

ABSTRACT

Title of Thesis: TRAFFIC IMPACT ANALYSIS OF SEVERAL
DYNAMIC LANE MANAGEMENT
STRATEGIES FOR CONGESTION
MITIGATION BASED ON DTA MODEL

Ke Zhang, Master in Science, 2016

Thesis Directed By: Professor,
Lei Zhang,
Department of Civil and Environmental
Engineering

Persistent daily congestion has been increasing in recent years, particularly along major corridors during selected periods in the mornings and evenings. On certain segments, these roadways are often at or near capacity. However, a conventional Predefined control strategy did not fit the demands that changed over time, making it necessary to implement the various dynamical lane management strategies discussed in this thesis. Those strategies include hard shoulder running, reversible HOV lanes, dynamic tolls and variable speed limit.

A mesoscopic agent-based DTA model is used to simulate different strategies and scenarios. From the analyses, all strategies aim to mitigate congestion in terms of the average speed and average density. The largest improvement can be found in hard shoulder running and reversible HOV lanes while the other two provide more stable traffic. In terms of average speed and travel time, hard shoulder running is the most congested strategy for I-270 to help relieve the traffic pressure.

TRAFFIC IMPACT ANALYSIS OF SEVERAL DYNAMIC LANE
MANAGEMENT STRATEGIES FOR CONGESTION MITIGATION BASED ON
DTA MODEL

By

Ke Zhang

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master in Science
2016

Advisory Committee:
Professor Lei Zhang, Chair
Professor Ali Haghani
Professor Paul M. Schonfeld

© Copyright by
Ke Zhang
2016

Acknowledgment

This thesis cannot be completed without the help of my advisor, Dr. Lei Zhang. I offer my sincere appreciation for the continuous help and encouragement provided by him. I'd also like to appreciate the help from my classmates, for all their help and suggestion when I got problem. Finally, thanks to my parents as well, thank you for supporting me studying abroad and being with me forever.

Table of Contents

Acknowledgment	ii
Table of Contents	iError! Bookmark not defined.
List of Tables	v
List of Figures	vi
Chapter 1: Introduction	1
1.1 Background	1
1.2 Objectives and Approach	5
1.3 Research Contribution	6
1.4 Thesis Organization	7
Chapter 2: Literature Review	8
2.1 Hard Shoulder Running and Reversible HOV Lanes	8
2.1.1 Influence	8
2.1.2 Previous Research	9
2.2 Dynamic Tolls	11
2.2.1 Developing History	11
2.2.2 Previous Research	13
2.3 Variable Speed Limit	14
2.3.1 Developing History	14
2.3.2 Algorithm Research	17
2.4 Dynamic Traffic Assignment.....	17
2.4.1 Previous Research	17
2.4.2 Application of DTA model	20
Chapter 3: Methodology	22
3.1 General Methodology	22
3.2 Hard Shoulder Running & Reversible HOV Lane	22
3.3 Dynamic Tolls.....	24
3.4 Variable Speed Limit	25
Chapter 4: Simulation Case	27
4.1 Study Area	27
4.2 Scenario Design	28
4.2.1 Hard Shoulder Running	28
4.2.2 Reversible HOV Lanes	28
4.2.3 Dynamic Tolls.....	29
4.2.4 Variable Speed Limit	29
Chapter 5: Results Analysis	30
5.1 Hard Shoulder Running	30
5.1.1 Average Speed and Average Density	30
5.1.2 Speed on I-270	31
5.1.3 Travel Time.....	33
5.2 Reversible HOV Lanes	34
5.2.1 Average Speed and Average Density	34
5.2.2 Speed Along with I-270 general purpose lane	35

5.2.3 Travel Time.....	37
5.3 Dynamic Tolls.....	38
5.3.1 Average Density.....	39
5.3.2 Relationship between Density and Tolls.....	39
5.4 Variable Speed Limit.....	42
5.4.1 Average Speed and Average Density	42
5.4.2 Speed on I-270	42
5.4.3 Travel Time.....	44
5.5 Results Comparison	45
5.5.1 Performance of Hard Shoulder Running and Reversible HOV Lanes.....	45
5.5.2 Performance of Dynamically Control and Predefined Operation Hour.....	45
5.5.3 Performance of Dynamic Tolls	46
5.5.4 Performance of Variable Speed Limit	46
Chapter 6: Conclusion and Future Research Direction.....	47
References:.....	49

List of Tables

Table 1.1: Number of vehicles in several different countries in 2013 and 2030

Table 3.1 Average density of I-270 toll lane with different K values

Table 4.1: Simulation scenarios of Hard Shoulder Running

Table 4.2: Simulation scenarios of Reversible HOV Lanes

Table 4.3: Simulation scenarios of Dynamic Tolls

Table 4.4: Simulation scenarios of Variable Speed Limit

Table 5.1: Average speed of congested general purpose lanes for different scenarios

Table 5.2: Average density of congested general purpose lanes for different scenarios

Table 5.3: Average speed of congested general purpose lanes and HOV lanes for different scenarios

Table 5.4: Average density of congested general purpose lanes and HOV lanes for different scenarios

Table 5.5: Average density of congested general purpose lanes and HOV lanes for different scenarios

Table 5.6: Average speed of congested general purpose lanes for different scenarios

Table 5.7: Average density of congested general purpose lanes for different scenarios

List of Figures

- Figure 1.1: Advanced economies: annual percentage change in advanced economies' wasted hours, 3-month rolling average (monthly data confirms this illustration)
- Figure 3.1: Frame work of dynamically controlled Hard Shoulder Running and Reversible HOV lane
- Figure 4.1: Map and Simulation Network of Research Area
- Figure 5.1: Speed on I-270 Southbound general purpose lane during A.M. peak period
- Figure 5.2: Speed on I-270 Northbound general purpose lane during P.M. peak period
- Figure 5.3: Travel time on I-270 Southbound general purpose lane during A.M. peak
- Figure 5.4: Travel time on I-270 Northbound general purpose lane during P.M. peak
- Figure 5.5: Speed on I-270 Southbound during A.M. peak period
- Figure 5.6: Speed on I-270 Northbound during P.M. peak period
- Figure 5.7: Travel time on I-270 Southbound during A.M. peak period
- Figure 5.8: Travel time on I-270 Northbound during A.M. peak period
- Figure 5.9: Density and toll rate on I-270 Southbound toll lane in A.M. peak
- Figure 5.10: Density and toll rate on I-270 Northbound toll lane in P.M. peak
- Figure 5.11: Speed along with I-270 Southbound general purpose lane at A.M. peak
- Figure 5.12: Speed along with I-270 Northbound general purpose lane at P.M. peak
- Figure 5.13: Travel time of I-270 southbound general purpose lane at A.M. peak
- Figure 5.14: Travel time of I-270 northbound general purpose lane at P.M. peak

Chapter 1: Introduction

1.1 Background

As the economy continues to develop and private car ownership grows, persistent daily congestion has been exponentially increasing during recent years, especially along major corridors. The volume can be at, near or even beyond capacity during extended periods, or in some cases, the entire day (1).

Statistical results reveal that the registered number of vehicles in the United States of America has grown from less than 200 million in 1990 to a current level of more than 250 million, which translates to an increase of nearly 25 percent¹. However, the development of a network's capacity does not directly correspond with the rising number of vehicles. Recent studies show that residents living in Washington, D.C. lose an average of 82 hours per year because of rush-hour slowdowns, which is the most in United States, followed by those living in Los Angeles, San Francisco and New York. In 2014, the annual hours lost per commuter in D.C area, which includes Washington D.C., Virginia and Maryland, is 82 hours. And the total annual hours of delay reaches 204.4 million, resulting to \$1,834 annual cost per commuter and total \$ 4.6 billion congestion cost.² Analysts from the Texas A&M Transportation Institute and INRIX Inc. report that compared to the situation in 2007, the number of drivers stuck in traffic during the pre-recession peak has increased by approximately 5 percent (2). After analyzing current levels of congestion in several countries including the United States, from the first season of 2011 to the fourth season of

¹ Source: US Department of Transportation; Federal Highway Administration

² Source: 2015 Urban Mobility Scorecard; by the Texas A&M Transportation Institute, and Inrix.

2014, despite slightly declining in some seasons, the annual percentage change in advanced economies' wasted hours increased significantly during this period, which is illustrated in Figure 1.1 (3). The US has the highest number of passenger vehicles per capita at 787 vehicles per thousand persons, and the absolute number of vehicles is predicted to continue to grow over the next twenty years as a result of the expanding population. Passenger vehicles on US roads are expected to grow by 13 percent between 2013 and 2030, for an estimated total of 281 million vehicles on the road by the year 2030 (3). Table 1.1 summarizes the predicted vehicle numbers by 2030 for US and selected European countries.

Figure 1.1: Advanced economies: annual percentage change in advanced economies' wasted hours, 3-month rolling average (monthly data confirms this illustration)



Table 1.1: Number of vehicles in several different countries in 2013 and 2030³

Country	Pax vehicles 2013	Pax vehicles 2030	% change 2013-2030
US	248.8	281.2	13.0
Germany	43.4	45.1	3.9
France	30.8	35.1	14
UK	28.7	31.9	11

³ Source: World Bank, DfT, US Census Bureau, Cebr analysis

Undoubtedly, congestion will lead to lost labor hours, high fuel costs and cause negative direct and indirect economic consequences. Research predicts a 33 percent rise in average direct and indirect costs of congestion per individual car commuting household on 2013 levels by 2030, from \$1736 to \$2301 (3).

The factors leading to congestion are varied, and congestion is divided into two different types. The first is expected congestion while the other is unexpected. Unexpected traffic is traditionally caused by work zones, traffic accidents, or inclement weather, all of which are challenging to avoid or mitigate. Typically, when congestion mitigation is discussed, it refers to expected or regular congestion.

Expected congestion occurs nearly every workday during Predefined peak periods. Generally speaking, an area that has experienced fast economic development and working opportunities is more likely to experience more severe congestion issues. Other factors include an increase in urban populations and lower fuel prices, both of which make driving less expensive and result in more extensive use of city roads.

Considering the high cost of resources necessary for building additional lanes, new construction is often the last option to effectively decrease congestion. Furthermore, construction is time-consuming and many areas of land cannot accommodate additional lanes. Therefore, it is necessary to apply more advanced operations to adequately deal with increasing levels of congestion, which supports the application of Dynamic Lane Control.

In the past, Dynamic Lane Control was simply divided into two distinct categories: Reversible Lane and Hard Shoulder Running. With the development of transportation

technology, Dynamic Tolls are also considered to be an important Dynamic Lane Control strategy.

Hard shoulder running functions just as the name suggests and is applied on hard shoulder. In regular traffic situations, hard shoulder running is designed for emergency use such as car incidents or emergency vehicles. However, when congestion worsens, hard shoulder running is considered to be open to vehicles in order to increase the temporal capacity to mitigate congestion, which assists in alleviating safety concerns.

Reversible lanes can be subdivided into two parts based on the properties of the corridor. Firstly, it can be used when the volume of two directions is completely different, especially during peak hours. In many cities, people work in urban areas but live in suburban areas. This is an outcome of home prices in the central parts of cities being too high for most people to realistically afford. As such, during morning peak periods, people commute from outside areas to the city center for work purposes. Meanwhile, during afternoon peak hours, they travel in the opposite direction from the city center to suburban areas. Due to especially high volumes during peak periods, those arteries are faced with mounting pressure. This technique can also be extended to HOV lanes. Research has proven that during peak times, HOV lanes are frequently less efficient compared to general purpose lanes. Thus, HOV lanes could be reversed in the less congested direction and used for the more highly-congested direction of traffic. Reversible lanes make it possible to increase the capacity of the peak direction through message boards and signs indicating if the lane can be used for a certain direction. For example, a lane entering an urban area could be used during the a.m. peak period and that same lane could be used to travel away from an urban area during p.m. peak times.

