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DYNAMIC TRAFFIC CONTROL:

THE TREATMENT OF LEFT TURNS IN AN URBAN GRID NETWORK

A Thesis in

Civil Engineering

by

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**ABSTRACT**

Urban traffic congestion is a significant issue that costs hundreds of billions of dollars annually in the United States alone from delay, fuel consumption, and environmental impacts (Schrank et al., 2105). Transportation engineers have tried to combat this congestion in a variety of ways, one of the most inexpensive methods being traffic control. Various attempts have been made to quantify how traffic control impacts the performance of urban transportation networks. A recent study examined the impacts of street directionality—specifically, the use of one-way vs. two-way streets—on traffic network performance (Gayah and Daganzo, 2012) and found that the capacity of two-way street networks could always be increased by simply restricting left turn movements at signalized intersections. The additional travel distance imposed by doing so is more than made up for by the additional capacity that would be available at signalized intersections, and this results in shorter vehicle travel times when the network is operating at capacity. However, because this study focused only on capacity conditions (i.e., the maximum throughput allowed by the networks), it failed to consider the full range of all anticipated traffic conditions, including both uncongested and congested states. Furthermore, this study only focused on static strategies in which one control scheme (either allowing or banning left turns) was applied at all times. This is a limitation as traffic networks are dynamic, and traffic control should also be dynamic to reflect the existing traffic conditions.
In light of this, the current research examines the impact of accommodating or restricting left turn movements on traffic network performance across the full range of traffic states that can be expected. Grid networks of different sizes and with different link lengths were created and simulated in the Aimsun micro-simulation software to examine their performance under various left turn control strategies. The performance measures considered include: fuel consumption, vehicle emissions, and measures of traffic performance—specifically, using the Network Exit Function (NEF) and the Macroscopic Fundamental Diagram (MFD). These performance measures are calculated and presented as a function of the current traffic state, measured by the accumulation or number of vehicles using the traffic network. This can be used to easily identify accumulations for which left turns should be allowed or restricted. Additionally, this study also examines the benefits of allowing or restricting left turns dynamically based on the current traffic state. Overall, the results find that restricting left turns can be very beneficial as a network starts to become congested; however, restricting left turns actually reduces performance when the network is relatively empty. The optimal performance is thus achieved by allowing left turns when few vehicles are in the network and then restricting left turns when the network becomes more crowded. This dynamic strategy maximizes the traffic performance of the network at all times and results in the lowest vehicle travel times and reduced delays.
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“With God all things are possible.”
Chapter 1
Introduction

It is imperative that traffic engineers introduce innovative methods to improve the operation of urban transportation systems, particularly as congestion in these networks continues to increase. Doing so allows practitioners to more efficiently use existing transportation infrastructure, helping to improve urban mobility and the quality of transportation services.

1.1. Research Motivation

Traffic congestion is a significant problem that plagues urban environments and costs the general public over 160 billion dollars annually in delay, fuel consumption, and vehicle emissions (Schrank et al. 2015). Urban traffic networks serve high volumes of vehicles daily, and improving their operations can help save money, reduce frustration, and improve quality of life. These operational advances can also improve air quality in urban areas, which is also of growing concern; in fact, the Environmental Protection Agency (EPA) estimates that 27 percent of greenhouse gases are directly associated with transportation in the United States. Thus, proper management of urban transportation networks can have a profound effect on both society and human health.

There are several strategies transportation engineers have at their disposal to manage congestion. Examples include: managing travel demand through pricing to reduce the number of trips, adding additional capacity through new infrastructure investments, and implementing new vehicular technologies to make traffic streams more efficient. Strategies involving traffic control tend to be lower cost measures that can improve the
performance of urban systems, because they generally do not require additional user fees or significant upgrades to existing infrastructure. When considering traffic control measures to optimize traffic network performance, it has often been found that there are certain conditions under which different control strategies perform best (Zhang et al. 2012). However, urban traffic networks are complex and can be diverse with varying demand patterns. Since traffic conditions change as the level of demand changes, researchers should consider how traffic control can be applied for the range of travel demands that a network may experience. If performance differs as demand changes, then the traffic control should adapt to this and change as well. Changing the traffic control potentially increases network productivity without having to upgrade existing infrastructure. This solution permits traffic networks to adapt to peak periods of demand and is practical for special events or other periods of high demand. For periods of low demand, a more appropriate form of traffic control can be in place, one that may not improve capacity but increase flows at low accumulations.

This thesis focuses on traffic control strategies applied at signalized intersections. These locations tend to serve as the major bottlenecks for vehicle flow in urban transportation networks. If it is possible to improve the operation of intersections and increase their capacity, then the overall operation of networks can be improved significantly. The reason that intersections are so influential of a network’s capacity is that they are points of conflict for vehicle movement. Safely managing these conflicts generally results in reduced intersection capacity, higher vehicle delays and increased congestion in networks. However, if some of these conflicts can be eliminated, then a network’s capacity can be increased as a result.
The most common example of this is the treatment of conflicting left turns at signalized intersections. These maneuvers require vehicles to turn into the path of oncoming traffic, which could potentially create a safety hazard. There are many ways these movements can be safely accommodated in practice. This includes providing dedicated phases in which left turns move while the oncoming traffic is stopped (protected left turn phasing), allowing left turning vehicles to select gaps in the oncoming traffic to make the left turn maneuvers (permitted left turn phasing) or a combination of the two (protected-permitted phasing). The disadvantage to this strategy, however, is that accommodating left turns in these ways can reduce the capacity for total vehicle throughput at the intersection. For example, additional (dedicated or protected) phases result in increased lost times and less total time available for vehicle movement. The left turn phases also take time away from other movements which typically have more lanes and higher flows. Even when left turns are permitted, vehicles waiting to turn left can queue and block the movement of other vehicles at the intersection. There are several ways to help alleviate this. For example, dedicated left turn pockets can be installed to provide space for left turning vehicles to queue so that they do not interfere with other movements at the intersection. This can help reduce vehicle conflicts for yielding left turning vehicles and can increase network efficiency, depending on the length of the left turn pocket. More innovative ways to manage left turns also exist, specifically left turn restrictions (i.e., restricting all left turn movements at signalized intersections). In this case, vehicles wishing to turn left must find an alternate route through the network, most often by taking three right turns once proceeding through the intersection at which the left turn was desired. This is shown by the blue line in Figure 1.1. In some cases, median U-Turns can be installed
when left turns are restricted so that vehicles wishing to turn left could have a shorter path to reach their destination. These latter two strategies completely eliminate the conflicting left turn movements at signalized intersections, which increases the overall capacity of the intersection. However, these strategies also have a drawback: they increase the average trip length a vehicle would have to travel through the network. Figure 1.1 provides an example of the shortest path for the same trip with left turns (left) and without left turns (right).

![Vehicle Routing Example]

**Figure 1.1: Route Length Effects with Left Turn Restrictions**

It may not be appropriate to always restrict left turns and increase a driver’s trip length. While it does improve operations by reducing vehicle conflicts, there may not be enough vehicle conflicts to make this beneficial during times of operation when there is not high demand. In fact, most networks operate with low demand during the majority of the day; thus, restricting left turns may only be beneficial during busy peak operation periods. This strategy has been implemented at individual intersections in practice where turning movements are restricted certain times of the day or signals change their operation.
However, the overall impact of such a strategy across an entire transportation network has not been studied in detail.

1.2. Research Objectives

In light of the aforementioned scenarios, the objectives of this research are to examine the network-wide impacts of various left turn treatments on urban transportation networks. This includes the operational impacts (i.e., how these treatments impact the efficiency of the network to serve traffic) as well as the impacts on environmental considerations, such as fuel consumption and vehicle emissions. The research begins by studying static treatments, defined as those that are implemented throughout the range of traffic conditions. This facilitates the exploration of dynamic strategies in which the left turn treatment is modified in response to the traffic conditions dynamically to maximize operations in the network. The static analysis seeks to identify the conditions under which each treatment might be the most beneficial on network-wide traffic operations.

Knowledge gleaned from the static analysis will facilitate the testing of dynamic strategies in which the type of left turn treatment changes based on prevailing traffic conditions. Considering elements such as mobility, vehicle emissions, etc. these dynamic left turn treatments could become a tool for practitioners to optimize a network’s performance. This research quantifies the best times to apply the left turn treatment transitions, rather than applying restrictions ad-hoc at peak periods of demand. The research finds that such a dynamic strategy appears to improve network productivity for the range of traffic conditions considered here.
This research utilizes macroscopic performance measures to compare the various left turn treatments. From an operational perspective, the Network Exit Function (NEF) is used to quantify the rate that vehicles are able to complete their trips, quantified at different levels of accumulation. This metric can be used to compare various treatments efficiently, quantifying how quickly vehicles are able to reach their destinations. This metric better represents the purpose of a transportation network, which is to allow vehicles to reach their destination as quickly as possible and to leave the network. This is compared to traditional metrics such as flow, which only quantify the rate that vehicles are able to move through a given location. Other metrics consider environmental impacts, measured as the total fuel consumption or vehicle emissions. These are provided as aggregate quantities that reflect the output of all vehicles or individual vehicles. Including measures for all vehicles is justified since the overall impact to the environment depends on the total amount of emissions produced or fuel consumed. By considering elements of both operational and environmental performance, this work can provide practitioners with more insight into the optimal left turn treatment to apply under a range of scenarios.
Chapter 2
Literature Review

This chapter provides a review of common and novel left turn treatments and efforts to study network-wide impacts of large-scale implementation of these treatments on urban traffic networks. The literature discussed in this chapter discusses different treatments of traffic and left turns: left turns permitted, left turns protected, left turns protected-permitted, left turns restricted, and median U-Turns. In addition, this chapter includes a description of existing studies relating to the treatment of left turns, contemporary methods to quantify network performance, and applications relating traffic flow and control to vehicle emissions and fuel consumption.

2.1. Treatment of Left Turns

Traffic engineers can accommodate conflicting left turn movements at signalized intersections in several manners. Typical treatments consist of allowing left turns simultaneously with opposing through vehicles (i.e., permitted left turn phasing), providing a dedicated left turn phase (i.e., protected left turn phasing) or a combination (i.e., permitted-protected phasing). These signal timing strategies can be performed both with and without dedicated left turn lanes. Some novel approaches to the management of left turns in this thesis include dynamic left turn restrictions.

There are numerous guidelines from design manuals and literature that can be polled to investigate the effects of left turns in transportation. The effects of left turns on driver safety, access management, and trip routing have all been well documented (Vu et
al., 2002; Vanhove and Fack, 2012; Li et al., 2015; Dixon et al., 2015). The Highway Capacity Manual (HCM) methodology converts left turns to equivalent through vehicles. This is because vehicles incur delay based on factors such as the probability of overflow at a dedicated left turn lane. Left turning vehicles are converted to a lower number of through vehicles. This shows, intuitively, that having left turns reduces the capacity of intersections, and a network. Finally, the AASHTO Green Book cites several left turn treatments, and mentions that left turn restrictions are a solution to reducing vehicle conflicts when left turning vehicles impose on the continuity of traffic. The AASHTO Green Book also cites the potential impact of the additional trip length and how dedicated left turn lanes can impact traffic.

The current literature studying the network-wide effect of these left turn treatments in urban areas, however, is severely lacking. Previous work focusing on operational effects from the treatment of left turns primarily focuses on vehicle routing or access management (Vu et al., 2002; Vanhove and Fack, 2012; Li et al., 2015; Dixon et al., 2015). The current research on the treatment of left turns does not account for the different ways in which left turns are commonly treated on an urban scale: permitted, protected permitted, protected. This thesis quantifies the effect that turning pockets have on operations, something not previously quantified for urban grid networks. Since an intersection with left turn restrictions (or median U-Turns) does not require a left turn pocket, a comparison of operations should be drawn for this reason as well. This could lead to better management of space in urban networks, particularly if there is not lane space in a network and if the effects of a dedicated left turn lane are found to be negligible.
The remainder of this section investigates the use and effects of different left turn treatments, including: left turns permitted, left turns protected, left turns protected-permitted, left turns restricted, and median U-Turns. Each of these left turn treatments have different associated benefits and drawbacks with their operations.

2.1.1. Left Turns Permitted

When considering the management of traffic at signalized intersections, the use of permitted left turn phases is the most typical and basic form of treatment. This left turn treatment allows left turns to move simultaneously with opposing through vehicles. With this type of treatment, left turning vehicles must select an appropriate gap between the opposing through vehicles to move. Allowing left turns in this way causes vehicles to incur delay when these left turning vehicles do not immediately find an appropriate gap and are forced to yield. The presence of permitted left turns can reduce the capacity of an intersection if these yielding left turning vehicles block through vehicles from discharging through the intersection. Each left turning movement typically takes longer than a through movement since vehicles must wait for an appropriate gap and then make the left turn. For this reason, permitted left turn vehicles are treated as the equivalent of multiple through vehicles when implementing the HCM methodology (HCM, 2010). This methodology accounts for the reduction of capacity in an intersection and can even account for the probability of the overflow of a dedicated left turn lane. This thesis investigates left turns permitted with and without a dedicated left turn lane to observe the operational effects this may have. If the demand for left turning vehicles is low enough, and a dedicated left turn
lane is present, through and right turning vehicles may not incur any additional delay due to yielding left turning vehicles.

2.1.2. Left Turns Protected

Another common technique is to have a separate phase dedicated for left turn vehicle movement. These “protected” left turn phases tend to exist at locations where a high ratio of left turning vehicles is found to exist at an intersection. A protected left turn phase facilitates left turn movements (often both opposing left turn movements) while stopping the opposing through vehicle traffic. This allows for a higher volume of left turning vehicles to move through the intersection per cycle because they do not have to yield to through vehicles.

This left turn treatment does have several associated drawbacks, however. Because there is a dedicated phase to the movement of left turns, other movements are stopped during the time that left turns are allowed to move. If a signal is operating in fixed signal timing, then sufficient left turning volumes are needed to fully utilize that dedicated phase. If lower left turning volumes exist, then a portion of the left turn phase (and thus some portion of the intersection’s capacity) is wasted. This requires careful observations, simulation, and studies to determine how much left turn demand there may be and how much queuing space is available when allocating time from the cycle to a left turn protected phase. With the addition of another phase to the cycle, there is also an increase in lost time. Due to the factors of lost time and impediment, these intersections operate with a reduced capacity as opposed to those without dedicated left turn phases.
2.1.3. Left Turns Protected-Permitted

When considering protected phasing at a signalized intersection, protected-permitted left turn treatments are often applied. Protected-permitted left turn treatments combine protected and permitted phasing, maintaining the protected phase for left turning vehicles while also allowing left turning vehicles to move through the intersection during the green phase for through and right turning vehicles. If there is a low proportion of through vehicles or an acceptable gap during opposing through vehicle (and right turning vehicle) movements, then left turning vehicles are able to progress through the intersection during this phase as well. This increases the capacity of the intersection when compared to protected left turn treatments. This increased throughput is an improvement in operations, allowing left turn vehicles to utilize more time from the cycle to make left turns. There are some safety concerns with this strategy, however, considering that the movements are no longer separated in different phases. The presence of the separate protected left turn phase also results in reduced intersection capacity.

