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Banning left turns the right ways: Studies of turn prohibitions and their interaction with congestion pricing

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Banning left turns the right ways: Studies of turn prohibitions and their interaction with congestion pricing

by

Ibrahim Itani

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of the

University of California, Berkeley

Committee in charge:

Professor Michael Cassidy, Chair
Professor Carlos Daganzo
Professor Rhonda Righter

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Abstract

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This dissertation aims to increase the understanding of supply- and demand-side congestion management strategies. In particular, the work focuses on left-turn bans and congestion pricing. It proves the existence of an optimal spatiotemporal zone within which to ban left turns during the morning rush in cities with central business districts. The optimal ban is capable of reducing vehicle hours travelled significantly. Contrary to popular assumptions, left-turn bans are also capable of reducing vehicle miles traveled. The effectiveness of turn prohibitions is impacted by the distribution of origins and destinations, route lengths and time of day. Moreover, this dissertation explores the effects of combining turn prohibitions with different types of congestion pricing strategies. For the case of Stockholm, simulations show that combining cordon-based congestion pricing with the optimal portion left-turn ban creates a win-win scenario. Either additional travel time benefits are gained at the original toll levels; or the original benefits are maintained at reduced toll levels. Combining the two measures also highlights the importance of optimizing left-turn bans since banning turns in wholesale fashion does not improve Stockholm's travel conditions. Furthermore, combining turn prohibitions with distance-based congestion pricing for a case study of downtown LA creates synergistic benefits. The reductions in travel costs due to the joint deployment of both strategies is greater than the sum of the reduction due to each strategy on its own. Adding turn prohibitions to a priced network allows commuters to arrive to their destinations both faster and closer to their desired arrival time.

To my family, for their never-ending support.

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Acknowledgments

At an early age, I was taught that you are affected by the people with whom you associate. I am lucky because, while pursuing this PhD, I was surrounded by people that have left a positive impact on me. I am eternally grateful for all those who helped make this feat possible.

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Chapter 1

Introduction

The motivation driving this research effort is presented in Section 1.1. Section 1.2 presents the main research questions to be answered, and Section 1.3 describes the organization of the chapters that follow.

1.1 Motivation

Around the world, some strategies for managing urban traffic congestion are applied without a full understanding of how they work. Peak hour traffic in the narrow streets of Beirut, Lebanon, for example, can be extremely congested. Some intersections cannot serve all the left-turning vehicles due to queue spillovers in the streets into which the vehicles want to turn. The resulting left-turning queue further aggravates the situation at intersections upstream. To mitigate this problem, local traffic officers are dispatched at certain times of the day to ban left turns at select intersections and force vehicles to execute through movements instead. This action ends the state of disrupted flow and forces drivers to make their left turns onto less congested streets downstream, or make several right turns instead. This practiced strategy, though not optimized or fully studied, yields positive results and raises questions about the possible presence of an optimal way to ban left-turns.

Moreover, cities facing congestion problems may apply multiple measures to help reduce congestion. Yet, there is very little consideration of how these measures would react with each other. For example, to increase travel speeds in London, the government imposed a toll on all vehicles entering the city. It also increased the number of public busses running in the tolled region. The number of people thereafter entering the city by bus exceeded expectations by more than 50% (Leape, 2006). Both of these measures decrease the number of vehicles entering the city, which increases travel speed. While the net effect was positive, the increase in slower and frequently stopping busses reduces street-network capacity (Johari et al., 2020). As a result, jointly implementing two seemingly effective congestion management strategies failed to achieve the full potential of each strategy combined. Congestion pricing, which is becoming prevalent nowadays, might react differently to strategies that increase road speeds like turn prohibitions.

Managing city-street traffic congestion can be thought of much like managing an office workspace. Inefficiencies occur in the workplace when, for example, a desktop is piled to the ceiling with tasks to be done. To solve this problem, it makes sense to bring in a more efficient worker who reorganizes tasks in a way that increases their productivity. It similarly makes sense to manage city traffic by reorganizing flows in congested neighborhoods, to reduce a street network's instantaneous workload (congestion). Reorganizing those flows can improve the network's productivity by reducing the effort (vehicle miles travelled, VMT) and time (vehicle hours travelled, VHT) needed to serve traffic. Banning left turns is such a reorganization strategy. It is a supply-side strategy that affects a network's capacity and vehicle routes. In addition to reorganizing tasks, reducing their total number can also help get the job (completing trips) done. Congestion pricing is a strategy that is capable of both reorganizing trips and reducing them. It is a demand-side strategy that affects if, when and how people travel. Cordon-based tolls can reduce the total number of car trips made. VMT-based tolls are more distance- and time-dependent and also reorganize when people travel. Exploring the joint deployment of turn prohibitions and the two distinct pricing strategies is interesting because they work on different fronts and can possibly interact with other traffic management strategies in distinct ways.

1.2 Research Questions

There are several worthwhile questions regarding turn prohibitions and congestion pricing. This dissertation answers the following:

- Does an optimal spatiotemporal left-turn ban zone exist for a congested city with a central business district?
- If such a zone exists, what are some factors affecting it?
- How do turn prohibitions impact the effectiveness of cordon- and distance-based congestion pricing strategies?
- If an interactive impact exists, does that call for a change in tolls when cordon-based pricing is also involved?
- Can the joint deployment of supply- and demand-side congestion management strategies achieve synergistic benefits that exceed the sum of the benefits of each strategy on its own?

