output of the developed SD model to real-world historical data to ensure that the data sets matched closely enough to conclude that the model's behavior accurately represented the behavior of the system in reality. For this purpose, the results of the system for four key parameters were compared with available historical data (Figure 2.10) obtained from different reports and studies published by government organizations.

In this study, two statistical tests were performed to compare the actual data with the outputs of the system: the one-way ANOVA test and the normality test. Before the one-way ANOVA test could be performed, the normality test had to be performed for both the actual data and the model output (Egilmez & Tatari, 2012). If the results showed that both data sets were normal, then the one-way ANOVA test could be performed. If not, then another test had to be performed instead. The normality test was performed using SPSS software, and the results are shown in Table 2.3. The table shows that all four parameters passed the normality test for both the reference mode data and the SD model because the sigma value was greater than 0.05 for all four parameters.

Table 2.3 - Normality test results

		Kolmogorov-Smirnov			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
VMT	Model	0.088	14	0.2*	0.970	14	0.879
	Data	0.124	14	0.200*	0.931	14	0.319
GDP	Model	0.091	14	0.2*	0.963	14	0.777
	Data	0.093	14	0.200*	0.96	14	0.730
Fatalities	Model	0.089	14	0.2*	0.97	14	0.875
	Data	0.123	14	0.200*	0.98	14	0.974
CO2 emission	Model	0.122	14	0.2*	0.936	14	0.364
	Data	0.096	14	0.200*	0.962	14	0.752

Now that the data were confirmed to be normal, the next step was to use the one-way ANOVA test to investigate whether there was a significant statistical difference between the reference modes and the SD model outputs. The results of the one-way ANOVA test are shown in table 2.4 for the four different parameters. The p-values for the four parameters were all greater than the selected confidence (α) value of 0.05, which meant that there was no significant statistical difference between the mean values of the obtained results from the SD model and those of the actual historical data.

Table 2.4 - Results of the one-way ANOVA test

ANOVA for VMT

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.68366E+23	1	1.68E+23	2.703019	0.112198	4.225201
Within Groups	1.61949E+24	26	6.23E+22			
Total	1.78785E+24	27				

ANOVA for GDP

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.41258E+21	1	4.41E+21	0.000829	0.977256	4.225201
Within Groups	1.3846E+26	26	5.33E+24			
Total	1.38464E+26	27				

ANOVA for CO_2

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.17658E+15	1	3.18E+15	2.799947	0.106259	4.225201
Within Groups	2.94973E+16	26	1.13E+15			
Total	3.26739E+16	27				

ANOVA for fatalities

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4736859.841	1	4736860	2.155553	0.15405	4.225201
Within Groups	57135382.81	26	2197515			
Total	61872242.65	27				

2.4 Policy Analysis

The three main policy areas investigated in this study were fuel efficiency improvements, travel demand reduction, and vehicle safety improvements. Any change in one or more of these policy areas could potentially affect other parts of the system, so the investigation into the proposed policies consequently had many interdependencies; in other words, these policy areas functioned as explained in the CLD (Figure 2.2) and had different impacts in contrast to the results of traditional modeling approaches. Table 2.5, Table 2.6, and Table 2.7 provide more specific details about the proposed policy options. The climate change–road safety–economy nexus was investigated by conducting the following policy tests:

increasing the vehicle fleet's overall fuel efficiency by 25%, 50%, and 75%; reducing travel demand by 25% and 40%; and improving the vehicle safety index by 10% and 15%. Detailed explanations and the respective results of these policies are presented in the following sections.

2.5 Discussion and Results

2.5.1 Reducing CO_2 Emissions by Increasing Fuel Efficiency

After releasing the climate action plan, the government committed to a partnership with industries and stakeholders to develop new standards for increasing vehicle fuel efficiencies in order to reduce the negative consequences (health issues, climate change, etc.) of excessive fuel consumption in the U.S. Based on this plan, the average fuel economy levels of new cars and light trucks should double and increase to 54.5 miles per gallon by 2025, which is a 100% increase in fuel efficiency compared to the present-day fuel economy. From environmental and economic perspectives, this major increase in fuel efficiency could save $1.7 trillion at the pump and slash GHG emissions by as much as 6 billion metric tons over the respective lifetimes of the vehicles sold in almost 10 years (United States, 2014). For the purposes of this study, however, this model was used to test relatively smaller fuel efficiency increases of 25%, 50%, and 75% in order to show how smaller changes in fuel efficiency compared to what was already planned for reducing fuel usage and GHG emissions.