2.1.4. Alternative Left Turn Treatments

In recent years, as traffic congestion becomes more of an issue, more innovative left turn treatments have been developed to improve traffic operations. Two examples of these innovative alternative left turn treatments are median U-Turns and left turn restrictions. Left turn restrictions do not allow left turns at an intersection, either at all times or during peak demand periods. Vehicles wishing to make a left turn would instead have to re-route to avoid any left turn maneuvers. In many cases, the simplest solution is to make
right turns in lieu of a left turn movement. However, this is not always necessary if a driver plans for the left turn restriction at the beginning of a trip.

Median U-Turns also remove left turns at the intersection, but to make this left turn a vehicle would only have to go through or right at the intersection and then make a U-Turn in the median as shown in Figure 2.1. Intuitively, it can be inferred that this would require a shorter trip deviation than required by left turn restriction: replacing a left turn movement with a median U-Turn and right turn movement should be shorter than several right turn movements. Median U-Turns have also been associated with safety and operational improvements but have not been previously studied at a network level (AASHTO, 2011; HCM, 2010).

![Figure 2.1: Example Median U-Turn (MUT) (Hughes et al., 2010)](image)

2.1.4.1. Left Turn Restrictions

When left turns are banned there is the potential to accommodate more vehicles than if left turns are allowed. This becomes very important when the network is operating at its peak capacity. While most literature involving the treatment of left turns considers
the effects of safety, vehicle routing, access management, and economic impact (Vu et al., 2002; Vanhove and Fack, 2012; Li et al., 2015; Dixon et al., 2015), this thesis explicitly considers the operational impacts associated with grid networks. Previous operational research in this area is limited. The most relevant literature finds that the capacity of networks with left turn restrictions is typically higher than that of those which accommodate left turns through protected or permitted phases (Gayah and Daganzo, 2012). The reason for this is that the removal of left turns reduces the number of conflicts at the intersection, which in turn increases intersection capacity. Since signalized intersections are temporary bottlenecks, increasing their capacity increases network capacity. The drawback, however, is that left turn restrictions increase the average length vehicles have to travel within the network to reach their destination. Even still, left turn restrictions at a network level might improve operations within the network, though they reroute vehicles and increases their trip length. Improved operational performance is due to the increase in intersection capacity and reduction in vehicle conflicts.

Restricting left turns have been associated with improved safety, efficiency, and reduced environmental impacts. For example, the United Parcel Service (UPS) enacted a company policy to reduce fuel consumption and vehicle emissions. With new routing strategies and the utilization of new trip routing software, ORION (On-Road Integrated Optimization and Navigation), they have been able to do so while also reducing delivery times. Utilizing ORION has saved UPS millions of dollars and reduced their fuel consumption by millions of gallons. The success for the approximate 96,000 truck fleet was attributed to the estimated 90 percent reduction in left turns that these vehicles make (Ohm, 2016). In another example, Market Street in San Francisco has removed left turns
to reduce vehicle to pedestrian and vehicle to bicycle conflicts (SFMTA, 2016). These applications of left turn restrictions exemplify the potential benefits that have been quantified by Gayah and Daganzo (2012) for improving network productivity.

Left turn restrictions are not appropriate for use in all networks. Depending on the vehicle demand, the likelihood of a left turning vehicle having to yield or requiring a dedicated left turn phase may vary. As previously discussed, with low vehicle demand, the likelihood of vehicle conflicts between left turning and through vehicles is reduced, and thus left turns can easily find more gaps in the opposing through traffic to make a permitted left turn. If vehicle demand is increased, the number of through vehicles is increased and it becomes difficult for left turning vehicles to attain gap acceptance, subsequently hindering left turn movement. Several other factors can influence the operation of these left turn treatments as well, and are studied in this thesis.

If the average trip length of a driver is significantly small, then the extra length traveled that a left turn restriction adds may become more significant, decreasing network efficiency. This intuitively makes sense and has been supported by statements in the American Association of State Highway and Transportation Official’s “A Policy on Geometric Design of Highways and Streets” or ‘the Green Book’ (2011). This logic assumes that the user demand of a traffic network is restricted to only one mode: vehicles. When considering mode choice, if routes get progressively shorter, the likelihood of modes such as walking, biking, or transit become more likely. The “Green Book” also points out that for left turn restrictions to be effective, a relatively short, alternative route should be available (AASHTO, 2011). For this thesis, the effects of this are simulated by varying the link length in simulation.
2.1.4.2. Median U-Turns

The median U-Turn is an alternative intersection form that is usually utilized for safety and access management. The Federal Highway Administration’s (FHWA) Alternative Intersections/Interchanges Informational Report (AIIR) shows the practicality and benefits of applying alternative intersections, such as median U-Turns (Hughes et al., 2010). Median U-Turns are effective for access management to restrict cross-median travel to only these median U-Turn locations. This, along with restricting left turns at the intersections, has led to improvements in traffic safety. The removal of left turns at an intersection reduces the number of conflicts, but improves the operations of that intersection. When considering left turn restrictions in urban grid networks, one of the largest drawbacks to their deployment is the potential for added trip distance. However, Median U-Turns can have a less significant impact on increases to trip distance. Rather than make several right turns, a vehicle only has to make one left turn downstream from the intersection. The median U-Turn is designed to occur mid-block in this thesis. This is fairly consistent with design guidelines of median U-Turn placement in the FHWA’s AIIR report.

Chowdhury et al. (2003) noted the potential for operational improvements of median U-Turns. Comparing different intersection treatments where left turns were found to be a safety concern, median U-Turns were found to be an effective safety treatment. Median U-Turns were found to be able to sustain moderate and high traffic volumes, particularly when the median U-Turns were on the minor approaches of an intersection. Chowdhury et al. (2005) also quantified their impact on access management, where it was
found that restricting left turns at high flow intersections with median U-Turns allowed for better operation of intersections, leading to reduced delay and better access management. A median U-Turn can be more flexible when considering an alternative intersection design that does not impose on existing right-of-way. A median U-Turn can be deployed if an existing median is present by replacing a center two-way left turn lane with a median turning area, or by using “loons”, which extend the edge of the pavement to accommodate a larger turn radius. One goal of this thesis and research is to explore the possibility of operational applications for median U-Turns in urban networks at a network level.

A formal study involving different treatments for left turns and the factors that influence them has not been done. The main goal of this thesis is to investigate how left turns can be treated in urban networks and the effect that this has on the operation of an urban network.

2.2. Performance of Street Network Configurations

This thesis investigates the operational performance of several different left turn treatments (left turns permitted, left turns protected, left turns protected and permitted, left turns restricted; and median U-Turns) under various network accumulations. Variations in performance can be easy to conceptualize when considering a single signalized intersection. When this intersection is under-saturated, allowing left turn movements provides a direct travel path, unlikely to be impeded by traffic conflicts. When a signal is oversaturated, vehicle conflicts become more likely; thus, several treatments can be implemented to help accommodate left turns: protected phasing, protected-permitted
phasing, or median U-Turns (Chowdhury, 2005; Gayah, 2012). Applying this logic to an urban grid network, it is possible that as the accumulation varies, different left turn treatments can be applied. This results in better operational performance as the accumulation varies in the network, rather than having one static traffic control system that may not operate as well as the accumulation changes. It is possible to find strategies similar to this already in place, where the permission of a turning movement may change during peak-period signal timings. These changes were made in practice due to the changes in the demand (or accumulation) and the operational differences associated with the strategies mentioned. This thesis considers these effects at a macroscopic network level, something that the current literature fails to do.

Different types of left turn treatments are used with different motivations. Permissive movements allow vehicles to move in conflict with opposing through vehicles and therefore are not always safe. Protected movements can be used to combat any concerns regarding safety and facilitation of the movement. These have the potential of reducing capacity. Left turn restrictions or Median U-Turns can be applied, but these increase the vehicle-miles traveled (due to the additional travel lengths associated).

Safety benefits are associated with left turn restrictions and median U-Turns (Hughes et al., 2010). There have been some operational benefits to these left turn treatments as well. However, these left turn treatments could have major environmental drawbacks. When the trip length is increased, the fuel consumption and vehicle emission increases as well. Traffic control directly impacts the mobility and congestion present in a network. This thesis considers the effects signal plans have on measures of traffic operations, fuel consumption, and vehicle-emissions for a network. Studying the impact
that traffic control has on these measures, a city planner or metropolitan planning organization can be better informed to develop a traffic control system to address different issues that may be present in that area. For example, if an organization is aiming to reduce vehicle emissions or fuel consumption, then it may be possible to do so through a network’s traffic control. Using the dynamic traffic control strategy discussed in this thesis, it is possible to do this for any metric, traffic operations; fuel consumption; or vehicle emissions, which can be associated with the accumulation of a network.

The performance of urban grid networks is highly dependent on the efficient operation of traffic control systems to move vehicles. Since traffic control at intersections creates temporary bottlenecks at which queues form, the management of their operation directly impacts the performance of a network. Multiple strategies have been suggested to improve network performance in an urban grid network, involving signal timing or vehicle routing.

### 2.2.1 One-Way Two-Way Networks

The influence traffic operations have on daily life has generated much debate in the general public, influencing the operation of urban grid networks. Considering the implementation of one-way versus two-way networks has led to the utilization of the left turn treatment, left turn restrictions. Discussed in this section is the motivation for studying left turn treatments (the potential societal benefits this may hold), the effects of how urban grid networks are managed, and the potential benefits from the study of dynamic traffic
control. While operational benefits are easily quantified, this study shows how far-reaching the results for an operational strategy of dynamic traffic control can be.

One decision that urban planners have been plagued by is the choice between one-way and two-way urban networks. Walker et al. (2000) discussed the impacts that the conversion from two-way to one-way networks has had in urban grid networks. The debate stands that while one-way networks may be able to increase traffic operational performance, they are generally not readily accepted by the public. This was due to the fact that people were concerned about the impacts this conversion may have on livability in urban grid networks, focusing mainly on drivers being able to navigate these one-way networks, the safety concerns associated with conflicts between pedestrians and vehicles now traveling at faster speeds, and the occurrence of “store eclipsing”. Store eclipsing is a phenomenon that occurs on one-way streets where, due to the direction vehicles travel being changed, some storefronts are not visible from the roadway. This can have severe impacts on the traffic operation, economy, and livability of urban grid networks.

More recent studies show that the economic impact from this conversion may prove to be significant. A study by Riggs and Appleyard (2016) showed that job growth can potentially decrease from neighborhoods that have undergone a one-way to two-way street conversion. This conversion can also decrease livability by affecting the exposure homes have to traffic throughout the day.

Gayah and Daganzo (2012) further researched the operational effects of two-way streets being converted to one-way streets. When comparing one-way and two-way street networks, two-way street networks perform better than one-way networks if the average trip length is relatively small. However, left turn restrictions on two-way networks always
performed better than one-way networks independent of the trip length. The deployment of this method allows for livable conditions in urban grid networks to be maintained while improving network traffic performance.

Left turn restrictions have been studied relative to performance of one-way and two-way networks. This is because left turn restrictions have been found to match the operational performance of one-way networks (Gayah and Daganzo, 2012). The left turn restriction left turn treatment is also a two-way network. Two-way networks have been found to significantly improve the livability of urban networks (Riggs and Appleyard, 2016). Ortigosa et al. (2014) studied the effects of traffic demand for the analysis of one-way, two-way, and two-way restricted left turn urban grid networks. This research was quantified through the rate trips are completed in the network. Findings supporting whether or not left turn restrictions operated better than other traffic control strategies were highly dependent on the demand pattern present. Vehicles being able to dynamically route themselves and the resilience of drivers also influenced the operational benefits of two-way networks over one-way networks, and whether or not one-way networks perform better than two-way networks. If drivers are very adaptive (able to reroute themselves to avoid congestion), then one-way networks perform best. If drivers are not as adaptive, then left turn restrictions perform better. While vehicles have to potentially take longer routes to reach their destinations, it has been found that two-way street networks can be kept in place and the rate at which trips are completed is increased to a one-way street level (Ortigosa et al., 2014). The only change to the traffic system required to improve operations is restricting left turns at intersections within the network. This allows for improved livability while also improving traffic operations.
2.2.2. Dynamic Traffic Control

Through the availability of real-time network data and advances in dynamic traffic control, traffic control centers can better manage the operation of traffic. There is the potential to significantly improve traffic operations during peak periods of vehicle demand, when most delay is incurred. However, most of the existing research in dynamically applying traffic control focuses on the sole fact that the signal’s timing can be optimized to improve the flow of traffic. The more sophisticated these signal timing models are, the less practical and more computationally intensive they become, to the point that deployment of these strategies become impractical. However, redefining how signalized intersections operate could improve network performance either through the addition or removal of a movement at the intersection. For example, this can be implemented using different left turn treatments dynamically throughout a day. Dynamic traffic control is the change or adaptation of how traffic is managed in a network depending on external stimuli. In this thesis, the treatment of left turns change depending on the rate at which vehicles are able to reach their destination as accumulation changes. There is potential for dynamic traffic control to be used as a tool for the optimization of an urban grid network through different traffic control strategies based on the demand (accumulation) currently present in the network.

Dynamic traffic control in this thesis is defined as the change in the traffic control strategy. This can include the signal timing, phasing, and permission of movements. The body of literature on dynamic traffic control about to be discussed supports the idea that its implementation can improve network performance. Changing the traffic control based
on demand or accumulation makes sense, conceptually. If considering that there are few vehicles on the network with few vehicle conflicts, allowing left turns until a certain level of congestion makes sense. If considering that there are many vehicles on the network with many vehicle conflicts, then it would be best to change traffic control to left turns being restricted. This could also help quantify previously discussed situations where agencies want to allow left turns during non-peak hours and restrict them during peak demand. While dynamic left turn restrictions may not be viable in some situations, specifically where the additional trip length or proportion of left turning vehicles make restricting left turns impractical, it holds the potential for improving network operations. The operational and influential factors of left turn treatments are one topic this thesis investigates.

The concept of dynamically changing the network traffic control depending on the demand is already in practice. This is observable in the field of traffic engineering as the restriction of turning movements during certain times of day, typically peak periods of demand. This is also done during low demand periods when traffic control is changed to a red ball or similar strategy. This allows vehicles to avoid unnecessary control delays (Phull and Harman, 2011). Sometimes lane use is also changed based on the traffic control (Zeng et al., 2010). Quantifying operational performance at a network level could provide insight for how to better operate urban grid networks, taking advantage of more recent advancements in technology for the management of traffic.

The removal of turning movements in an urban grid network has been shown to provide a viable way to increase network performance. To improve traveling conditions and reduce driver frustrations in urban grid networks, networks can allow or restrict left turns at intersections based on the demand. A case study allowing left turns during non-
peak periods and restricting them during peak demand periods, dynamic left turn restrictions, by Zhao et al. (2015) found dynamic left turn restrictions beneficial at serving and distributing demand during peak periods. Dynamic left turn restrictions were also found significant in reducing network intersections’ degree of saturation. While this research mentions the potential effects these strategies may have at adjacent intersections, it does not apply these traffic control changes at a network level or use more prominent and robust macroscopic traffic measures. There is ongoing research in this field by McNally further investigating the effects of removing left turns in an urban context (McNally, 2016). McNally’s research investigates driver expectancy using microsimulation tools to test the practicality of left turn restrictions on an arterial network.