1.3 Organization

The remainder of this dissertation aims at answering the questions posed in Section 1.2. Chapter 2 presents background information regarding turn prohibitions, congestion pricing and the potential benefits of applying them in concert. Chapter 3 provides simulation-based evidence of the existence of an optimal spatiotemporal left-turn ban zone and some of the factors affecting it. Chapter 4 focuses on the implications of the joint deployment of optimal turn prohibitions and cordon-based congestion pricing in the context of a city with a central business district resembling Stockholm. Chapter 5 turns attention toward the synergies that can be achieved through the joint deployment of turn prohibitions and distance-based congestion pricing in the context of a city like downtown LA where destinations are distributed uniformly over space. Finally, Chapter 6 concludes the dissertation with a summary of the main takeaways and discusses future work.

Chapter 2

Background

This chapter provides useful background from the literature on the topics at hand. Section 2.1 focuses on left-turn bans; Section 2.2 on congestion pricing; and Section 2.3 focuses on potential benefits of combining these strategies.

2.1 Left-Turn Bans

Left turn maneuvers are an integral part of traffic signal design and control. These maneuvers could be protected by having their own phase, or unprotected so they proceed with through traffic. There are multiple factors to take into account when considering the provision of a protected left-turn phase. These include delay, left-turn flow, through traffic flow, crash experience, intersection geometrics, speed, and other considerations (Agent, 1979; Cottrell and Benjamin, 1986; Stamatiadis et al., 1997; Zhang and Tong, 2008). However, in congested cities, providing separate phases for protected left turns might be infeasible because this takes away valuable green time from through traffic. In those cases, a proportion of the vehicles that want to turn left wait for acceptable gaps in the opposing traffic, a phenomenon referred to as gap acceptance. Newell (1959) modeled the effect of left turns on the capacity of an intersection on a highway with two lanes in each direction. He shows that vehicles waiting for an acceptable gap can block through moving vehicles behind them and reduce the capacity of an intersection by more than 30%. Fambro et al. (1977) confirmed these results and analyzed them through simulations for different lane numbers and opposing vehicle flows supported by field observations. Another study showed through field observations that left turning vehicles from the opposite direction also hinder left-turning vehicles in the studied direction, further reducing capacity (Yan and Radwan, 2007). In many cases, turn bays are added to intersections to store the vehicles waiting to make their left turns. However, in congested cities, the capacity of these bays may be insufficient. Messer and Fambro (1977) showed that when turning volumes are high, and turning bay lengths are short, the reduction in capacity can be quite significant and these maneuvers can lead to queue spillovers from the turn bay, and delays result.

Moreover, in networks with severe congestion, queue spillovers can occur from one link onto others. It has been shown by Ni and Cassidy (2020) that queue spillovers can form circular chain patterns, where the start of the queue spillover meets its end. These patterns can be noticed when the network is viewed from a graph theory perspective. Turn Graphs of Congested Segments (TGCS) can be used to identify the strongly connected components (SCC) of the network which represent the movements that might cause gridlock inducing patterns to appear, see Figure 2.1. These chains can often be broken by changing turning movements to through-moving ones.

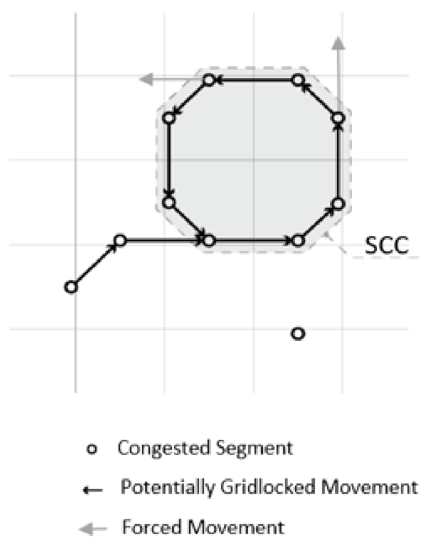


Figure 2.1: Turn graph of congested segments in gridlock

Due to the reasons mentioned above, banning left-turns has become a prevalent congestion management strategy. Banning left turns has been shown through several studies to reduce congestion and improve the system's trip serving capacity. Hajbabaie et al. (2010) showed that banning left turns along a corridor increases throughput capacity and reduces delay significantly. Gayah and Daganzo (2012) went further by considering a network of streets. That study compared through simulations the trip serving capacity of two-way and one-way networks. Banning left turns allowed two-way networks to be more efficient than their one way counterparts. The results thus showed that banning left turns is almost always beneficial for two-way networks. Ortigosa et al. (2019) also found through simulations that banning left turns increases trip completion rates, especially when adaptive routing algorithms are considered. These studies considered cities with origins and destinations distributed uniformly over space and left-turn bans in a wholesale fashion.

