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16. Abstract
The safety benefits of variable speed limits (VSL) have already been widely recognized. However, the environmental benefits of variable speed limits have been largely ignored. This paper presents a study of the potential benefits of variable speed limits in reducing mobile emissions. A Monte Carlo simulation approach is developed to evaluate the effectiveness of the idea of using variable speed limits to manage and reduce mobile emissions. A case study is performed on the IH-35 corridor in Austin, Texas. The numerical results indicate that on "Ozone Action" days, by managing the freeway/expressway traffic speeds at appropriate levels through VSL, the major pollutants, such as Nitrogen Oxides (NOx) emissions, could be significantly reduced. Considering the large contribution from freeway/expressway traffic to mobile emissions, a variable speed limit strategy could be an effective measure to balance travelers' need for mobility with conservation of the environment.

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AN INVESTIGATION ON THE ENVIRONMENTAL BENEFITS OF A VARIABLE SPEED CONTROL STRATEGY

by

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Research Report SWUTC/06/473700-00072-1

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DISCLAIMER

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ABSTRACT

The safety benefits of variable speed limits (VSL) have already been widely recognized. However, the environmental benefits of variable speed limits have been largely ignored. This paper presents a study of the potential benefits of variable speed limits in reducing mobile emissions. A Monte Carlo simulation approach is developed to evaluate the effectiveness of the idea of using variable speed limits to manage and reduce mobile emissions. A case study is performed on the IH-35 corridor in Austin, Texas. The numerical results indicate that on "Ozone Action" days, by managing the freeway/expressway traffic speeds at appropriate levels through VSL, the major pollutants, such as Nitrogen Oxides (NOx) emissions, could be significantly reduced. Considering the large contribution from freeway/expressway traffic to mobile emissions, a variable speed limit strategy could be an effective measure to balance travelers' need for mobility with conservation of the environment.

EXECUTIVE SUMMARY

Traffic engineers in the U.S. and worldwide rely on the 85th percentile speed to establish speed limits. In recent years, some jurisdictions have begun experimenting with variable speed limits (VSL) that change with road congestion and other factors such as adverse weather conditions. It is generally recognized that a variable speed limit system provides real-time information about appropriate speeds for current conditions based on traffic flow, traffic speed, weather, and other inputs.

The development and applications of VSL in freeway operations, work zones, and adverse weather conditions were reviewed in the first part of this study. Worldwide applications and studies indicate that variable speed limits are potentially effective in improving highway operations and traffic safety. However, it was found that the environmental benefits of variable speed limits have been largely ignored. In order to better understand the potential benefits of variable speed limits in reducing mobile emissions, a Monte Carlo simulation approach is developed to evaluate the effectiveness of the idea of using variable speed limits to manage and reduce mobile emissions.

Two steps are proposed to perform the Monte Carlo simulation: 1) Identify the probability distribution of the average vehicle speed under the adjusted VSL speed limit; and 2) Generate the appropriate values of the random variable, which is the average vehicle speed. Then, the mobile emissions were estimated using the vehicle-miles of travel (VMT) and emission factors from the MOBILE6 model. Because the MOBILE6 model considers driving cycles that involve vehicle acceleration and deceleration, the VMT were allocated to certain driving cycles according to the average speed and facility type. In addition, the vehicle fleet composition was considered because the emission factors vary with different types of vehicles.

A case study was performed on the IH-35 corridor in Austin, Texas using traffic data collected by the Texas Department of Transportation in 2003. The numerical results indicate that on "Ozone Action" days, by managing the freeway/expressway traffic speeds at appropriate levels through VSL, the major pollutants, such as Nitrogen Oxides (NOx) emissions, could be significantly reduced. A comparison of NOx emissions under the 65 mph regular speed limit and the 55 mph new speed limit shows that if the VSL is operated day in an "Ozone Action Day," the variable speed limit strategy can help reduce emissions in morning off-peak hours, daytime off-

peak hours, and evening off-peak hours with a daily reduction of 10.8 percent. Considering the large contribution from freeway/expressway traffic to mobile emissions, a variable speed limit strategy could be an effective measure to balance travelers' need for mobility with conservation of the environment.

The development of technology accelerates the integration of traffic management. Through variable speed limits, speed control may also be integrated into traffic management systems to achieve the systems' optimization goals. However, there are several challenges associated with VSL implementations. The selection of variable speed scheme, driver's compliance, and speed enforcement may be the major obstacles for the implementation of VSL.

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CHAPTER 1. BACKGROUND REVIEW

1.1 INTRODUCTION

It is well known that speed limits are determined based on many factors, such as road features, crash records, legal statutes, administrative judgment, and engineering judgment. Two common measures for setting speed limits are the design speed of the road, and the 85th percentile of travel speeds.

In the U.S., the design speed is officially defined as "a selected speed used to determine the various geometric design features of the roadway," according to the 2001 American Association of State Highway and Transportation Officials (AASHTO) highway design manual, commonly referred to as the "Green Book." Previous versions of the Green Book referred to design speed as the "maximum safe speed that can be maintained over a specific section of highway when conditions are so favorable that the design features of the highway govern." However, the 2001 edition Green Book removed the term “safe” in order to avoid the misperception that speeds greater than the design speed are “unsafe.”

Safe observed operating speeds may exceed nominal design speeds for two reasons. First, the design speed specifies the roadway's most restrictive feature, such as a curve, bottleneck, or hill, rather than representative features along a roadway section. Second, actual roadway design may exceed the minimum design specifications. On busy roads, capacity and congestion are primary limiting factors on speeds. Therefore, design speed is considered only a "first guess" at an appropriate speed limit.

Traffic engineers in the U.S. and worldwide rely on the 85th percentile speed to establish speed limits. The 85th percentile is approximately two standard deviations above the mean of a normal distribution. According to the Federal Highway Administration (FHWA), all states and most local agencies in the U.S. use the 85th percentile speed of free-flowing traffic as the basic factor in establishing speed limits. The idea is that the speed limit should be set to the speed that separates the bottom 85 percent of vehicle speeds from the top 15 percent of vehicle speeds. Traffic engineers have observed that the majority of drivers drive in a safe and reasonable manner, as demonstrated by consistently favorable driving records. Studies have found that vehicles traveling faster than the 85th percentile speed or faster than the traffic flow have a higher crash risk than vehicles traveling around or modestly below the 85th percentile speed.

According to an Institute of Transportation Engineers (ITE) study (ITE, 2004), a realistic speed limit can:

- Encourage compliance from the majority of drivers;
- Give a clear reminder of reasonable and prudent speeds;
- Provide an effective enforcement tool to the police;
- Minimize public antagonism toward police enforcement, which results from seemingly unreasonable regulations; and
- Encourage drivers to travel at speeds for which the risk of crash involvement is the lowest.

An unrealistic speed limit may:

- Discourage voluntary compliance;
- Create the perception of "speed traps";
- Cause public antagonism toward the police;
- Create a bad image for a community in the eyes of tourists; and
- Increase the potential for crashes.

In recent years, some jurisdictions have begun experimenting with variable speed limits (VSL) that change with road congestion and other factors, which is distinct from France's reduction of speed limits during adverse weather (Wikipedia, 2006). It is generally recognized that a variable speed limit system provides real-time information about appropriate speeds for current conditions based on traffic flow, traffic speed, weather, and other inputs. Perhaps most importantly, the speed limit may be varied according to location, time of day, weather conditions, and road and traffic conditions.

One example of a variable speed limit application is on Britain's M25 motorway, which circumnavigates London. On the most heavily-traveled 22-kilometer (14-mile) section of the M25, variable speed limits combined with automated enforcement have been in force since 1995. Initial results of the 1995 trial indicated savings in journey times, smoother- flowing traffic, and a decrease in the number of accidents, so the trial implementation was made permanent in 1997. However, further trials on M25 have been thus far inconclusive (Bourn, 2004).

Variable speed limit systems have been around for the last 30 years and currently are successfully being used and/or tested in parts of Europe and Australia (SAIC, 2000). Emerging Intelligent Transportation System (ITS) technologies provide an opportunity to use more comprehensive variable speed control systems to improve traffic operations. Although many jurisdictions have expressed interest in variable speed limits, with the exception of school zones, variable speed limit deployments in the U.S. have been limited. Variable speed limit applications have not become more widespread primarily because of concerns over their legal basis, the level and type of enforcement required, and the lack of information regarding their proven benefits.

1.2 VARIABLE SPEED LIMIT APPLICATIONS

In many cases, a variable speed limit system is part of a larger incident management, congestion management, weather advisory, or motorist warning system. The most recognized benefit of variable speed limits thus far is improving safety. For example, Zarean (2001) reported a recently FHWA-initiated study focusing on the role that speeding plays in rural crash causalities and describes foreign and domestic applications of VSL systems. A variety of applications and studies have shown that variable speed limits can improve traffic operations in work zones and in adverse weather conditions.

Such applications have been found worldwide in Australia, Great Britain, Germany, Finland, France, the Netherlands, and the U.S. to control speed, promote safety, and reduce congestion (Zarean, 2001). In the U.S., variable speed limit systems have been deployed in Arizona, Colorado, Michigan, Minnesota, Nevada, New Jersey, New Mexico, Oregon, and Washington. These applications will be reviewed and summarized in this report.

1.2.1 VSL Applications for Freeway Operations

Worldwide applications and studies indicate that variable speed limits are potentially effective in improving highway operations. Most of the studies to date have focused on the impacts of safety-related issues. For example, Lee et al (2004) developed a method for evaluating the effectiveness of variable speed limits in reducing freeway crash potential. The real-time crash prediction model that was developed in earlier studies was used to estimate the crash potential for different control strategies of variable speed limits. The authors used a microscopic traffic simulation model to mimic realistic responses of drivers to changes in speed limits. The simulation results indicate that the total crash potential over the entire freeway segment could be significantly reduced under variable speed limit controls, with a minimal increase in travel time compared to the fixed speed limit.

In Germany, a variable speed limit system has been used since the 1970s on the Autobahn between Salzburg and Munich, between Sieburg and Cologne, and near Karlsruhe, to stabilize traffic flow in congestion and thereby reduce the probability of crashes (Zarean, 2001). Similar applications can also be found to manage traffic congestions in London, where speed limits are lowered according to vehicle volumes detected by using loop detectors and closed-circuit television. The system also "monitors traffic speeds and stationary traffic to slow vehicles down approaching a queue, and has additional logic to stop speed limit settings fluctuation too often." (NCHRP, 2002)

Morden (2003) presents an application of variable speed limits in Australia. The author described the experience of VicRoads, the state's highway agency, with variable speed limits, which sets limits between 50 kilometers an hour (31 miles/hour) and 100 kilometers an hour (62.5 miles/hour), depending on conditions. Speed limits were conveyed to motorists by a collection of seventy-four roadside electronic light-emitting diode (LED) variable speed limit signs on the freeway and its access points. Enforcement methods, data collection, and motorist acceptance were also discussed. The evaluation results indicate that by installing variable speed limit systems on the 26-kilometer (16 mile) Western Ring Road around Melbourne, Australia appears to be successfully easing traffic congestion and reducing traffic accidents.