When dynamic traffic control is applied, vehicles may have to change their routing. This means that dynamic traffic assignment, vehicles dynamically changing their routes as time progresses, should be used to realistically model vehicle routing with dynamic traffic control present. Mahmassani et al. (2013) investigated how dynamic traffic assignment would affect traffic operations when applied during congested periods of traffic. Mahmassani et al. (2013) found the effects of dynamic traffic assignment on traffic operations: the number of routes available impact the jam density and gridlock forms quicker in the presence of less adaptive drivers. Mahmassani et al. (2013) also found that during heavy congestion with dynamic traffic assignment, with a higher percentage of adaptive drivers that are present, congestion would propagate slower through an urban grid network, and recovery would occur more quickly. A higher number of routes available to an adaptive driver lead to increases in the jam density of the network. This occurs as a result of drivers being able to adaptively change their routes, and in doing so, they are then
able to avoid areas that are becoming congested, slowing the propagation of congestion as it occurs. Also, if they have multiple routes to choose from, this provides more of the network’s roadway for drivers to use, allowing for a more even distribution of traffic as congestion occurs and increasing the maximum density that can occur, the jam density of the network. When considering the effects that dynamic traffic assignment can have on urban grid networks it is important to take influential factors into consideration. The analysis of the performance of urban grid networks using dynamic traffic control requires dynamic traffic assignment, so that vehicles can reroute themselves once the traffic control has been changed.

Dynamic traffic control would be applied during different traffic states, congested and uncongested. Gayah et al. (2014) considered network stability when networks become very congested. Once congestion in a network begins, spatial inhomogeneity begins to form for the network. Since all macroscopic measurements assume homogeneity within the network, this could become an issue. If it is possible to better distribute vehicles through the use of adaptive signal control, then researchers can better understand how these networks are operating during heavy congestion and what is influencing these changes.

The impacts that adaptive traffic control can have on a network’s capacity were recently investigated by Zhang et al. (2012). This research proposed several different factors that impacted the performance of urban grid networks when using adaptive traffic control systems such as Self Organizing Traffic Lights (SOTL) and the Sydney Coordinated Adaptive Traffic System (SCATS). When quantifying the effect of these dynamic control systems with macroscopic traffic measures, several trends can be observed: demand periods highly influenced the capacity, critical density, and jam density
of these networks; directional bias was found to create a rapid rate of congestion to jamming in the network; the flow of vehicles was highly influenced by the homogeneous nature of the grid network being analyzed; and as the probability of turning occurring increased both the network capacity and jam density were found to decrease.

Al-Holou et al. (2012) investigated the effects of adaptive signal timing with the presence of vehicle to infrastructure (V2I) communication through probe vehicles. Given this information, a strategy was developed to adapt signal timing patterns and change vehicle routing to improve traffic delay and reduce greenhouse emissions respectively. These strategies were simulated using available network data and found to reduce greenhouse gases by approximately ten percent while still reducing delay, queues, and travel time.

The utilization of Intelligent Transportation Systems (ITS) has allowed improvements for various areas. The application of ITS to operations and their use in urban grid networks can allow for improved operational performance. This has allowed for traffic control centers to have real time data available and better manage traffic control. Several strategies are already able to utilize ITS through real time data in a variety of ways. This can be found in adaptive traffic control which changes its timing in response to traffic conditions, and more advanced strategies such as perimeter gating. Through the implementation of advancing technologies, dynamic traffic control provides a practical and viable way in which traffic engineers can improve network operations. This thesis focuses on dynamic traffic control in the respect of optimizing performance respective to left turn treatments.
2.3. Macroscopic Traffic Performance Measures

This thesis uses macroscopic traffic measures to quantify the operational performance of a street network. The primary macroscopic metrics used in this thesis are the Macroscopic Fundamental Diagram (MFD), the Network Exit Function (NEF), network-wide vehicle emissions, and network-wide fuel consumption. The evolution and development of these measures is discussed in this portion of this thesis. The intent of this section is to provide a background to the development of these metrics as well as their application for this research.

2.3.1. The Macroscopic Fundamental Diagram and Network Exit Function

There are a number of traffic metrics that can be used to quantify the performance of street networks. Since the goal of a network is to get drivers to their destination as quickly as possible, the rate at which vehicles reach their destination has been used as a new method to quantify network performance. The dynamic traffic control strategy discussed in this thesis is formed on the basis of the Network Exit Function (NEF), which quantifies the rate at which vehicles are able to reach their destination as accumulation varies, as shown in Figure 2.2.
Another traffic metric, the MFD, is used to quantify network performance in this thesis, shown in Figure 2.3. The MFD uses macroscopic aggregated traffic data of a homogeneous system to represent the flow of vehicles measured in a network as density increases.

The MFD can display network attributes such as capacity, free flow speed, jam density, critical density, as well as congested and uncongested states as shown in Figure 2.3. Both
of these metrics provide aggregate measures to quantify network performance. The NEF was used as the tool to quantify the efficiency of one-way, two-way, and left turn restricted streets at network levels in previous studies (Ortigosa et al., 2014a; Ortigosa et al., 2014b). However, both the NEF and MFD allow for analysis of how a network is managing traffic through the use of aggregate traffic data. While a relatively new method of analysis, this method of analysis is supported by a substantial amount of literature.

When considering the appropriateness of each tool, there are several factors to bear in mind. While the MFD is invaluable in analysis of the state of traffic and operating conditions, there are some drawbacks to its application in an urban grid network. Since the left turn treatments being considered can influence trip length (as previously discussed), the flow of vehicles may not accurately represent the performance of the network. Vehicles may flow at a higher rate but if unable to reach their destination as quickly as before, due to an increase in trip length, operational performance may not have been improved. Since the purpose of a traffic network is to get vehicles from their origin to their destination, the rate at which vehicles reach their destination (the NEF) is much more appropriate for quantifying network performance.

These types of macroscopic traffic measures are not new. Ardekani and Herman (1987) used graphical representations of aggregate traffic data to represent macroscopic network properties. The two-fluid traffic model was used in their work to predict the average speed of vehicles in a network given the number of stopped vehicles and the use of space mean and time mean data to quantify network operations. Their findings included a unique way of considering macroscopic data: given flow-density and speed-density relationships, a regression model was created as a tool to visualize macroscopic traffic
relationships. This paper also discussed the influence that the jam density has on a network, as well as the capacity, and used aggregate data to analyze macroscopic traffic data.

Edie (1961) defines general traffic parameters for vehicles in traffic analysis. Under these definitions, vehicles are defined as trajectories in time and space. For any Gaussian region in time and space it is possible to define the flow, density, and speed of vehicles. Flow is the number of vehicles observed passing one point over a defined time, density is the number of vehicles over a given space in one given moment of time, and speed is the flow of vehicles divided by the density of vehicles. Speed can be defined as a time mean or space mean. The time mean speed is the average speed of vehicles observed at one point as time progresses. The space mean speed is the average speed of all vehicles instantaneously occurring on a defined stretch of roadway (Cassidy and Coifman, 1997). Stationary conditions are defined as when vehicles maintain a constant speed for a long duration of time and all vehicles are assumed to maintain the same constant spacing and headway. These definitions lay the basis for traffic flow theory and the analysis in this thesis.

Macroscopic traffic measures from aggregate traffic data need to be from a homogeneous region to be representative of the actual traffic condition; in an urban grid network well-defined homogeneous sub-networks exist that have distinct homogeneous traffic states. The existence of these smaller urban grid networks could improve operations by quantifying the capacity, critical density, and jam density of a network through the Macroscopic Fundamental Diagram at a network level. With this data it is possible to better manage traffic networks and try to maintain densities below the critical density to avoid congestion and delays. The Macroscopic Fundamental Diagram was shown to exist as a
single well defined relationship by Geroliminis and Daganzo (2008). This study was done using data from probe vehicles and loop detectors where this well-defined relationship was observed between flow and density. This study proves that the Macroscopic Fundamental Diagram exists for an urban grid network. Using macroscopic traffic tools such as the Macroscopic Fundamental Diagram, traffic engineers can better manage traffic. An example of how the MFD can be applied to improve traffic conditions is perimeter metering. Perimeter metering is where if a network approaches critical density, then the operational performance can be improved by using traffic control to prevent more vehicles from entering each of these subnetworks. Doing so prevents networks from becoming congested.

A study of aggregate generalized models was done by Daganzo et al. (2012) to further understand parsimonious models, or predictive models whose structure is simple but still able to provide accurate insight as a predictive tool. Parsimonious models are considered to describe the basis of the Macroscopic Fundamental Diagram, where, through some simplifications, it is possible to develop a very simplistic model that provides valuable insight into the operation of an urban network. The benefits of parsimonious models are that they are not computationally intensive and easy to apply. Due to the uncertainty of some objects of models, less detailed models are sometimes beneficial. While parsimonious modeling was intended to be applied to the Macroscopic Fundamental Diagram, it is possible to also apply these conclusions to the emission models and their findings, the structure of which is discussed in the next section of this thesis.

Some variability exists in the macroscopic diagram; multiple phenomena have been found to influence macroscopic traffic performance (Daganzo et al., 2011; Mahmassani et
al., 2013). This should be considered when observing the results. Urban grid networks have a reduced network capacity when compared to highways or their theoretical capacity (Buisson and Ladier, 2009). This was found to be due to the presence of traffic control within the network (Gayah and Daganzo, 2011). Therefore, when considering Figure 2.3 in comparison to the results, it is important to keep in mind these influences.

There are also some instabilities in traffic flow theory when considering the Macroscopic Fundamental Diagram. One issue is shown by Gayah et al. (2014); depending on how traffic is treated, multiple states in the Macroscopic Fundamental Diagram may occur. Hysteresis loops have also been shown to occur at macroscopic levels when more realistic conditions are assumed and an increasing and decreasing demand is observed (Zhang, 1999). Hysteresis occurs from variations from steady state vehicle trajectories due to an individual anticipating or overreacting when accelerating or decelerating. When considering the Macroscopic Fundamental Diagram over time, it is important to take into consideration the fact that traffic is time dependent (Laval, 2011). The current traffic state is dependent on the previous traffic state. This is theorized to be related to microscopic variations from steady state assumptions due to acceleration and deceleration. This simply relates to the human behavior of anticipation and overreaction. This phenomenon of hysteresis loops can happen at a network level, theorized in a slightly different manner. Because traffic flow is able to occur at higher rates as congestion propagates than when it alleviates, the occurrence of a hysteresis loop is observed. This is due to the nature of traffic. It is possible for vehicles to load onto a network at a faster rate than the dissipation of this congestion, and due to this a drop in the capacity of vehicle flow is observed, consisting of a hysteresis loop. Hysteresis loops sometimes also form and represent
increased flow as demand decreases. This could be due to how the congestion has propagated, how the vehicles are platooned, how the capacity changes, and if there are any factors at a bottleneck causing congestion to alleviate slowly. Therefore, the Macroscopic Fundamental Diagram does exist and although homogeneity and congestion may influence the representation of it, an accurate Macroscopic Fundamental Diagram is still attainable.

This prior research provides the basis analyzing traffic operations using parsimonious network-wide measures such as the Macroscopic Fundamental Diagram and the Network Exit Function. Through traffic flow theory, these models allow utilization of aggregate data to consider the effects any change has on traffic operations at a network-wide level. This includes quantifying the capacity a network can sustain before becoming congested and the speed of traffic at different traffic states, as well as more advanced and detailed analyses.

2.3.2. Vehicle Emissions and Fuel Consumption in Transportation

The amount of vehicle-emissions generated has been found to be related to the vehicle miles traveled in a network. If operations can be improved while increasing the trip length, the rate at which pollution is generated could also inadvertently be affected. An increase in trip length would lead to an increase in vehicle emissions, but an increase in operations could also reach a point where vehicle emissions are reduced. Ideally, operational and environmental improvements would always coincide, but this is not always the case. Investments can be made to improve vehicles and their fuel economies, a prominent way that environmental concerns in transportation have been recently addressed.
The benefits of driving a fuel efficient vehicle would be minimized if a driver were stuck in congestion however, wasting fuel and generating pollutants regardless. This can have widespread implications for urban networks, even on health impacts from ambient air pollution on densely populated urban city centers. In addition to operational impacts, this thesis considers the effects that left turn treatments have on fuel consumption and vehicle emissions.

Interest in how the management of traffic flow relates to the amount of fuel consumed first came about in the 1970s, with the oil crisis and energy crisis in the United States. The conservation of fuel was now considered of national interest, and if able to predict the amount of fuel consumed by vehicles it was possible to manage traffic to help conserve this resource. Today this issue now also considers the effects that the consumption of fuel has as greenhouse gas emissions as airborne pollutants become larger environmental and health concerns. By using predictive models to generate estimates of these impacts on a network level, it is possible for urban planners to better manage network traffic control.

The United Nations Environmental Program (UNEP), United States Climate Action Report (CAR), as well as several other agencies have begun to address the importance of airborne pollutants and their relation to energy consumption when addressing human welfare. The World Health Organization (WHO) identifies outdoor air pollution as the cause of 3.7 million premature deaths worldwide in 2012 (WHO, 2014). Compared to the 1.25 million people who die in traffic accidents and along with the confounding effects of global warming, the effects pollutants generated through transportation (contributing to 45 percent of all airborne pollution in the United States) will have just as significant and long lasting effects on the environment and humanity (WHO,
The Environmental Protection Agency (EPA) has found in 2015 that 27 percent of all greenhouse gas emissions in the United States are related to the transportation sector, and that in this sector, emissions have increased significantly (by 16 percent since 1990) (EPA, 2015). This has been contributed to increases of the vehicle miles traveled in the United States. It has been deemed that trillions of dollars can be saved nationally by improving the rate at which fuel is consumed. This can also remove billions of tons of greenhouse gases from the atmosphere.

Since urban grid networks are predominantly stop and go traffic with large populations of people exposed to the pollutants, it is highly relevant to try to quantify the vehicle-emissions based on traffic control in urban grid networks. This literature also supports the integration of emission and traffic flow models, something that this thesis hopes to study. The necessity of this research has been magnified in 2014, with many new directions in which the issue of vehicle emissions and fuel consumption could be addressed. One proposed way to manage these pollutants was the deployment of Intelligent Transportation Systems (ITS), such as adaptive traffic control (Cambridge Systematics, 2009).

While some studies have been done to quantify vehicle emissions, other studies have tried to optimize trip routing or signal timing to minimize vehicle emissions (Han et al., 2014). This research has not investigated what effect different left turn treatments (intersection configurations) may have on vehicle emissions or fuel consumption. If a city has targeted reducing vehicle emissions and improving air quality, there is no operational strategy to do so. An excellent, and possibly infamous, example of this situation is the Beijing Olympics. During the Beijing Olympics, government officials strove to increase
air quality for competing athletes and tourists (Maureen, 2008). The solution was to remove vehicles from the system and not allow motorists to drive their vehicles depending on their license plate number. While successful, this reduced accessibility for a number of people and would not have favorable public opinion. If a correlation between traffic management and air pollution is found, this could have a significant impact on how some cities manage their networks.