However, banning left turns can have adverse effects on the network, as it might cause trips to be longer (in space), and thereby increase the instantaneous accumulation in the system and decrease the instantaneous flow (DePrator et al., 2017; Gayah, 2012; Levitin et al., 2009). The possible increase in VMT might make this strategy unattractive especially with the recent shift away from evaluating transportation measures in terms of level-of-service, which is based on delay to VMT (Lee and Handy 2018; Volker et al 2019). Moreover, Tang and Friedrish (2016) argued that left turns should not be banned at all intersections. They studied traffic at each intersection in their simulation and determined whether it needed a left-turn ban. The research showed that banning left turns at certain intersections on a network while allowing left turns at others yielded the best results. Another study suggested limiting left-turn bans to street segments with overflowing queues (Gayah and Daganzo, 2011). Deprator et al. (2017) also found that left-turns should not be banned during certain times of the day. Under their assumed simulation conditions, they found that it was counterproductive to ban left turns when the network was uncongested or too heavily congested. These works suggest that an optimal spatiotemporal left-turn ban zone might exist, a topic that is explored in Chapter 3.

2.2 Congestion Pricing

Another increasingly popular congestion management strategy is congestion pricing, also referred to as tolling. When discussing tolls, one must make the distinction between tolls created for revenue purposes and tolls designed for congestion management purposes. While most tolls serve both of these purposes, the way they are designed is different. Tolls for revenue purposes can be used to offset the cost of building or operating a roadway segment, or can be used in other transportation programs. For example, under the build-operate-transfer model, state departments of transportation can authorize a third party to build a road and collect tolls from its users for a set period of time as a form of payment (SM Levy, 1996). California uses some of the bay bridge toll revenues, which amounted to more than $241 million in 2018, to fund transit operations and other investments (MTC, 2021). Although it is not their original purpose, these tolls still manage to reduce traffic congestion (Franklin, 2007; Hirschman et al., 1995).

On the other hand, when tolls are designed to reduce congestion, they can influence commuter behaviors in terms of if, how, and when commuters travel (Albert and Mahalel, 2006; Franklin, 2007). Travel making decisions are often thought to depend on utility maximization or cost reduction (Ben-Akiva et al., 1985; Gkiotsalitis and Stathopoulos, 2015). Captive commuters, who have to travel and are limited in their mode choice, react to congestion pricing by shifting the times when they travel (Vickrey, 1969). Noncaptive commuter can also opt not to travel or switch to another mode (Asensio, 2002). Choice modeling is a whole subfield in transportation that deals with incorporating costs like tolls into the decision-making process.

On a small scale, congestion pricing has been applied to individual highway segments or express lanes (Alshayeb et al., 2021; Casady et al., 2020). On a larger scale, it has been applied to cities and metropolitan areas. One of the largest metropolitan areas to have congestion pricing is London. It first enacted a cordon-based congestion pricing scheme in

2003. Almost every inbound vehicle that crosses the cordon boundary surrounding the city from 7 AM to 10 PM has to pay a flat rate congestion charge. Initially this charge was £5 and has increased to £15 in recent years. In its first year, the toll reduced the number of inbound cars by 33%. It also had an effect on mode choice. This was reflected by the 22% increase in inbound busses. It had an overall positive impact on network speeds as they increased by 17% from 14.3 Km/h to 16.7 Km/h (Leape, 2006).

Another very well studied cordon-based congestion pricing scheme was the one applied to Stockholm. It was introduced in 2006 for a trial period and was later made permanent. The toll was applied to most inbound and outbound traffic from 6:30 AM to 6:30 PM. This toll varied by time of day and was highest between 7:30 AM and 8:30 AM, and between 4 PM and 5:30 PM. The toll was effective. It triggered and maintained a 22% drop in traffic compared to 2005 levels. In fact, for a brief period between the trial and the final implementation, the toll was suspended, and traffic went back up to its original pre-toll levels (Eliasson, 2008). The toll also managed to change trip distributions. Trips originating from the suburbs to the inner city dropped by 15%. Suburb-to-suburb trips that crossed the toll boundary decreased by 25% while those that did not increased by 3%. Inner city trips also dropped by 12%. This reduction in traffic and change in trip distribution led to a 24% increase in travel speed (Mattsson, 2008). Both the London and Stockholm congestion pricing schemes were cordon-based. That is because the agencies governing these cities wanted to alleviate congestion in the central business district caused by commuters living in suburbs.

Another type of scheme in the literature is distance-dependent congestion pricing (Daganzo and Lehe, 2015; Kockelman and Kalmanje, 2005; Meng et al., 2012). The toll paid depends on the distance travelled in the network and the time of day. The nature of this toll makes it better suited for cities with destinations that are uniformly distributed over space like downtown Los Angeles. One of these noteworthy schemes is the time- and VMT-based toll strategy developed by Daganzo and Lehe (2015). It penalizes longer distance trips and trips that travel closer to the peak congestion time. It treats commuters as decision makers who can shift their departure times from day to day until a user-equilibrium is reached. This toll pushes longer-distance trips away from congestion peak time and shorter trips towards it. The change managed to increase trip completion rates, and the study showed that costs for the median commuter could be decreased by as much as 50%, despite the added tolls. What is also interesting about this strategy is that, at user equilibrium, tolls were an insignificant portion of total travel cost. Moreover, this distance- and time- dependent strategy is sensitive to changes in system performance and route choices. This sensitivity makes it prone to being affected by supply-side strategies like turn prohibitions.