Dynamic tolls allows SOV drivers to temporarily use HOV lanes by paying tolls. In theory, they have a similar function to Reversible HOV Lanes, considering both of them increase the capacity of the congested direction when necessary. The ratio of SOV on American roads is much higher than HOV during peak hours, resulting in higher congestion in general purpose lanes. Therefore, drivers with high time cost are likely to be more willing to pay to use HOV Lanes rather than dealing with gridlock in the general purpose lane.

Another congestion mitigation strategy is variable speed limit (VSL), which is first used to reduce safety risks when there is work zone or roadway congestion. Later research proved that it might also aid in reducing congestion by limiting the number of vehicles arriving in the congested section. Thus, when a detector tests congestion at the downstream, the speed limit at the upstream will be updated in the meantime to adapt to real traffic conditions.

In summary, dynamic lane management helps improve traffic operation and through more effective management, it assists us in reducing congestion and increasing overall system efficiency.

1.2 Objectives and Approach

The objective of this thesis is to integrate dynamic lane control with an dynamic traffic assignment model, and subsequently analyzing the impact on regional traffic. Dynamic lane control is a useful strategy to improve the overall efficiency of the traffic network. Using this model, real-time traffic performance can be obtained and dynamic operation can be implemented based on real-time traffic performance.

Furthermore, dynamically-controlled strategies are evaluated in this thesis and compared with predefined operation hours. During peak periods, congestion is not always a serious

concern. Conversely, during off-peak periods, it does not mean that there will be no possibility of congestion. For that reason, the dynamically-controlled hard shoulder, reversible HOV Lanes and toll rates are tested in order to observe their influence on congestion mitigation. For hard shoulder running and reversible HOV Lanes, it is expected that the traffic performance of dynamically-controlled operation will be more severe than predefined operation time during peak periods. However, in this thesis, the simulation will reveal the scope of this difference, and whether or not it is applicable in real-time for various traffic times and volumes.

1.3 Research Contribution

Although dynamic lane control is currently applied to a variety of real-world situations, most of them, especially hard shoulder running or reversible HOV ILanes, operate during predefined hours, for which efforts to improve are undertaken. The regional traffic impact of a dynamically-controlled hard shoulder, HOV lanes or toll rates is analyzed using an agent-based model. For dynamic tolls, which are applied in numerous different locations and corridors, the algorithm of dynamic tolls is still in development, and the result of dynamic tolls under a DTA model will be discussed at length in this thesis. Previous simulations for variable speed limit have traditionally used microscopic models, or a classic traffic assignment model, and here the DTA model is employed to analyze this strategy.

The simulation also uncovered some potential problems that dynamic lane control strategies might cause, which are thus necessary to avoid during the decision-making process.

1.4 Thesis Organization

This thesis is organized in several sections. The first section contains a literature review regarding the introduction and development history of the three applications of dynamic lane control, followed by existing research. Subsequently, the thesis discusses the simulation model and tools. The area of study and various scenarios are also introduced in this chapter. The final portion of the main thesis is the results analysis and conclusion. Additionally, acknowledgments and other add-ons can be found at the beginning and end of the thesis.

Chapter 2: Literature Review

2.1 Hard Shoulder Running and Reversible HOV Lanes

2.1.1 Influence

The influence of hard shoulder running (HSR) is shown in several different aspects such as safety, environment and network efficiency.

The negative impacts on safety apply when broken-down vehicles are required to stop. Existing research indicates an increase of between 10 and 11 percent in accident frequency when converting four lanes to five lanes, while a smaller increase takes place when converting five lanes to six lanes, which may be the result of accident migration caused by the relocation of traffic operational bottlenecks (4). To avoid this, HSR sections of the road must be controlled, and the operator's response to such a situation has to be as swift as possible. Generally, areas of limited length and turbulent flow conditions are an ideal fit for this strategy, as it represents a viable alternative for achieving a smoother flow. Otherwise, it could potentially cause measurable negative impacts on overall safety conditions (5).

Contrarily, hard shoulder running can provide positive effects in certain situations. The Dutch HSR, which has 25 kilometers of total use, has led to congestion and reductions in accident density (6). This might be a result of less density due to increasing capacity.

In terms of environment, research has shown that emission levels are higher when a vehicle is stuck in congestion conditions than that when it is travelling at normal speeds. Thus, HSR can help reduce air pollution by decreasing travel time and fuel emissions (7).

Likewise, one of the key benefits of HSR is its high influence on the network. By opening the hard shoulder, it helps increase the temperate capacity, which contributes to a more consistent traffic flow (7).

2.1.2 Previous Research

Due to the positive influence of dynamic lane control on efficiency, extensive research has been performed in this area.

The study conducted by M. Aron, et al. (8) primarily discusses two French hard shoulder running operations, one operating HSR over the course of an entire day and the other operating HSR only when the occupancy level is high. Traffic efficiency of the dynamic management is based on the fundamental diagram relationships, including Free-Flow speed, road capacity, local speed and congestion. Result showed that both cases reduce the congestion, while the first one attracted extra traffic.

Germany has also applied temporary hard shoulder running, and Justin Geistefeldt explored its application in Germany. The data originates from a loop detector, and by comparing the data before and after the temporary hard shoulder applications, it was determined that the capacity could be increased without affecting overall road safety (9).

P. Chase and E. Avineri (10) examined the strengths and limitations of HSR as viewed by stakeholders in the United Kingdom. They attempted to record the opinions of stakeholders through semi-constructed interviews, as well as record their overall attitudes regarding the benefits of HSR, which tended to be weaker than those of the limitations.

Tay Richard and Choi Jaisung (11) examined the effectiveness of pictograms in dynamic lane control system in South Korea. Pictograms have been used increasingly in electronic

message display boards to provide drivers with a simple and clear message. In dynamic lane control systems, the variable pictograms are usually implemented to modify lane control. To evaluate these variable pictograms, the research team administered a test with 40 participants and tested their comprehension of the signs.

The National Cooperative Highway Research Program (NCHRP) sponsored a project to investigate and document reversible roadway practices to further understand their application, impact on safety, operating environment and design requirements (12).

In the reversible lane system, it is essential to determine which and how many lanes should be adjusted. This is an optimization issue that J.J. Wu et al. (13) approached using an advanced traveler information system to treat optimization problems as a network design challenge by employing the strategy of reversible lanes.

Berger and Maurer conducted a cost-benefit analysis to ascertain under what circumstances the opening of emergency lanes for driving were economically viable (14). Their research provided methods to determine specific thresholds of the AADT (average annual daily traffic), above which the national economy would benefit from an additional lane. Otherwise, an emergent bay might be sufficient. The research also suggested that the best cost-benefit relationship could be achieved with a hard shoulder open only under high traffic volumes, combined with a reduced speed limit and a variable message sign.

When a hard shoulder is opened to additional traffic, the maximum allowed speed limit can also increase, which leads to decreased travel time and an increase in average travel speed. It might not, however, lead to a larger throughput (15).

To implement hard shoulder running, the study indicated that significant operational, environmental, and economic benefits from the potential temporary use of the left shoulder lane within an ATM environment. More favorable results can be expected if it is combined with advanced active management methods (16).

Virginia Center for Transportation Innovation and Research conducted research on how to develop and test the effectiveness of active traffic management strategies for reducing recurring congestion on a simulated model of I-95 and I-66 in Northern Virginia. After testing twenty-four scenarios for both variable speed limit and hard shoulder running, the results verified that temporary capacity upgrades, such as the use of hard shoulder running (HSR), were the most effective in enhancing traffic performance on these two corridors. In addition, improved results could be expected if it was combined with a variable speed limit strategy. Considering that HSR systems are capable of reducing congestion levels to a certain point, they represent model conditions for VSLs to operate efficiently (17).

The application of hard shoulder running can be modified based on local conditions. In Germany, during peak periods, drivers are informed 1 kilometer in advance that they will be permitted to use the hard shoulder, while in Holdorf, electronic message boards indicate whether or not the hard shoulder of a 1 kilometer section can be used for regular traffic (18).

2.2 Dynamic Tolls

2.2.1 Developing History

Because of its practical implications, dynamic congestion pricing has become an important alternative for congestion mitigation and has spawned growing research attention.

However, at the outset, it is primarily considered to be an economic problem, and is frequently advocated by economists because of the economic theory used in the research. Since the 1920s, Pigou has encouraged a road pricing strategy as an alternative to congestion mitigation (19). However, the application of dynamic tolls requires advanced technology, which limits their adequate development. For that reason, it is also referred to as Electronic Road Pricing to reflect the impact of the new technology (20).

In actuality, road pricing (or congestion pricing) has several practical applications. It performs differently in various countries based on specific situations. In 1975, an Area Licensing Scheme was implemented in Singapore, and access to the central area of the city was restricted for vehicles. Norway operated the first toll ring in 1986, located in Bergen, and two additional examples were situated in Oslo and Trondheim. From February of 2003, drivers of vehicles in London which sought entry to the city's central area were required to pay a five pound daily fee, which was subject to later increases (20).

In the US, a more prevalent form of congestion pricing is HOT lanes, which refer to HOV facilities that allow lower-occupancy vehicles to pay tolls in order to gain access (21). Research revealed that HOV lanes accommodate more people than general purpose lanes during peak hours (22). However, they are not often fully used during peak periods. The FHWA formerly defined that the primary purpose of time operation policies of HOT lanes is to provide superior free-flow traffic service on the toll lanes, while the second objective is to maximize the throughput rate of the freeway (23).

The first charging HOV lane in the US is State Route 91 in Orange County, California and was created in 1995 (23). Since that time, the pricing policy has become progressively more popular among government and transportation officials, leading to other charging roads being implemented, such as I-394 (24).

2.2.2 Previous Research

Extensive research has been undertaken on determining toll rates, of which the majority are time-dependent or predefined.

In terms of dynamic tolls, their application reaches far beyond theoretical research. For instance, I-394 has a pre-defined “look-up” table, and the toll rate is changed based on the variations in occupancy in 3 minute intervals (24). The toll rate of I-15 HOT lanes in San Diego, California, varies from \$0.50 to \$4, depending on the time of day (20). This application of dynamic tolls during early hours is similar to time-dependent tolls.

Tomer Toledo, Omar Mansour and Jack Haddad performed a simulation-based optimization for HOT lane tolls. The optimization objective of this model was to maintain the level of service on the toll lane. It could also be implemented to predict driver behaviors regarding whether or not to use the HOV lanes (25).

However, to dynamically operate toll rates, the amount should be adjusted based on real-time traffic situations. Previous studies indicated time-varying tolls for bottlenecks.

A self-learning approach was developed to maximize the number of vehicles passing through the downstream bottleneck, using people’s willingness to pay as one of the key parameters (20). Another feedback control mechanism considers the traffic conditions on

both HOT and GP lanes to determine toll rates. Therefore, the speed on both types of lanes should be detected to calculate the fluctuation in tolling rates (22).

Terry L. Friesz et al. proposed a model to dynamically adjust the congestion toll, taking mobile sources of emission into consideration (26). In this model, all vehicle drivers are assumed to selfishly choose the route with the minimum travel cost, while the central authority acts to minimize the total travel cost and emissions of all vehicles in the network. A mathematical program with complementarity constraints was formulated to model this problem and can be solved using a quadratic penalty-based gradient projection algorithm.

Considering the uncertainty of the demand, certain approach also proposed to deal with this kind of uncertainty based on a bi-level cellular particle swarm optimization (BCPSO) (27). This toll issue is constrained by the equilibrium and compared with two other optimization methods. As a consequence, it improved the average travel cost and the varying range of the total travel cost.

Time-vary tolls are also used to optimize the truck arrival patterns through a two-phase optimization approach (28). The time-dependent truck queuing process was calculated through a point-wise stationary approximation model. After acquiring the system optimal truck arriving patterns, time-vary tolls were established, which resulted in this optimization pattern.

2.3 Variable Speed Limit

2.3.1 Developing History

Variable speed limit was initially proposed to reduce the safety risks in work zones or in other situations that might cause congestion along the route. These scenarios include car

accidents and extreme weather, and its function of increasing safety has been confirmed by several different studies.