Torday, et al (2001) presented a study that used a computer simulation tool for analyzing the effect of variable speed limit signs on traffic flow in Switzerland. The aim of this study was to determine the effects of implementation of variable speed limit signs on a heavily traveled motorway stretch. The evaluation tool, MITSIM Laboratory, was designed to model traffic flow in networks using telematics for traffic regulation and user information. Loop sensors were installed to measure traffic flow and video camera footage was used to calibrate the behavioral parameters of the model. A first series of simulations was aimed at evaluating the efficacy of the variable speed limit in terms of capacity and its effect on created congestion. No clear improvement in motorway performance was shown. A second series of simulations estimated the efficacy of the signs on road user safety. Again, no obvious benefits were seen. Finally, a progressive decrease in speed limits in the approach to an accident occurrence was studied, but again no clear difference in driver behavior occurred. According to the authors, the use of the simulation tool was considered justified.

The Washington State Department of Transportation is operating a variable speed limit system on I 90 across the Snoqualmie Pass. This system was installed because of high operating speeds and speed variances, which were found to contribute to winter collisions, primarily rear-end, sideswipe, and run-off-the-road collisions. In this study, it was found that (Steel et al, 2005): 1) Motorists usually drive as fast as the law allows and pay little attention to prevailing roadway conditions. Variable speed limits may lose their effectiveness without enforcement by the Washington State Patrol; 2) The reduction in mean speed and increase in speed deviation were significantly greater at the variable speed limit site than at the non-variable speed limit site, indicating that the effect of the variable speed limit was to reduce the mean speed and increase the deviation.

From March 1989 to August 1998, a variable speed limit system was in operation along IH 40 in Albuquerque. It was designed to operate in all freeway environments. This system responded quickly to changes in traffic conditions. In many situations, secondary accidents are a major problem when visibility is reduced. It was found that secondary accidents were significantly reduced by alerting motorists to driving conditions ahead using the variable speed limit system.

1.2.2 VSL Applications in Work Zones

In recent years, a variety of new and innovative technologies have been developed to make traffic operations in work zones safer and more efficient. Variable speed limits offer considerable promise in restoring the credibility of speed limits and improving safety by restricting speeds in work zones.

According to the U.S. Department of Transportation’s ITS Program, because of the continually changing nature of work zones and the fact that safe speeds depend on roadway conditions, variable speed limits can be particularly useful. Using VSL in work zones may result in increased credibility of speed limits, greater speed compliance, improved safety, and improved traffic flow (Petsi et al, 2004).

The FHWA has participated in cooperative agreements with three states—Maryland, Michigan, and Virginia—to evaluate the use of variable speed limits in work zones. These projects are a joint effort between the Safety and ITS Joint Project Offices. Field tests have been carried out in cooperation with Maryland and Michigan to implement and analyze the effectiveness of variable speed limits in work zones. The variable speed limits are displayed on portable trailers and rely on the input of vehicle speeds, presence of road work activity, and other information to post appropriate speed limits, which allows motorists to maintain the most efficient and safe speeds without endangering themselves, other drivers, or workers. Results of several deployments in an 18-mi work zone in Michigan indicate that speed limit compliance is affected, the credibility of the speed limits is increased, safety is improved, and traffic flow is improved (USDOT, 2004).

Lin et al (2004) present two online algorithms for VSL controls in highway work zones that can take full advantage of all dynamic functions and concurrently achieve the objectives of queue reduction or throughput maximization. The authors conducted extensive experiments to evaluate the effectiveness of these proposed algorithms, based on simulated highway systems that have been calibrated with field data. The results of these simulation analyses have confirmed that variable speed limit algorithms can yield a substantial increase in work-zone throughputs as well as a reduction in total vehicle delays. The results also indicate that traffic flows that implement variable speed limit controls through work zones tend to exhibit lower speed variances than those without variable speed limit controls. The proposed variable speed limit control algorithms appear to offer promise for contending with congestion and safety-related issues in highway work zones.

1.2.3 VSL Applications in Adverse Weather Conditions

Rama (1999) presents a variable speed limit application on the weather-controlled E 18 road in Southeast Finland. In this study, speed limits are controlled by data from unmanned road weather stations. The speed limits are lowered automatically during adverse road conditions and, in some cases, signs for slippery road conditions are displayed as well. The effects of the system on the two-lane section were as expected, assuming the system had been used appropriately. The results showed that raising the speed limit from 80 km/h (50 mile/h) to 100 km/h (62.5 mile/h) increased the mean speed by 3.9 km/h for cars traveling in free-flow traffic in good road surface conditions. Under adverse road conditions, the variable speed limits decreased the mean speed and increased the headways between vehicles, which was desirable for traffic safety. Drivers generally accepted variable speed limits on the E 18 road because 96 percent of the drivers indicated that variable speed limit signs based on real-time weather and road condition data were worthwhile. Interviews showed that drivers assessed the system in terms of traffic safety improvement, fluency of traffic flow, and compliance with speed limits. The findings suggested that the use of variable speed limits calls for a sophisticated control system. Inadequate speed limits increased the mean speed excessively and decreased headways substantially, which compromised traffic safety. Drivers both accepted variable speed limits and relied on the system.

The Washington State Department of Transportation (WSDOT) (2005) installed eight variable speed limit signs and an electronic message sign on a 23-mile segment of US 2 over Stevens Pass. The variable speed limit system allows a quick response to changing weather conditions by adjusting the speed limits to safer levels and by activating the electronic message sign, which warns drivers about specific problems. Web cameras, environmental sensor stations, and roadway sensors provide up-to-the-minute information about weather and roadway conditions to the traffic management center that operates the Variable Speed Limit System. According to WSDOT, this project improved safety for both vehicular traffic and pedestrians over Stevens Pass.

From 1998 to 1999, a fuzzy variable speed limit system was developed in Arizona (USDOT-ITS, 2006). An experimental prototype of a variable speed limit software program for rural highways was developed using information from a typical road weather information station. Traffic information inputs included traffic flow density data and traffic speed data. The anticipated output from the proposed system included a speed limit reduction recommendation, which could be broadcasted on a preprogrammed speed limit sign or traffic message board. However, since these early project phases were proof-of-concept tests, no hardware or equipment of any type needed specifically for future variable speed limit field tests was ever procured or deployed. The physical work involved in this effort was restricted to software development only.

1.3 COMPONENTS OF A VARIABLE SPEED LIMIT SYSTEM

In general, variable speed limit systems use sensors to monitor prevailing traffic and/or weather conditions, posting appropriate enforceable speed limits on dynamic message signs. A typical variable speed limit system contains the following components:

- Traffic and speed detectors
- Variable speed signs
- Microprocessor
- Communication
- Environmental sensors
- Base station for recording speed limit changes

Figure 1.1 shows a variable speed limit system on I 90 at Snoqualmie Pass in Washington State. Because of the rapid evolvement of ITS technologies, many types of signs and control devices for variable speed limit systems, particularly the technology and placement of variable message signs, have been developed. Transportation agencies can choose these technologies and products according to their needs and budgets.

Figure 1.1: Variable Speed Limit System on I 90 at Snoqualmie Pass
(Source: Washing State DOT, 2006)

1.4 RESEARCH OBJECTIVE

A variable speed limit system displays flexible speed limits to match traffic and environmental conditions. Although it has been in use for more than 30 years, it has not been widely utilized in the U.S. because of reasons such as unclear benefits, legal issues, and enforcement issues. Experiences with variable speed limits indicate that traffic flow can be improved and safety enhanced with these systems.

In the projects implemented in the U.S. and worldwide, the general objectives and potential benefits of variable speed limit deployments include:

- Enabling real-time/dynamic freeway traffic control
- Smoothing traffic flows and reducing the incidences of stop-and-go driving
- Improving traffic safety in work zones or bad weather conditions

- Improving traffic safety on rural roads
- Increasing compliance by reducing the number of speed violations

The safety benefits of variable speed limits have been widely recognized. However, the potential environmental benefits of variable speed limits have been generally ignored. Previous studies have shown that mobile emissions are highly correlated with vehicle speeds and can be significantly reduced if traffic speeds are maintained at appropriate levels. Some transportation agencies have proposed a 55 mile/hour speed limit as a traffic control measure to reduce vehicle emissions.

Because many "non-attainment" areas are struggling with making mobile emissions meet the Environmental Protection Agency (EPA) standards, the variable speed limits, as an effective traffic control measure, can play an important role among those emission-mitigation methods. For example, a variable speed limit system may be used to mitigate air pollution based on the forecasts of ozone levels: When the ozone risk is low, a variable speed limit system could post the regular speed limit. On "ozone action" days, variable speed limits can be used to maintain traffic speeds at appropriate levels so that vehicle emissions can be reduced to lower levels.

In order to better understand the air quality benefits of variable speed limits, further research is needed to quantify the air quality benefits and examine the implementation issues. The overall objective of this project is to evaluate the environmental benefits of a variable speed control strategy and provide recommendations for variable speed limit deployments. Three objectives will be accomplished in the project: 1) The mobile emission factors at different speed levels will be examined; 2) A Monte Carlo simulation model will be developed to quantify the environmental benefits of the variable speed control strategy; 3) A case study will be conducted to illustrate the results.

1.5 REPORT ORGANIZATION

This report is organized in the following manner: Chapter 2 covers the necessary background information regarding mobile emission factors and the impact of traffic speed on emission rates. Chapter 3 introduces a Monte Carlo simulation method to quantify the potential air quality benefits of variable speed limits. Chapter 4 summarizes the findings of this study, provides conclusions, and makes recommendations for future studies.

CHAPTER 2. MOBILE EMISSIONS AND VEHICLE SPEEDS

2.1 VEHICLE EMISSIONS AND AIR POLLUTION

According to the Federal Clean Air Act, which was last amended in 1990, any area that violates the national ambient air quality standards for any of the six criteria pollutants as infrequently as one time per year and as often as four times over a 3-year period is classified as a "nonattainment" area. The following common pollutants, also referred to as "criteria" pollutants, have been used by the EPA to set national air quality standards:

- Ozone
- Carbon Monoxide
- Nitrogen Dioxide
- Sulfur Dioxide
- Particulate Matter
- Lead

Nonattainment areas for ozone, carbon monoxide, and PM10 are classified according to how severely they are polluting the air. If a nonattainment area fails to comply with air pollution standards by a specified deadline, the EPA may extend the deadline but impose more stringent requirements to meet the standards. In 1997, for example, the EPA rejected Dallas-Fort Worth's bid for an extension to comply with the deadlines set for "moderate" ozone nonattainment areas, and instead, the EPA reclassified the area as a "serious" ozone nonattainment area because of lack of progress in meeting the ozone standard (Loftis et al., 1997). In addition, if a state fails to develop a proper state implementation plan or fails to implement the plan, the EPA may develop a federal implementation plan for the area and may also impose sanctions for noncompliance, including the loss of federal highway construction funds, bans or stiffer limits on further industrial expansion, and the loss of federal Air Pollution Control Program grant funds.