Despite the benefits that can be achieved by congestion pricing, the measure faces challenges. One of the main challenges is public opposition. This comes due to an aversion to out-of-pocket costs, despite savings in travel time (Hårsman and Quigley, 2010; Reiter et al., 2009). Also, tolls raise concerns regarding equity. For example, a flat rate favors high-income commuters at the expense of low-income ones. High-income commuters have higher values of time and are affected less by tolls. These commuters are therefore less likely to shift from the peak desired arrival time (Eliasson and Mattsson, 2006; Giuliano, 1994). Another challenge is the logistical application of the toll (Eliasson, 2008; Leape, 2006; Phang and Toh, 1997). Cordon-based tolls require tolling stations/detectors at all city entrances. VMT-based tolls require individual vehicle tracking inside the city.

2.3 Supply- and Demand- Side Strategy Interaction

Much literature exists on how to manage city-street congestion created by cars. Part of it targets the demand side of the problem. As previously mentioned, congestion pricing does this by reducing or reorganizing demand for car travel. Other demand-side measures of this kind include turn-taking schemes that ration capacity by partitioning cars into groups, and alternating the days when distinct groups are allowed to enter downtowns; e.g. Thomson (1967), Ayland and Emmott (1990), Han et al. (2010), Nie and Yin (2013), Liu et al. (2014). Other examples include: use of traffic signals to meter cars entering downtowns ; (e.g. Rathi (1991), Lovell and Daganzo (2000), Daganzo (2007), and Hajbabaie et al., (2010)) and schemes to reduce vehicle miles traveled (VMT) by inducing commuters to shift from cars to transit (e.g. Bhat (1997), Zhang (2006), Guo and Peeta (2020), and Shin (2020)).

In contrast, the other part of the literature targets the supply side of the problem. As previously mentioned left-turn prohibition is such a strategy because it increases the capacity of intersections in a network; e.g. Shin (1997), Glass and Ni (1992), Gayah and Daganzo (2012), Tang and Friedrich (2016). Other supply-side measures also increase capacity either by adding to a network's physical infrastructure (e.g. Sanchez-Robles (1998), Henisz (2002), Fields et al. (2009), and Peeta et al. (2010)), or by better managing it (e.g. Yang and Bell (1997), Cassidy and Rudjanakanoknad (2005), and Fajardo et al. (2011)).

Despite the large literature on these strategies, there is little to no discussion of the potential interactions, especially the benefits, that can arise from combining strategies. To delve more into the potential interactions, consider the macroscopic fundamental diagram (MFD) of a network. The MFD, as seen in Figure 2.2, relates network-wide vehicle accumulation to the flow of vehicles in the system. A comparable relation exists between flow and trip completion capacity of the network (Daganzo, 2007). Thus, maintaining an accumulation level in the system with high flow improves efficiency. The MFD can help in understanding congestion management strategies.

Supply-side strategies, like turn prohibitions, can shift the entire relationship and increase capacity. This is because turn prohibitions can induce either reductions or increases in VMT. Consider a base state S_1 on the smaller MFD in Figure 2.2. When left-turns prohibitions are applied, the network operates on the larger MFD instead. If the increase in accumulation is modest (from n_1 to n_2), the new state S_2 would have a higher flow than the baseline state S_1. If the increase in accumulation is severe (n_1 to n_3), the new state S_3 would have a lower flow that the baseline. On the other hand, demand-side strategies like congestion pricing do not change the MFD. They only reorganize and reduce traffic demand, which decreases accumulation. As previously mentioned, cordon-based schemes mainly focus on reducing the number of vehicles entering the city while VMT-based schemes mainly focus on reorganizing when people travel. These strategies can decrease accumulation (n_1 to n_4) and move the system to a higher flow state (S_4). However, when both measures are applied together, there is potential to achieve results that are better than applying each measure on its own. The system would follow a higher MFD at lower accumulations. Implementing congestion pricing on network along with turn prohibitions (state S_2) can reduce accumulation (n_2 to n_5) and achieve a state (S_5) of high flow that could not be achieved by either measure on its own. For this reason, the potential benefits of combining turn prohibitions and congestion pricing are explored in Chapters 4 and 5.