Dating back to the 1990s, the Committee for Guidance on Setting and Enforcing Speed Limits has conducted studies and found that the risk of rear-end collisions could be reduced through limiting the travel speed of approaching vehicles (29).

Studies by the highway agency in the United Kingdom revealed that with dynamic speed limits, driver's behaviors are more regulated and uniformed on the roadway. This led to fewer sharp breaks and accidents (30). As a result, a 10 percent reduction in the accident rate was achieved, as well as a 0.7 decibel reduction in overall traffic noise. In the meantime, the emission rate was reduced by 2 percent for a total of 8 percent.

In Orlando, Florida, using a simulation of a section, the improvement of real-time freeway safety was evaluated by comparing the real-time crash likelihood with or without VSL (31). The speed limit on the upstream was slightly lower than the downstream, and it facilitated improved safety at medium and high speeds. In low-speed situations or congested areas, the effect was not significant.

Chris Lee et al. proposed a real-time prediction model to evaluate potential safety risks on a short-term variation of traffic flow characteristics (32). This microscopic model investigated the effect of the strategy, which yielded a 5 to 17 percent reduction in potential crashes. In addition to the improvements in safety, this result also demonstrated decreased total travel time.

Unlike safety risk reduction, the application of variable speed limit on congestion mitigation remains under discussion.

In actuality, the potentiality of variable speed limit depends highly on the driver's response to the displayed message.

Borrough engaged in a study to prove that during congestion, the number of drivers that may change lanes will frequently decrease (33).

With the assistance of his partner, Albania Nissan evaluated the impact of variable speed limit and the level of service on motorway capacity. The findings showed no significant impact on traffic conditions (30). In this research, statistical tests were used to evaluate the equality of coefficients across the before and after scenarios.

Various research studies have demonstrated a broad spectrum of results. The conclusion of one study on highway work-zone operations indicated that variable speed limit helped to decrease total travel delays and increase total throughputs of the work-zone (29).

It has also been coordinated with ramp metering on the corridor, which is one of the newly-developed strategies for effective traffic control.

Combined with ramp metering, variable speed limit could theoretically prevent traffic breakdowns and result in less spent travel time, even when ramp metering was out of use, as evidenced in a simulation conducted by Andreas Hegyi et al. (34). Ramp metering has its own on-ramp queue constraints, while speed limitations curtail the main-stream flow. Thus, the decision should be implemented depending on specific regional traffic demands.

Lu et al. presented a model that combined these two methods and first designed the speed limit through other factors, including on-ramp demand and length (35). The result demonstrated a significant increase in the bottleneck's throughput.

2.3.2 Algorithm Research

Based on various areas of study, existing applications and research reveal that there are several different algorithms which can be applied.

It could be narrowed down to a binary issue, and speed limit changes might occur between high and low speeds based on the traffic information provided by the detector. It could also be considered using a two-module model to reduce the variance of speed (36). Taking drivers' responses into account, the proposed speed limit would be dynamically-adjusted at each location. Consequently, the speed would be determined in order to minimize potential queue length, depending on drivers' reactions to the speed adjustment.

Maximizing the throughput in a work zone could also be an optimal objective in certain algorithms, although simulation results indicated that it failed to perform better in terms of decreasing the variance in speed, compared to the algorithm in which the objective was to minimize the queue length (35).

To decrease the speed differences between the upstream and downstream, the speed limit was set as the average value of the observed speed of the upstream and downstream (32). Accordingly, the speed of the vehicles varied more regularly and thus reduced potential safety risks.

2.4 Dynamic Traffic Assignment

2.4.1 Previous Research

The 4-step traffic model is very well-known, and consists of traffic generation, traffic distribution, mode choice and traffic assignment. Classic traffic assignment does not consider fluctuations in travel duration when calculating the path with the shortest travel

time. One possible result of this stable assessment is that the traffic situation might change considerably by the time an agent arrives at that section, which limits the real-time optimization and planning applications. The major difference of dynamic traffic assignment compared to the traditional one is that time-dependent travel time is considered when estimating the shortest path.

Previous research regarding the DTA model can be divided into different aspects. It is first considered to be a mathematical problem, and different formulations are used to describe it. Likewise, it can be considered as an optimal control formulation to reach the system optimum (SO) or user equilibrium (UE) objectives, and the simulation-based DTA model is discussed because of the limitations of mathematical methodology (37).

The dynamic traffic assignment was first formulated in 1978 as a mathematical issue with discretized time-setting by Merchant and Nemhauser (38). However, it only dealt with deterministic demand and single destination situations. In the 1990s, Carey reformulated this model, making it possible to use the extend it to solve multi-destination problems, although there were remaining challenges from the first-in, first-out requirements (39). A further allowance of this model is extending the assumption and making O-D desires known to the entire planning horizon, which was initiated in 1993 by Birge and Ho. The link-based optimal control formulations were discussed for the single-destination in 1989, resulting in a continuous time formulation more than a discrete-time version (40). From that time forward, extensive research concerning the link-based system optimization model or user-equilibrium DTA model was completed to confront issues from the single-destination to multi-destination problem.

The attention on simulation-based model originates from the limitations of the mathematical formulation problem because many parameters which are commonly used to represent traffic flow are challenging to analyze through appropriate mathematical formulations. Several mesoscopic traffic DTA simulation models were developed in the 1990s to resolve system optimization and user-equilibrium issues, but the O-D demand is with Predefined departure time (37).

Ghali and Smith have engaged in extensive research on the simulation-based DTA model. A single user class formulation was first proposed to solve the deterministic system optimization DTA problem. This model helps in dealing with several modeling issues which might limit realistic applications. However, the system optimization results could not be guaranteed using this model (41). As a result, they improved the methodology to compute marginal travel time at different levels (42).

In 1999, a dynamic traffic assignment model was formulated by C.O. Tong and S.C. Wong for congested capacity-constrained road networks (43). Nevertheless, they only tested this model on a simple 4-corridor network, which did not provide sufficient detail, particularly in terms of functionality in realistic networks.

R. Jayakrishnan et al. developed a dynamic traffic assignment model to improve the assumption in conventional traffic assignment methods (44). In the previous method, the O-D demand was assumed to uniformly distribute over time, which was not realistic, especially during peak periods. When traffic became more congested, the demand varied with time, thus the authors used the traffic-flow relationship based on a bi-level optimization. In other words, the traffic flow variable was replaced by the link volume on a specified time interval.

Bruce N. Janson formulated a dynamic user-equilibrium assignment problem to simulate urban road networks (45). It addressed the multiple origin and destination problems, and compared with conventional user equilibrium, dynamic user equilibrium has some inherent constraints to ensuring continuous paths of flow.

When it comes to the real-time simulation, Peeta proposed a rolling horizon approach. In this case, the near-term forecast was estimated using current traffic parameters, which was more accurate than the perfect knowledge assumption. (46) Daganzo developed a mesoscopic model for traffic propagation (47), which was eventually integrated with an internet-based GIS system by Ziliaskopoulos and Waller, who suggested using it as the simulator. The new model includes traffic signals and more effectively represents practical situations (48).

2.4.2 Application of DTA model

As one of the most popular research topics, the DTA model has been applied in several areas, particularly for Intelligent Traffic Systems. The success operation of the Advanced Transportation Systems requires traffic travel information for the vehicle flow pertaining to speed, density and other factors in order to provide accurate travel guidance for all vehicles.

The testing of dynamic traffic assignment for Advanced Traffic Management System (ATMS) from the Federal Highway Administration dates back to 1993, when a simulation model was developed for the ATMS to address two main purposes of this system (49). First of all, it helps to determine to which route the driver should be directed based on the

network optimization objectives. The second purpose is to predict traffic performance changes on each link, varying with time resulting from routing guidance.

Michael Florian et al. applied a simulation-based dynamic traffic assignment model on mid-size networks to evaluate the ITS system performance for both on-line evaluations and off-line applications (50). The testing results indicated that this model meshed well with mid-size networks, and the calculation time was deemed reasonable.

Hani S. Mahmassani also utilized a dynamic network traffic assignment and simulation methodology to evaluate the application of ITS (51). This model was built to provide details regarding changing traffic patterns when specific routing advice was given to individual drivers while the network was under certain control strategies. It is applied to evaluate the ITS effectiveness under incident conditions.

Some DTA models under emergent incidents were also proposed by Xun Ji and others, and are referred to as stochastic dynamic traffic assignment models (52). In the research, the optimization objective is the user-equilibrium and the influence of emergent incidents on the node and link capacity, as well as the probable variations in network structure. In addition, the efficiency of this model was also tested by numerical example, and the results were shown to be applicable.

Chapter 3: Methodology

3.1 General Methodology

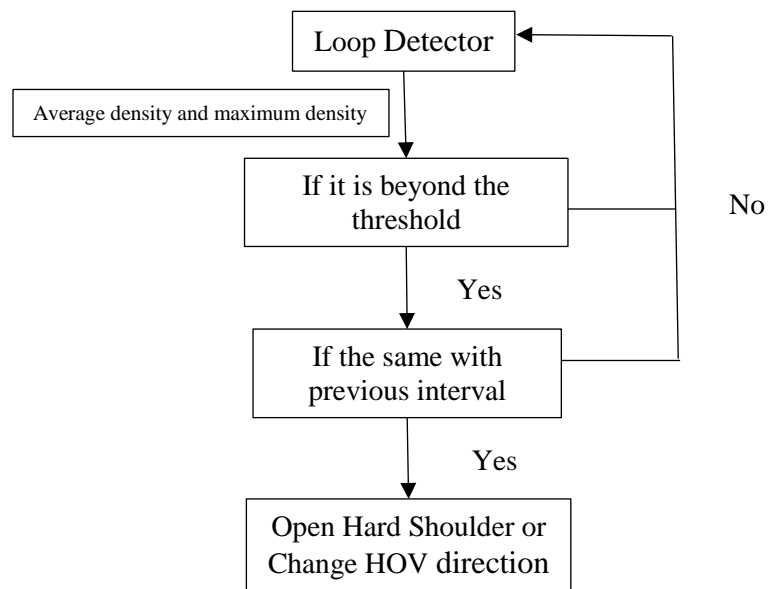
For this research, DTALite was selected as a simulation tool. DTALite is an open-source dynamic traffic assignment model based on a mesoscopic simulation-assignment framework. Data preparation is more straightforward since the software only requires a minimal set of static traffic assignment data and some time-dependent OD demand pattern estimates. Even still, the traffic queuing model is not as basic as Newell's simplified kinematic wave model, which is implemented with a point-queue based DNL model. Moreover, an agent-based DTA model is integrated with DTALite to execute the simulation. (53)

3.2 Hard Shoulder Running & Reversible HOV Lane

The problem is a binary issue since there are only two options: opening or closing the hard shoulder and HOV lanes. However, it should not be construed as a simple optimization challenge. If only capacity or maximizing the vehicle number passing through the bottleneck are considered, the answer is obtained easily, and proves that the hard shoulder or HOV lanes should be open at all times, or at least during peak periods. Nonetheless, opening the hard shoulder indefinitely will cause some potential safety issues since vehicles have no place to park if they need to pull over. If the hard shoulder is only opened during Predefined peak hours in heavily-congested corridors, the traffic situation will worsen, even during off-peak periods, and Predefined operation hours will not assist in solving congestion problems during off-peak periods.

Previous research has revealed that the benefit the whole system can derive from opening the hard shoulder or reversing the HOV lane has a positive correlation with the average speed or density on the road. Thus, it is necessary to take the average density of the entire research corridor as an index to be the trigger for HSR or reversible HOV lanes. Another important index is the maximum density along all the sections of the research corridor due to the impact of the bottleneck on the entire corridor. The framework of this algorithm is illustrated in the figure below:

Figure 3.1 Frame work of dynamically controlled hard shoulder running and reversible HOV lane



In many cases, a detector is installed on the road to collect relevant information regarding traffic conditions, and through this traffic-monitoring data, the decision system will determine if the traffic demand is high enough or time arrives at the open point. Additionally, the decision system can be controlled by manual request. Once the decision system evaluates the traffic state and establishes the best course of action, it will open the

hard shoulder or HOV lanes after safeguarding precautions are taken. Otherwise, the monitoring system will continue to detect current conditions the road. Considerations are similar when the decision system receives the information and subsequently closes the hard shoulder. When demand decreases or time reaches the close point, the hard shoulder will be shut down, and some additional time will be allotted to clear the vehicles driving on the hard shoulder or HOV Lanes.