Pandian et al. (2009) showed the impact that acceleration and deceleration could have when considering the concentration of vehicle-emissions, particularly carbon monoxide, hydrocarbons, and nitrogen oxide, depending on vehicle type. Ciskos et al (2012) developed a method to quantify the dispersion of vehicle emissions based off of vehicle emission models and while the concentration is highly dependent on site conditions, it is also possible for emission concentrations to be proportional to the number of vehicles. Akcelik (1983) created a model for fuel consumption of vehicles and the effects speed and other dependent variables could have. These regression models are parts of complex systems and when taking into consideration unobservable effects, it may be better to try to draw comparisons between outputs rather than consider this as finite analysis. This is now more relevant than ever, particularly with the availability of data through traffic simulation software. Traffic simulation software can produce large amounts of stochastic data, which can then be quantified with real data in application.

Ahn et al. (2002) integrated fuel consumption and vehicle emission models dependent on the instantaneous speed and acceleration of vehicles. Models of this nature make it more practical to quantify environmental impacts. Panis et al. (2006) developed a similar vehicle emissions model based on aggregate traffic data. These models have
macroscopic applications with the use of aggregate data and were furthered by Cappiello et al. (2002) where the development of a load based model was introduced. Using aggregate data, if the fuel consumption in a network is predicted, then the emissions of vehicles in a network can be analyzed by considering the rate at which fuel is consumed, which represents the load on an engine. This differs from kinematic models which are solely based on variables such as speed and acceleration or time based variables such as the time spent accelerating or cruising. This model type can be more easily applied, while some other models have been proven to be more difficult and cumbersome to quantify on a macroscopic level. This is because the load based model innovatively uses different independent variables to predict vehicle emissions, and regression models can be used to calibrate the model to local conditions. While this model can be run with only speed, acceleration, and vehicle type data, the availability of more data can make these models more robust.

In 2010 the EPA released MOVES2010 as an emissions model with diverse applications to apply vehicle-emissions through transportation engineering. Koupal et al. (2010) discussed the necessity for MOVES2010 to be calibrated to the vehicle fleet, vehicle age, vehicle miles traveled, local vehicle emissions, emission rate standards, road type, and driving patterns to accurately predict the vehicle-pollutions in an area. Smit et al. (2010) attempted to quantify the overall precision on the impact of vehicle emissions. When quantifying approximately 50 vehicle-emission models, the authors found that there was a high degree of variability due to tradeoffs existing between data accuracy and model detail. Overly elaborate models were found not to be representative while simplistic models were found to not be accurate. Depending on the pollutant being quantified, these errors could
range from 130 percent to 300 percent when trying to predict vehicle emissions. Complex models were not found to outperform the simplistic models by Smit et al. (2010). An ideal model for predicting vehicle emissions was deemed to be in a “middle-ground” between these two modeling strategies. Smith et al. proposed the validation of emission models integrated into the prediction on the grounds that data was a commonly misrepresented factor in these models.

Shabihkhani and Gonzales (2013) investigated the integration of emission models with traffic flow theory. The authors integrated emissions models with kinematic wave theory analytically to predict various pollutants based on macroscopic traffic properties at an isolated signalized intersection (e.g., signal green time and demand flow). The experiment was quantified using MOVES and traffic simulation software; however, this method is not appropriate or practical to apply to more complex urban systems with multiple intersections that interact. Zegeye et al. (2013) showed that the use of macroscopic flow data and macroscopic emission models reduce computational loads for calculating emissions; however, considering that traffic systems as complex and nonlinear systems with numerous internal and external factors, there are many unobservable variables to consider. By accounting for spatial and temporal inhomogeneity in their paper, a framework was developed which integrated macroscopic traffic flow models with microscopic emission models while also representing the expected error from macroscopic traffic models being used on microscopic vehicle-emission models. These errors were found to be relatively small. Osorio and Nanduri (2014) revisited the potential for vehicle emission models and traffic models to be integrated and macroscopic and microscopic models to be integrated. They found that the integration of both macroscopic and
microscopic data modeled network conditions best to represent local and network conditions. When using traffic simulation software, there is the potential for benefits through signal retiming as well as a reduction in vehicle emissions.

As the integration of traffic data into vehicle-emission models occurred, Ciskos et al. (2015) further considered the integration of traffic parameters into emissions modeling. Using the network fundamental diagram, it was possible to model vehicle emissions. Given the network vehicle miles traveled and average speed, it was possible to model emissions while considering the effects of traffic management and signal optimization, they found traffic flow data can be used to accurately predict emissions, with relatively low errors. With the usage of macroscopic traffic measures, it is possible to better integrate traffic flow theory and transportation environmental impacts. This can lead to better operation of traffic networks for both the user and the environment.

Farnoush and Christofa (2015) considered the application of vehicle trajectory data with queuing diagrams to optimize signal timings on an emissions basis, which can be done simply for isolated intersections. Li et al. (2015) found that grid networks can be optimized for pollutants by the distribution of vehicles within a network and how they are routed. Adaptive optimization of traffic control has also been studied in attempts to reduce pollution through traffic operations (Han et al., 2014; Pandazis and Winder 2015). Signal optimization and infrastructure to vehicle communications were found to significantly improve conditions for reducing vehicle emissions in relation to traffic control. Most of these adaptive traffic control studies focus on changing signal timings but do not specifically consider changing signal phasing patterns—and the treatment of left turns—and the associated emissions impacts. Adaptive traffic control studies fail to provide a
generalized overview at the impact different types of traffic control have on emissions in an urban grid network.

There have not been any direct studies linking how different traffic signal configurations affect the rate of vehicle emissions and fuel consumption for urban networks. The literature supports the integration of traffic operations and vehicle emissions. While there are very advanced models, there are several factors that make them inappropriate for use in this thesis. Some of these models have high relative errors (Smit et al., 2010). Even if the relative errors are small, all models would need to be calibrated for local conditions to be accurate (Koupal et al., 2010). Since this study uses a generalized network to make findings relative to multiple cities, it does not make sense to apply a highly sophisticated model or calibrate this model to “local” conditions. Most models also become very computationally intensive when considering an entire traffic network. Aimsun has integrated fuel consumption and vehicle emission models into its software. Since the nature of this research is to see how traffic control can influence vehicle emissions, these models seemed most appropriate. These conclusions do have some drawbacks: these models are based on “idealized” traffic networks and therefore are not applicable to any one specific traffic network. This thesis only investigates the effect traffic control strategies can have relative to each other on vehicle emissions and fuel consumption, since all measures are relative all errors are assumed to be relative as well. Using fuel consumption and vehicle emission models, it is possible to observe the effects that the management of traffic has on fuel consumption and vehicle emissions.
2.4. Literature Summary

This chapter discusses several key points concerning analysis of the treatment of left turns on urban grid networks: current uses and known effects of left turn treatments, the influence left turn treatments can have at a network level, the concept of dynamic traffic control, and traffic performance measures applicable to analysis. By changing the configuration of the network, performance is changed. There is a tradeoff between these two treatments, and under some conditions a tradeoff occurs where for different trip lengths the ideal treatment changes.

Applying this concept to the treatment of left turns in urban grid network, this thesis investigates how different left turn treatments perform, and under what conditions. This thesis considers several operational and environmental metrics to quantify performance for these treatments. Using the performance of different left turn treatments at different traffic states, it is also possible to simulate a dynamic traffic control scenario.
Chapter 3
Methodology

The methodology section of this thesis outlines the development of the idealized networks created on the traffic microsimulation platform *Aimsun* that were used for testing the different left turn treatments considered. This section of the thesis describes the networks that were created, including the differences between the networks used. This section also outlines how the various metrics were used to quantify the performance of urban grid networks, in both static and dynamic traffic control scenarios. The application of different metrics to quantify traffic performance and environmental impact allow the characterization of different left turn treatments.

3.1. Simulation Scenarios

This thesis used idealized grid networks to represent traffic networks that might be observed in various cities. The networks tested can be used to relate findings in this thesis to different cities or traffic systems. Using these findings, an urban planner or traffic engineer can quantify the potential benefits of changing the treatment of left turns in that network.

This thesis tested three different grid sizes: 9X9, 15X15, and 21X21, as shown in Figure 3.1. These grid sizes can be used to represent small, medium, and large cities. The grids simulated were simulated as perfect grid systems. Two block lengths were also tested, as shown in Figure 3.2: 125m and 250m. These block sizes and link lengths represent the configurations of different grid networks and influence the conditions for vehicles to travel
through them. These parameters of grid size and link length can be used to represent local conditions and give insight to how different traffic control measures perform under different conditions, particularly a varying travel length. Since the demand is uniform, and the size of the network is varied, trip lengths are expected to vary as well.

There were several different treatments of left turns considered: left turns permitted, left turns protected permitted, left turns protected, left turns restricted, and median U-Turns. Scenarios of left turns permitted, left turns restricted, and median U-Turns were tested without dedicated left turn lanes at the intersection, while left turns permitted, left turns protected permitted, and left turns protected were tested with dedicated turn lanes at intersections. The presence of dedicated left turn lanes and the treatment of left turns can
significantly influence traffic performance in networks. Ten iterations of each of these scenarios were performed. These iterations were performed to show that a trend developed in the results, and that no results occurred randomly. The number of scenarios that were tested can be found in Table 3.1.

<table>
<thead>
<tr>
<th>Number of Scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td>$9 \times 9$ Grid</td>
</tr>
<tr>
<td>$15 \times 15$ Grid</td>
</tr>
<tr>
<td>$21 \times 21$ Grid</td>
</tr>
</tbody>
</table>

Each network scenario was tested through ten replications to define observable trends between treatment groups. Ten replications of the idealized networks are tested for precision in the results quantified through traffic operation metrics built in Matlab. Each replication is generated randomly through the use of a pseudorandom seed.

### 3.2. Idealized Network and Simulation Setup

This thesis investigates factors that influence the effectiveness of different left turn treatments at different congestion levels/traffic states. This study shows that some left turn treatments may be better than others under certain traffic conditions. Because of this, transitioning between different left turn treatments based on prevailing traffic conditions can influence and improve the network operations.
The performance of different left turn treatments was simulated through the traffic simulation software *Aimsun*. This software allows for the creation of idealized networks that are identical in every aspect except for a particular feature of interest. In this case, the feature of interest is the treatment of left turns at the signalized intersections. This allows the use of multiple networks to make precise comparisons between the performances of different left turn treatments.

Idealized square grid networks were created that were made up of perfect grids in which each block had the exact same size and all intersections shared the same left turn treatment and signal parameters. Furthermore, the idealized grids assumed homogeneous traffic patterns throughout. While these conditions are not expected to occur in reality, they provide a “best case” for traffic performance and facilitate the use of the macroscopic traffic performance measures that are considered in this thesis.

Multiple network sizes were considered, both in the number of blocks used to make up the network (9x9, 15x15, 21x21) and the length of individual links that make up these blocks (125 meters and 250 meters). For a given network size, multiple networks were created with the only difference being the left turn treatment implemented. Since all other parameters are identical, this allows for any changes in traffic performance to be associated with the treatment of left turns.

### 3.2.1. Geometric Design

All grid networks were simulated with a uniform geometry and uniform traffic control at each intersection. Each link consisted of three-meter lane widths for each traveled lane and a nine-meter median. The speed limit on each of these links was 50
kilometers per hour. Each intersection without left turns present at the intersection – left turn restrictions and median U-Turns – had one through travel lane and one shared through and right turn travel lane at each intersection approach. Median U-Turn networks had a median U-Turn offset from the intersections on every approach, as illustrated in Figure 3.3: 115 meter offsets for 250-meter link lengths, and 52.5 meter offsets for 125-meter link lengths.

Figure 3.3: Median U-Turn Configuration
Left turn permitted networks without dedicated left turn lanes have one shared through and left turn travel lane and one shared through and right turn travel lane at intersection approaches. For the remaining networks – left turns permitted (with left turn pockets), left turns protected, and left turns protected-permitted – intersection approaches consisted of one dedicated left turn pocket, one through lane, and one shared through and right turn lane. The lengths of all left turn pockets are equal to one quarter of the link length: 62.5 meters for 250-meter link lengths and 31.25 meters for 125-meter link lengths. All permitted left turn movements were configured to yield to through movements while all right turn movements were allowed to make “right turn on red” movements. These intersection configurations, as described, are depicted in Figure 3.4.
Any other lane configuration parameters were consistent with initial Aimsun conditions. These conditions lay out the geometry for these networks. This geometry is uniform for each network. This was possible through the use of the Aimsun scripting platform, where a traffic network can be generated through the use of Python. No simulations were run where a network had several left turn treatments present simultaneously.

3.2.2. Traffic Control

All intersections in these networks were modeled as signalized intersections, except for the median U-Turns in that specific network type. In the median U-Turn network, the U-Turn locations were unsignalized but U-Turning vehicles were programmed to yield to oncoming traffic. A common cycle length of 90 seconds was applied to each signalized intersection. For each phase change, an all red time of one second was applied while the yellow time was set to three seconds. Green times varied based on the phasing scheme chosen, which was a function of the left turn treatment applied. The allocation of time in a
cycle between conflicting approaches were allocated similarly, while northbound-southbound and eastbound-westbound travel directions were allocated equal time. All demand in the network was uniform to ensure representative macroscopic measures. This also means that any form of signal coordination was expected to be unnecessary and withheld from this study. In fact, a previous study found signal coordination to be no more helpful in grid networks than having zero offsets (as was done here) (Girault et al., 2016).

Phase (Ø) configurations and signal timings are shown in Figure 3.5 and Table 3.2 respectively. In Figure 3.5, solid areas represent protected movements while striped areas represent permissive movements. Table 3.2 lists the green (G), yellow (Y), and all-red (AR) time allocations used for each of the left turn treatments considered. These signal timings are configured to manage the traffic demand present in the networks while also maintaining comparability.
All signals operated at fixed times for each left turn treatment. These times do not deviate from Table 3.2. While the timing of a signal can influence operations, the primary focus was to gauge the effects of the treatment of left turns. The following sections describe the performance of different left turn treatments in greater detail.

### 3.2.2.1. Left Turns Permitted

Permitted left turns are a standard treatment of left turns in which all left turning vehicles must wait for a gap in the oncoming through vehicle stream to make the left turn maneuver. Permitting left turns while not providing protected phasing or applying any innovative traffic control strategies provides a baseline for the treatment of left turns. This baseline was tested with and without dedicated left turn lanes as well. This shows the effects of the separation of traffic for when left turns are allowed. In this study, permitted left turns
are accommodated by applying two-phase signal timing plans at each intersection: one for all north-south movements and one for all east-west movements. During each phase, all movements from opposing approaches are allowed to move.

3.2.2.2. Left Turns Protected

Protected left turns provide a dedicated signal phase to the movement of left turning vehicles. While this does separate vehicle conflicts, it also increases the lost time of an intersection and increasing lost time reduces the capacity of an intersection. Protected left turns are typically applied to separate movements of traffic and are expected to improve the safety of an intersection. This left turn treatment shows the influence that dedicating time to left turning vehicles can have on a network’s operational performance. In this study, protected left turns were accommodated using four-phase signal timing plans at all intersections. Two phases are provided for each conflicting direction: north-south and east-west. For each direction, a phase is provided to serve opposing left turn movements (only) and a separate phase is provided to serve opposing through and right-turning movements (only).