The transportation sector is a primary source of air pollutants in nearly all metropolitan areas, causing many urban areas to be “nonattainment” areas. The harmful pollutants emitted by motor vehicles include Nitrogen Oxides (NOx), Carbon Monoxides (CO), Hydrocarbons (HC), and others. These pollutants, especially the NOx, have been linked to some serious health and environmental problems such as respiratory ailments, global warming, ground-level ozone (smog), acid rain, visibility impairment, and nutrient overload that deteriorates water quality. For example, hydrocarbons react with nitrogen oxides in the presence of sunlight and elevated temperatures to form ground-level ozone. This can cause eye irritation, coughing, wheezing, and shortness of breath and can lead to permanent lung damage. Nitrogen oxides (NOx) also contribute to the formation of ozone and acid rain, as well as contributing to water quality problems. Carbon monoxide is a colorless, odorless, deadly gas that reduces the flow of oxygen in the bloodstream and can impair mental functions and visual perception. Motor vehicles also emit large amounts of carbon dioxide, which has the potential to trap the earth's heat and cause global warning.

Pollution control measures and automobile technologies have drastically reduced emissions per vehicle in the past 20 years. However, during that time, the total vehicle miles traveled (VMT) has doubled, resulting in higher levels of air pollutants in many parts of the country. Batchman et al. (2000) have estimated that the estimation for the amount of pollutants produced by automobiles ranges from 33 percent to 97 percent of CO, 33 percent to 50 percent of NOx, 40 percent to 50 percent of HC, 50 percent of ozone precursors, and at least one-fourth of volatile organic compounds (VOC) (Chatterjee et al., 1997; SCAQMD, 1996; USEPA, 1995; CARB, 1994; USDOT, 1993).

In many urban areas, motor vehicles are the single largest contributor to ground-level ozone, a major component of smog, and the most serious air pollution problem in many states. According to a study of the U.S. EPA, the transportation sector is the largest source of NOx and contributes 55 percent of the total NOx emissions (U.S. EPA, 2006). Figure 2.1 presents an overview of manmade sources of nitrogen oxide emissions in 2003. Nitrogen oxides are generated when fuel is burned at high temperatures, as in a combustion process. As shown in Figure 2.1, the primary sources of NOx from human activities include motor vehicles, electric utilities, and other industrial, commercial, and residential sources that burn fuels. NOx can also be formed naturally. In order to reduce the NOx emissions, the EPA and local governments have worked on strategies such as vehicle inspection and maintenance programs, fuel improvement programs, trip reduction programs, transit-oriented development, and transportation control measures. Although these strategies have been effective in mitigating emissions, many metropolitan areas are still facing the overwhelming pressure of reducing NOx levels. Therefore, it is especially necessary to find innovative measures that help reduce mobile emissions such as NOx.

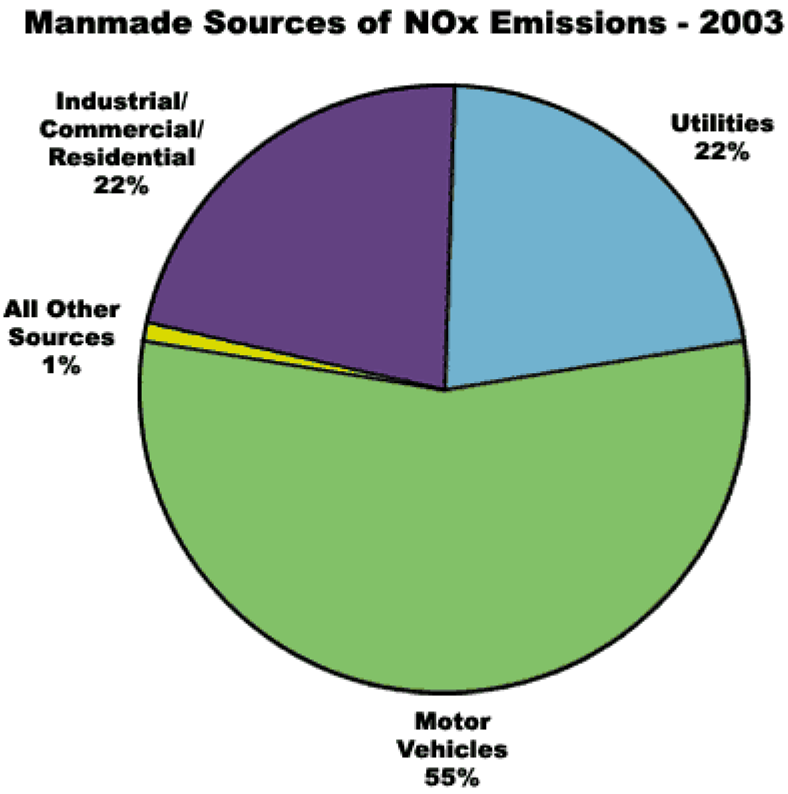


Figure 2.1: An Overview of Manmade Sources of NOx Emissions in 2003
(Source: U.S. EPA, 2006)

Because of the harmful nature of these pollutants, the U.S. Environmental Protection Agency (EPA), state agencies, and local governments have been working together to mitigate mobile emissions. Metropolitan areas with unacceptable air quality levels, i.e., nonattainment areas, must develop effective strategies to reduce air pollution. Currently, the EPA considers reducing NOx emissions a crucial component of its strategy for cleaner air (U.S. EPA, 2006).

2.2 VEHICLE OPERATION AND EMISSIONS

In general, motor vehicles release pollutants in two ways: from the tailpipe as the result of the fuel combustion process and from under the hood and throughout the fuel system when heat causes fuel evaporation. It has been widely recognized that evaporative emissions occur at these times:

- When outside temperatures on hot/sunny days cause fuel to evaporate
- When the hot engine and exhaust system of a running car cause the fuel to become heated
- When the car is turned off and remains hot enough to cause fuel to evaporate
- During refueling, when gasoline vapors escape into the air from the gas tank and the gas hose nozzle

During the fuel combustion process, a significant number of tailpipe pollutants are released during the *cold start* phase, or the first few minutes it takes a car to warm up. Since a car warms up faster when it is moving, drivers are advised to limit warm-up time to reduce emissions. Combining trips also decreases motor vehicle emissions because it reduces the number of cold starts and VMTs.

Figure 2.2 shows an example of the emissions of a typical car in a 5-mile trip. The emission data can be found in the Environmental Science Activities for the 21st Century study (ESA21 project website: http://esa21.kennesaw.edu/). The estimates of pollutants derived are based on the MOBILE 5a outputs. Volatile Organic Compounds (VOC) are emitted from both the tailpipe and through fuel evaporation. When the engine is warm, approximately 2.7 grams of VOC are emitted from the tailpipe in a 5-mile trip, and evaporative emissions (during travel and while cooling down) result in 2.8 grams of VOC. However, when the engine is started cold, an extra 2.5 grams of VOC will be generated. On hot summer days, even when a car has been parked all day, approximately 3.8 grams of VOC are emitted from the vehicle's fuel tank. On the other hand, the vehicle emits about 6.7 grams of NOx and 32.5 grams of CO if the engine is started warm. However, if the engine is started cold, an additional 2.1 grams of NOx and 19.7 grams of CO are generated. Therefore, for a 5-mile trip, starting the car cold generates approximately 30 percent more NOx and 60 percent more CO than starting the car warm.

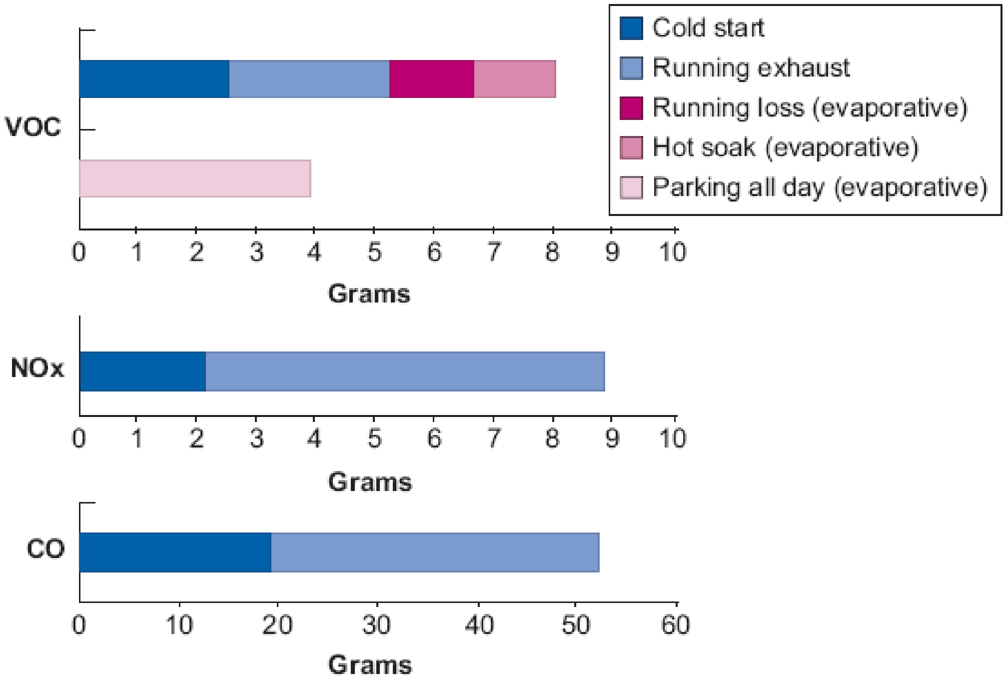


Figure 2.2: Vehicle Emissions for a Typical Car in a 5-mile Trip

(Source: Estimates developed using MOBILE 5a, assuming basic inspection and maintenance, summer temperature 62-72 degrees, 32 miles per hour average speed.)

Because vehicle emission rates vary at different speeds and in different operation patterns, it has been suggested by the EPA and other national councils that drivers help reduce motor vehicle emissions in the following ways:

- Reduce driving and VMTs. This can be achieved by carpooling, car sharing, using public transportation, and planning ahead to combine trips. It is estimated that one person using mass transit for an entire year, instead of driving to work, can keep an average of 9.1 lbs of hydrocarbons, 62.5 lbs of carbon monoxide, and 4.9 lbs of nitrogen oxides from being discharged into the air. One full, 40-ft bus also takes 58 cars off the road. A 10 percent nationwide increase in transit ridership would save 135 million gallons of gasoline a year (National Safety Council, 2006).
- Drive at moderate speeds (lowest emission rates can be reached between 35 and 45 miles per hour), and reducing idling time. High speeds result in greater emissions, and idling for more than half a minute burns more fuel than it takes to restart the engine.