3.3 Dynamic Tolls

As mentioned previously, there are several algorithms for dynamic tolls based on different optimization goals. Here, a feed-back algorithm is applied in this research. The function of calculating the toll rate is shown below (20):

$$\beta(t + 1) = \beta(t) + K \times \max((o(t + 1) - o^*), 0)$$

In which $\beta(t + 1)$ and $\beta(t)$ stand for the toll rate in time interval t+1 and t, $o(t + 1)$ is the occupancy of time interval t+1, and K is a predefined parameter while o^* is also a predefined occupancy value.

To apply this algorithm, several parameters must be determined in advance. In this research, a 5 minute time interval was used to consider real-world applications. The predefined occupancy threshold was typically set as equal to or less than the critical occupancy, which corresponded to the critical density. In most cases, the volume increased with the traffic density. As for the parameter K, previous research demonstrated that when $K < 0.05$, higher throughput can be gotten but longer queues is expected (20). Several different K values are taking into simulation and the result is shown in table 3.1. We could find the average density is not very sensitive to the K value, thus, we take K =

0.12 as the final parameter which provide the smallest average density. What's more, to avoid incredibly high toll rate, the maximum toll rate for the whole corridor can never beyond 1 dollar in the morning and 2 dollars in the afternoon, since high toll rates will increase the density on general purpose lane.

Table 3.1 Average density of I-270 toll lane with different K values

Testing No.	K value	Average Density (veh/mile/lane)	
		South HOV	North HOV
1	0.08	23.1	22
2	0.10	23.2	22.2
3	0.12	23	22
4	0.15	23.1	22.1

Testing No.	maximum	Average Density (veh/mile/lane)	
		South HOV	North HOV
1	1	23	26
2	2	24	22
3	4	25	28

3.4 Variable Speed Limit

In our case, the variable speed limit is set as the average speed of the observed speed of upstream and downstream link. (32) The speed decided through this algorithm is called as “transit speed”, and the function is shown below.

$$SL(x_{i,t+1}) = \frac{s(x_{i+1,t}) + s(x_{i-1,t})}{2}$$

where $SL(x_{i,t+1})$ stand for the speed at link i at time interval t+1, then

$s(x_{i+1,t})$ and $s(x_{i-1,t})$ represent the observed speed of the upstream link i-1 and downstream link i+1 at time interval t.

The speed limit was also constrained by the maximum and minimum speed limits. The maximum was considered to ensure traffic safety, while the minimum limit was defined to ensure normal traffic flow on the highway. Therefore:

$$V_{i,min} \leq V_{i,t+1} \leq V_{i,max}$$

where $V_{i,min}$ and $V_{i,max}$ represents the minimum and maximum constraint of the speed limit at link i .

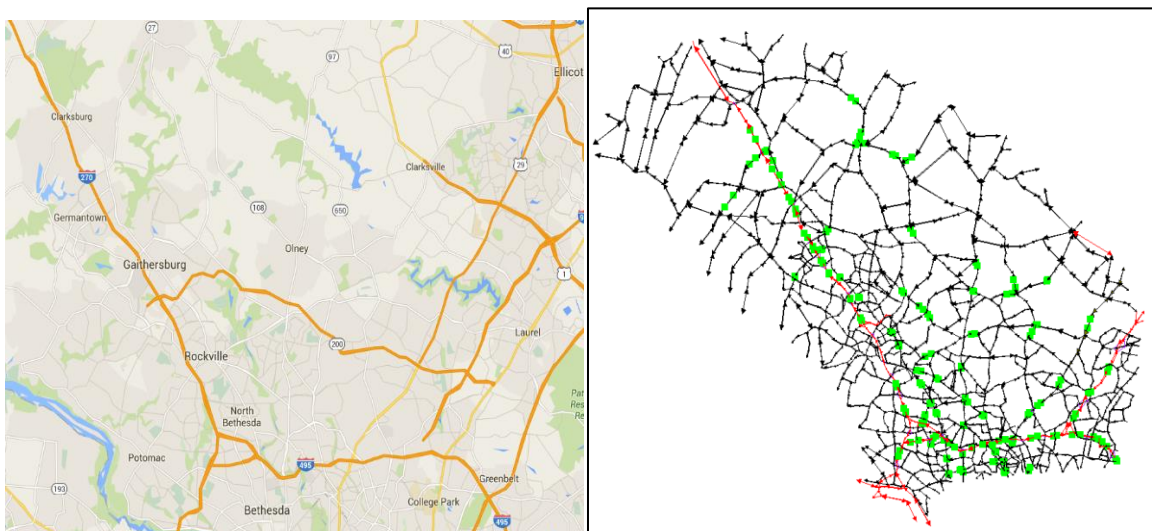
Chapter 4: Simulation Case

4.1 Study Area

In this research, I-270 was used as the research corridor for two significant reasons. Firstly, I-270 is one of the most advanced corridors in Maryland. Therefore, many new strategies, especially some advanced intelligent facilities are typically the first to be applied on I-270. Secondly, as a primary corridor in the D.C. area, thousands of vehicles travel daily in both directions on I-270 to commute into and out of Washington D.C., making I-270 one of the most congested corridors in the region. Lastly, I-270 contains both hard shoulder and HOV lanes, which provides basic conditions for applying all three strategies discussed in this thesis.

The adjacent corridor and nearby route were also included in the research area to provide an effective overall traffic impact analysis. The research area is shown in Figure 4.1. The research section spans from the intersection of US-109 and the intersection where I-270 connects to I-495.

Figure 4.1: Map and Simulation Network of Research Area



4.2 Scenario Design

4.2.1 Hard Shoulder Running

Both AM peak (6 a.m. to 9:30 a.m.) and PM peak (4 p.m. to 7:30 p.m.) in 2015 were taken into consideration, and three different scenarios were tested for Hard shoulder running. These include base scenario, Predefined operation and dynamical operation. Further detail can be found in the following table:

Table 4.1: Simulation scenarios of hard shoulder running

Strategies	Scenarios			
Hard shoulder running	2015 AM	Base	Predefined Operation Scenario	Dynamical Operation Scenario
	2015 PM	Base	Predefined Operation Scenario	Dynamical Operation Scenario

In predefined operation scenario, the hard shoulder only open from 8:00 am to 9:00 am during the A.M. peak period or from 6:00 pm to 7:00 pm during the P.M. peak period. And In the dynamical operation scenario, the hard shoulder is activated based on the traffic situation on general purpose lane.

4.2.2 Reversible HOV Lanes

The research area and period are the same as with hard shoulder running, and the scenario is shown in Table 4.2:

Table 4.2: Simulation scenarios of reversible HOV lanes

Strategies	Scenarios			
Reversible HOV Lane	2015 AM	Base	Predefined Operation Scenario	Dynamical Operation Scenario
	2015 PM	Base	Predefined Operation Scenario	Dynamical Operation Scenario

The predefined operation hour for the reversible HOV lanes is as the same as that for Hard shoulder running, which is from 8:00 a.m. to 9:00 a.m. in the morning and from 6:00 p.m. to 7:00 p.m. in the afternoon.

4.2.3 Dynamic Tolls

The research area and period are the same as with hard shoulder running, and the scenario is expressed below:

Table 4.3: Simulation scenarios of dynamic tolls

Strategies	Scenarios		
Dynamic Tolls	2015 AM	Base	Dynamic Tolls
	2015 PM	Base	Dynamic Tolls

The strategy of dynamic tolls operates from 6:00 a.m. to 9:00a.m in the morning or from 4:00 p.m. to 7:00 p.m. in the afternoon.

4.2.4 Variable Speed Limit

The scenario of variable speed limit is listed in Table 4.4:

Table 4.4: Simulation scenarios of Variable Speed Limit

Strategies	Scenarios		
Variable Speed Limit	2015 AM	Base	Variable Speed Limit
	2015 PM	Base	Variable Speed Limit

The operation hour of variable speed limit is as the same as dynamic tolls, which is from 6:00 a.m. to 9:00 a.m. and from 4:00 p.m. to 7:00 p.m.

Chapter 5: Results Analysis

5.1 Hard Shoulder Running

5.1.1 Average Speed and Average Density

The average speed and average density of the southbound and northbound general purpose lane of I-270 is shown below:

Table 5.1: Average speed of congested general purpose lanes for different scenarios (mile/hr)

Scenario	Direction	Base	Predefined Operation	Dynamical Operation
2015-AM	Southbound	43	51	55
2015-PM	Northbound	36	40	55

Table 5.2: Average density of congested general purpose lanes for different scenarios (veh/mile/lane)

Scenario	Direction	Base	Predefined Operation	Dynamical Operation
2015-AM	Southbound	31	24	22
2015-PM	Northbound	30	21	20

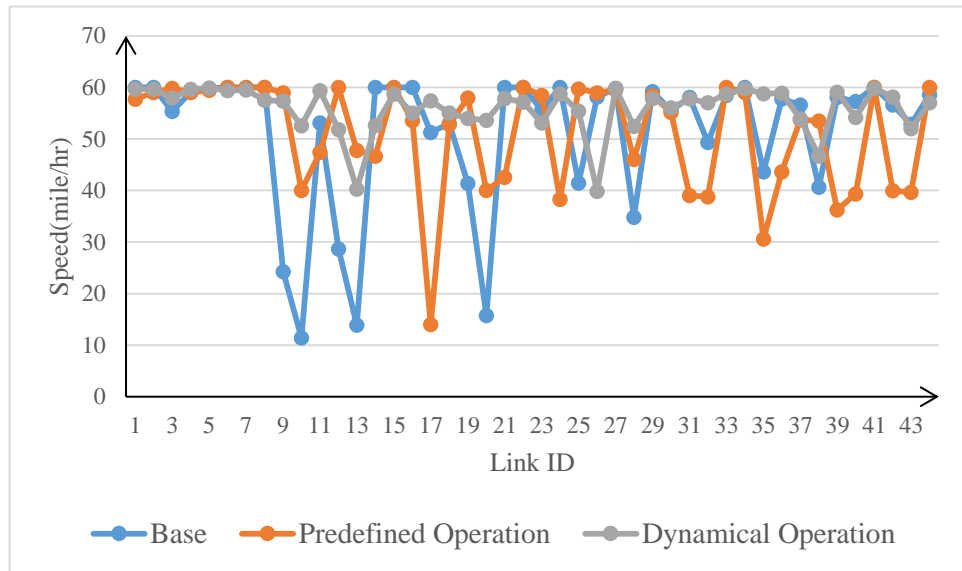
Through the average speed and average density of both 2015 AM and PM, when hard shoulder running was applied, regardless of the predefined operation hour or dynamic controls, the average speed increased by approximately 25 percent and the density decreased as well.

During the A.M. peak period, when the hard shoulder is dynamically activated, it will open at the 6:25 am and close at 9:20 when the traffic becomes better. The operation hour for the P.M. peak period will be changed from 4:10 pm to 7:25 pm. Both of the operation hour of A.M. peak and P.M. peak becomes longer and covers the original predefined operation hour.