3.2.2.3. Left Turns Protected-Permitted

Protected-Permitted left turns combine both protective and permissive left turn movements in one strategy through phasing and signal timing. This left turn treatment provides a dedicated left turn phase while also increasing throughput by allowing left turn
vehicles to move when there is an allowable gap. This treatment is able to provide benefits associated with both protected and permitted left turn movements. In this study, protected-permitted left turn treatment is accommodated using a four phase signal timing plan. This timing plan is the same as used for protected left turns, except opposing left turns are also allowed in a permitted fashion during the through/right turn phase.

3.2.2.4. Left Turn Restrictions

Left turn restrictions are a two-phase signal timing at signalized intersections, similar to that of permitting left turns but distinguished by not allowing left turns at the intersection. In urban grid networks, the rerouting of vehicles that would have had to turn left adds three blocks to the trip distance (for a perfect grid network, one that forms perfectly uniform squares) as shown in Figure 1.1. By restricting left turns and reducing vehicle conflicts the capacity of the intersection is expected to increase. Studying the additional trip length for different sized networks provides insight into how left turn restrictions may perform on different networks. This operation is the same as left turns permitted; however, no left turn movements are allowed at the intersection.

3.2.2.5. Median U-Turns

Median U-Turns (alternatively referred to as a MUT, Michigan Left, or Michigan U-Turn) are an alternative intersection and left turn treatment becoming more prominent in traffic engineering. These treatments operate similarly to left turn restrictions, but allow
left turns through the medians on the links of a roadway, which effectively separates left turn movements from intersections. The median U-Turn was installed mid-block on every link, as shown in Figure 3.3. Median U-Turns operate the same traffic control as the left turn restriction treatment at intersections, but these treatments allow left turns through a dedicated left turn lane separated from the intersection. This lane is located midblock of the link. When compared to other left turn treatments, median U-Turns are able to decrease additional trip lengths for left turning vehicles while increasing intersection capacity. The study of this relationship should show the influence of shortening the additional trip length on network performance. Vehicles turning left using the Median U-Turn have a shorter additional trip length (compared to left turn restrictions), but the Median U-Turn can reduce the capacity of the links once left turning vehicles queue at the median U-Turn.

3.2.3. Vehicle Demand

Each grid network was simulated with origin and destination points at the exact midpoint of every link for all networks. This midblock location represents generic access points along each of the individual blocks. These origins and destinations were then used to evenly distribute vehicle demand for the duration of all experiments. A homogenous traffic demand was used where each origin exchanged the same number of trips (on average) with each destination. This was assumed because it is a best-case scenario that reveals the best traffic performance for each of the left turn treatments that were considered. Origin-Destination routes that could not be completed on a network with left
turn restrictions were removed from all networks, so that the same demand patterns could be kept between all networks, allowing unbiased comparison.

Dynamic traffic assignment models were applied to determine the routing for each vehicle. Vehicle route choice was modeled using a c-logit model. Dynamic Traffic assignment allows for vehicles to change their route to minimize their travel time. The c-logit model was configured in Aimsun with the following parameters: three “initial K-SPs” and a maximum number of ten routes available. Twenty-five percent of the vehicles were set to follow this route choice model while traveling in Aimsun. All other vehicles traveled based on their free flow travel time, the shortest path available in the network. All other parameters for vehicle route choice follow default Aimsun values. Vehicles are able to change their routes both at the time they entered the network and while traveling towards their destination, providing a more realistic simulation. Vehicles change their routes for numerous reasons when driving, and this behavior would be expected if the treatment of left turns was changed as the traffic state changed. If a route became unavailable to a driver because of the restriction of a turning movement while in route, then that vehicle would be expected to change its route choice. In Aimsun, vehicles use dynamic traffic assignment to achieve this.

Two different types of demand were simulated in Aimsun. An ‘increasing demand’ profile was created to observe the performance of different left turn treatments for all possible traffic states in a network. A ‘peak demand’ profile was created to represent a more realistic demand pattern that represented a typical rush period. Using the peak demand profile, it was possible to observe the influence that the different left turn treatments had on hysteresis patterns in the macroscopic traffic performance measures.
Figures 3.6 and 3.7 can be referred to for the demand patterns simulated in Aimsun. In these demand patterns, the average rate of trip generation incrementally changes at ten minute intervals. The demand was scaled to the number of origins and destinations present in different grids using the Aimsun global scale factor parameter, because the number of origins and destinations influences the number of trips generated. The number of origins and destinations is also dependent on the number of links in a network. For each link, an O/D pair is located in the middle. The sequencing of trips was indiscriminately generated based on a random seed for the simulation being run.

Figure 3.6: Increasing Demand Profile
3.3. Metrics to Quantify Network Performance

The relative effectiveness of each left turn treatment in this thesis was quantified through various measures of performance. Operational performance measures in this thesis include trip length, speed, delay, travel time, the Macroscopic Fundamental Diagram (MFD), the Network Exit Function (NEF), the number of stops a vehicle makes, fuel consumption, and vehicle emissions: carbon monoxide (CO), carbon dioxide (CO2), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOC). The vehicle emissions and fuel consumption were represented using the fuel consumption, QUARTET, and Panis et al. models simulated in Aimsun (TSS, 2012). For the different left turn treatments tested in this thesis, each network is gauged using these operational performance metrics. These metrics represent the different objectives that a traffic engineer or urban planner may have. This may be the rate at which vehicles reach their destination, flow, or vehicle emissions. By knowing how different traffic control systems perform, based on each of these performance measures, it is possible to decide when to apply different left turn treatments. Better management of left turn
strategies allow for reductions in transportation costs – such as fuel consumption, vehicle emissions, and delay.

### 3.3.1 Traffic based Metrics

Traffic based metrics are metrics based on the conditions of vehicles within a network. These can be measures of conditions such as speed, flow and density and are potentially aggregated to different levels. All traffic based metrics are calculated using vehicle trajectory data of position and time for each vehicle every 12 seconds or 24 seconds. All data used to calculate traffic based metrics was collected using the Aimsun API (Application Programming Interface). These data were aggregated for five to ten minute intervals in Matlab. Variability in the way these data were calculated was due to limitation of the traffic simulation software when networks became exceedingly large. 21X21 grid networks with 250-meter link lengths used 24 second trajectory data that were aggregated to every ten minutes. All other networks used 12 second trajectory data that were aggregated to every five minutes. These trajectory data were used to obtain the cumulative trips begun, cumulative trips completed, average trip distance, cumulative travel time, average speed, density, accumulation, Macroscopic Fundamental Diagram (MFD) and Network Exit Function (NEF). These metrics were all obtained by post-processing the trajectory data in Matlab. These variables are defined as macroscopic measures at a network level.

Accumulation is defined as the number of vehicles present in the traffic network on the roadway at any time. This was calculated by recording the number of vehicles that
reported trajectory data within a time interval. The density of vehicles was defined as the number of vehicles on the network (accumulation) divided by the length of the roadways present in the network.

Average trip distance is the average distance that a vehicle travels within the network. This was recorded for every time interval as vehicles (all vehicles, counted cumulatively) complete their trips. The count at every time interval was a cumulative count accounting for the average trip distance of vehicles having finished their trips up to that point. Average speed is calculated by the change in distance traveled and time passed for this distance traveled through the trajectory data, determining the average vehicle speed for an individual traffic state.

Cumulative travel time is the cumulative sum of the travel time for all vehicles over time as the simulation progresses. Cumulative trips begun is the number of vehicles that have begun their trip for every time interval. This is calculated by the first trajectory data reported for an individual vehicle. Cumulative trips completed is the number of vehicles that have completed their trip for every time interval. This is calculated by the last trajectory data reported for an individual vehicle.

The Macroscopic Fundamental Diagram (MFD) describes the relationship between average network flow and density. From the Macroscopic Fundamental Diagram, it is possible to derive the flow capacity of a network, the maximum flow a network has; the critical density that a network has, the density at which capacity is reached; the jam density, the maximum density that is theoretically reached on the MFD; and the average speed or free flow speed, the slope of a line drawn from the origin to a traffic state or a traffic state at capacity or with a density lower than the critical density respectively. However, this does
not take into account the fact that people may have to travel further to reach their destination and that it may take them longer to do so.

A new approach to solving this problem is quantifying traffic performance in a new way. The goal of any traffic network is to get traffic from its origin to its destination, not to sustain a high flow rate. The Network Exit Function (NEF) is a relatively new traffic metric that can measure the former value. The NEF provides a relationship between the rate trips are completed and the accumulation, which shows how efficiently vehicles are able to reach their destinations as the traffic state changes within the network. The trip completion rate was calculated for trajectory data ending as vehicles completed their trips, and then was aggregated into five or ten minute rates. These data were then distributed for every accumulation interval.

3.3.2. Vehicle Emissions and Fuel Consumption

The Aimsun traffic microsimulation software was used to directly quantify the environmental metrics considered in these simulations. Three models were used: a fuel consumption model, the QUARTET vehicle emission model, and, the Panis et al. vehicle emission model (TSS 2012). These models were used to quantify the volume of fuel consumed and vehicle emissions of carbon monoxide (CO), carbon dioxide (CO2), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOC). Aimsun also recorded the number of stops each vehicle made and other traffic related parameters required for these models, which were not used in quantifying
the previously discussed traffic based metrics. These measures are calculated as vehicles within the network complete their trips.

When considering fuel consumption, Aimsun calculates fuel consumption as a rate in milliliters per second on a per-vehicle basis collecting data on whether a vehicle is idling, traveling at a cruising speed, accelerating, or decelerating. For each of these vehicle states, a different fuel consumption model is applied. Idling and decelerating vehicles are assumed to have a constant fuel consumption rate. Accelerating vehicles consume fuel at a different rate that is modeled by the equation:

$$F_a = (c_1 + c_2a\nu)$$

Where $c_1$ and $c_2$ are constant factors based on the vehicle and $a$ and $\nu$ represent the instantaneous acceleration and velocity of the vehicle, respectively. Fuel consumption while a vehicle is cruising or holding a constant speed was defined by the fuel consumption model (Akcelik 1982):

$$\frac{dF}{dt} = k_1 \left(1 + \frac{\nu^3}{2v_m^3}\right) + k_2\nu$$

$v_m$ is where a lower boundary velocity for fuel consumption, approximately 50 kilometers per hour. $k_1$ and $k_2$ are fuel consumption constants defined as follows for this model:

$$k_1 = \frac{(F_1 - F_2)v_1v_2v_m^3}{180(2v_2v_m^3 - 2v_1v_m^3 + v_2v_1^3 - v_1v_2^3)}$$

$$k_2 = \frac{2F_2v_2v_m^3 - 2F_1v_1v_m^3 + F_2v_2v_1^3 - F_1v_1v_2^3}{360(2v_2v_m^3 - 2v_1v_m^3 + v_2v_1^3 - v_1v_2^3)}$$

Here $F_1$ and $F_2$ are defined by data provided by the United Kingdom Department of Transportation in a 1994 study that provides fuel consumption factors for every 100
kilometers and are assumed for 90 kilometers per hour and 120 kilometers per hour respectively from the data provided in this study. The constants previously mentioned were set at their recommended values where $F_i = 0.33\frac{ml}{s}, c_1 = 0.42\frac{ml}{s}, c_2 = 0.26\frac{ml}{s}, F_d = 0.53\frac{ml}{s}, F_1 = 4.70\frac{l}{100km}; F_2 = 6.50\frac{l}{100km}$. These values are calculated once every five or ten minutes for these simulations. These values are then extrapolated over each five-minute or ten-minute simulation step set in the Aimsun microsimulation software. These models provide the cumulative vehicle miles traveled and the total fuel consumed over those miles, which can provide insight into the effects of these different traffic control systems.

The second model used in Aimsun to help quantify environmental impacts is the QUARTET Pollution Emission Model (QUARTET 1992). The QUARTET model also determines the vehicle state of all the vehicles in the simulation, whether it is idling, cruising, accelerating, or decelerating, and then the vehicle’s speed and acceleration are used to evaluate the vehicle emissions. This model outputs the emission rates of Carbon Monoxide (CO), Nitrogen Oxide (NOx), and Hydrocarbons (HC) in grams per second given what speed interval (or bin) the vehicle is traveling at as well as the state given typical emission values as shown in Table 3.3. This thesis ignores the impacts that grade may have on emissions in this model, which is reasonable since these idealized networks are being used to study relative changes for left turn treatments. The mixture of heavy vehicles or buses into the traffic stream was also not accounted for, so the effects of cars have only been observed within the network. However, since the extent of this work is to only draw comparisons from these idealized models, accuracy is considered a relative measure.
between the different simulations that were taken into consideration. This model outputs the grams of pollutants emitted as a rate over each simulation step as these traffic simulations run.

### Table 3.3: QUARTET Pollution Emission Model Factors

<table>
<thead>
<tr>
<th>Emission Rates for Cars</th>
<th>CO (g/s)</th>
<th>NOx (g/s)</th>
<th>HC (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idling emission rate</td>
<td>0.06</td>
<td>0.0008</td>
<td>0.0067</td>
</tr>
<tr>
<td>Accelerating emission rate</td>
<td>0.377</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Decelerating emission rate</td>
<td>0.072</td>
<td>0.0005</td>
<td>0.0067</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cruising Emission Rates</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10 km/hr</td>
<td>0.06</td>
<td>0.0006</td>
<td>0.0063</td>
</tr>
<tr>
<td>20 km/hr</td>
<td>0.091</td>
<td>0.0006</td>
<td>0.0078</td>
</tr>
<tr>
<td>30 km/hr</td>
<td>0.13</td>
<td>0.0017</td>
<td>0.0083</td>
</tr>
<tr>
<td>40 km/hr</td>
<td>0.129</td>
<td>0.0022</td>
<td>0.0128</td>
</tr>
<tr>
<td>50 km/hr</td>
<td>0.09</td>
<td>0.0042</td>
<td>0.0097</td>
</tr>
<tr>
<td>60 km/hr</td>
<td>0.11</td>
<td>0.005</td>
<td>0.0117</td>
</tr>
<tr>
<td>70 km/hr</td>
<td>0.177</td>
<td>0.0058</td>
<td>0.0136</td>
</tr>
</tbody>
</table>

Finally, the Panis et al. Emission Model is an emission model that uses a similar structure to the QUARTET Pollution Emission model (Panis et al. 2006). For each predefined time interval during a simulation, different factors are considered from Table 3.4 to help account for vehicle type, fuel type, and instantaneous acceleration and deceleration. This model also considers the following pollutants: Carbon Dioxide (CO2), Nitrogen Oxide (NOx), Volatile Organic Compounds (VOC); and Particulate Matter (PM). The non-linear regression model developed in this thesis for an instantaneous speed and acceleration emission model is as follows:

\[
E_n(t) = \max [E_0, f_1 + f_2 v_n(t) + f_3 v_n(t)^2 + f_4 a_n(t) + f_5 a_n(t)^2 + f_5 v_n(t)a_n(t)]
\]

Where \( v_n(t) \) and \( a_n(t) \) are the instantaneous speed and acceleration respectively of vehicle \( n \) at time \( t \). In these simulations the factors listed above were defined in accordance with the Panis et al. emissions model as shown in Table 3.4. This model outputs the
pollutants discussed in grams of the given pollutant and grams of the given pollutant per kilometer.