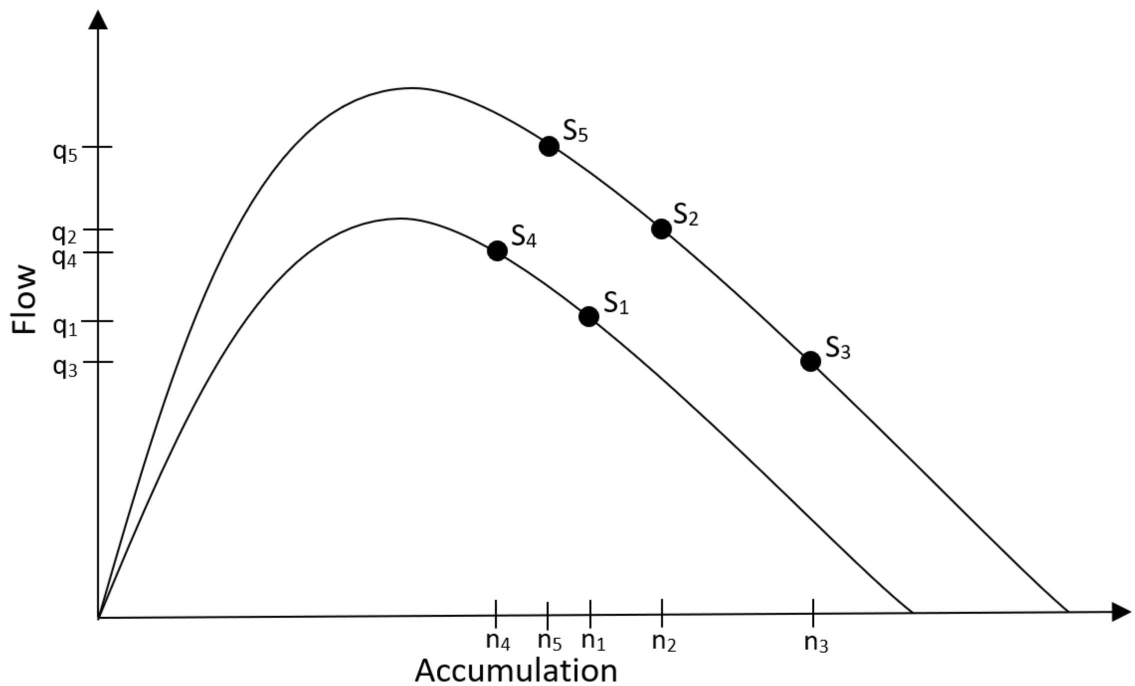


Figure 2.2: Macroscopic fundamental diagrams of a city and the corresponding traffic states under different congestion management strategies

Chapter 3

Optimal Spatiotemporal Zones for Banning Left Turns

Section 2.1 highlighted the effectiveness of banning left turns as a congestion management tool. However, the majority of studies to date have focused on the effects of banning left turns only. This chapter focuses on how to best ban left turns in certain scenarios and on the factors involved. The discussion shows that for certain network setups, there exists an optimal spatiotemporal placement of a left-turn ban zone. Section 3.1 focuses on the traffic dynamics involved in banning left turns and possible ways of exploiting them for better system performance. These dynamics are studied in Section 3.2 through simulated experiments.

3.1 Dynamics

The following discusses the dynamics involved in designing an optimal ban zone.

3.1.1 Zone Size and Location

Consider the following representation of a city shown in Figure 3.1. The city is divided into two zones, labelled Zone B (for banned) and Zone NB (Not Banned). This example can be used to illustrate how the physical size of a ban zone can have several interacting effects on network flow.

It is proposed that there exists an optimal ban zone size that will be investigated. To do so, we start by noting that banning left turns reorganizes flows in three ways, two of which can be counteracting. The first reorganizing effect is well known: converting left turns into other, less-disruptive movements raises intersection capacity (Messer and Fambro, 1977; Newell, 1959). This enhances the productivity of city streets by increasing flow and trip completion rates, which saves vehicle hours travelled (VHT). Hence, the turning ban is a bit like combining and simplifying tasks stored on a workplace desk.

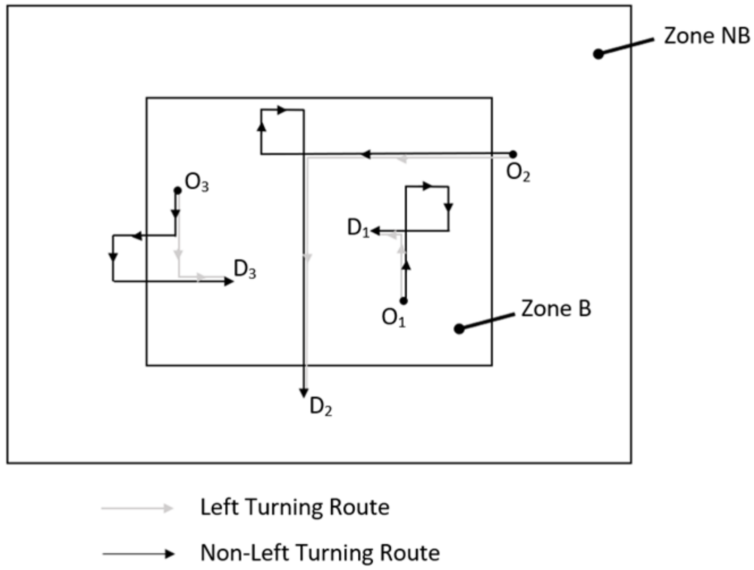


Figure 3.1: City with left-turn ban zone and three lengthened routes

The second effect follows from the first. The enhanced productivity brought by restricting turn maneuvers can diminish congestion on many street links. We find that the de-congesting of these links can reduce diversionary maneuvers to other links; i.e. drivers travel more directly to destinations when confronted with less-congested streets. This saves VHT, and also vehicle miles travelled (VMT). The latter savings come by having reduced the workload on a network, which is akin to efficiently organizing work items on a desk.