5.1.2 Speed on I-270

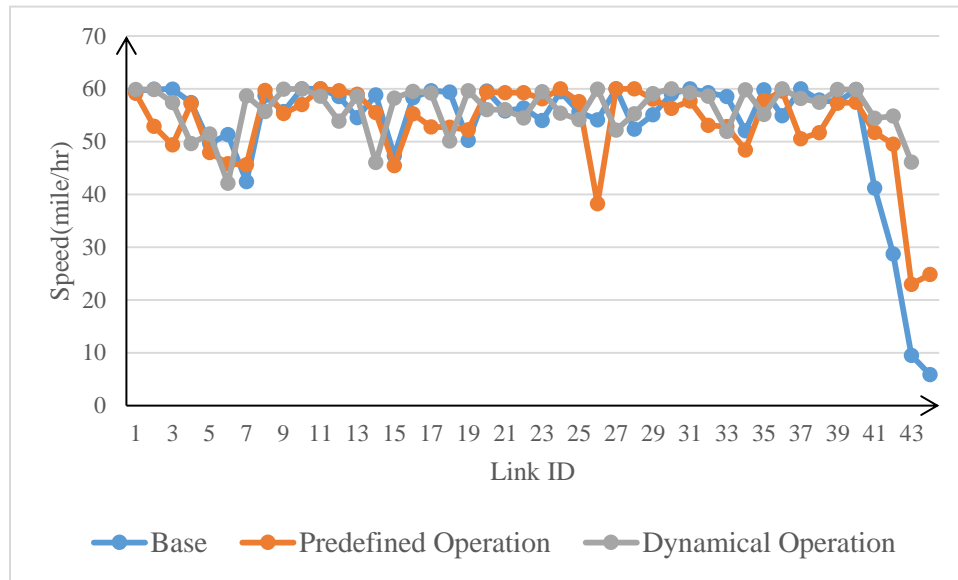
The following figure 5.1 and figure 5.2 shows the average speed along the corridor for all three a.m. scenarios. The horizontal axis indicates the link ID, in which a smaller ID number represents the upstream. The vertical axis shows the average speed (unit: mile/hour).

Figure 5.1: Speed on I-270 southbound general purpose lane during A.M. peak period



From the above figure, hard shoulder running will not cause any new bottleneck on I-270, and since dynamical operation scenario will open the hard shoulder for longer time, the speed of the majority links has highest speed among all the three scenarios. Predefined operation scenario also makes the contribution of increase the speed, although the result is not good compared to the result of the dynamical operation scenario.

Figure 5.2: Speed on I-270 northbound general purpose lane during P.M. peak period



Things in P.M. peak period might be a little different compared to what in A.M. peak period. The traffic performance of P.M. peak period is highly decided by the bottleneck at the boundary, thus opening the hard shoulder doesn't cause too much different at the upstream link since the traffic is not heavy. Checking the bottleneck at the boundary, with Hard shoulder running, the location where vehicle started to get congested moves to downstream which indicates the congestion mitigation.

5.1.3 Travel Time

The travel times during a.m. and p.m. peak periods are shown below:

Figure 5.3: Travel time on I-270 southbound general purpose lane during A.M. peak

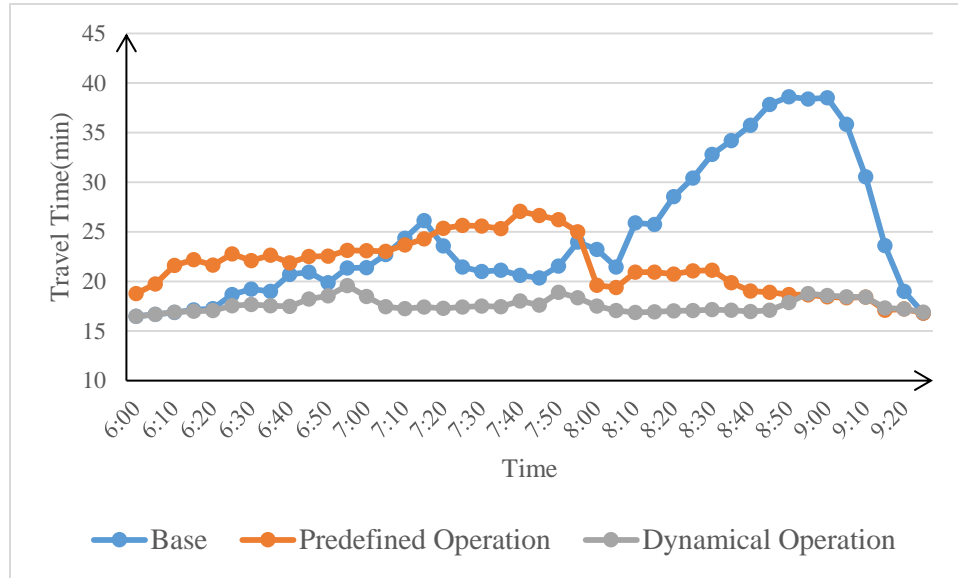
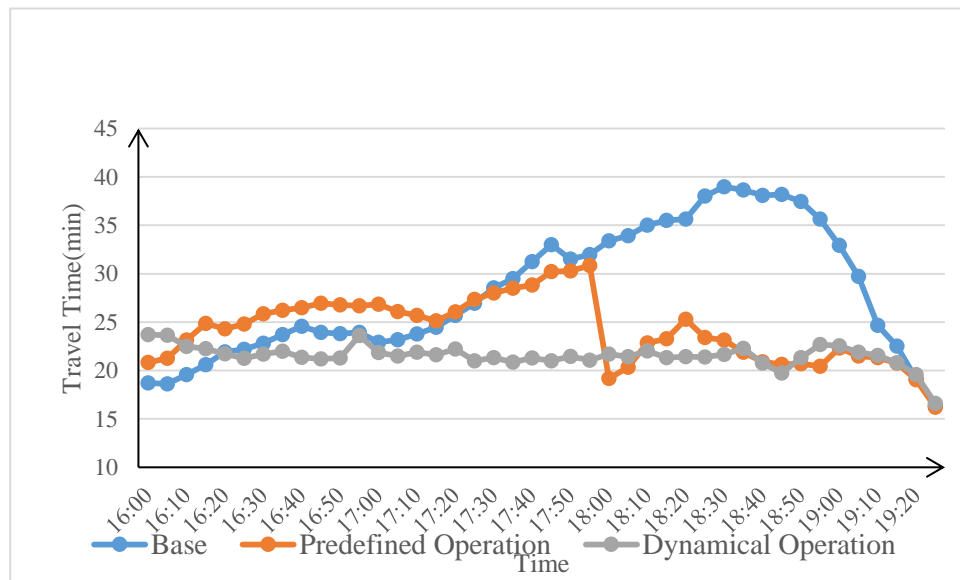


Figure 5.4: Travel time on I-270 northbound general purpose lane during P.M. peak



The total travel time of I-270 increases with time changes because of the traffic congestion getting worse in the base scenario. For both A.M. and P.M. peak period, when hard shoulder open at the predefined hour, the travel time starts to reduce at the starting time of the operation period. However, if the hard shoulder is activated by the traffic situation, hard shoulder get opened once the traffic is becoming worse, and the travel time becomes more stable when dynamically controlled hard shoulder running is applied.

5.2 Reversible HOV Lanes

Unlike Hard shoulder running, there are often physical obstacles between HOV lanes and general purpose lanes to divide HOV and SOV. Therefore, if HOV lanes are open to all vehicles, it might present some merging issues when vehicles move between the two types of lanes. This issue will be further discussed in the following section.

5.2.1 Average Speed and Average Density

The average speed on I-270 is shown in the following table:

Table 5.3: Average speed in congested general purpose lanes and HOV lanes for different scenarios (mile/hr)

Scenario	Direction	Base	Predefined Operation	Dynamical Operation
2015-AM	Southbound	43	50	53
	South HOV	44	54	56
2015-PM	Northbound	36	46	52
	North HOV	47	57	58

Table 5.4: Average density of congested general purpose lanes for different scenarios (veh/mile/lane)

Scenario	Direction	Base	Predefined Operation	Dynamical Operation
2015-AM	Southbound	31	30	26
	South HOV	30	20	14
2015-PM	Northbound	30	22	20
	North HOV	26	18	13

Similar with hard shoulder running, when reversible HOV Lanes is applied, no matter it's dynamically operated or operated during the predefined hour, it helps a lot to optimize the traffic performance in terms of average speed and average density on both general purpose lane and the HOV lanes. Moreover, it's acceptable that the average speed of Predefined Operation Scenario is smaller than the dynamical one, since in the dynamic operation scenario the HOV lanes is open earlier than the that when it is operated only during the predefined operation period. The same situation also happened for average density. The predefined operation hour is from 8:00 a.m. to 9:00 a.m. during the morning and from 6:00 p.m. to 7:00 p.m. during the afternoon. And when it is dynamically controlled, the reversible HOV lanes is activated at 6:20 a.m. or 4:00 p.m. Taking the improvement of predefined operation scenario and dynamical operation scenario into comparison, the improvement on general purpose lane of applying dynamical operation strategy is larger than that on the HOV lanes.

5.2.2 Speed Along with I-270 general purpose lane

The following figures show the speed diversity along the corridor at a specific moment for all scenarios, while others demonstrate the speed change for the corridor as time passed.

Figure 5.5: Speed on I-270 southbound during A.M. peak period

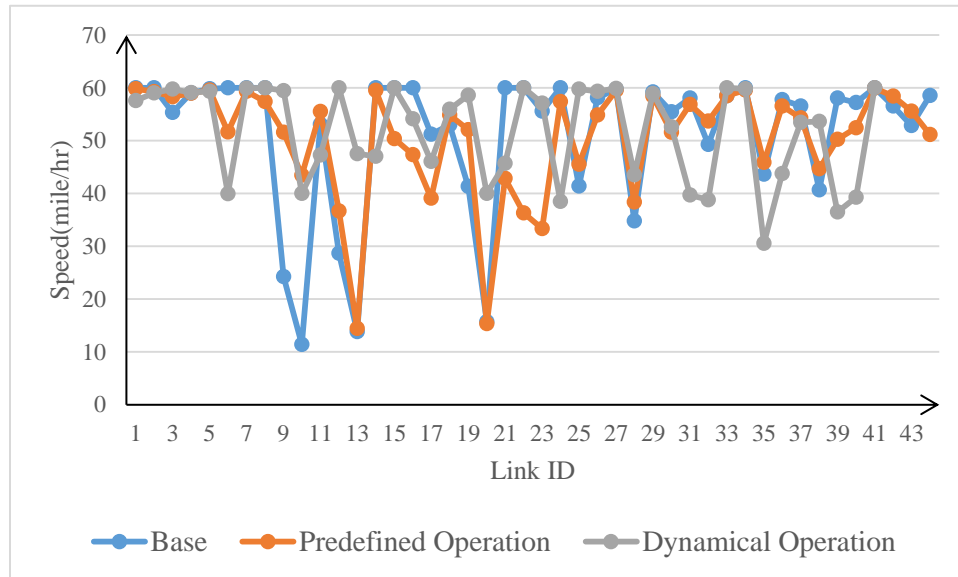
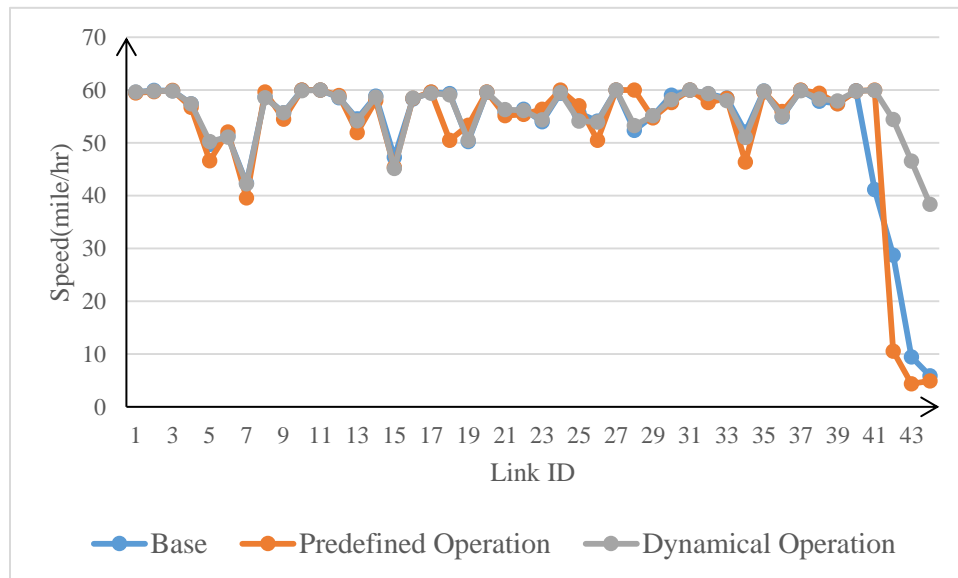


Figure 5.6: Speed on I-270 northbound during P.M. peak period



For a.m. peak period, the dynamical operation scenario provides the best performance on vehicles' speed. When the HOV lanes only be reversed during the predefined operation period, although the speed of the links increase, the bottleneck is still there. However, in

the dynamical operation scenario, the speed of the majority links is near the free-flow speed and there is no significant bottleneck.