Table 3.4: Panis et al. Emission Model factors (TSS, 2012)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Vehicle type</th>
<th>$E_0$</th>
<th>$f_1$</th>
<th>$f_2$</th>
<th>$f_3$</th>
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<td>CO$_2$</td>
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<tr>
<td></td>
<td>Diesel car</td>
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<td>8.59e-02</td>
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<td></td>
<td>LPG car</td>
<td>0.00e-01</td>
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<td>-7.74e-03</td>
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<td></td>
<td>HDV</td>
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<td>5.88e+00</td>
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<tr>
<td></td>
<td>Bus</td>
<td>0.90e-01</td>
<td>1.13e+00</td>
<td>-4.27e-02</td>
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<td>NO$_x$</td>
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<td></td>
<td>LPG car</td>
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<td>4.11e-04</td>
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<td>1.50e-03</td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>Bus</td>
<td>8.92e-04</td>
<td>1.61e-05</td>
<td>-8.06e-07</td>
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<td>7.60e-05</td>
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<tr>
<td>VOC</td>
<td>Petrol car</td>
<td>3.43e-04</td>
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<td>0.00e+00</td>
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<td>Diesel car</td>
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<td>4.94e-06</td>
<td>1.66e-06</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>0.00e+00</td>
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<tr>
<td></td>
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<td>1.69e-05</td>
<td>3.75e-06</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HDV</td>
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<td>7.22e-06</td>
<td>-1.87e-07</td>
<td>0.00e+00</td>
<td>-1.02e-05</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Bus</td>
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<td>1.74e-07</td>
<td>-6.82e-09</td>
<td>-8.11e-07</td>
<td>1.18e-06</td>
<td>3.90e-07</td>
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<tr>
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<td>Petrol car</td>
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<td>0.00e+00</td>
<td>0.00e+00</td>
<td>0.00e+00</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>2.10e-04</td>
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</tr>
<tr>
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</tr>
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<td>3.75e-05</td>
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</tr>
</tbody>
</table>

These models form the basis of quantifying the environmental impacts in the traffic simulations of this thesis. Using these models in Aimsun, this thesis quantifies the differences in environmental impacts between various left turn treatments and how they operate.

3.3.3. Other Metrics

There is one other metric calculated to analyze the effectiveness of different left turn treatments. This is the number of stops for vehicles within the network. This metric is used to qualitatively analyze the performance of different left turn treatments.
One concern with left turn restrictions and median U-Turns is that by increasing the trip length, it is possible to also increase the number of times a vehicle has to stop, impeding vehicle progression. This was quantified using Aimsun which recorded the number of stops that a vehicle has made within a defined time interval (either five or ten minutes, as previously described). The number of stops is an output in the Aimsun software defined as the average number of stops per vehicle per kilometer. This is calculated by dividing the total number of stops a vehicle makes by the total distance a vehicle travels, and then taking the mean value for all vehicles in the network. By recording how many stops a vehicle had to make within a time interval it is possible to quantify the number of stops that vehicles within a network have to make as demand, accumulation, and congestion increase within the network as well.
Chapter 4
Analysis of Static Networks

The behavior of static networks, defined as networks with a single left turn treatment applied, is first analyzed. Simulating static networks allows comparisons to be made between the different left turn treatments using the metrics previously defined. This chapter of the thesis discusses the performance of different left turn treatments, and how the grid size, link length, demand pattern, and presence of dedicated left turn lanes influence their operation. The entire set of metrics for the range of grid sizes, link lengths and demands are provided in Appendices A, B, C, and D. In this chapter, only a selection of representative figures is presented and used for relations discussed in this section. This is because most observed general trends are the same. These representative figures may not include all performance measures discussed, but all performance measures can be found in the appendices and were used to support the analysis of left turn treatments. Any significant differences between the behaviors of different sized networks are highlighted in the text.

4.1. Analysis of Increasing Demand

The analysis of networks under an increasing demand profile (a demand profile which continues increasing until a network approaches jam density) allows for the treatment of left turns to be analyzed for all traffic states, congested and uncongested. 9x9, 15x15, and 21x21 grid networks of both 125-meter and 250-meter link lengths were tested for this scenario.
The rerouting of vehicles is one of the most influential factors when considering left turn alternatives: left turn restrictions and median U-Turns. For the simulations tested, it would be expected that the trip distance would increase for these treatments as vehicles that previously made left turns at the intersection would now have to reroute. When these vehicles reroute mid-trip, there is an additional three blocks added on to their trips for the left turn restriction strategy and one additional block for the median U-Turn strategy. However, this additional travel distance is reduced for vehicles that consider the left turn treatment at the trip origin.

Figure 4.1 shows the average trip length of all vehicles that completed their trip up to that point in the simulation. As expected, networks with alternative left turn treatments (left turn restrictions and median U-Turns) exhibit longer trip lengths than those with conventional left turn treatments (permitted, protected and protected-permitted). For left turn treatments where left turns are allowed at the intersection, the average trip distance seems to be fairly consistent. Some variance can be seen, but this has been attributed to variations in the additional trip length and vehicle route choices. When vehicles begin to complete their trips, there is some randomness in the average trip distance since some vehicles are able to complete their trips in a short time (vehicles with shorter trip distances). After a period of time, longer trips are able to be completed. With sufficient time, all trips in the network are able to be completed. This leads to an increase in the average trip distance. Once a steady trend in these results is reached, the average trip distance for alternative left turn treatments is observed to be greater than that of left turn treatments that allow left turns.
Figure 4.1: Average Trip Length

When considering the average operating speed vehicles were able to sustain while traveling through the network, vehicles were able to move at a much higher speed on networks with alternative left turn treatments compared to conventional left turn treatments. As shown in Figure 4.2, the average speed from highest to lowest follows the following trend: left turns restricted, median U-Turns, left turns permitted, left turns permitted without a dedicated turning lane, left turns protected-permitted, and left turns protected. This trend follows until the network reaches congestion, at which point the treatment of left turns with no dedicated left turn lane becomes the lowest performing treatment. All treatments steadily approach a speed of zero at jam density from this point.
The number of stops shows that progression is not interrupted for left turn treatments restricting left turns. In fact, left turn treatments restricting left turns had a lower number of stops per kilometer for trips completed than left turn treatments permitting left turns. This is shown in Figure 4.3 and Appendix B.

Network performance may be improved with alternative left turn treatments, even if increases in vehicle speeds come at the cost of increased travel distances. To accurately portray network performance, macroscopic traffic measures such as the Macroscopic...
Fundamental Diagram are used, as shown in Figure 4.4. The Macroscopic Fundamental Diagram shows the network flow capacity.

![Macroscopic Fundamental Diagram](image)

Figure 4.4: The Macroscopic Fundamental Diagram

From the flow-density relationships in the MFD, the performance observed of left turn treatments follows that similar to the average speed of a network. This is because the slope from the origin to any traffic state in the MFD is the speed of that traffic state. Networks with left turn restrictions maintain the highest flow capacity, from greatest flow capacity to least flow capacity as follows: median U-Turns, left turns permitted, left turns protected-permitted, left turns protected, and left turns permitted without dedicated left turn lanes, for 250-meter link networks. These results are consistent with 125-meter link networks; excluding the flow capacity of left turns protected exceeds that of protected-permitted. This change in network performance does not seem to be significant, however. These results are representative of 9x9 and 21x21 networks, shown in Appendix A.

The Network Exit Function is the representation of the trip completion rate as accumulation in the network increases. The trip completion rate is a macroscopic measure quantifying the main goal of any traffic, which is to allow vehicles to complete their trip
as quickly as possible. Figure 4.5 shows the Network Exit Function of 15x15 networks, as a representative of all networks tested. This figure may seem similar to Figure 4.4 of the Macroscopic Fundamental Diagram, but it is important to consider the changes in scale and the different implications that this measure has. The relative change in performance between alternative left turn treatments and left turn treatments allowing left turns has decreased due to the additional trip distance penalty for left turning vehicles. For example, this is why a decrease in the increased performance of restricting left turns compared to other left turn treatments is observed. The Network Exit Function is a more accurate measure of network performance. It quantifies the rate at which vehicles are able to reach their destinations.

Figure 4.5: The Network Exit Function

As shown in Figure 4.5, for 15x15 urban grid networks, left turn restrictions outperform other measures for the maximum trip completion rate or trip serving capacity, followed in descending order by median U-Turns, left turns permitted, left turns protected-permitted, left turns protected, and left turns without a dedicated left turn lane for 250-
meter link networks. The one variation for 125-meter networks is that the trip serving capacity for left turns protected exceeds that of left turns protected-permitted.

When compared with 21x21 networks, the ranking of left turn treatments was fairly consistent to that of 15x15. Alternative left turn treatments did not perform relatively better on larger networks compared to other left turn treatments, however. This is because the average trip length for a network of 21x21 is longer, and so the penalty of the left turn treatment strategy (an additional distance traveled for those vehicles that would have made left turns) is not as significant due to the smaller relative increase in the average trip length.

This trend also occurs when trip lengths are shorter. When compared to 9x9 networks, the opposite effect can be noted. Because of the relatively short average trip lengths for 9x9 networks, the left turn restriction strategy was not relatively as effective. Trip length penalties to left turning vehicles for alternative left turn treatments were far more significant. For 125-meter 9x9 grid networks, the left turn restriction strategy remained the treatment with the highest performing trip completion rate. For 250-meter 9x9 networks, the median U-Turn left turn treatment outperformed the left turn restriction left turn treatment. This is due to the median U-Turn strategy reducing the additional length for vehicles that would have turned left, while removing left turns from the intersection, increasing intersection flow capacity. The median U-Turn strategy can also reduce segment flow capacity however, if left turning vehicles generate a queue that spills into the travel way. Spillback to the intersection may also be why the median U-Turn strategy did not outperform the left turn restriction left turn treatment for 9x9 125-meter grids.

These results show the effects that grid size and link length have for different left turn treatments on an increasing demand pattern. When considering the presence of a
dedicated left turn lane, the gains in performance are significant, as shown with left turns permitted with no dedicated left turn lane compared to left turns restricted and median U-Turns. With the presence of a dedicated left turn lane, however, these alternative left turn treatments still outperform those that allow left turns, providing larger flow capacities and larger trip completion rates for higher accumulations. The removal of left turns at an intersection has the potential to increase operational performance significantly for urban grid networks.

### 4.1.1. Environmental Impacts

This section describes the environmental impacts of the proposed left turn treatments analyzed in this chapter. Changes in distance traveled and operational performance can greatly influence vehicle emissions and fuel consumption. A tradeoff exists where fuel consumption and vehicle emissions can either be increased or decreased due to increased traveled distance or decreased delays respectively. This study can give better understanding to whether or not it is more environmentally friendly to incur delay but have a shorter trip distance, or travel a further distance but reduce the amount of delay. Vehicles stuck in delay would incur a penalty, not being able to move but generating emissions and consuming fuel; however, idling vehicles tend to emit less and use less fuel that those that are moving.

These fuel consumption and vehicle emission models have been built into the Aimsun software. While more sophisticated models exist, current vehicle emission and fuel consumption modeling standards are to calibrate models to existing conditions, reducing
possible errors. Since this thesis considers idealized grid networks, the default values are used to get an overall sense of the impacts of left turn treatments on environmental factors. These models are used to compare the environmental impacts of different left turn treatments relative to each other. This defines the heuristic nature of this analysis. This section leads to a better understanding of how traffic control influences the amount of fuel motorists consume and the impact the resulting vehicle emissions can have on the environment. This is a preliminary comparison of environmental impact to traffic control.

The impact of traffic control on vehicle emissions and fuel consumption can be found in Appendix B. Appendix B shows the resulting vehicle emissions and fuel consumption for vehicles having exited the network within a specified five-minute period. As shown in Figure 4.6 and Figure 4.7, it seems that there is a correlation between the travel distance and these metrics. Left turn restrictions and median U-Turns perform considerably worse (higher fuel consumption and vehicle emissions) than measures with a reduced trip distance. Median U-Turns for 125 meter link lengths did not perform nearly as poorly, but this treatment also has a considerably shorter trip length penalty for left turning vehicles.
While these figures do portray the fuel consumption and vehicle emissions within a network, they do not consider exposure. Based on the NEF, some of these treatments serviced more cars than others, so more pollution and vehicle emissions would be naturally expected. The results in Appendix C were rescaled to show the vehicle emissions and fuel consumption created per completed trip. This is presented in Figure 4.8 and Figure 4.9. All fuel consumption and vehicle emissions are calculated for those vehicles having completed their trips. Dividing by the trip completion rate provides the average amount of fuel that was consumed or emissions generated on a per vehicle basis.
Figure 4.8: Fuel Consumption Rescaled to the Trip Completion Rate

Figure 4.9: CO2 Vehicle Emissions Rescaled to the Trip Completion Rate

Once these figures have been rescaled, those strategies that increase the trip length are not observed to necessarily lead to more fuel consumed or more vehicle emissions when considered on a per-vehicle basis. While these results are model dependent, they do show that if considering a per-vehicle basis, an entirely different picture for the environmental impact of left turn treatments can be observed: increases to trip length may improve environmental conditions if operations are improved. The exact proportion of these two factors required to improve environmental conditions falls outside of the scope of this
thesis. Improvements to operations could have profound impacts on the environmental impact of transportation.

4.2. Analysis of Peak Demand

The performance of left turn treatments for increasing demand profiles allows observation of the performance of different left turn treatments for the full spectrum of traffic states. Traffic does not always increase until jam density is reached, and as previously discussed traffic is influenced by hysteresis, the next traffic state is dependent on the previous traffic state. Therefore, to model more realistic demand patterns, simulations of an increasing and then decreasing demand pattern to simulate a ‘peak’ demand pattern are used.

Two patterns were simulated to observe the different effects of hysteresis on the left turn treatments, which can be found in Appendix D: ‘Peak Demand Pattern 1’ and ‘Peak Demand Pattern 2’. Peak demand pattern 1 was used to define the performance of left turn treatments for a lower demand while peak demand pattern 2 was used to define the performance of left turn treatments for a higher demand, showing the full effect of networks under the influence of hysteresis. Peak demand pattern 1 and peak demand pattern 2 both follow the same demand pattern. The difference between peak demand pattern 1 and peak demand pattern 2 is that they are scaled at different demands using the global scale factor.
As shown in Figure 4.10, as a representative of the results found in Appendix D, the effects of hysteresis do not change the general ranking of the performance of these left turn treatments, considering the trip serving capacity or flow capacity.

![Figure 4.10: Peak Demand Pattern 1 Network Exit Function](image)

One result of interest is that the alternative left turn treatments experienced counterclockwise hysteresis loops. Traffic influenced by hysteresis typically experiences a decrease in trip serving, shown by left turns protected in Figure 4.9. Both strategies restricting left turns from the intersection experienced a counterclockwise hysteresis loop, an increase in network performance. This does show that even under the effects of hysteresis, alternative left turn treatments are able to improve traffic operations. This is the result of the rate that congestion is able to alleviate.