- Keep vehicles in good condition. Poorly maintained or malfunctioning vehicles can release as much as 10 times the emissions of a well-maintained one. Motorists should follow the manufacturer's instructions on routine maintenance, such as oil and filter changes, and have the vehicle inspected regularly. It is also suggested that motorists keep track of fuel economy and watch the exhaust. A loss in economy usually means an increase in emissions. If the exhaust is black, there is too much gas in the fuel mixture and the fuel injection system needs to be checked. If the exhaust is blue, the car is burning oil and releasing excess hydrocarbons. If the air conditioning leaks, fix it immediately.
- Use clean fuels, when available. When refueling, motorists should make sure the gas cap fits properly to avoid spills. Clean fuels include reformulated gasoline, oxygenated gasoline, and alternative fuels. The EPA estimates that reformulated gasoline reduces ozone-forming emissions and toxic air pollutants by 15 to 17 percent. Reformulated gasoline will be required in areas where ozone levels exceed the federal health standard. Oxygenated gasoline is federally mandated in areas that do not meet the federal health standard for carbon monoxide. It contains at least 2.7 percent oxygen on average. It is sold during the colder months of the year when carbon monoxide is more of a problem. Alternatively fueled vehicles run on a variety of fuels, including methanol, ethanol, compressed natural gas, and electricity, all of which reduce emissions.
- Choose newer, less-polluting cars, such as low-emission, hybrid, and alternatively-fueled vehicles.

In summary, from the aspect of vehicle operations, emissions can be reduced by reducing VMTs, maintaining vehicles in good condition, using clean fuels if available, choosing newer and less-polluting vehicles, and driving vehicles at moderate speeds.

2.3 EMISSION RATES ESTIMATION MODELS

Mobile source emission prediction models used by state and federal agencies include the Environmental Protection Agency's (EPA) MOBILE and California Air Resources Board's EMFAC model. The MOBILE model has been widely applied by state DOTs and metropolitan planning organizations (MPOs) in transportation planning and environmental impact analysis. MOBILE6 is the newest mobile source emission factor model developed and published by the EPA (2003) for mobile emissions prediction. It is a software package that can provide predictions of current and future emissions from on-road traffic. The MOBILE6 model is capable of analyzing three common criteria pollutants: hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx). This model can calculate emission rates under different conditions affecting in-use emission levels, as specified by the modeler, to address a wide variety of air pollution modeling needs.

In order to assure that the MOBILE6 is based on the best data and calculation methodologies available, the EPA has made tremendous efforts. For example, the EPA staff has produced more than forty technical reports explaining the data analysis behind the MOBILE6 estimates and the methods used in the model. All papers and reports were extensively reviewed within the EPA, and papers reporting major new data analyses were sent to external experts for independent peer reviews. All comments were considered as they were received, and the MOBILE6 methodologies were revised in response to comments as necessary (U.S. EPA, 2003).

2.4 VEHICLE SPEEDS VERSUS EMISSIONS RATES

Travel distance and emission rate are typical factors that affect the amount of pollutants generated by a vehicle. When the travel distance is fixed, the emission rate then becomes the key factor affecting the total amount of emissions. According to the EPA's emission factor model, MOBILE 6, the facility type and the speed range are primary factors influencing the vehicle emission rates. Emission rates vary at different speeds when a vehicle is running. The EPA's MOBILE 6 model explains how speed affects emission rates: volatile organic compounds (VOC) emission rates typically drop as speed increases, whereas NOx and CO emission rates increase at high speeds. In general, emission rates at all speeds have been falling over time as newer, more advanced vehicles enter the fleet.

Figure 2.3 gives an example of the emission rate curve of NOx based on the MOBILE 6 model outputs.

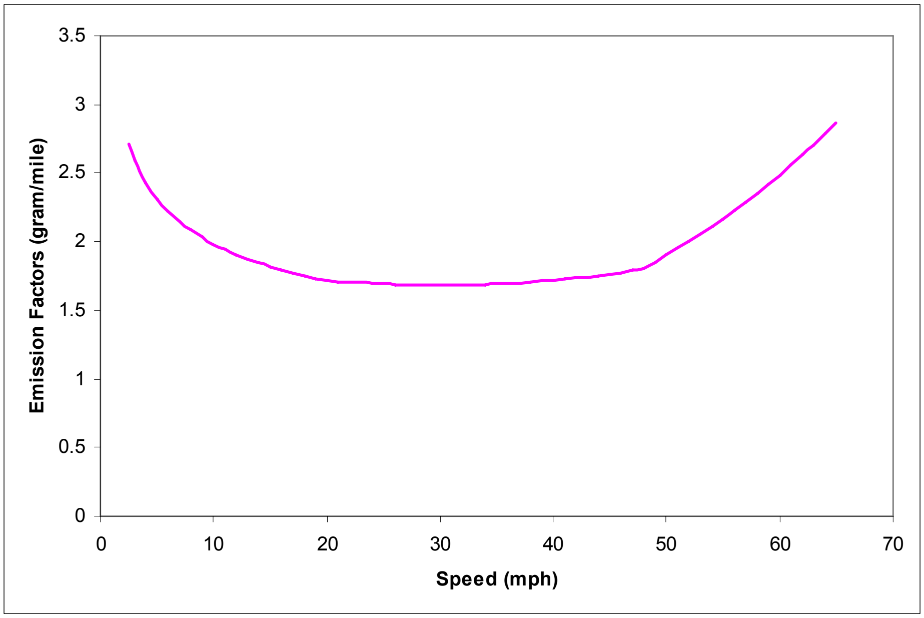


Figure 2.3: Emission Rates of NOx from the EPA MOBILE6 Model

Figure 2.3 shows that the emission rates of NOx first decrease as speed increases and then increase as the speed increases over a certain value. An “optimal” speed exists, thus providing us an opportunity to use speed control strategies to reduce mobile emissions.

According to the EPA, the curve does not represent the full range of effects associated with travel at different speeds. Emission rates are higher during stop-and-go, congested traffic conditions than during free flow conditions operating at the same average speed. Modeling improvements are still underway to capture these effects. At present, the EPA's MOBILE 6 model only provides vehicle emission rates for speeds of 65 mph and lower, which limits the ability of analysts to assess the implications of actions that affect vehicles operating at speeds higher than 65 mph. This limitation may be a major issue when speed limits are increased from 75 mph to 80 mph on freeways and toll roads in many areas.

Standard emission factor models such as the MOBILE 6 derive emission rates as a function of vehicle speed. By applying speed-based emission rates, the emission impacts of strategies affecting traffic flow can be estimated to some extent. In this study, as a traffic flow control strategy, variable speed limit’s impact on vehicle emissions will be evaluated, based on speed-based emission rates.

CHAPTER 3. THE ENVIRONMENTAL BENEFITS OF A VARIABLE SPEED LIMIT STRATEGY

3.1 POTENTIAL ENVIRONMENTAL BENEFITS OF VARIABLE SPEED LIMITS

In practice, there are two basic types of speed control strategies: the static speed limit and the variable speed limit (VSL). The focus of this study is on variable speed limits. As introduced in Chapter 1, the safety benefits of VSL have already been widely recognized. However, the potential environmental benefits of VSL have been largely ignored. Since emission rates are highly affected by vehicle speeds, applying traffic speed control strategies such as variable speed limits could be an effective method to reduce vehicle emissions. Based on speed-based emission rates, the impact of variable speed limit strategies can be quantified to some extent.

In a recent study (Wang and Walton, 2003), it was found that over 40 percent of NOx could be generated by the traffic on the freeways and expressways in a metropolitan area such as Austin, Texas. Traffic flow-speed patterns on freeways and expressways seen in a 24-hour period hint that proper speed control operations can possibly reduce mobile emissions by managing the traffic speed at an appropriate level. Figure 3.1 depicts a typical 24-hour freeway/expressway traffic speed and flow pattern with a 65 mph speed limit. In general, a 24-hour traffic operation can be classified into five periods: morning off-peak hours, morning peak hours, daytime off-peak hours, evening peak hours, and evening off-peak hours. As shown in Figure 3.1, period A, B, and C represent morning off-peak hours, daytime off-peak hours, and evening off-peak hours, respectively. During off-peak hours, free-flow traffic speeds are normally distributed with a mean around the posted speed limit. It is widely recogonized that high speeds usually cause high vehicle emissions. If traffic speeds can be limited to lower levels during periods A (morning off-peak hours), B (daytime off-peak hours) and C (evening off-peak hours,) based on the forecast of environmental risk, it might be possible to decrease vehicle emission rates and the resulting mobile emissions. For example, if the VSL is operated on the freeway/expressway at an optimal speed limit on the predicted “Ozone Action” days and at the regular speed limit on normal days, the environmental risk could be reduced without causing a great deal of negative impact. Since many “nonattainment” areas are struggling against mobile emissions to meet the EPA standards, the VSL could play an important role among emission mitigation measures.

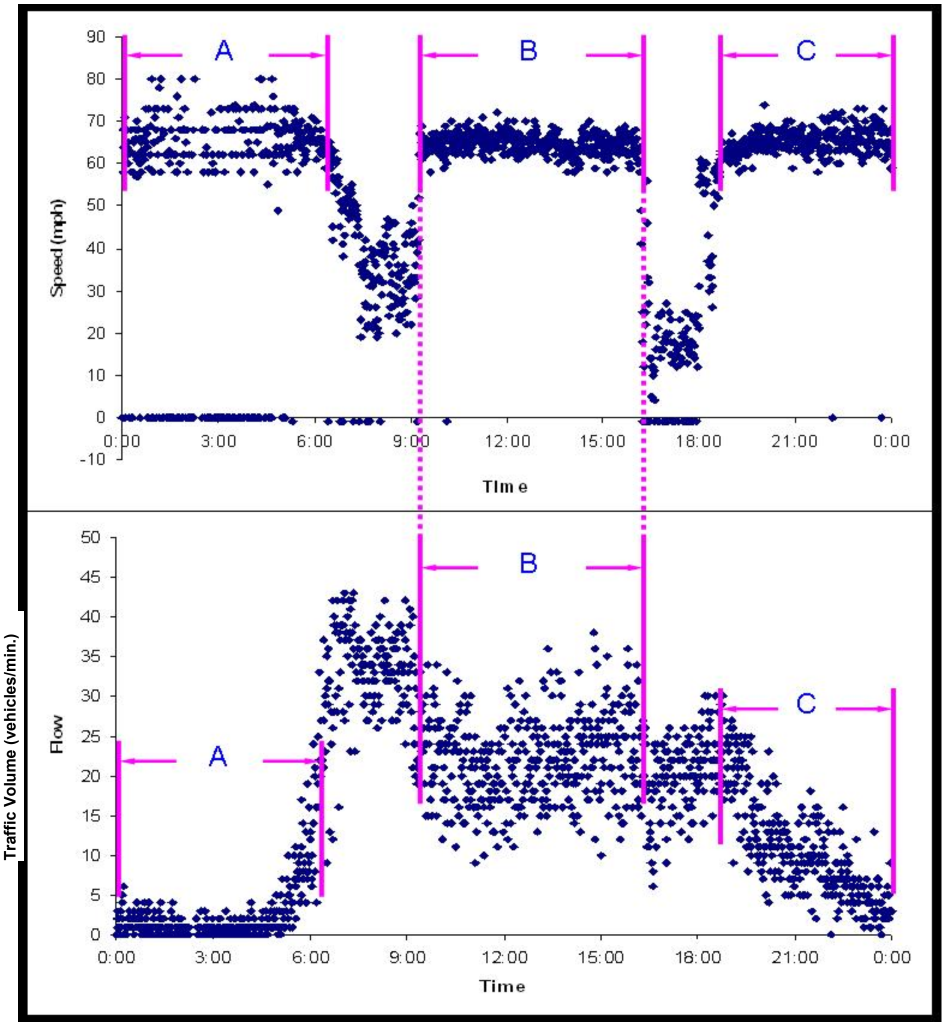


Figure 3.1: A Typical 24-hr Freeway Traffic Speed and Flow Pattern with a 65 mph Speed Limit

With the idea proposed above, a question needs to be answered: How effective is the VSL? To answer this question, a Monte Carlo simulation approach was developed and the numerical analysis is presented in this document.