Both of the above effects argue for larger-sized ban zones. Yet there is a third effect that counteracts the second, and that can be explained with the aid of Figure 3.1. The figure presents examples of three shortest-path routes that were physically lengthened due to the turn restrictions in Zone B. Expanding the size of that zone would grow the number of circuitous routes traveled, like the three elongated routes shown in Figure 3.1. This would be undesirable, since the lengthened routes impose extra workload on the network by adding to VMT and VHT. Also, increased circuity diminishes how much the increase in productivity can be translated to an increase in the trip completion rate, which is a main measure of system performance. These interacting effects warrant studying the ban zone size rather than relying on the status quo of banning all or none.

Moreover, origin/destination (O/D) distributions affect traffic patterns. These patterns determine where congestion is located, and thus, where left-turn bans are warranted. Having destinations concentrated at the center of a city, for example, creates localized congestion and logically warrants a centered ban zone, as in Figure 3.1. The traffic patterns generated by different O/D distributions might favor different ban zone sizes and locations. For example, limiting the size of the ban zone can be counterproductive when the O/D distribution is homogeneous over the entire network. Moreover, the O/D distribution affects trip lengths. A route deviation caused by banning left turns potentially has a much larger relative effect on shorter trips than longer ones. These concepts were studied, and outcomes are presented in Section 3.2.4.

3.1.2 Scheduling Bans in Time

The best time of day to schedule left-turn bans was also investigated. Banning left turns when the system is uncongested increases the circuity of trips at times when this control is unnecessary. However, banning left turns only after severely congested conditions arise might forgo some or all benefits that could be achieved by controlling traffic in the early stages of congestion. The optimal time to schedule the ban was investigated based on several factors including the progress of demand rates throughout the day.

Additionally, the morning rush O/D distribution is opposite to that of the evening rush. The first has dispersed origins and concentrated destinations. The latter has concentrated origins and dispersed destinations. The travel patterns created by these distributions are very different and might require a different approach to banning left turns.

3.2 Simulation Findings

Findings regarding the optimal ban zone size and schedule were obtained through simulation experiments. The subsections to follow discuss the: (i) simulated network, (ii) study of the effects of a total, wholesale left-turn ban on that network and the even better results that were achieved by limiting the size of the ban zone, (iii) discussion and outcomes of scheduling these ban zones in time, and (iv) study of the effects of different O/Ds on the optimally sized ban-zone design.

3.2.1 Simulated Network

The network of major streets in similar to those of downtown Los Angeles was idealized as a homogeneous square grid of 20 N-S and 20 E-W streets with pre-timed traffic signals at every intersection; see Figure 3.2. Links were 200m in length and four lanes wide, with two lanes in each direction. All signals had a 90s cycle and two equal phases with unprotected left turns. Effective green times were 41s, and the lost time was 4s per phase. Offsets were random, meaning that signals were not coordinated on the network.

To simulate the morning peak demand, trip origins were uniformly distributed throughout the network, and the trip destinations were distributed normally around the network center. This O/D distribution is not reflective of downtown Los Angeles which is a relatively homogeneous because that type of distribution would calls for a total ban and not warrant studying different ban zones. The distribution used depicts a city with a central business district (CBD) and heterogeneous levels of congestion during the rush. A rush of generated vehicles that lasted for one hour and twenty minutes was used to simulate the morning peak.

The simulated drivers were informed of the locations where left turns were banned. This could be done in real life situations through the placement of variable message signs, onboard messages, or other means. Scenarios that tested different ban zone sizes and ban schedules were conducted, and ten replications of every scenario were performed to obtain suitable averages (Casas et al., 2010).

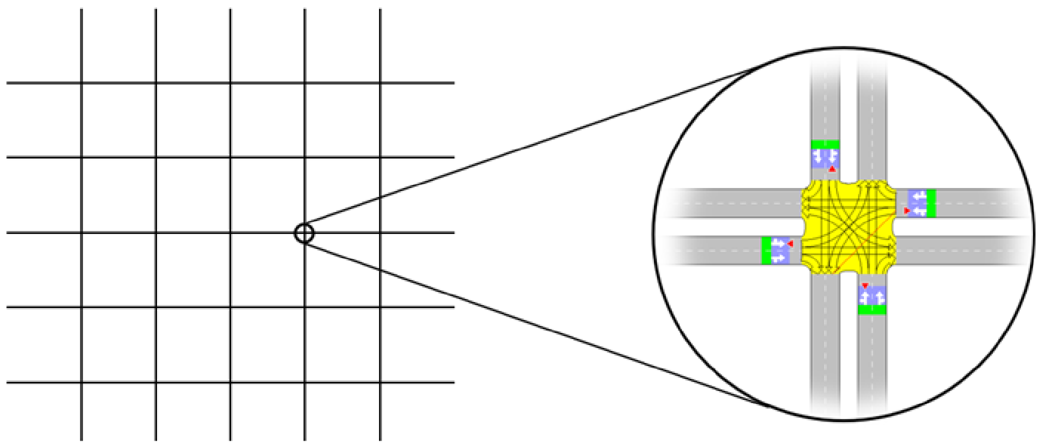


Figure 3.2: Representation of the simulated city and the street configuration

3.2.2 Optimal Portion Ban

To identify the optimal portion of the network where turns should be banned, several zone sizes were tested. Given the centered distribution of destinations, the ban zones were centered in the middle of the city. The average delay associated with each of them was obtained; see Figure 3.3.