When it comes to the p.m. peak, dynamic operation scenario makes large contribution to reduce the congestion at the end point of the general purpose lane and decreases the overall speed of I-270 general purpose lane.

5.2.3 Travel Time

Figures 5.9 and 5.10 display the total travel time of the research section. The horizontal axis represents the moments in time, which are from 6 a.m. to 9:30 a.m. in the morning and 4 p.m. to 7:30 p.m. in the evening.

Regardless of whether it was a.m. or p.m. peak period, the total travel time in the base scenario increased as time elapsed, indicating that the congestion became increasingly serious. After applying reversible HOV lanes, for A.M. peak period, the shortest travel time can be gotten in the dynamic operation scenario. When it comes to the predefined operation scenario, the travel time also become shorter and it reduces a little at 7:00 am when the HOV lane is reversed to the congested direction. The change for P.M. peak period is more significant. When the HOV lanes only open to the congested direction during the peak hour, the travel time decrease a little at the starting point and increase at the ending time as the HOV lane is closed. However, when the reversible HOV lanes is activated by the dynamic traffic situation which starts from 4:10 p.m., the travel time always keeps at a low level.

Figure 5.7: Travel time on I-270 southbound during A.M. peak period

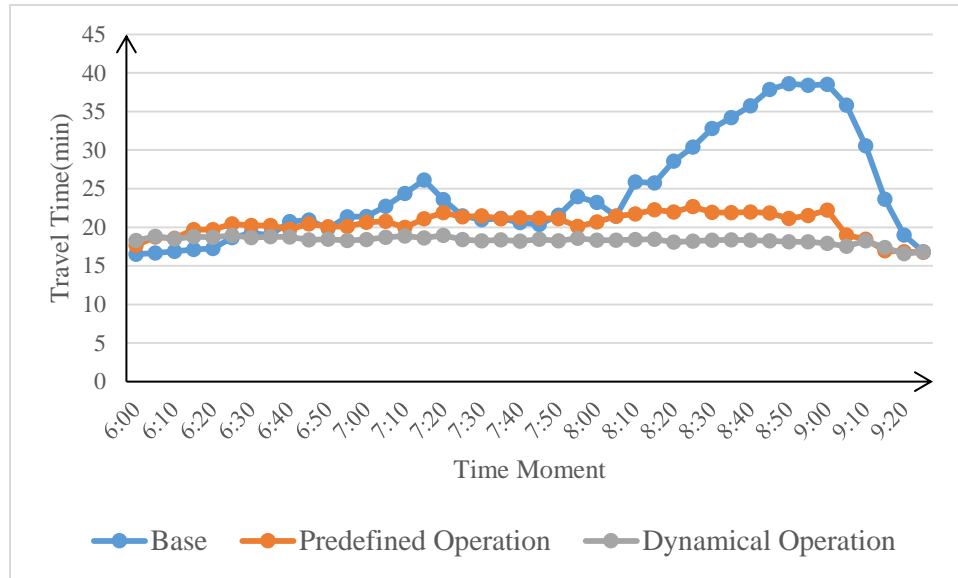
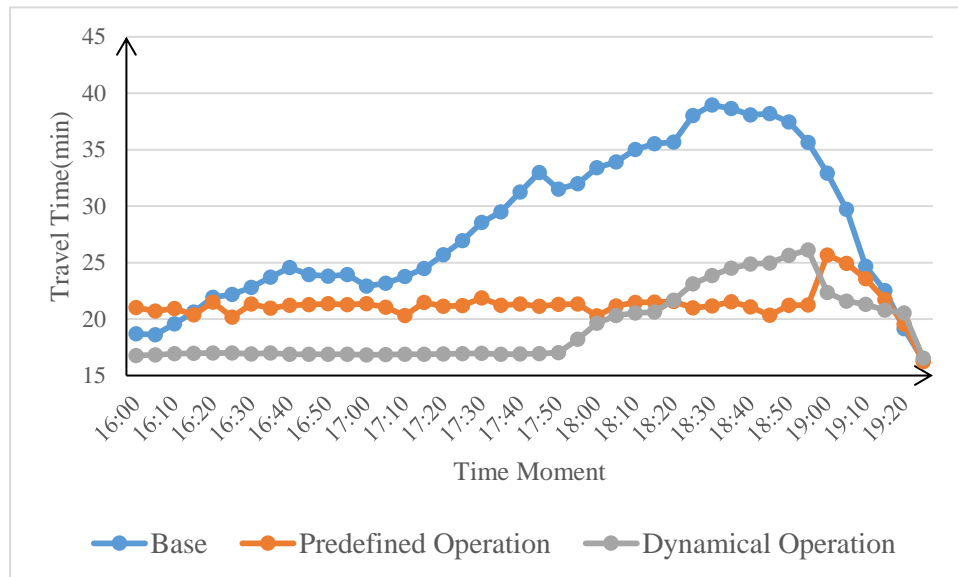


Figure 5.8: Travel time on I-270 northbound during A.M. peak period



5.3 Dynamic Tolls

Unlike the scenario settings for hard shoulder running or reversible HOV Lanes, the scenario for dynamic tolls, apart from the base one, was determined by identifying whether or not the toll lane is applied with dynamic tolls strategy.

5.3.1 Average Density

The average density on I-270 during both a.m. and p.m. peak periods is shown in table

5.3:

Table 5.5: Average density of congested general purpose lanes and HOV lanes for different scenarios (veh/mile/lane)

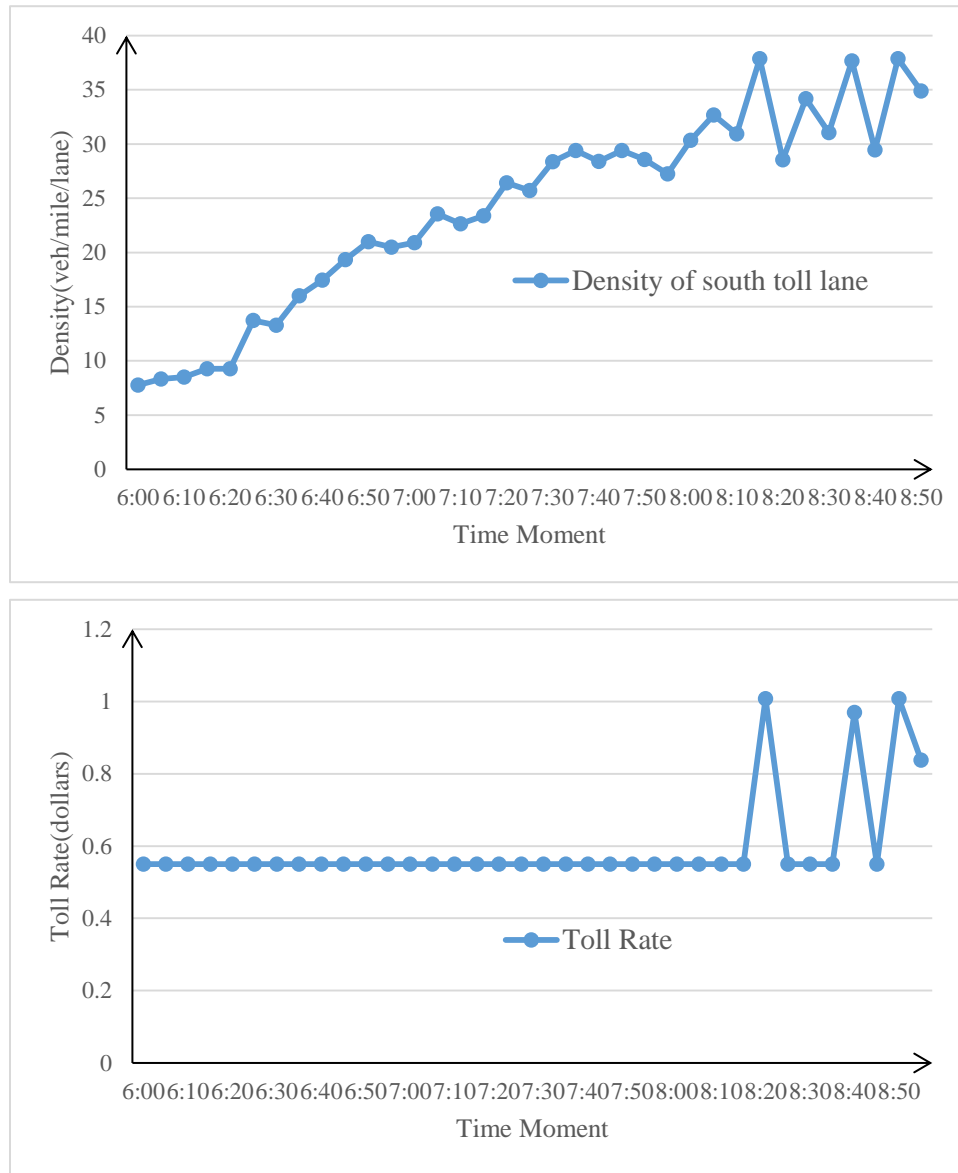
Scenario	Direction	Base	Dynamic Toll
2015-AM	Southbound	31	26
	South HOV	30	23
2015-PM	Northbound	30	27
	North HOV	26	22

From the average density, it is easy to find the average density decreases on the general purpose lane, as well as the toll lane at the mean time. Once the traffic on toll lane is getting worse, toll rate rises with the worse traffic situation and helps to relieve the congestion.

5.3.2 Relationship between Density and Tolls

The following figures show the density and toll rate of I-270 toll lane for both A.M. peak period and P.M. peak period.

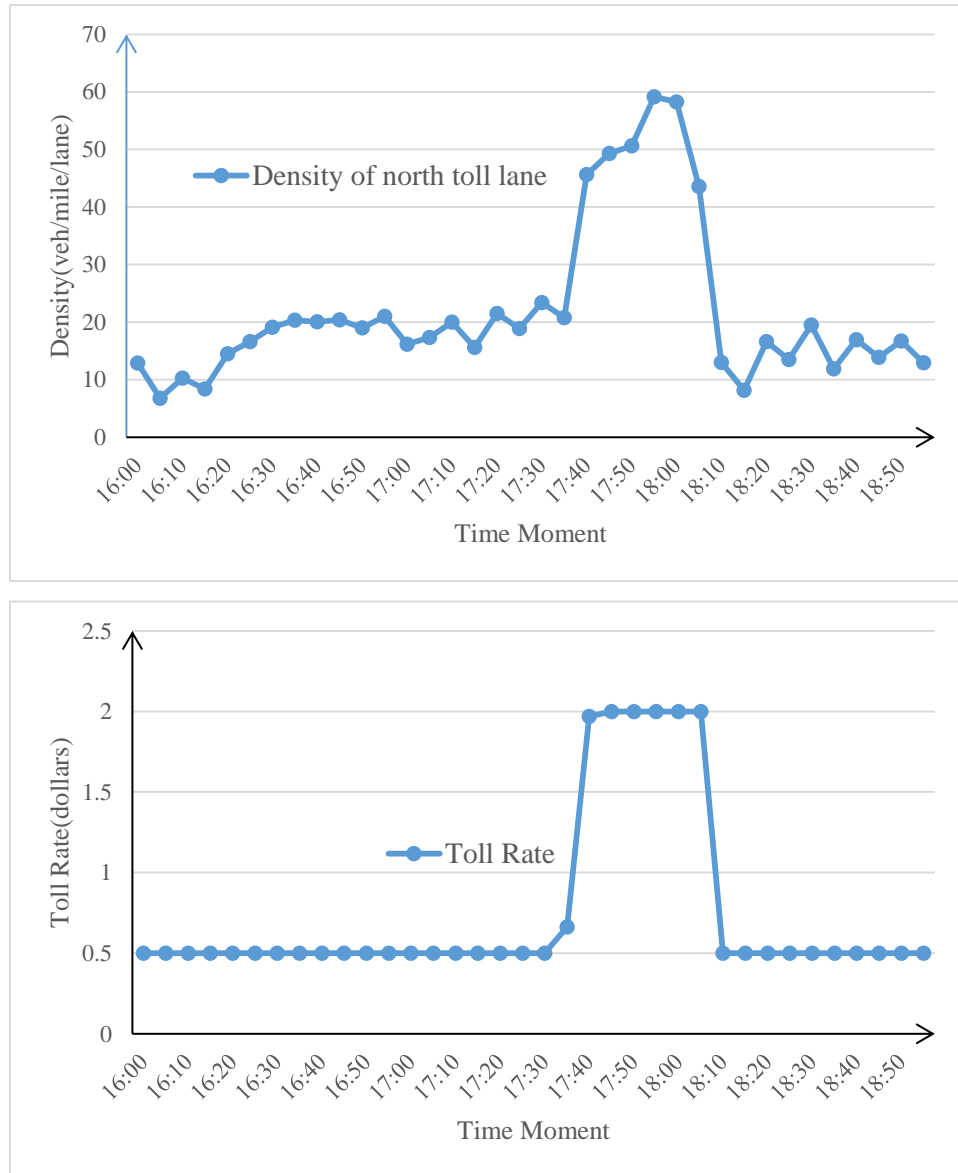
Figure 5.9: Density and toll rate on I-270 southbound toll lane in A.M. peak