3.2 EMISSION ESTIMATION METHODOLOGY

To estimate the total amount of the emissions from motor vehicles, the following formula is introduced:

$$E_i = \sum_{j=1}^{N} \sum_{k=1}^{V} C_{ijk} \cdot D_{jk} \qquad \text{(Equation 3.1)}$$

where

E_i — the total amount of pollutant i (gram), i represents NOx, CO, and HC

C_{ijk} — the emission rate of vehicle j with average speed k for pollutant i (gram/mile or gram/km)

D_{jk} — the distance vehicle j traveled with average speed k (mile or km)

N — traffic volume

V — the speed range of the moving traffic on that road segment

The equation above contains two variables: one is the emission factor, which represents the emission rate of a motor vehicle at a certain average speed, the other is the travel distance. The travel distance can be easily measured and the emission factors can be derived from the EPA MOBILE6 model.

As described earlier, MOBILE6 is a computer software program that estimates hydrocarbon (HC), carbon monoxide (CO), and nitrogen oxides (NOx) emission factors for motor vehicles with gasoline and diesel engines. It can be customized by users according to local ambient temperatures, travel speeds, operating modes, fuel volatility, and mileage accrual rates. Please see the EPA's MOBILE6 web page at *http://www.epa.gov/otaq/models.htm* for details.

The mobile emissions can be estimated using the vehicle-miles of travel (VMT) as the activity factor and emission factors from the MOBILE6 model. Because the MOBILE6 model considers driving cycles that involve vehicle acceleration and deceleration, the VMT needs to be allocated to certain driving cycles according to the average speed and facility type. In addition, the vehicle fleet composition should also be considered because the emission factors vary with different types of vehicles. However, in this study, the cold starts of vehicles are not considered since the concern is regarding freeway/expressway travel.

The simplest way to examine the effectiveness of using the VSL to reduce mobile emissions is to compare the emission levels under the regular speed limit to the emission levels under the adjusted speed limit. The total amount of pollutants under the regular speed limit can be easily computed with the on-site collected traffic data. There are two possible ways to calculate the total amount of pollutants under the adjusted speed limit: one is to perform a field experiment and collect the necessary data, the other is to use a simulation method to replicate the data. Since the purpose of this study is to theoretically examine the effectiveness of the idea of using the VSL to reduce mobile emissions, a simulation method is more suitable. Hence, a Monte Carlo simulation approach is introduced instead of the field experiment approach in this study.

The Monte Carlo simulation method is usually applied to address problems involving random variables with known or assumed probability distributions. With the simulation, a sample data set can be obtained to represent the field experimental observations. In this study, the Monte Carlo simulation approach was used to simulate the average vehicle speeds under the adjusted speed limit to be posted on the VSL signs during high environmental risk periods such as "Ozone Action" days. Two steps are proposed to perform the Monte Carlo simulation:

1) Identify the probability distribution of the average vehicle speed under the adjusted VSL speed limit. In many literatures, the vehicle speed is assumed normally distributed. In this study, a goodness-of-fit test on field-collected data is employed to identify the probability distribution of average vehicle speed on a freeway/expressway under the adjusted VSL speed limit.
2) Generate the appropriate values of the random variable, which is the average vehicle speed in this study. When the probability distribution of the variable is specified, a computer can be used to generate the random values. This can be accomplished by first generating uniformly distributed random numbers between 0 and 1 and then transforming the uniform random numbers into corresponding random numbers with specified distribution.

Once the sample of average vehicle speeds is obtained, the total emissions under the adjusted speed limit can be estimated through equation 3.1 and compared to the total emissions under the regular speed limit. With multi-day traffic flow-speed data, a reliability analysis can be performed on the effectiveness of the variable speed limit. A prediction interval for the emission reductions and the analysis of variance can be provided.

3.3 A CASE STUDY IN AUSTIN, TEXAS

A case study was performed in Austin, Texas using the methodology proposed to examine the effectiveness of a variable speed limit strategy in reducing mobile emissions. The Interstate Highway 35 (IH-35) Corridor was chosen for numerical analysis. IH-35 is the largest corridor in Austin, and its daily traffic volume in both directions exceeds 130,000 vehicles. A recent study shows that 32 percent of the NOx in the Austin area is contributed by the traffic on IH-35 (Wang and Walton, 2003).

The current speed limit on the selected IH-35 segment is fixed at 65 mph. With the assumption that the current fixed speed limit sign is replaced by a variable speed limit sign, which will be operated with a 65 mph limit during normal days and a 55 mph limit during the predicted “Ozone Action” days, the effectiveness and potential environmental benefits of the variable speed limit during the “Ozone Action” days are investigated with the single-day and multi-day traffic data. Three assumptions are made in the numerical analysis:

1) The emission factors from the MOBILE6 model are reasonable for use.
2) Drivers comply with the speed limit on variable speed limit signs.
3) The new speed limit will not cause congestion on the freeway/expressway and adjacent streets when operated. Namely, the level of service will not be significantly affected by variable speed limits during off-peak hours.

3.3.1 Vehicle Fleet Composition

The vehicle fleet composition is a factor that must be considered in using the MOBILE6 model to derive emissions rates. Travis County (863,026 registered vehicles) and Williamson County (234,674 registered vehicles) vehicle registration data was obtained from the Texas Department of Transportation (TxDOT). A sample of the vehicle registration data is provided in Table 3.1.

Table 3.1: A Sample of the Vehicle Registration Data

VIN	YEAR	MAKE	MODEL	ENGINE TYPE	ADDRESS		ZIP
2T1FF28P61C529126	2001	TOYT	CEE	0	AUSTIN	TX	78759
1G1JC5119K7142575	1989	CHEV	CAV	0	AUSTIN	TX	78759
JHMCG5646XC039392	1999	HOND	ALX	0	AUSTIN	TX	78759
1G4HP54K624161564	2002	BUIC	LCF	0	AUSTIN	TX	78759
3G4AG55N0PS623389	1993	BUIC	CSP	0	AUSTIN	TX	78759
1G1JC5244V7121954	1997	CHEV	CAV	0	AUSTIN	TX	78759
19UYA42681A013570	2001	ACUR	32S	0	AUSTIN	TX	78759
1FMDU34X1PUC15061	1993	FORD	EPR	0	AUSTIN	TX	78759
WVWAH63B41P047943	2001	VOLK	PGS	0	AUSTIN	TX	78759
1HGCD5620RA009717	1994	HOND	UDX	0	AUSTIN	TX	78759
1FAFP40491F226851	2001	FORD	MUS	0	AUSTIN	TX	78759
1HGEJ6678TL057707	1996	HOND	UCL	0	AUSTIN	TX	78759
JH4DC2382SS000156	1995	ACUR	GSR	0	AUSTIN	TX	78759

The information contained in the data set gives the vehicle identification number (VIN), year, make, model, and engine type (gasoline/diesel). Since the EPA MOBILE6 model is used to calculate the mobile emission rates, the vehicle classification standards suggested by the EPA are employed in this study. According to the user's guide to the MOBILE6 (U.S. EPA, 2003), the vehicles in the U.S. can be categorized into 28 types. The classification standards are shown in Appendix A. Many of these individual classes are in pairs: a gasoline-fueled class and a corresponding diesel-fueled class.

Most of the registered vehicles in Travis County and Williamson County are light duty gasoline vehicles and light duty gasoline trucks. Light-Duty Gasoline Vehicles (LDGV) contain regular passenger cars such as sedans, couples, wagons, compact SUVs, and minivans. Light-Duty Gasoline Trucks (LDGT) are small trucks and full-size SUVs. Following EPA guidance, all registered vehicles in Travis County and Williamson County were classified into the following five categories according to vehicle year, make, engine type, and model:

1) LDGV: Light-Duty Gasoline Vehicles (Passenger Cars);
2) LDGT1: Light-Duty Gasoline Trucks 1 (0-6,000 lbs. GVWR, 0-3,750 lbs. LVW);
3) LDDV: Light-Duty Diesel Vehicles (Passenger Cars);
4) LDDT12: Light-Duty Diesel Trucks 1and 2 (0-6,000 lbs. GVWR);
5) LDDT34: Light-Duty Diesel Trucks 3 and 4 (6,001-8,500 lbs. GVWR).

The analysis shows that the vehicle fleet in Travis County is composed of 66.04 percent LDGV, 31.62 percent LDGT1, 0.17 percent LDDV, 1.78 percent LDDT12, and 0.39 percent LDDT34. Figure 3.2 shows the fleet composition in the Austin area. Based on the IH-35 traffic data, it was found that on IH-35, the heavy duty commercial trucks account for 11 percent of the traffic volume. Therefore, it was assumed that 11 percent of the traffic on IH-35 are large trucks and the rest are LDGV, LDGT1, LDDV, LDDT12, and LDDT34 vehicles proportional to their percentages in the vehicle registration data base.

One problem encountered in this study was the classification of sports utility vehicles (SUV). Most of the SUVs are actually equipped with the same or similar engines and platforms as light-duty trucks. Considering that emission rates are basically determined by the engine type, gross weight of the vehicle, and vehicle speed, the SUVs were defined as light-duty gasoline trucks (LDGT) in this study.

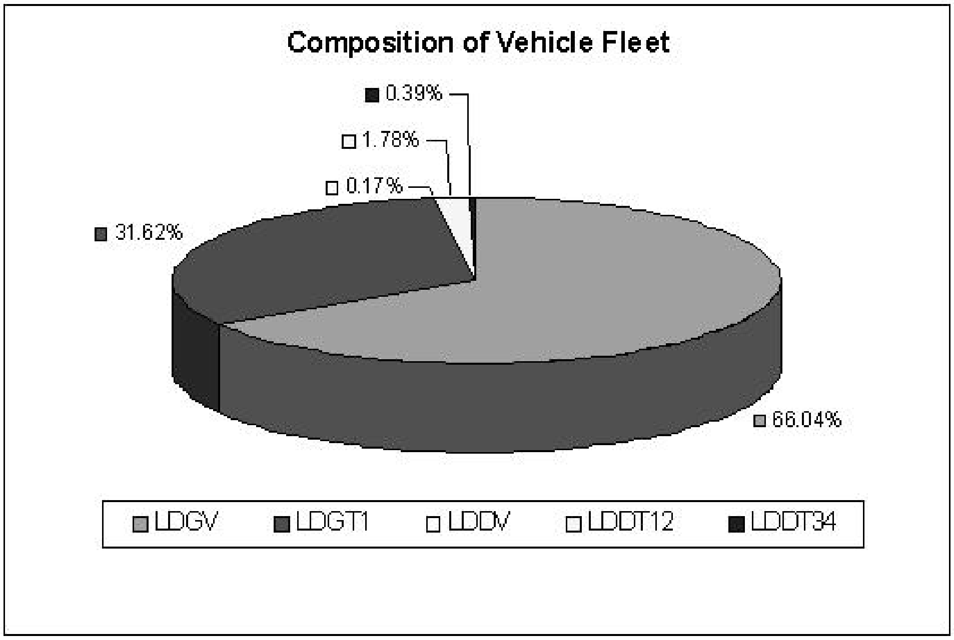


Figure 3.2: Fleet Composition of Registered Vehicles in Austin, TX

3.3.2 MOBILE6 Emission Rates

The emission factors for HC, NOx and CO are developed with the EPA MOBILE6 Model. As described in Chapter 2, the MOBILE6 Model is a software package that can provide estimates of current and future emissions from all types of automobiles. According to the user's manual of the MOBILE6 Model (U.S. EPA, 2003), it can be used to calculate average in-use fleet emission factors for:

- Three criteria pollutants: hydrocarbons (HC), carbon monoxide (CO), and oxide nitrogen (NOx).
- Gas, diesel and natural-gas-fueled cars, trucks, buses, and motorcycles.
- Calendar years between 1952 and 2050.