Several observations were noted. Banning left turns in the most congested central 4x4 block region had detrimental effects on traffic. The ban caused vehicles in that zone to be rerouted to already congested neighboring zones. This rerouting caused gridlock in several replications. However, increasing the size to a still relatively small 6x6 block zone, encompassing only 9% of all intersections, was large enough to provide results better than the status quo. Delay continues to decrease as we increase the zone size up a 14x14 block zone. Beyond that, the benefits of banning left turns start to diminish. The 14x14 block zone around the center was deemed the optimal portion of the network to ban left turns.

Figure 3.4 presents the input-output diagrams for 3 scenarios: (i) no ban scenario which was considered to be the baseline; (ii) total ban scenario; and (iii) optimal portion ban scenario that was found by trial and error to reduce network VHT and VMT. The dashed cumulative count curves in Figure 3.4 illustrate the cumulative number of vehicles to reach their destinations when no ban was imposed during simulations. The slopes of these output curves are the time-varying rates that trips were completed on the network for the various simulation runs (Vickrey, 1969). The case where the output curve plateaued reflects the occurrence of gridlock (gridlock did not occur when left turns were banned).

The dash-dot curves in the figure, which are the output curves of the total ban scenario, had higher slopes than those of the baseline case; i.e. the wholesale banning of left turns led to an increase in trip completion rates when compared to the baseline. Additionally, since both these scenarios share the same demand curve, the increase in trip completion rates translates to a decrease in area between the input and output curves. This area is the network VHT (Daganzo, 1997). The average network VHT annotations on Figure 3.4 reveal that banning left turns across the entire network led to a 43% decrease in VHT when compared to the baseline.

However, it was found that better results were achieved by limiting the ban zone size. The 14x14 block region around the center of the network was found to be the optimal portion of the network to ban left turns. The dotted cumulative count curves in Figure 3.4 are the output curves for this optimal-portion ban scenario. These curves show that the optimal portion ban led to an increased trip completion rates. The network VHT decreased by an additional 29% relative to the total ban, confirming the benefits of limiting the size of the ban zone.

The productivity and workload effects that gave rise to these outcomes are revealed in Figure 3.5. It presents average sample paths on the flow-density plane. These were generated from the average of ten simulations of the rush period's build-up for each of the three scenarios[1]. The paths map the relations between the network's average circulating flow (i.e. instantaneous productivity) and average traffic density (instantaneous workload). The figure also shows the VMTs accrued over the full period of the baseline, total ban and optimal portion ban scenarios. Note from Figure 3.5 the higher circulating flows produced at the heights of the rush when turns were banned. The highest of these were generated for the optimal portion ban, which is why that scenario achieved the highest trip-completion rates and lowest VHT, as previously shown in Figure 3.4. The annotations in Figure 3.5 reveal that left-turn bans not only saved VHT, but VMT as well. The greatest savings were once again achieved in the optimal portion ban scenario; a 12% reduction in VMT compared to the baseline. The decrease in this case indicates that the increased productivity and uncongested route availability overcame the effect of the increase in circuity on VMT. Banning left turns only in a portion of the network maintained the best balance between the aforementioned interacting effects.

[1]The period when queues dissipated toward the end of the rush are not shown in Figure 3.5 to avoid clutter.