As shown in Table 2.5, continuing the current situation will cause the CO_2 emitted from the transportation sector to continuously increase until 2100, meaning CO_2 emissions will increase to 3.2E+9 in 2100 from 4.44E+8 in 2015. The first policy test was to investigate the effects of increasing fuel efficiency by different values in order to reduce fuel usage and, by extension, reduce CO_2 emissions. For this purpose, four different values were considered in order to test their effects on fuel usage and CO_2 emission reductions. Figure 2.11 shows the effects of different fuel economies on CO_2 emission.

Table 2.5 - Fuel usage for different policies

Policy Name	F.E.	2020	2050	2100
P-FE1	1	2.1E+11	3.35E+11	8.21E+11
P-FE2	1.25	1.69E+11	2.69E+11	6.57E+11
P-FE3	1.5	1.41E+11	2.24E+11	5.48E+11
P-FE4	1.75	1.22E+11	1.93E+11	4.7E+11

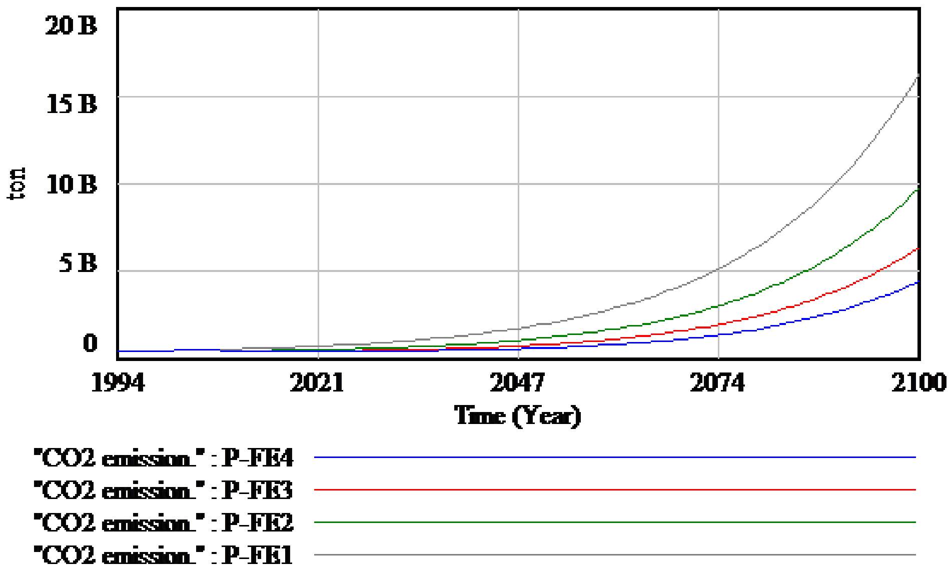

Figure 2.11 - CO_2 emissions for different policies

After analyzing the model, the effects of vehicle fuel efficiency changes alone on atmospheric temperature change were found to be less important than the other parameters. One reason was because the total "rate of CO_2 emissions from the rest of the world" had a much larger value compared to CO_2 emissions solely from the U.S. transportation sector, so the effect of changing CO_2 emissions in the U.S. could not be clearly recognized in this case. Thus, although changing the fuel economy reduced CO_2 emissions from the U.S. transportation sector, it did not have as much of an effect on climate change or road safety.

To clarify this further, another policy initiative was tested based on worldwide CO_2 emissions reductions, reducing the global CO_2 emissions to targets of 25% and 50% to see if such worldwide reduction goals had any significant effects on temperature change or on road safety. In this scenario, 0% reduction indicates what would happen if no action was taken to reduce GHG emissions. As seen in Table 2.6, this time the effect of CO_2 reductions on temperature change became immediately obvious.

Table 2.6 - Atmospheric temperature changes for different policies

Policy Name	Reduction%	2020	2050	2100
P-WR1	0	0.58	0.55	0.51
P-WR2	25	1.08	0.89	0.69
P-WR3	50	1.78	1.46	1.11

Figure 2.12 clearly shows the effect of CO_2 reduction on reducing the number of fatalities due to extreme weather events. The numbers of injuries and property damage only from crashes have the same attitude.