In the MOBILE6.0 model, there are twenty-six input parameters. These parameters are provided as below:

- Calendar year
- Month (January, July)
- Hourly Temperature
- Altitude (High, low)
- Weekend/weekday
- Fuel characteristics (Reid vapor pressure, sulfur, Reformulated gasoline)
- Humidity, solar load, and air-conditioning fractions
- Registration (age) distribution by vehicle class
- Annual mileage accumulation by vehicle class
- Diesel sales fractions by vehicle class and model year
- Average speed distribution by hour and roadway
- Distribution of vehicle miles traveled by roadway type
- Engine starts per day and distribution by hour
- Engine start soak time distribution by hour
- Trip end distribution by hour
- Average trip length distribution
- Hot soak duration
- Distribution of vehicle miles traveled by vehicle class

- Full, partial, and multiple diurnal distribution by hour
- Inspection and maintenance (I/M) program description
- Anti-tampering inspection program description
- Stage II refueling emissions inspection program description
- Air-conditioning usage rates
- Natural gas vehicle fractions
- HC species output
- Output format specifications and selections

Some of these twenty-six input parameters are difficult to obtain. However, most of these inputs are optional because the MOBILE6 model supplies default values unless alternate data is provided. The minimum requirements for the input data include calendar year, minimum and maximum daily temperature, and fuel volatility. The default values represent "national average" values. Users who desire a more precise estimate of local emissions can substitute information that more specifically reflects local conditions. Use of local input data will be particularly common when the local emission inventory is to be built up from separate estimates of roadways, geographic areas, or times of day, in which fleet or traffic conditions vary considerably.

The descriptive output from the MOBILE6 model provides emission rates in grams of pollutant (HC, CO, or NOx) per vehicle mile traveled (g/mi). For a given vehicle category, the change in emission rates over time is due to fleet turnover, through which older vehicles built to less stringent emission standards are replaced by newer vehicles built to comply with more stringent standards. Therefore, emission rates from the MOBILE6 model can be combined with estimates of travel activity (total vehicle miles traveled, or VMT), which also change over time, to develop highway vehicle emission inventories expressed in terms of tons per hour, day, month, season, or year.

With adjustments to the basic emission rates, the emission rates of nitrogen oxides (NOx) are derived from the MOBILE6 model. Appendix B provides the emission rates output. For detailed information about emission rates, please see Appendix B.

3.3.3 Probability Distribution of Vehicle Speeds

The goodness-of-fit test is employed to examine the probability distribution of the average vehicle speeds under the 55 mph speed limit. In this particular problem, the average vehicle speeds can be represented by the space-mean-speed (May, 1990). The space-mean-speed was calculated as

$$\overline{\mu_{SMS}} = \frac{1}{1/n\sum_{i=1}^{n} t_i} \qquad \text{(Equation 3.2)}$$

where $\overline{\mu_{SMS}}$ = space-mean-speed (mile/h)

t_i = travel time of vehicle i, hour/mile

n = number of observations in sample

The vehicle speed data for the goodness-of-fit test was collected during off-peak hours on an uncongested IH-35 freeway segment with a 55 mph speed limit. The collected speed data are observed individual point vehicle speeds. According to Equation 3.2, with two vehicles in each group, the space-mean-speed is calculated and the sample of space-mean-speeds is established. Then, the hypothesis can be stated as follows:

H_o: the average vehicle speed on IH-35 is normally distributed during the off-peak hours under the 55 mph speed limit.

H_a: the average vehicle speed on IH-35 is not normally distributed during the off-peak hours under the 55 mph speed limit.

In order to test the normality of traffic speeds under a certain speed limit, the Wilk-Shapiro normality test was applied. In statistics, the Wilk-Shapiro test tests the null hypothesis that a sample $x_1, ..., x_n$ came from a normally distributed population. The test statistic is

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \qquad \text{(Equation 3.3)}$$

Where

$x_{(i)}$ (with parentheses enclosing the subscript index i) is the ith order statistic, i.e., the ith-smallest number in the sample;

$\overline{x} = (x_1 + \cdots + x_n)/n$ is the sample mean;

the constants a_i are given by

$$(a_1, \ldots, a_n) = \frac{m^\top V^{-1}}{m^\top V^{-1} V^{-1} m} \qquad \text{(Equation 3.4)}$$

Where

$$m = (m_1, \ldots, m_n)^\top$$

m_1, ..., m_n are the expected values of the order statistics of an identical independent distribution sample from the standard normal distribution, and V is the covariance matrix of those order statistics.

The test rejects the null hypothesis if W is too small (Shapiro and Wilk, 1965).

Based on the Wilk-Shapiro test method, the normality test was performed with statistics software JUMPIN4.0. The Wilk-Shapiro normality test returns the following results:

W: 0.9672 Prob < W: 0.1174

Since the p-value is greater than 0.10, the null hypothesis can not be rejected. It is reasonable to assume that the average vehicle speed on IH-35 is normally distributed during the off-peak hours under the 55 mph speed limit.

3.3.4 Simulation of Traffic Speeds

The traffic speeds under the variable speed limit were simulated with a Monte Carlo method in this study. Simulation is the process of replicating the real world based on a set of assumptions and conceived models of reality. For engineering purposes, simulation may be applied to predict or study the performance and response of a system. With a prescribed set of values for the system parameters, the simulation process yields a specific measure of performance or response. Through repeated simulations, the sensitivity of the system performance to variation in the system parameters can be examined or assessed. In this study, the objective of the simulation is to examine the effectiveness of the variable speed limit in reducing vehicle emissions. By using a simulation method, the traffic speeds under the variable speed limit will be generated and the resulting vehicle emissions will be compared to those under the regular fixed speed limit.

The Monte Carlo simulation method has been widely applied to the problems involving random variables with known or assumed probability distributions. In general, the Monte Carlo simulation method is a sampling technique. One of the main tasks in a Monte Carlo simulation is the generation of random numbers from prescribed probability distributions. For a given set of generated random numbers, the simulation process is deterministic. For each uncertain variable (vehicle speed in this case), possible values are generated with a probability distribution. The type of distribution is based on the conditions surrounding that variable. Figure 3.3 reveals the basic principal behind the Monte Carlo simulation.

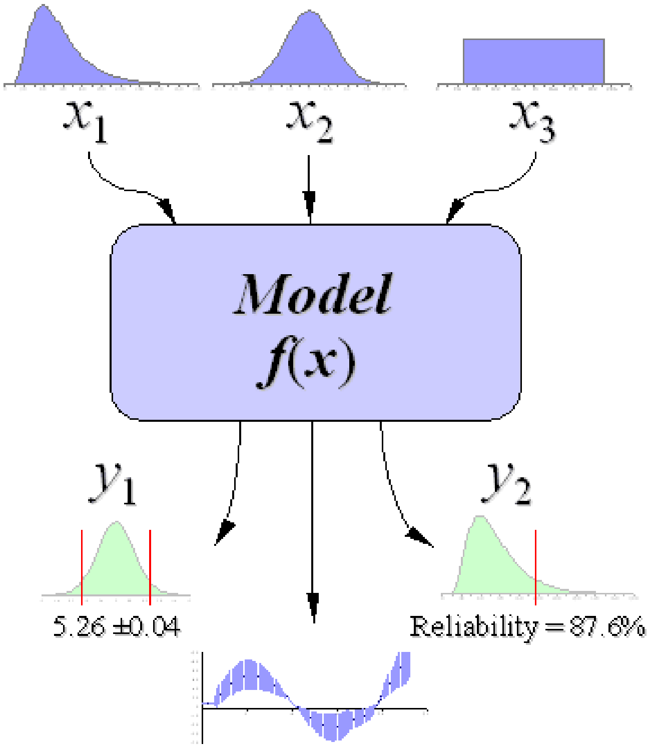


Figure 3.3: The Basic Principle behind Monte Carlo Simulation
(Source: A Practical Guide to Monte Carlo Simulation by Vertex42)

The Monte Carlo method is one of many methods for analyzing uncertainty propagation, where the goal is to determine how random variation, lack of knowledge, or error affects the sensitivity, performance, or reliability of the system that is being modeled. The Monte Carlo simulation is categorized as a sampling method because the inputs are randomly generated from probability distributions to simulate the process of sampling from an actual population. Therefore, a distribution for the inputs that most closely matches data should be selected based on the real world data to best represent the current state of knowledge. The data generated from the simulation can be represented as probability distributions, histograms, or converted to error bars, reliability predictions, tolerance zones, and confidence intervals.

In this case, the probability distribution of traffic speeds has been tested as normal. Therefore, the probability distribution of traffic speeds with variable speed limits is assumed normal. The parameters of traffic speed probability distribution with 55 mph are set to be (55, 8), which means the sample has a mean of 55 and a variance of 8.

3.3.5 Numerical Results

The variable speed limit's effectiveness to reduce emissions is examined based on the traffic data collected by the Texas Department of Transportation (TxDOT) on February 6, 2003. This date is randomly chosen out of this study's database. The vehicle speeds were randomly generated based on the collected field data. Emission rates were generated using the EPA's MOBILE6 model. The total NOx emissions from that day on the selected IH-35 segment were then calculated based on Equation 3.1.

Figure 3.4 compares the NOx emissions under the 65 mph regular speed limit and the 55 mph new speed limit. It can be seen that, if the operation day is an "Ozone Action Day", the variable speed limit strategy can help reduce emissions in morning off-peak hours (0:00AM~7:30AM), daytime off-peak hours (9:00AM~4:00PM), and evening off-peak hours (7:30PM~12:00PM). During the peak hours, variable speed limits cannot help reduce mobile emissions because all vehicles move far below the speed limit due to the heavy congestion. The numerical results show that, compared to the 65 mph speed limit, the 55 mph limit can help reduce NOx by 12.3 percent during morning off-peak hours, by 8.4 percent during daytime off-peak hours, by 14.2 percent during the evening off-peak hours, and by 10.8 percent daily.