During the first several hours of the a.m. period, since the average density was not at a high level, the toll rate on HOV lanes was maintained at a base level. Then the toll rate experienced an increase when the density increased and the density in next time interval decreased. That's why there was some change for both density and toll rate during the last simulation hour.

The density and toll rate changing with time during the p.m. period is illustrated in Figure 5.14:

Figure 5.10: Density and toll rate on I-270 northbound toll lane in P.M. peak



Similar patterns of change were discovered during the p.m. peak period. The time intervals of high density and high toll rate are overlapped with each other, which is similar with A.M. peak period. And it indicates the function of dynamic tolls on congestion mitigation.

5.4 Variable Speed Limit

5.4.1 Average Speed and Average Density

Table 5.6: Average speed of congested general purpose lanes for different scenarios (mile/hr)

Scenario	Direction	Base	Variable Speed Limit
2015-AM	Southbound	43	51
2015-PM	Northbound	36	51

Table 5.7: Average density of congested general purpose lanes for different scenarios (veh/mile/lane)

Scenario	Direction	Base	Variable Speed Limit
2015-AM	Southbound	31	28
2015-PM	Northbound	30	26

In this section, it was found that an increase in average speed in the general purpose lane after the application of variable speed limit reflected a positive influence on congestion mitigation. However, higher improvements were observed during the p.m. peak period, from 36 miles per hour to 51 miles per hour, when the two increasing ratios of a.m. and p.m. peak periods were compared. More details is discussed in the following section.

5.4.2 Speed on I-270

Figure 5.11: Speed along with I-270 southbound general purpose lane at A.M. peak

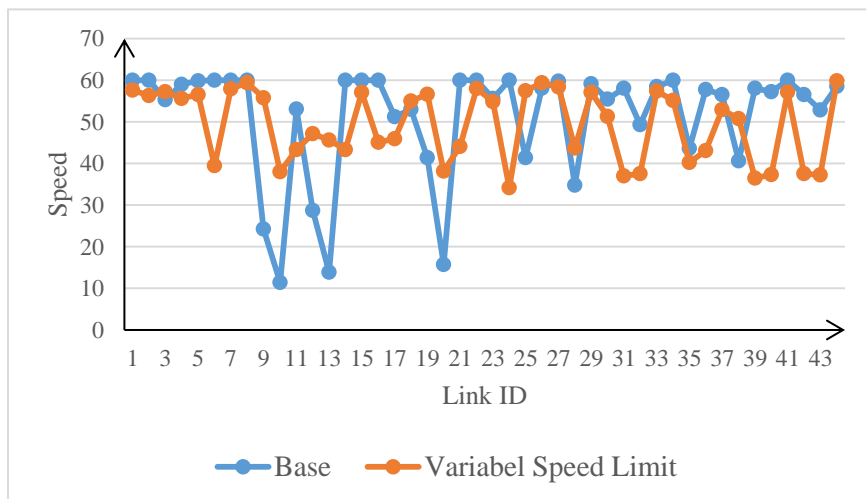
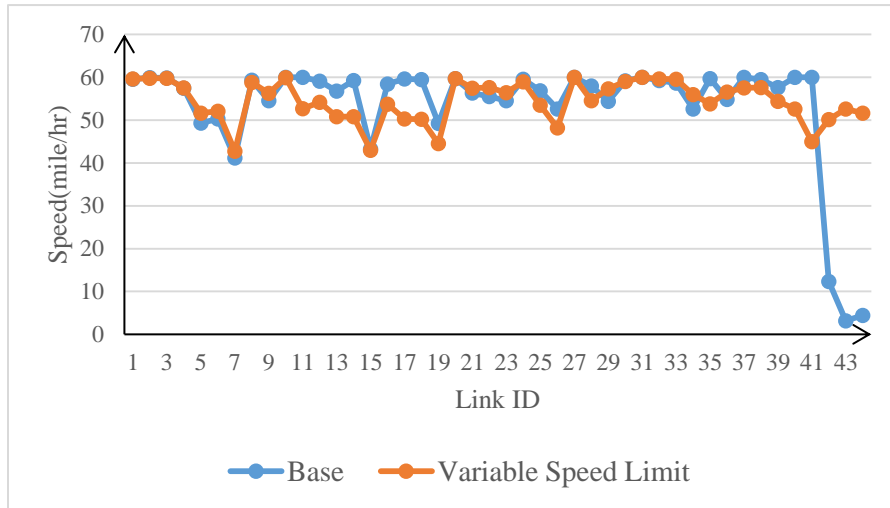


Figure 5.12: Speed along with I-270 northbound general purpose lane at P.M. peak



Through checking the speed of every link, it's easy to find that first, variable speed limit doesn't cause any new bottleneck and helps to reduce the variance of all links' speed and decrease the rear-collision risk.

For the a.m. peak period, the speed of every link along I-270 was more stable compared to the base scenario. It was determined that for the majority of bottlenecks, the speed of that link was larger when variable speed limit was applied, which proved the effect of variable speed limit on congestion mitigation. . However, variable speed limit would influence the speed of the link which is at the upstream of the bottleneck. Taking link No. 11, link No. 12 and link No. 13 as an example, smaller link number indicates the link which is at the upstream. Since there was a bottleneck at link No. 12 and link No. 13, speed increases from less 30 miles/hr to more than 40 miles/hr, resulting to the speed reduction at upstream link No. 11. Such situation can be found at several locations on I-270 southbound.

As discussed previously, in the p.m. peak situation, northbound traffic significantly decreased at the huge bottleneck at the northbound section of the simulation area, which increased the length of the queue and caused additional problems. With variable speed limit, the situation at the upstream didn't change too much, but the situation at the north boundary improved a lot. Besides, similar with the situation in A.M. peak period, the link at the upstream of the bottleneck was influenced and reduced due to the speed limit reduction.

5.4.3 Travel Time

Figure 5.13: Travel time of I-270 southbound general purpose lane at A.M. peak

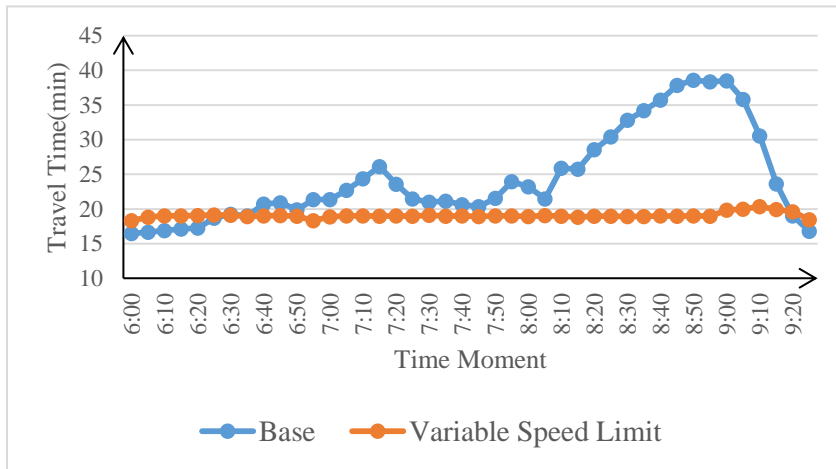
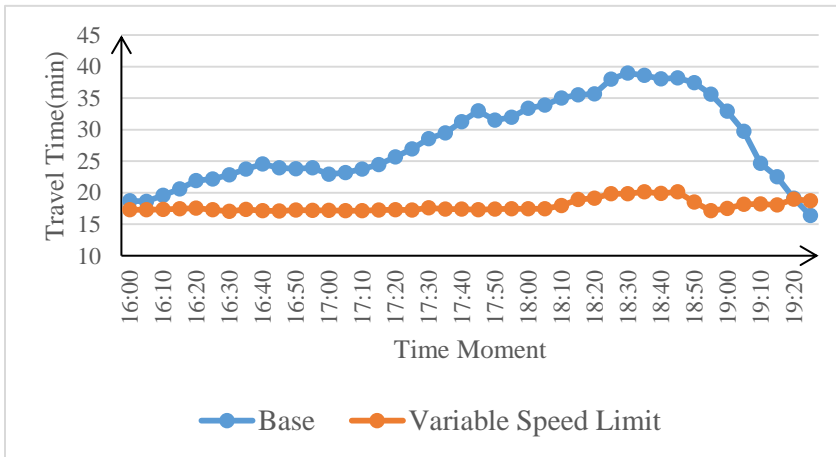


Figure 5.14: Travel time of I-270 northbound general purpose lane at P.M. peak



For both a.m. and p.m. peak periods, it was established that variable speed limit makes contribution to reduce the total travel time. And during the most congested hour, which is both the third hour of the simulation period for A.M. and P.M. peak period, the travel time increases a little because of the traffic situation, as the same as that in base scenario.

5.5 Results Comparison

5.5.1 Performance of Hard Shoulder Running and Reversible HOV Lanes

Hard shoulder running and reversible HOV lanes share some commonalities. They both increase the temporal capacity of the corridor, while their impact on the corridor is different. Taking into account the average speed, it was found to increase, while applying hard shoulder running was larger than when reversible HOV lanes were applied. The cause of this difference is that if reversible HOV lanes were open to all vehicles for not only for long distance travel, new congestion occurred on the connecting links between the general purpose lane and HOV lanes. Thus, when choosing between these lane strategies, it is important to note that hard shoulder running often results in much more congestion.

5.5.2 Performance of Dynamically Control and Predefined Operation Hour

The predefined operation hour is decided based on the traffic situation, which is the most congested hour during the whole simulation period, and in terms of the travel time and average speed, it do help to relieve the traffic pressure. However, when the should lane or HOV lane is activated by the traffic situation or, in other words, is dynamically controlled, the travel time is much more stable and kept at a lower level to ensure that vehicles can always drive smoothly.

Thus dynamically controlled strategy is much more recommended compared with the predefined operation strategy. It will prevent the congestion from getting worse once any potentiality is detected.

5.5.3 Performance of Dynamic Tolls

Analysis of the density on I-270 revealed that dynamic tolls assisted in decreasing the average density. When the traffic situation is getting worse, higher toll rate is applied and helps to relieve the traffic pressure, which proves the function of dynamic tolls. However, in terms of average density, the impact of dynamic tolls is less significant compared to hard shoulder running or reversible HOV lanes, because dynamic tolls do not increase the lane capacity but influence the route choice.