4.3. General Remarks

The comparison of left turn treatments under static traffic control conditions (a left turn treatment analyzed for the duration of increasing or peak demand) demonstrated the
operational and environmental performance of various left turn treatments performed relative to each other. The strategies restricting left turns and providing median U-Turns were found to be very effective left turn treatments, in some cases increasing the trip serving capacity by 50 percent and nearly doubling network flow capacity (there is a reduction in the trip completion rate due to the increased average travel distance but the flow capacity is able to accommodate this). These results show the potential for traffic operations applying these left turn treatments on an urban grid network.

There are some limitations to the application of these strategies. These alternative left turn treatments are innovative in how they control the movement of vehicles, and in doing so contradict driver expectancy. While exposure to these treatments can combat this, it is important for the deployment of these strategies to investigate existing left turn restriction sites for appropriate signage to inform drivers of the change in traffic control. This change against driver expectations, and the compliance of new traffic rules, could have severe impacts on network safety. It is important to take into consideration these factors when considering changing the treatment of left turns in a traffic network.

These alternative left turn treatments are highly applicable in scenarios where space for a dedicated left turn lane is unavailable. The application of a left turn restriction strategy only requires signals to be retimed and appropriate signage to be installed at intersections for the restriction of left turns. Median U-Turns do require higher investment, signage at the median U-Turn, and potentially the paving of left turn lanes or the extension of the right of way if existing lane space is inadequate. The application of median U-Turns was also found to be most efficient for smaller networks, making the impact of this investment less
significant when compared to its deployment on larger networks. These findings support the applications of alternative left turn treatments in urban grid networks.

In this chapter, the performance of different left turn treatments has been discussed. From the results of this analysis it can be observed that the effectiveness of different left turn treatments is dependent on the traffic state. Accommodating left turns seems to provide higher network productivities for small network accumulations (i.e., when there are few vehicles in the network), while restricting left turns appears to perform better when the network operates near capacity (i.e., for higher accumulations). At very large accumulations (when the network is extremely congested), accommodating left turns appears to again provide the highest productivity. In this next chapter, a dynamic traffic control strategy is proposed that can optimize network performance by changing the left turn treatment based on the current accumulation to improve traffic operations.
Chapter 5
Analysis of Dynamic Networks

The previous chapter quantified and compared the performance of left turn treatments in urban grid networks. The chapter discussed potential improvements in flow capacity and trip serving capacity to urban grid networks. The MFD and NEF in that chapter also show that the best performing left turn treatment may change based on the density or accumulation present in the network. This chapter discusses the presence of dynamic traffic control, a strategy where the left turn treatment is changed based on the number of vehicles utilizing the network, allowing for increases in the maximum network performance during all traffic states.

5.1. Dynamic Traffic Control

The relative performance of networks with different left turn treatments can vary depending on the traffic state being considered. In general, the results from Chapter 4 and in Appendix A suggest that permitted left turns perform best under low accumulations, while restricted left turns perform best for higher accumulations. Similar interactions were found between strategies that allowed left turns (left turns permitted, left turns protected-permitted, and left turns permitted-2 lanes) and those that restricted them (left turn restrictions and median U-Turns) where treatments allowing left turns performed best under low accumulations and those that restricted left turns performed best under higher accumulations. Left turns protected perform better with higher vehicle accumulations.
With enough vehicles using the network, there are enough left turning vehicles to fully utilize protected phasing.

This concept is shown in Figure 5.1, where left turns are either allowed or banned. The optimal traffic control would change the left turn treatment to maximize the performance of the network at all accumulations.

![Figure 5.1: Dynamic Optimization Conceptualized](image)

These results support the idea that the utilization of different left turn treatments should be used at different levels of accumulation. Points in time where these levels of accumulation are reached should use different left turn treatments to control traffic. In this thesis, dynamic traffic control suggests using the left turn treatment that maximizes performance based on the accumulation within the network.
5.2. Dynamic Traffic Control Configuration

The configuration of a dynamic traffic control strategy has been based on the performance of different left turn treatments in static traffic control conditions. The NEF was used to measure the performance of different left turn treatments at different accumulations. The accumulations at which the best performing left turn treatment changed were noted as the accumulation for which the dynamic strategy would be activated.

These dynamic changes in traffic control were performed on the basis of the accumulation where performance changed and the time this accumulation was reached. Because the left turn restriction strategy performed best for higher accumulations, and the left turns permitted strategy performed best for lower accumulations, these two treatments were used to test the dynamic traffic control scenario. The results of these tests can be found in Appendix E. Dynamic traffic control was applied to 9x9, 15x15, and 21x21 grid networks of 125-meter and 250-meter link lengths.

Table 5.1: Dynamic Strategy Transition Time and Accumulation

<table>
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<th>250 9X9</th>
<th>125 15X15</th>
<th>250 15X15</th>
<th>125 21X21</th>
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<td>Critical Accumulation (vehicles)</td>
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<td>Transition Time (minutes)</td>
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<td>50</td>
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<td>80</td>
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<td>90</td>
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The configuration of dynamic traffic control was done utilizing Aimsun traffic management strategies. The time for transition in performance, the time at which dynamic traffic control changes the left turn treatment, was defined by the Network Exit Function as shown in Figure 5.2. This traffic control is changed based on the network accumulation. Using data gathered (providing the accumulations at all times in the simulation), a time was assigned in Aimsun for a transition in traffic control to take place. Table 5.1 shows the
time at which the critical accumulations were reached, and the time at which the dynamic traffic control was initiated, for networks of different sizes. As a transition in the traffic control was approached, left turns were restricted using built-in traffic management tools within Aimsun. This was done one cycle length (90 seconds) in advance of the dynamic traffic control change. During this transition, left turns were banned, and all vehicles were forced to vacate the left turn lanes for the duration of one cycle. The restriction of left turning lanes also had full compliance, and no vehicles were able to make left turns during this time. At the time where the accumulation reached and exceeded the critical accumulation, as shown in Figure 5.2 by the guideline, traffic control at the intersection was shifted to left turns being restricted. This was done using the Aimsun Initial State traffic management tool, through the removal of all left turn movements and all dedicated left turn lanes. The Initial State tool allows for all traffic from individual traffic states to be imported from one Aimsun network file to another, also allowing traffic to retain all routing, origin destination, and any other data associated. These Aimsun network files were then modified to be consistent with the left turn treatments tested in the analysis of static networks, allowing for unbiased simulation of dynamic left turn treatments.
Applying these left turn treatments dynamically allows investigation of optimal operational solutions for traffic networks that vary the left turn treatment used based on network accumulation. Different demand patterns on different grid sizes and link lengths are used to show how left turn treatments can be applied in a dynamic setting to improve traffic operations for urban grid networks. The practice of dynamic traffic control can improve traffic operations over all traffic states for the duration of a day, improving network conditions for all users.

5.3. Analysis of Increasing Demand

Increasing demand profiles were used to observe the effectiveness of dynamic traffic control when transitioning between different left turn treatments. This section uses 9x9, 15x15, and 21x21 grid networks with link lengths of 125 meters and 250 meters to apply permitted and restricted left turns dynamically based on the accumulation. The results of this section quantify the performance of these left turn strategies in a dynamic traffic control scenario.
Dynamic traffic control is used to increase traffic performance at multiple traffic states. Taking all traffic states into consideration allows for optimal traffic performance during all time periods, not only peak periods. The number of vehicles in the network was found to influence dynamic traffic control. Dynamic traffic control was tested using left turns permitted and left turns restricted because left turns permitted was the best performing treatment during low levels of accumulation, while left turn restrictions performed as the best treatment during high levels of accumulation. Testing the dynamic strategy by permitting left turns at low accumulations and restricting left turns at high accumulations provides an optimal traffic operations solution, creating an upper envelope in network performance, shown by macroscopic traffic performance measures.

Analysis of dynamic traffic control can be found detailed in Appendix E. Restricting left turns increases the trip completion rate in networks when the accumulation in the network exceeds a critical value – the critical accumulation. When comparing the critical accumulation for dynamic traffic control between networks, the critical accumulation was found to increase with link length and grid size.

The NEF results shown in Figure 5.3 were consistent with those NEF results of the static traffic control, the results of which are shown in grayscale to contrast the dynamic strategy, shown in color. These results are fairly consistent, except for a slight drop in performance immediately after the transition between left turn treatments. This drop in performance impacts the first five minutes of left turn restrictions. This is because vehicles were forced to reroute for a period of 90 seconds before the transition between left turn treatments. Vehicles, during this 90 second period, are forced to exit the left turn lane. It takes five minutes once the transition between left turn treatments has taken place for
vehicles to be able to route themselves and reach their destinations as expected, shown by the network NEF performance. Because this rerouting of vehicles only affects the trip length and how quickly vehicles can reach their destination, it explains why no similar trend was observed in the MFD. Finally, this is consistent with the expectations of real drivers on a network, finding that they have been forced to reroute themselves due to a change in traffic control, they may not be able to reach their destination as quickly.

These results support the use of dynamic traffic control. Dynamic traffic control of left turn treatments can improve traffic operations without any considerable impacts to network performance. This means that traffic can be accommodated during peak hours and regular hours.

![Figure 5.3: Dynamic Network Exit Function](image)

Dynamic traffic control improved network performance based on macroscopic traffic measures – the MFD and NEF. The use of dynamic traffic control allows for improved network performance for all traffic states of a network. Low demand periods account for most of the time that traffic networks perform. Influencing traffic control during this time has a significant impact on network operations. Allowing left turns during
these times can improve operational performance and reduce driver confusion or frustration when trying to navigate a network with left turn restrictions. Left turn restrictions allow a high trip completion capacity to be maintained for peak demand periods with dynamic traffic control, as shown in Figure 5.3. The use of dynamic traffic control could lead to the optimization of network traffic control, improving traffic conditions to better meet demand.

The implications of this research are that if the performance of several left turn treatments for a traffic state is known, either through simulation or traffic data, using dynamic traffic control can allow the best left turn treatment for any traffic state.

5.3.1. Sensitivity Analysis

A significant benefit to dynamic traffic control is the operation of the best performing left turn treatment for each traffic state. This requires the proper left turn treatment to be applied at the appropriate time, as discussed previously with Figure 5.2. However, applying the correct left turn treatment at the appropriate time requires precise real time data, providing enough information to reconstruct the network’s full NEF. Even with the appropriate data, bias may occur for any number of reasons, and the appropriate transition time for traffic control may not be selected. This section of the thesis investigates the influence of network performance that may occur when there is some error in the selection of a transition time.

One 15x15 grid network with 250-meter link lengths was tested to observe the sensitivity of performance to the transition time. Two tests of ten replications were run to observe what would happen if the transition in traffic control from the left turn treatment
of permitted to restricted occurred 30 minutes before and 30 minutes after the ideal transition time. The results of this sensitivity test can be found in Figure 5.4 for the MFD and Figure 5.5 for the NEF.

Figure 5.4: Sensitivity Analysis using the Macroscopic Fundamental Diagram

Figure 5.5: Sensitivity Analysis using the Network Exit Function

Variation in the transition time of this sensitivity test showed that networks can be very resilient when considering transitions in traffic control. If left turns are restricted too early or too late, the results show that the network is still able to achieve the high trip completion rates that would be expected from restricting left turns at the appropriate time. The only drawback to applying the dynamic traffic control at the inappropriate time would
be a small time period during which slightly lower performance is observed compared to if the correct time was selected. For an early transition, this is caused by the network transitioning to the left turn restricted performance too soon. For a late transition, this is caused by the network entering the congested regime for the left turns permitted strategy. Nevertheless, these results suggest that the dynamic strategy can still provide large benefits even if it is not implemented at the exact time shown in Table 5.1.

5.4. Analysis of Peak Demand

The analysis of dynamic control was also performed for peak demand patterns. This was done for high demand and low demand to simulate the full spectrum of hysteresis results—peak demand pattern 1 and peak demand pattern 2, respectively. Static analysis of left turn treatments under the effects of hysteresis showed that left turn restrictions showed a counterclockwise hysteresis loop, an increase in the trip completion rate. Typically, when traffic is subjected to hysteresis, drops in flow of the MFD or in the trip completion rate of the NEF are observed. Studying the effects of hysteresis on dynamic traffic control with peak traffic demands not only subjects the traffic control strategy to more realistic conditions, but also explores whether or not the observed effects of hysteresis on dynamic traffic control are also consistent form the tests of static traffic control.

Dynamic traffic control was simulated consistently between both demand patterns. Dynamic traffic control of grid size 15x15 was tested to represent the effects of hysteresis on dynamic traffic control, the results of which can be found in Appendix F. Figure 5.6 shows the results of this test. Hysteresis was not found to have any considerable effects on
dynamic traffic control, and counterclockwise hysteresis loops were observed, similar to those of static traffic control.

![Figure 5.6: Peak Demand Pattern 1 Dynamic Network Exit Function](image)

The results shown in Figure 5.6 and Appendix F show that the effects of hysteresis do not heavily influence dynamic traffic control, compared to the effects of hysteresis on static traffic control. Dynamic traffic control has also been found to be applicable under more realistic conditions. It is important to note that transitions in traffic control are successful when demand is increasing, as well as decreasing. The use of dynamic traffic control is a viable solution to improving a traffic network’s operational conditions.

### 5.5. General Remarks

Dynamic traffic control allows for network performance to be maximized for all traffic states by changing the left turn treatment over time. This switches the focus from selecting the optimal left turn treatment to maximize capacity, which has been the subject of most recent research, to the selection of the optimal left turn treatment to maximize
traffic network performance for all traffic states. Choosing the appropriate left turn treatments at all traffic states improves operational conditions for all traffic.

Several limitations may exist to the application of dynamic traffic control. While changing the treatment of left turns has been shown to improve operations, this may contradict driver expectancy. With the application of dynamic traffic control, it will be important to provide drivers with adequate information. The application of dynamic traffic control can improve the operations of traffic networks, but require real-time data to be best applied. While time-based strategies that change the operation of traffic control based on the time of day exist, this does not provide an optimal solution for operations. Time-based strategies lack the advantages of real-time data, while peak periods may be accommodated. Time based strategies are also unable to react to variations in traffic demand that can occur from events or holidays. Fortunately, the sensitivity analysis has shown that these strategies can still benefit from the change in operations; however, periods of time are left where, based on the actual traffic state, another left turn treatment could have better improved performance. A slight drop in the trip completion rate was also shown in the first five minutes after the transition time of dynamic traffic control. This is accounted to vehicles having to reroute and adapt to the change in the left turn treatment. This reflects actual applications, where drivers may be caught off-guard once the traffic control changes while they are in the network.