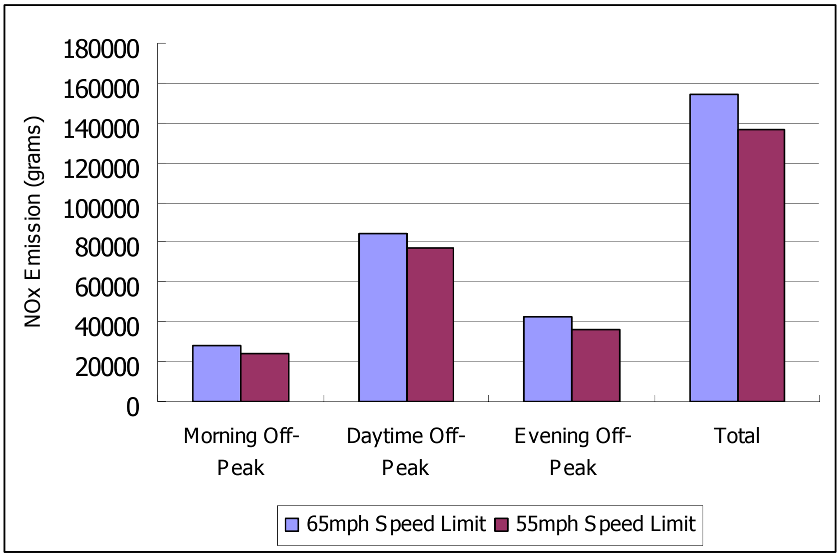
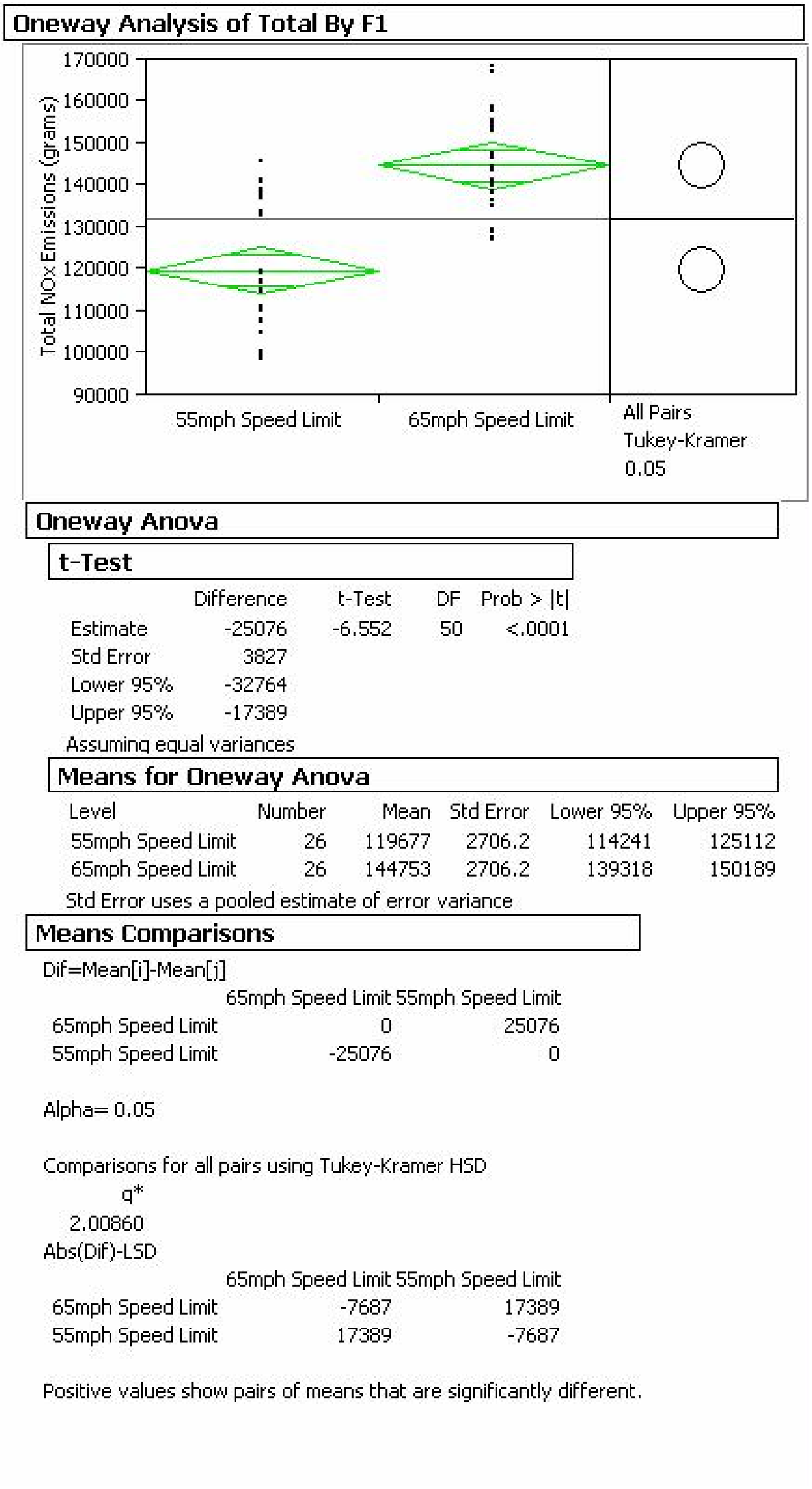


Figure 3.4: NOx Emission Levels Under Two Speed Limit Schemes (Flow Data on 02/06/2003)

Because the traffic volumes and speeds change day by day, a multiple day analysis is performed to examine the long-term performance of the variable speed limit strategy. The multiple-day data, which ranges from 01/09/2003 to 02/14/2003, was provided by TxDOT. For the numerical analysis, the weekend data are excluded and only the data on weekdays are used. Figure 3.5 shows a comparison of daily NOx emissions under the two speed limits using multi-day data. By varying the speed limit from 65 mph to 55 mph on “Ozone Action Days”, the average daily total NOx emission can be reduced by 17.3 percent (from 144,753 grams to 119,677 grams) on the selected IH-35 segment. The comparison between the two speed limits shows that the long-term average daily NOx emission under the 55 mph speed limit is significantly lower than the average daily NOx emission under the 65 mph speed limit.



```
Oneway Anova
  t-Test
                  Difference    t-Test    DF   Prob > |t|
    Estimate          -25076    -6.552    50      <.0001
    Std Error           3827
    Lower 95%         -32764
    Upper 95%         -17389
   Assuming equal variances
  Means for Oneway Anova
    Level              Number      Mean   Std Error   Lower 95%   Upper 95%
    55mph Speed Limit      26    119677      2706.2      114241      125112
    65mph Speed Limit      26    144753      2706.2      139318      150189
   Std Error uses a pooled estimate of error variance
Means Comparisons
 Dif=Mean[i]-Mean[j]
                    65mph Speed Limit 55mph Speed Limit
  65mph Speed Limit                 0             25076
  55mph Speed Limit            -25076                 0

 Alpha= 0.05

 Comparisons for all pairs using Tukey-Kramer HSD
          q*
    2.00860
 Abs(Dif)-LSD
                    65mph Speed Limit 55mph Speed Limit
  65mph Speed Limit             -7687             17389
  55mph Speed Limit             17389             -7687

 Positive values show pairs of means that are significantly different.
```

Figure 3.5: Comparison of Multi-Day NOx Emissions under Two Speed Limit Schemes

3.3.6 Summary

In this chapter, the idea of using the variable speed limit to reduce mobile emissions was examined. A Monte Carlo simulation method was developed to quantify the effectiveness of variable speed limits in reducing NOx emissions. The numerical analysis results indicate that:

1) During off-peak hours, lowering the freeway/expressway traffic speed through variable speed limits can help reduce NOx emissions. Considering the large contribution from freeway/expressway traffic to mobile emissions, a variable speed limit strategy can be an effective measure to reduce NOx on “Ozone Action” days, if applied properly.
2) Traffic flow and speed patterns are primary factors affecting the effectiveness of a variable speed limit strategy. Before the deployment of a variable speed limit, the flow and speed patterns of the selected freeway/expressway should be carefully investigated.
3) Compared to the fixed speed limits, the variable speed limit strategy can be a promising way to balance travelers’ need for mobility and the conservation of the environment.

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

The safety benefits of variable speed limits have been widely recognized. However, the potential environmental benefits of variable speed limits have been generally ignored. Previous studies have shown that mobile emissions are highly correlated with vehicle speeds and can be significantly reduced if traffic speeds are maintained at appropriate levels. On the other hand, the transportation sector is the primary source of air pollutants in urban areas. Many "non-attainment" areas in the U.S. are struggling to make mobile emissions meet the Environmental Protection Agency (EPA) standards. A variable speed limit strategy, as an effective traffic control measure, can play an important role among those emission mitigation methods. If a variable speed limit can be operated properly in response to the prediction of environmental risk, it may be a promising way to balance travelers' need for mobility and the conservation of the environment.

The overall objective of this study is to evaluate the environmental benefits of a variable speed control strategy and provide recommendations for variable speed limit deployments. In Chapter one, background information was presented on speed limit establishment, variable speed limit applications, and the basic idea of using variable speed limits to reduce air pollution. In Chapter two, the knowledge on vehicle emissions, emission rates estimations, and influential factors on vehicle emissions were introduced. In Chapter three, a Monte Carlo simulation method was developed to evaluate the effectiveness of variable speed limits, and a case study was performed to estimate the benefits of variable speed limits in reducing NOx emissions.

From this study it was found that during off-peak hours, lowering the freeway/expressway traffic speed through variable speed limits can help reduce NOx emissions and other air pollutants. Considering the large contribution from freeway/expressway traffic to mobile emissions, a variable speed limit strategy can be an effective measure to reduce NOx on "Ozone Action" days, if applied properly. By reducing the speed limit from 65 mph to 55 mph on "Ozone Action" days, the average daily total NOx emission in a 24-hr period can be reduced by approximately 17 percent on the selected IH-35 segment.

Traffic flow and speed patterns are primary factors affecting the effectiveness of a variable speed limit strategy. Before the deployment of variable speed limits, the flow and speed patterns of the selected freeway/expressway should be carefully investigated. Also, the idea is to apply variable speed limits only on predicted high environmental risk days, such as ozone days. Compared to the fixed speed limits, a variable speed limit strategy can be a promising way to balance travelers' need for mobility with the conservation of the environment.

One problem with this idea is that it may cause drivers' compliance and enforcement issues, which are the main reasons that variable speed limit applications have not widely spread in the United States. In fact, variable speed limit systems have been around for the last 30 years and currently are being used successfully and/or tested in the U.S. and other countries. Emerging ITS technologies provide an opportunity to use more comprehensive variable speed control systems to improve traffic operations. However, because of legal concerns, the level and type of enforcement required, and the lack of information on proven benefits, variable speed limit applications have not been more widespread, with the exception of school zones, in the U.S.. Although many jurisdictions have expressed interest in variable speed limits, the deployments of variable speed limits may still be limited in the near future unless some implementation issues are addressed.