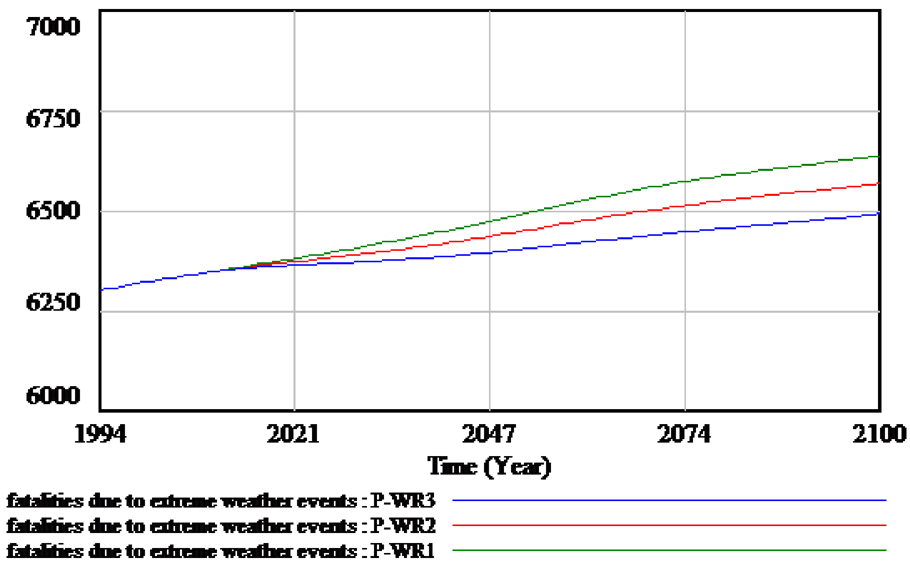

Figure 2.12 - Fatalities due to extreme weather change for different policies

2.5.2 Travel Demand Reduction

There is a growing concern about the negative impacts of transportation systems and their respective side effects, including GHG emissions, traffic congestion, air pollution, and so on. The parameter VMT is normally used to address these concerns. There have been several discussions about finding ways to reduce the VMT while still maintaining economic growth and social activities. This goal can be achieved by increasing the use of other types of transportation besides motorized passenger vehicles, including walking, cycling, using public transportation, etc. (Ecola & Wachs, 2012). This has become a widely discussed topic, especially with knowledge that the VMT and the GDP (as an economic indicator) are strongly coupled, so there should be an intermediate way in which the maximum effort is made to reduce the VMT without compromising economic growth.

Based on background attempts to reduce VMT, states and city areas are required to set target VMT reductions that they plan to achieve within a specified time limit. A report published by the FHWA has indicated that different states have set different targets for VMT reduction; for example, Denver, the Sacramento area, the San Francisco Bay area, and certain other areas have settled on target VMT reductions of 10% by 2035, while Seattle has set its target VMT reduction to 50% by 2050 (Ecola & Wachs, 2012). It can be concluded that the VMT reduction targets for different areas may vary based on their available infrastructures and accommodations. In this study, the target VMT reduction was set as the average target VMT reductions of different states.

The next scenario attempted to investigate the effects of travel demand reduction on VMT, as well as its effects on the number of fatalities and on other parameters involved in this system. For this purpose, two specific scenarios (see Table 2.7) were simulated as target travel demand reductions of 25% or 40%. The first scenario (0% reduction) indicated the situation if the current increasing trend of VMT continues unchanged.

Table 2.7 - Vehicle miles traveled changes for different policies

Policy Name	Reduction%	2020	2050	2100
P-ATM1	0	3.71E12	5.94E12	1.43E13
P-ATM2	25	2.78E12	4.45E12	1.07E13
P-ATM3	40	2.22E12	3.56E12	8.61E12

As shown in Table 2.7, the third scenario could reduce the VMT by almost six billion miles. This huge reduction in miles traveled could result in a reduction in the number of fatalities and injuries and could make roads safer by reducing the congestion index.