Dynamic traffic control allows for an optimal solution when considering alternatives in left turn treatments. Dynamic traffic control has been found to be resilient and improve traffic operations in the sensitivity analysis. The application of dynamic traffic control in this thesis has been shown to improve network operations. Several instances in
practice can be found where dynamic traffic control has almost been applied – engineers have applied treatments to traffic control during peak hours of traffic to help mitigate congestion. The research and development of the dynamic traffic control strategy discussed in this thesis provides quantifiable operational improvements for all traffic states.
Chapter 6
Conclusions

The selection of an optimal left turn treatment is a complex problem. Previous work has shown that left turn restrictions are not appropriate for all levels of congestion within a network (Ortigosa et al., 2014). Allowing left turns provides the best overall traffic network performance, as measured by the trip completion rate in the network, during low accumulations. This occurs because there are fewer conflicts, and vehicles can take the most direct routes. For high accumulations, the number of conflicts increases; therefore, in this case the best strategy is to restrict left turns to reduce conflicts at signalized intersections and increase intersection capacity. Doing so causes vehicles to travel longer distances, which is more than offset by the improved flow capacity. This results in larger trip completion rates by restricting left turns at higher accumulations.

By changing the left turn treatment applied based on the current accumulation, the trip completion rate in a network can be optimized at all times. If traffic control has an effect on vehicle emissions or other metrics used to quantify network performance, then the traffic control can also be dynamically changed in these situations to provide an optimal solution as well, depending on the objective being considered. This thesis investigated the operational benefits of several left turn treatments. The application of dynamic traffic control using these left turn treatments provided data to support alternative left turn treatment applications and the use of dynamic traffic control to improve operations for all traffic states.
6.1. Major Findings

While alternative left turn treatments hold the potential to improve traffic conditions, this is not true for all traffic states. This thesis studied the relative performance of left turn treatments at different traffic states with different network configurations. This thesis also studied the relative effects of different left turn treatments to be applied and improve performance at a network level. Dynamic traffic control was found to allow an optimal solution, where individual left turn treatments could be applied to different states in traffic.

Restricting left turns increases the trip completion rate in networks when the accumulation in the network exceeds a critical value. This critical value was found to increase with link length and grid size. Relative improvements from alternative left turn treatments were found to increase as the grid size increased and link length decreased. These factors are associated with the potential penalty of an increased trip length. Networks without ideal conditions for left turn restrictions still favor left turn restrictions for high accumulations, showing improvements in flow capacity and the trip serving capacity.

Dynamic traffic control was tested for the most effective left turn treatment of different traffic states. These tests were performed for the case where left turns were permitted at low accumulations and restricted at higher accumulations. Allowing left turns at low accumulations lead to an increase in the trip completion rate, and restricting left turns at high accumulations lead to an increase in the trip completion rate. This showed dynamic traffic control to be an effective measure for optimizing traffic control operations, designing a network for performance of all traffic states, not just the flow capacity.
This thesis also investigated the operation of alternative intersections, as they become more prevalent in traffic operations practices. The performance of median U-Turns in an urban grid network was quantified to show improvements in operations compared to conventional intersections. For small networks of large link lengths (unideal conditions for left turn restrictions), the median U-Turn was also shown to have the trip serving capacity compared to all other left turn treatments investigated in this thesis.

Finally, this thesis has integrated the studies of traffic control and vehicle emissions. Traditional metrics, such as vehicle miles traveled, have been associated with vehicle emissions and fuel consumption. Comparing the performance of different left turn treatments, fuel consumption and vehicle emissions do not increase with increases in the average trip length. In urban areas, operational performance has been shown to greatly influence the rate vehicles consume fuel or generate emissions. This study leads future research to investigate the impact that vehicles operating in congestion have on environmental impacts from transportation. This research supports the view that improving trip completion rates coincides with environmental improvements as related to transportation.

6.1.1. Network Simulation Validity

The results of this thesis make use of idealized urban grid networks. Idealized grid networks are practical for the testing and investigation of general traffic operations improvements. While the modeling of a specific urban grid network can provide accurate results showing more precise impacts that different treatments can have, there is limited
transferability of these results to other networks. To make the results of this thesis more widely applicable, idealized urban grid networks have been used. This is a prominent method of analysis found in the literature (Ortigosa et al., 2014a; Ortigosa et al., 2014b; Girault et al., 2015).

### 6.2. Suggestions for Future Research

This thesis has investigated several key areas in traffic operations: the influence of the treatment of left turns on operations, the integration of environmental measures in traffic operations research, and dynamic traffic control. While this thesis has expanded the current knowledge in these areas, there are still several questions both raised by this thesis and some areas of research that fell outside of the scope of this research.

The next step in this research would be to investigate other alternative intersections, such as continuous flow intersections, found outlined in the FHWA’s AIIR report. As these treatments become more prominent, the quantification of their operations become more so as well. This better quantifies the performance of these treatments as they become more readily available in practice and a more frequently used tool by practitioners, further integrated into traffic systems.

For homogeneity in these urban grid networks, this thesis assumed uniform demand with vehicles able to route themselves as previously defined. One major influential factor when considering the application of a left turn treatment is the proportion of left turning vehicles. Changing how vehicles route themselves and the proportion of left turns at intersections would influence the performance of a network. While the extents of this
application (the ratio of left turns required to affect network operation from one or multiple intersections) falls outside the scope of this thesis, it does suggest that left turn restrictions are not appropriate for every scenario. Analyzing the impact this could have on left turn treatments relative to each other could further influence traffic control in an urban grid network.

This thesis introduced a heuristic approach comparing environmental impacts of transportation to the operation of transportation networks. Tradeoffs between trip length and vehicle delays associated to the environmental impacts of transportation were observed in this thesis, and more sophisticated environmental models could be used to further quantify this analysis. Further integration of vehicle emissions and fuel consumption could provide better traffic management practices considering costs from environmental impacts.

This thesis outlined the application and quantification of dynamic traffic control for an urban grid network. Future research in dynamic traffic control could be expanded in several areas. Applications of dynamic traffic control have been applied in a sense, some signals and intersections change operations based on the time of day, but the application of a data driven dynamic change in traffic control would further improve traffic conditions. An application of dynamic traffic control can further validate the use of dynamic traffic control by giving a sense of how drivers would respond to this change in traffic control, and their acceptance of having to reroute. This thesis also proposed the use of left turn restrictions during high accumulations. Left turn restrictions reduce the number of conflict points at an intersection, but if considering crashes to be random events dependent on the distance traveled, the probability of them occurring may increase. While this thesis quantifies the operational effects (the additional distance traveled), this thesis raises the
question for future research: if additions to the distance a vehicle has to travel in an urban grid network can affect traffic safety.

Finally, hysteresis was found to have different effects on different left turn treatments. Hysteresis patterns for Left Turns Restricted and Median U-Turns were found to exhibit counterclockwise hysteresis loops for some scenarios, while all left turn treatments with left turns permitted were found to exhibit clockwise hysteresis loops. Future research could further investigate what influences these counterclockwise hysteresis patterns.
References


Girault, Jan-Torben et al. *An Exploratory Analysis of Signal Coordination Impacts on the Macroscopic Fundamental Diagram*. 2015.


Appendix A

Static Operational Figures

Figure A-1: Accumulation 9X9

Figure A-2: Accumulation 15X15
Figure A-3: Accumulation 21X21

Figure A-4: Average Speed 9X9
Figure A-5: Average Speed 15X15

Figure A-6: Average Speed 21X21
Figure A-7: Average Trip Distance 9X9

Figure A-8: Average Trip Distance 15X15
Figure A-9: Average Trip Distance 21X21

Figure A-10: Cumulative Travel Time 9X9
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Figure A-12: Cumulative Travel Time 21X21
Figure A-13: Cumulative Trips Begun 9X9

Figure A-14: Cumulative Trips Begun 15X15
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Figure A-16: Cumulative Trips Completed 9X9
Figure A-17: Cumulative Trips Completed 15X15

Figure A-18: Cumulative Trips Completed 21X21
Figure A-19: Macroscopic Fundamental Diagram 9X9

Figure A-20: Macroscopic Fundamental Diagram 15X15
Figure A-21: Macroscopic Fundamental Diagram 21X21

Figure A-22: Network Exit Function 9X9
Figure A-23: Network Exit Function 15X15

Figure A-24: Network Exit Function 21X21
Appendix B

Static Emission Figures

Figure B-1: Fuel Consumption 9X9 Akcelik Model

Figure B-2: Fuel Consumption 15X15 Akcelik Model
Figure B-3: Fuel Consumption 21X21 Akcelik Model

Figure B-4: CO 9X9 Quartet
Figure B-5: CO 15X15 Quartet

Figure B-6: CO 21X21 Quartet
Figure B-7: HC 9X9 Quartet

Figure B-8: HC 15X15 Quartet
Figure B-9: HC 21X21 Quartet

Figure B-10: NOX 9X9 Quartet
Figure B-11: NOX 15X15 Quartet

Figure B-12: NOX 21X21 Quartet
Figure B-13: CO2 9X9 Panis et al.

Figure B-14: CO2 15X15 Panis et al.
Figure B-15: CO2 21X21 Panis et al.

Figure B-16: CO2/km 9X9 Panis et al.
Figure B-17: CO2/km 15X15 Panis et al.

Figure B-18: CO2/km 21X21 Panis et al.
Figure B-19: NOx 9X9 Panis et al.

Figure B-20: NOx 15X15 Panis et al.
Figure B-21: NOx 21X21 Panis et al.

Figure B-22: NOx/km 9X9 Panis et al.
Figure B-23: NOx/km 15X15 Panis et al.

Figure B-24: NOx/km 21X21 Panis et al.
Figure B-25: PM 9X9 Panis et al.

Figure B-26: PM 15X15 Panis et al.
Figure B-27: PM 21X21 Panis et al.

Figure B-28: PM/km 9X9 Panis et al.
Figure B-29: PM/km 15X15 Panis et al.

Figure B-30: PM/km 21X21 Panis et al.
Figure B-31: VOC 9X9 Panis et al.

Figure B-32: VOC 15X15 Panis et al.
Figure B-33: VOC 21X21 Panis et al.

Figure B-34: VOC/km 9X9 Panis et al.
Figure B-35: VOC/km 15X15 Panis et al.

Figure B-36: VOC/km 21X21 Panis et al.
Figure B-37: Number of Stops 9X9 Aimsun

Figure B-38: Number of Stops 15X15 Aimsun
Figure B-39: Number of Stops 21X21 Aimsun
Appendix C

Static Emission Figures Rescaled to Trips Completed

Figure C-1: Fuel Consumption 9X9 Akcelik Model

Figure C-2: Fuel Consumption 15X15 Akcelik Model
Figure C-3: Fuel Consumption 21X21 Akcelik Model

Figure C-4: CO 9X9 Quartet
Figure C-5: CO 15X15 Quartet

Figure C-6: CO 21X21 Quartet
Figure C-7: HC 9X9 Quartet

Figure C-8: HC 15X15 Quartet
Figure C-9: HC 21X21 Quartet

Figure C-10: NOX 9X9 Quartet
Figure C-11: NOX 15X15 Quartet

Figure C-12: NOX 21X21 Quartet
Figure C-13: CO2 9X9 Panis et al.

Figure C-14: CO2 15X15 Panis et al.
Figure C-15: CO2 21X21 Panis et al.

Figure C-16: NOx 9X9 Panis et al.
Figure C-17: NOx 15X15 Panis et al.

Figure C-18: NOx 21X21 Panis et al.
Figure C-19: PM 9X9 Panis et al.

Figure C-20: PM 15X15 Panis et al.
Figure C-21: PM 21X21 Panis et al.

Figure C-22: VOC 9X9 Panis et al.
Figure C-23: VOC 15X15 Panis et al.

Figure C-24: VOC 21X21 Panis et al.
Appendix D

Static Hysteresis Figures

Figure D-1: Peak Demand Pattern 1 Accumulation 15X15

Figure D-2: Peak Demand Pattern 1 Average Speed 15X15
Figure D-3: Peak Demand Pattern 1 Average Trip Distance 15X15

Figure D-4: Peak Demand Pattern 1 Cumulative Trips Begun 15X15
Figure D-5: Peak Demand Pattern 1 Cumulative Trips Completed 15X15

Figure D-6: Peak Demand Pattern 1 Cumulative Travel Time 15X15
Figure D-7: Peak Demand Pattern 1 Macroscopic Fundamental Diagram 15X15

Figure D-8: Peak Demand Pattern 1 Network Exit Function 15X15
Figure D-9: Peak Demand Pattern 2 Accumulation 15X15

Figure D-10: Peak Demand Pattern 2 Average Speed 15X15
Figure D-11: Peak Demand Pattern 2 Average Trip Distance 15X15

Figure D-12: Peak Demand Pattern 2 Cumulative Travel Time 15X15
Figure D-13: Peak Demand Pattern 2 Cumulative Trips Begun 15X15

Figure D-14: Peak Demand Pattern 2 Cumulative Trips Completed 15X15
Figure D-15: Peak Demand Pattern 2 Macroscopic Fundamental Diagram 15X15

Figure D-16: Peak Demand Pattern 2 Network Exit Function 15X15
Appendix E

Dynamic Figures

Figure E-1: Accumulation 9X9

Figure E-2: Accumulation 15X15
Figure E-3: Accumulation 21X21

Figure E-4: Average Speed 9X9
Figure E-5: Average Speed 15X15

Figure E-6: Average Speed 21X21
Figure E-7: Average Trip Distance 9X9

Figure E-8: Average Trip Distance 15X15
Figure E-9: Average Trip Distance 21X21

Figure E-10: Cumulative Travel Time 9X9
Figure E-11: Cumulative Travel Time 15X15

Figure E-12: Cumulative Travel Time 21X21
Figure E-13: Cumulative Trips Begun 9X9

Figure E-14: Cumulative Trips Begun 15X15
Figure E-15: Cumulative Trips Begun 21X21

Figure E-16: Cumulative Trips Completed 9X9
Figure E-17: Cumulative Trips Completed 15X15

Figure E-18: Cumulative Trips Completed 21X21
Figure E-19: Macroscopic Fundamental Diagram 9X9

Figure E-20: Macroscopic Fundamental Diagram 15X15
Figure E-21: Macroscopic Fundamental Diagram 21X21

Figure E-22: Network Exit Function 9X9
Figure E-23: Network Exit Function 15X15

Figure E-24: Network Exit Function 21X21
Appendix F

Dynamic Hysteresis Figures

Figure F-1: Peak Demand Pattern 1 Accumulation 15X15

Figure F-2: Peak Demand Pattern 1 Average Speed 15X15
Figure F-3: Peak Demand Pattern 1 Average Trip Distance 15X15

Figure F-4: Peak Demand Pattern 1 Cumulative Travel Time 15X15
Figure F-5: Peak Demand Pattern 1 Cumulative Trips Begun 15X15

Figure F-6: Peak Demand Pattern 1 Cumulative Trips Completed 15X15
Figure F-7: Peak Demand Pattern 1 Macroscopic Fundamental Diagram

Figure F-8: Peak Demand Pattern 1 Network Exit Function
Figure F-9: Peak Demand Pattern 2 Accumulation 15X15

Figure F-10: Peak Demand Pattern 2 Average Speed 15X15
Figure F-11: Peak Demand Pattern 2 Average Trip Distance 15X15

Figure F-12: Peak Demand Pattern 2 Cumulative Travel Time 15X15
Figure F-13: Peak Demand Pattern 2 Cumulative Trips Begun 15X15

Figure F-14: Peak Demand Pattern 2 Cumulative Trips Completed 15X15
Figure F-15: Peak Demand Pattern 2 Macroscopic Fundamental Diagram

Figure F-16: Peak Demand Pattern 2 Network Exit Function