The first challenge is determining the proper speed limit. Establishing fixed speed limits is already a problem. Speed limits are typically established based on the 85th percentile speed and observed safe speed. The debate has been around for many years on increasing or decreasing, mainly for safety issues. Recently, Texas has decided to increase the speed limit on some freeways and toll roads to 80 mph. A state's authority to regulate traffic on public highways within the state has long been recognized as a valid exercise of police power, a safety measure to protect the public. Applying variable speed limits may be risky for legislators unless the implementation of VSL seems very necessary.

Drivers' compliance is another big issue in limiting variable speed limit applications. Although some studies have stated that variable speed limits can improve drivers' compliance to speed limits, the evidence is more anecdotal than confirmed. Sometimes it is the technology (speed limit signs) rather than changing speed limits that improves drivers' compliance. Using variable speed limits improperly may cause confusions to drivers and consequently reduce drivers' compliance.

Enforcement is another issue. The government has the authority to set the speed limit and prosecute violations. The more complex issue will arise when it comes to delegating the authority to set speed limits or to change existing speed limits. .Variable speed limits may cause complex issues in enforcement. In order for a state to use a system of variable speed limits and enforce those limits, the authority must be delegated by statute from the legislature to an administrative agency. In a study conducted by the Federal Highway Administration, it was concluded that, “as to creation and enforcement of proposed ‘variable speed limits’, the legal issues that will arise should be no different from the legal issues that have been considered by courts in adjudicating alleged violations of prima facie speed limits and other fixed maximum speed limits” (NCHRP, 2002).

The development of technology accelerates the integration of traffic management. Through variable speed limits, speed control may also be integrated into traffic management systems to achieve the systems’ optimization goals. A limitation of this study is that the traveler’s behavior under the variable speed limits was not investigated. A study on the traveler’s compliance to the variable speed limits is necessary. Because the variable speed limit is theoretically effective in reducing mobile emissions, a field experiment is recommended to examine its performance in practice.

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Appendix A: EPA MOBILE6.0 Vehicle Classifications

Number	Abbreviation	Description
1	LDGV	Light-Duty Gasoline Vehicles (Passenger Cars)
2	LDGT1	Light-Duty Gasoline Trucks 1 (0-6,000 lbs. GVWR*, 0-3,750 lbs. LVW**)
3	LDGT2	Light-Duty Gasoline Trucks 2 (0-6,000 lbs. GVWR, 3,751-5,750 lbs. LVW)
4	LDGT3	Light-Duty Gasoline Trucks 3 (6,001-8,500 lbs. GVWR, 0-5,750 lbs. ALVW***)
5	LDGT4	Light-Duty Gasoline Trucks 4 (6,001-8,500 lbs. GVWR, 5,751 lbs. and greater ALVW)
6	HDGV2b	Class 2b Heavy-Duty Gasoline Vehicles (8,501-10,000 lbs. GVWR)
7	HDGV3	Class 3 Heavy-Duty Gasoline Vehicles (10,001-14,000 lbs. GVWR)
8	HDGV4	Class 4 Heavy-Duty Gasoline Vehicles (14,001-16,000 lbs. GVWR)
9	HDGV5	Class 5 Heavy-Duty Gasoline Vehicles (16,001-19,500 lbs. GVWR)
10	HDGV6	Class 6 Heavy-Duty Gasoline Vehicles (19,501-26,000 lbs. GVWR)
11	HDGV7	Class 7 Heavy-Duty Gasoline Vehicles (26,001-33,000 lbs. GVWR)
12	HDGV8a	Class 8a Heavy-Duty Gasoline Vehicles (33,001-60,000 lbs. GVWR)
13	HDGV8b	Class 8b Heavy-Duty Gasoline Vehicles (>60,000 lbs. GVWR)
14	LDDV	Light-Duty Diesel Vehicles (Passenger Cars)
15	LDDT12	Light-Duty Diesel Trucks 1and 2 (0-6,000 lbs. GVWR)
16	HDDV2b	Class 2b Heavy-Duty Diesel Vehicles (8,501-10,000 lbs. GVWR)
17	HDDV3	Class 3 Heavy-Duty Diesel Vehicles (10,001-14,000 lbs. GVWR)
18	HDDV4	Class 4 Heavy-Duty Diesel Vehicles (14,001-16,000 lbs. GVWR)

EPA MOBILE6.0 Vehicle Classifications (continued)

Number	Abbreviation	Description
19	HDDV5	Class 5 Heavy-Duty Diesel Vehicles (16,001-19,500 lbs. GVWR)
20	HDDV6	Class 6 Heavy-Duty Diesel Vehicles (19,501-26,000 lbs. GVWR)
21	HDDV7	Class 7 Heavy-Duty Diesel Vehicles (26,001-33,000 lbs. GVWR)
22	HDDV8a	Class 8a Heavy-Duty Diesel Vehicles (33,001-60,000 lbs. GVWR)
23	HDDV8b	Class 8b Heavy-Duty Diesel Vehicles (>60,000 lbs. GVWR)
24	MC	Motorcycles (Gasoline)
25	HDGB	Gasoline Buses (School, Transit and Urban)
26	HDDBT	Diesel Transit and Urban Buses
27	HDDBS	Diesel School Buses
28	LDDT34	Light-Duty Diesel Trucks 3 and 4 (6,001-8,500 lbs. GVWR)

(Source: User's Guide to MOBILE6.0, EPA, 2000.)

Note: 1. GVWR—Gross Vehicle Weight Rating;
2. LVW—Loaded Vehicle Weight;
3. ALVW—Adjusted Load Vehicle Weight.

Appendix B: NOx Emission Rates Derived from MOBILE6 Model

Pollutant	Cal. Year	SPEED	LDGV ef	LDGT1 ef	LDDV ef	LDDT ef	HDDV ef	All Veh
NOx	2007	2.5	1.88	2.152	1.907	2.107	10.915	**2.622**
NOx	2007	3	1.759	2.013	1.866	2.061	10.677	**2.494**
NOx	2007	4	1.608	1.84	1.787	1.974	10.228	**2.326**
NOx	2007	5	1.517	1.736	1.714	1.894	9.811	**2.216**
NOx	2007	6	1.457	1.667	1.647	1.819	9.424	**2.135**
NOx	2007	7	1.414	1.618	1.584	1.75	9.066	**2.073**
NOx	2007	8	1.381	1.581	1.526	1.686	8.733	**2.022**
NOx	2007	9	1.356	1.552	1.472	1.626	8.425	**1.98**
NOx	2007	10	1.336	1.529	1.422	1.571	8.139	**1.944**
NOx	2007	11	1.319	1.51	1.376	1.52	7.875	**1.912**
NOx	2007	12	1.306	1.494	1.333	1.472	7.629	**1.885**
NOx	2007	13	1.294	1.481	1.293	1.429	7.402	**1.86**
NOx	2007	14	1.284	1.469	1.257	1.388	7.191	**1.839**
NOx	2007	15	1.275	1.459	1.223	1.35	6.997	**1.819**
NOx	2007	16	1.268	1.451	1.191	1.316	6.817	**1.802**
NOx	2007	17	1.261	1.443	1.162	1.284	6.652	**1.786**
NOx	2007	18	1.255	1.436	1.136	1.255	6.5	**1.772**
NOx	2007	19	1.25	1.43	1.111	1.228	6.36	**1.759**
NOx	2007	20	1.253	1.422	1.089	1.203	6.232	**1.752**
NOx	2007	21	1.261	1.424	1.069	1.18	6.116	**1.751**
NOx	2007	22	1.268	1.427	1.05	1.16	6.01	**1.751**
NOx	2007	23	1.275	1.429	1.033	1.141	5.914	**1.751**
NOx	2007	24	1.281	1.431	1.018	1.125	5.828	**1.751**
NOx	2007	25	1.287	1.432	1.005	1.11	5.752	**1.751**
NOx	2007	26	1.292	1.434	0.993	1.097	5.684	**1.752**
NOx	2007	27	1.297	1.436	0.983	1.086	5.626	**1.753**
NOx	2007	28	1.301	1.437	0.974	1.076	5.575	**1.754**
NOx	2007	29	1.306	1.438	0.967	1.068	5.534	**1.756**
NOx	2007	30	1.31	1.44	0.961	1.062	5.5	**1.758**
NOx	2007	31	1.313	1.441	0.957	1.057	5.474	**1.76**
NOx	2007	32	1.317	1.442	0.953	1.053	5.456	**1.763**
NOx	2007	33	1.32	1.443	0.952	1.051	5.446	**1.766**
NOx	2007	34	1.323	1.444	0.951	1.051	5.444	**1.77**
NOx	2007	35	1.326	1.445	0.952	1.052	5.449	**1.774**
NOx	2007	36	1.328	1.445	0.955	1.054	5.462	**1.778**
NOx	2007	37	1.331	1.446	0.958	1.058	5.483	**1.783**
NOx	2007	38	1.333	1.447	0.963	1.064	5.512	**1.788**
NOx	2007	39	1.336	1.448	0.97	1.071	5.549	**1.794**
NOx	2007	40	1.338	1.448	0.978	1.08	5.594	**1.8**
NOx	2007	41	1.34	1.449	0.987	1.09	5.648	**1.806**
NOx	2007	42	1.342	1.45	0.998	1.102	5.71	**1.813**
NOx	2007	43	1.344	1.45	1.01	1.116	5.781	**1.821**
NOx	2007	44	1.346	1.451	1.024	1.131	5.861	**1.829**
NOx	2007	45	1.347	1.451	1.04	1.149	5.95	**1.838**

NOx Emission Rates Derived from MOBILE6 Model (continued)

NOx	2007	46	1.349	1.452	1.057	1.168	6.05	**1.847**
NOx	2007	47	1.351	1.452	1.076	1.189	6.16	**1.857**
NOx	2007	48	1.352	1.453	1.098	1.212	6.281	**1.868**
NOx	2007	49	1.392	1.508	1.121	1.238	6.414	**1.918**
NOx	2007	50	1.432	1.563	1.146	1.266	6.558	**1.969**
NOx	2007	51	1.473	1.618	1.174	1.296	6.716	**2.021**
NOx	2007	52	1.513	1.672	1.203	1.329	6.886	**2.074**
NOx	2007	53	1.553	1.727	1.236	1.365	7.072	**2.128**
NOx	2007	54	1.593	1.782	1.271	1.404	7.272	**2.182**
NOx	2007	55	1.633	1.837	1.309	1.446	7.489	**2.238**
NOx	2007	56	1.674	1.892	1.35	1.491	7.724	**2.295**
NOx	2007	57	1.714	1.947	1.394	1.54	7.977	**2.353**
NOx	2007	58	1.754	2.002	1.442	1.592	8.25	**2.413**
NOx	2007	59	1.794	2.057	1.493	1.649	8.544	**2.474**
NOx	2007	60	1.834	2.112	1.548	1.71	8.862	**2.536**
NOx	2007	61	1.875	2.167	1.608	1.776	9.204	**2.601**
NOx	2007	62	1.915	2.222	1.673	1.848	9.573	**2.667**
NOx	2007	63	1.955	2.276	1.742	1.925	9.971	**2.734**
NOx	2007	64	1.995	2.331	1.817	2.007	10.401	**2.804**
NOx	2007	65	2.035	2.386	1.898	2.097	10.864	**2.877**