5.5.4 Performance of Variable Speed Limit

Variable speed limit decreases the speed limit at a location which is near the bottleneck. It helps to increase the average speed and reduce the total travel time, although it would cause some negative influence on the upstream link that is adjacent to the congested area. Compared with the average speed of dynamically controlled hard shoulder running or reversible HOV lanes, its performance on average speed is not as good as the other mentioned strategies. In other hand, variable speed limit helps to decrease the variance of the speed and has the smallest range in speed changing for all links.

Chapter 6: Conclusion and Future Research Direction

All of the strategies mentioned can assist in relieving congestion, but their efficiency has a close relationship with the level of travel demands and geometric characteristics. Of all the strategies, hard shoulder running and reversible HOV lanes have the highest average speed and tend to yield better performance.

Hard shoulder running and reversible HOV lanes both directly increase lane capacity and positively impact traffic, with the best improvement among all the strategies that are discussed in this thesis. Compared to the preset operation hour, dynamically controlled strategy would help these two strategies work more efficient. Once the traffic goes to get congested, the hard shoulder lane or HOV lane prevents traffic from getting worse and smooth the traffic.

Dynamic tolls and variable speed limit are less useful than the other two strategies in terms of average speed, average density and total travel time. However they help to provide a more stable traffic flow. Although variable speed limit's effect on speed is not as significant as hard shoulder running or reversible HOV lanes, it contributes greatly to decrease variations in speed, thus reducing potential safety risks. However, it also limits free-flow speed, resulting in several new bottlenecks, such as the one that occurred during the p.m. peak period.

In summary, all strategies can work effectively to mitigate congestion, and each have some inherent disadvantages. Before reaching a final decision, officials should consider regional traffic demands and specific geographic characteristics.

For future research, coordination with ramp metering should be accounted for in order to improve the contribution of the above-mentioned strategies. The results analysis showed that after applying certain strategies, there were selected congestion issues at the link connected to the on-ramp. Additionally, coordination between these strategies should be simulated. Another important research consideration is to integrate the current agent-based DTA model with behavior models to analyze changes in driver behavior and peak spreading phenomenon.

References:

1. Mazzenga, Nicholas J., and Michael J. Demetsky. *Investigation of Solutions to Recurring Congestion on Freeways*. No. VTRC 09-R10. 2009.
2. NBC Washington D.C. News. <http://www.nbcwashington.com/news/local/DC-Drivers-Spend-the-Most-Time-in-the-Car-Study-322923281.html>
3. Centre for Economics and Business Research. *The future economic and environmental costs of gridlock in 2030*. 2014.
4. Bauer, Karin, et al. "Safety effects of narrow lanes and shoulder-use lanes to increase capacity of urban freeways." *Transportation Research Record: Journal of the Transportation Research Board* 1897 (2004): 71-80.
5. Curren, J. E. *Use of shoulders and narrow lanes to increase freeway capacity*. Vol. 369. Transportation Research Board, 1995.
6. Chase, Paul, and Erel Avineri. "Maximizing motorway capacity through hard shoulder running: UK perspective." *The Open Transportation Journal* 2.1 (2008): 7-18.
7. European Commission. *Traffic Management: Services Hard Shoulder Running Deployment Guideline*. 2012
8. Aron, M., S. Cohen, and R. Seidowsky. "Two French Hard-Shoulder Running operations: Some comments on effectiveness and safety." *Intelligent Transportation Systems (ITSC), 2010 13th International IEEE Conference on*. IEEE, 2010.
9. Geistefeldt, Justin. "Operational Experience with Temporary Hard Shoulder Running in Germany." *Transportation Research Record: Journal of the Transportation Research Board* 2278 (2012): 67-73.
10. Chase, Paul, and Erel Avineri. "Maximizing motorway capacity through hard shoulder running: UK perspective." *The Open Transportation Journal* 2.1 (2008): 7-18.
11. Choi, Jaisung, and Richard Tay. "Development of pictograms for dynamic traffic control systems in South Korea." *Journal of Advanced Transportation* 42.1 (2008): 23-43.
12. Paul Brian Wolshon, Laurence Lambert, and National Cooperative Highway Research Program. *Convertible Roadways and Lanes: A Synthesis of Highway Practice*. Vol. 340. Transportation Research Board, 2004.
13. Wu, J. J., et al. "Reversible lane-based traffic network optimization with an advanced traveller information system." *Engineering Optimization* 41.1 (2009): 87-97.
14. Berger, W., and Peter Maurer. "Emergency bays versus emergency lanes on motorways—A cost benefit analysis." *Traffic Safety on Two Continents—10th International Conference, Mälmo*. Vol. 9. 1999.

15. Sultan, Beshr, et al. "M42 Active Traffic Management Pilot--Initial Results from Hard Shoulder Running Under 60mph Speed Limit." *16th ITS World Congress and Exhibition on Intelligent Transport Systems and Services*. 2009.
16. Sisiopiku, Virginia P., Andrew John Sullivan, and Germin Fadel. *Implementing active traffic management strategies in the US*. No. UTCA Report Number 08206. University Transportation Center for Alabama, 2009.
17. Fontaine, Michael D., and John S. Miller. *Planning for active traffic management in virginia: International Best Practices and Implementation Strategies*. No. VCTIR 13-R1. 2012.
18. Shahin, Mohamed, Frank Engelmann, and Bernhard Friedrich. "Using the motorway hard shoulder in congestion to allow drivers to exit." *Traffic engineering & control* 44.7 (2003): 258-263.
19. Pigou, Arthur Cecil. *Wealth and welfare*. Macmillan and Company, limited, 1912.
20. Lou, Yingyan, Yafeng Yin, and Jorge A. Laval. "Optimal dynamic pricing strategies for high-occupancy/toll lanes." *Transportation Research Part C: Emerging Technologies* 19.1 (2011): 64-74.
21. Orski, Kenneth. "Highway tolling has reached the tipping point." *Innovations Briefs* 14 (2006).
22. Zhang, Guohui, et al. "A feedback-based dynamic tolling algorithm for high-occupancy toll lane operations." *Transportation Research Record: Journal of the Transportation Research Board* 2065 (2008): 54-63.
23. Perez, Benjamin G., and Gian-Claudia Sciara. *A guide for HOT lane development*. US Department of Transportation, Federal Highway Administration, 2003.
24. Halvorson, Randy, and Kenneth R. Buckeye. "High-occupancy toll lane innovations: I-394 MnPASS." *Public Works Management & Policy* 10.3 (2006): 242-255.
25. Toledo, Tomer, Omar Mansour, and Jack Haddad. "Simulation-based Optimization of HOT Lane Tolls." *Transportation Research Procedia* 6 (2015): 189-197.
26. Friesz, Terry L., David Bernstein, and Niko Kydes. "Dynamic congestion pricing in disequilibrium." *Networks and Spatial Economics* 4.2 (2004): 181-202.
27. Do Chung, Byung, et al. "Dynamic congestion pricing with demand uncertainty: a robust optimization approach." *Transportation Research Part B: Methodological* 46.10 (2012): 1504-1518.
28. Chen, Xiaoming, Xuesong Zhou, and George F. List. "Using time-varying tolls to optimize truck arrivals at ports." *Transportation Research Part E: Logistics and Transportation Review* 47.6 (2011): 965-982.
29. Lin, Pei-Wei, Kyeong-Pyo Kang, and Gang-Len Chang. "Exploring the effectiveness of variable speed limit controls on highway work-zone operations." *Intelligent transportation systems*. Vol. 8. No. 3. Taylor & Francis Group, 2004.

30. Nissan, Albania, and Haris N. Koutsopoulosb. "Evaluation of the impact of advisory variable speed limits on motorway capacity and level of service." *Procedia-Social and Behavioral Sciences* 16 (2011): 100-109.
31. Abdel-Aty, Mohamed, et al. "Dynamic variable speed limit strategies for real-time crash risk reduction on freeways." *Transportation Research Record: Journal of the Transportation Research Board* 2078 (2008): 108-116.
32. Lee, Chris, Bruce Hellinga, and Frank Saccomanno. "Evaluation of variable speed limits to improve traffic safety." *Transportation research part C: emerging technologies* 14.3 (2006): 213-228.
33. Borrough, P. "Variable speed limits reduce crashes significantly in the UK." *The Urban Transportation Monitor* (1997).
34. Hegyi, Andreas, Bart De Schutter, and Hans Hellendoorn. "Model predictive control for optimal coordination of ramp metering and variable speed limits." *Transportation Research Part C: Emerging Technologies* 13.3 (2005): 185-209.
35. Lu, Xiao-Yun, et al. "Novel freeway traffic control with variable speed limit and coordinated ramp metering." *Transportation Research Record: Journal of the Transportation Research Board* 2229 (2011): 55-65.
36. Chang, Gang-Len, Sung Park, and Jawad Paracha. "Intelligent transportation system field demonstration: integration of variable speed limit control and travel time estimation for a recurrently congested highway." *Transportation Research Record: Journal of the Transportation Research Board* 2243 (2011): 55-66.
37. Peeta, Srinivas, and Athanasios K. Ziliaskopoulos. "Foundations of dynamic traffic assignment: The past, the present and the future." *Networks and Spatial Economics* 1.3-4 (2001): 233-265.
38. Merchant, Deepak K., and George L. Nemhauser. "Optimality conditions for a dynamic traffic assignment model." *Transportation Science* 12.3 (1978): 200-207.
39. Carey, Malachy. "Nonconvexity of the dynamic traffic assignment problem." *Transportation Research Part B: Methodological* 26.2 (1992): 127-133.
40. Birge, John R., and James K. Ho. "Optimal flows in stochastic dynamic networks with congestion." *Operations Research* 41.1 (1993): 203-216.
41. Ghali, M.O. and Smith, M.J. (1992a). *A Dynamic Traffic Assignment Model*, presented at the 71st TRB Annual Meeting, Washington D.C.
42. Ghali, M.O. and Smith, M.J. (1992b). *Dynamic Road Pricing and Dynamic Traffic Assignment for Congested Large Networks*, presented at the 39th North American Regional Science Association International Conference, Chicago.
43. Tong, C. O., and S. C. Wong. "A predictive dynamic traffic assignment model in congested capacity-constrained road networks." *Transportation Research Part B: Methodological* 34.8 (2000): 625-644.

44. Jayakrishnan, R., Wei K. Tsai, and Anthony Chen. "A dynamic traffic assignment model with traffic-flow relationships." *Transportation Research Part C: Emerging Technologies* 3.1 (1995): 51-72..
45. Janson, Bruce N. "Dynamic traffic assignment for urban road networks." *Transportation Research Part B: Methodological* 25.2 (1991): 143-161.
46. Peeta, Srinivas, and Hani S. Mahmassani. "Multiple user classes real-time traffic assignment for online operations: a rolling horizon solution framework." *Transportation Research Part C: Emerging Technologies* 3.2 (1995): 83-98.
47. Daganzo, Carlos F. "The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory." *Transportation Research Part B: Methodological* 28.4 (1994): 269-287.
48. Ziliaskopoulos, Athanasios K., and S. Travis Waller. "An Internet-based geographic information system that integrates data, models and users for transportation applications." *Transportation Research Part C: Emerging Technologies* 8.1 (2000): 427-444.
49. Mahmassani, Hani S. "Development and testing of dynamic traffic assignment and simulation procedures for ATIS/ATMS applications." (1994).
50. Florian, Michael, Michael Mahut, and Nicolas Tremblay. "Application of a simulation-based dynamic traffic assignment model." *European Journal of Operational Research* 189.3 (2008): 1381-1392.
51. Mahmassani, Hani S. "Dynamic network traffic assignment and simulation methodology for advanced system management applications." *Networks and spatial economics* 1.3-4 (2001): 267-292.
52. Ji, Xun, Chunfu Shao, and Bobin Wang. "Stochastic Dynamic Traffic Assignment Model under Emergent Incidents." *Procedia Engineering* 137 (2016): 620-629.
53. DTALite Homepage <https://sites.google.com/site/dtalite/>