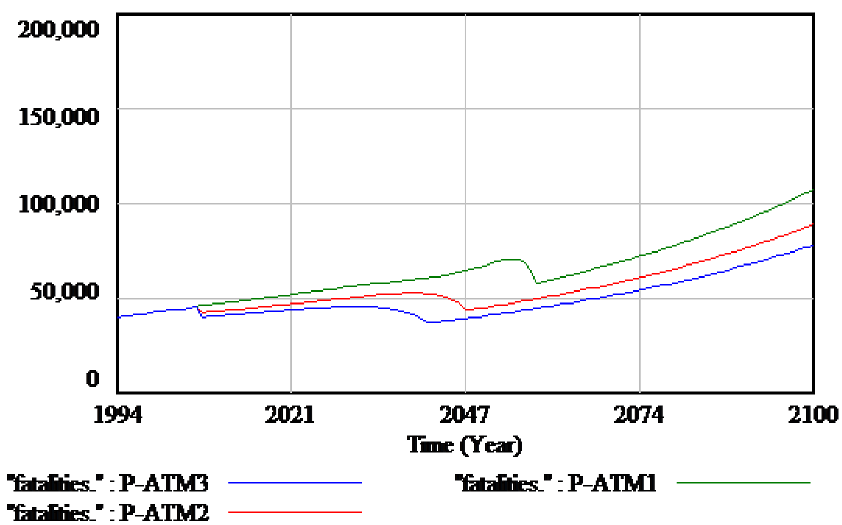

Figure 2.13 - Number of road accident fatalities for different policies

2.5.3 Vehicular Safety Index Increase

There is a strong consensus that vehicle safety improvements are crucial to reducing the number of fatalities and injuries in roadway accidents. In studies and reports published by government or international organizations, different technologies and tools have been introduced that are still helpful in increasing vehicle safety. For example, in a report published by the WHO (2011), one chapter encouraged the harmonization of the relevant global standards to accelerate the uptake of new vehicle safety technologies.

Early vehicle safety efforts were focused on increasing the capability of vehicles to withstand a crash by improving the structural design, materials, and safety systems of the vehicles in question (United States Department of Transportation, 2010). This step started by ensuring that every vehicle had certain basic safety performance measures, such as seat belts and airbags, and continues to promote the more widespread use of crash avoidance technologies such as electronic stability controls and anti-lock braking systems (World Health Organization, 2011). These technologies aim to prevent crashes from occurring in the first place and make vehicles more intelligent as they become more able to sense and communicate with other vehicles and with roadside infrastructure (United States Department of Transportation, 2010). In order to promote such systems, policymakers are considering offering incentives for manufacturers to employ these technologies. For example, the USDOT recognized the need to reward commercial motor carriers for deploying safety technologies in their fleets and even for considering investing in V2V and V2I communication programs (United States Department of Transportation, 2010).

In this study, the increasing vehicle safety scenario was focused on decreasing the roadway accidents and number of fatalities and injuries through increasing the safety index of the vehicles. For this purpose, two different scenarios were tested to see their effects on increasing the safety of the passengers (see Table 2.8 and Figure 2.14).

Table 2.8 - Vehicular safety index changes for different policies

Policy Name	Increase%	2020	2030
P-ATM1	0	70.75	90.32
P-ATM2	10	77.83	99.35
P-ATM3	15	81.37	103.87

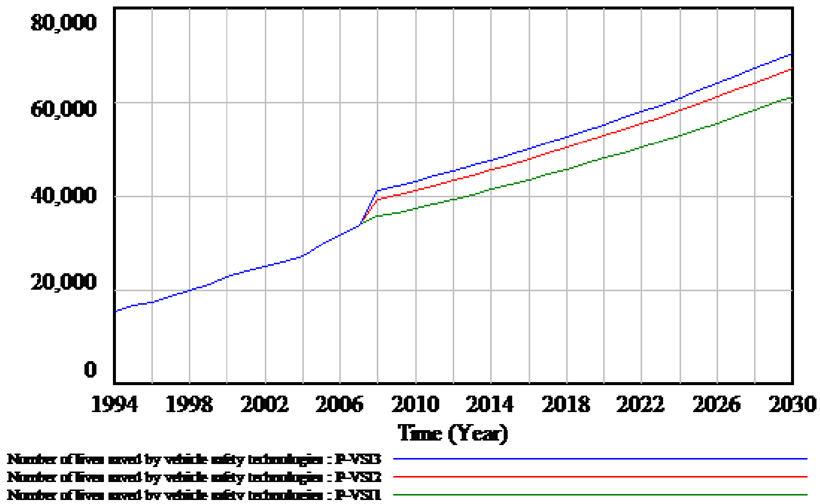

Figure 2.14 - Number of lives saved by vehicle safety technologies for different policies

2.6 Conclusions

In this study, the climate change–road safety–economy nexus was investigated, and several related policies were analyzed to explore ways to reduce the accident rate in the U.S. The policies aimed to increase fuel efficiency and reduce transportation-related emissions. However, reducing transportation-related emissions had a negligible impact on slowing the atmospheric temperature rise, which meant it could not eliminate or reduce negative effects of climate change on road safety. Hence, as a second policy area, extreme worldwide emissions reduction policies were explored to show how climate change affected road safety. According to this policy area, reducing GHG emissions worldwide could significantly reduce the fatalities from roadway accidents due to fewer extreme weather events, less infrastructure damage, and less distraction to drivers. As a third policy area, reducing travel demand was investigated and resulted in a significant decrease in the rate of fatalities. This policy area was found to be a more effective way of reducing accidents than were policies aiming to increase fuel efficiency. Lastly, the effects of improving the vehicle safety index on recurring fatalities were investigated. Improving the vehicle safety index could significantly reduce the number of fatalities and should be prioritized.

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