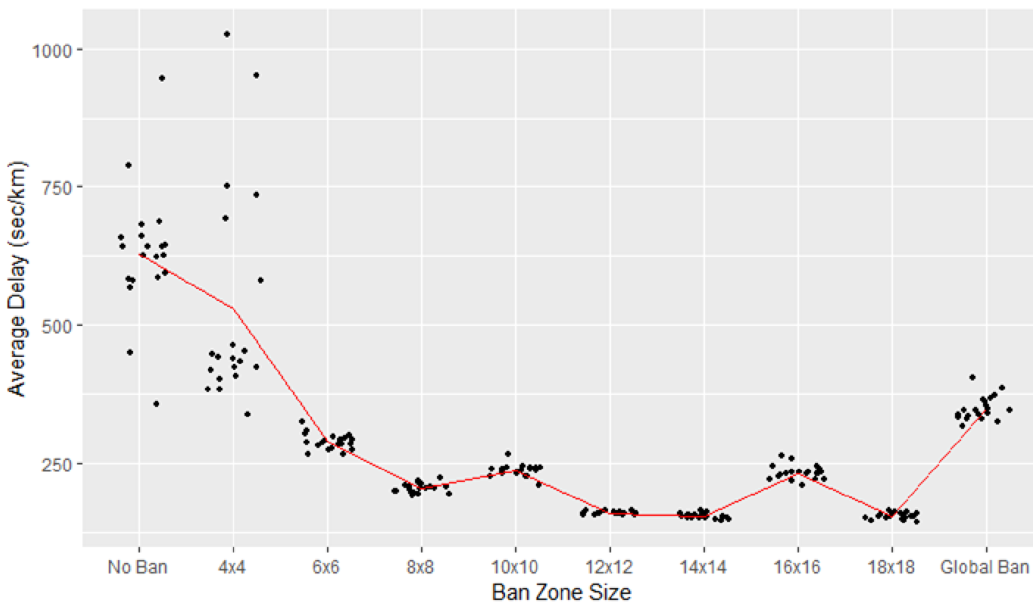


Figure 3.3: Average delay associated with different ban zone sizes

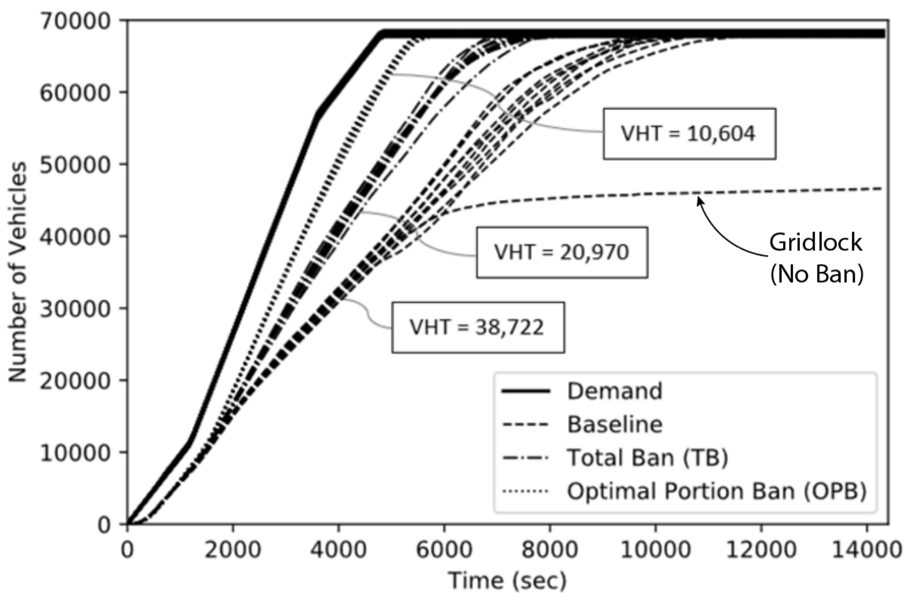


Figure 3.4: Input output diagrams for different ban zone scenarios

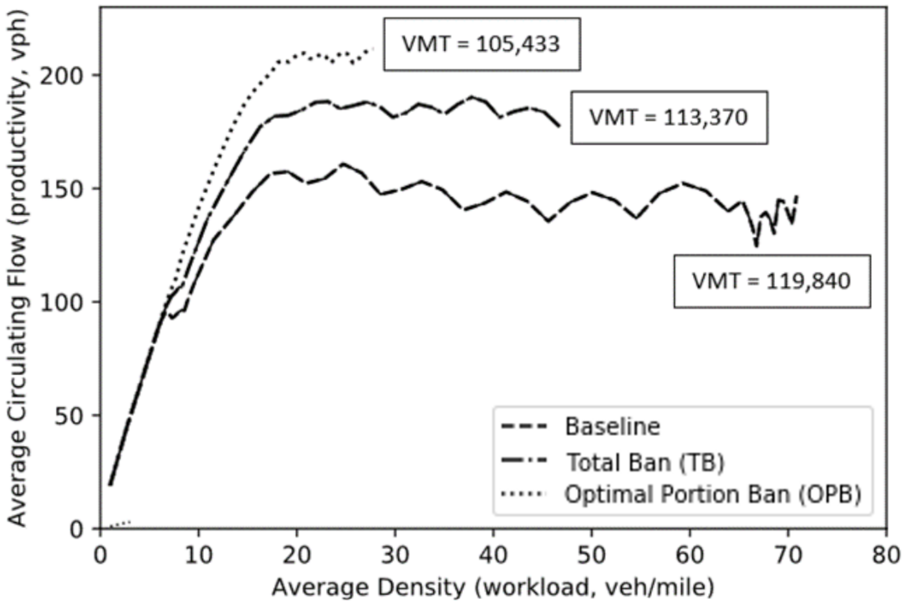


Figure 3.5: Sample paths for different ban zone scenarios

3.2.3 Optimally Scheduled Ban

In the previous subsection, we showed that traffic agencies do not need to ban all left turns in a network to achieve optimal results. This subsection shows that the ban does not need to be implemented all day long. It suffices instead to implement the ban shortly before the start of the rush. Evidence follows.

To explore the optimal ban schedule, the period extending from slightly before the rush starts to slightly after it ends was studied, as can be inferred the solid black curve in Figure 3.6. The figure also presents the output curves for four scenarios: (i) no-ban scenario shown by the dashed line which was again considered the baseline, (ii) optimal portion ban that starts 100 min into the simulation of this scenario and is shown by the dotted line, (iii) optimal portion ban where the ban starts 40 min into the simulation of this scenario (shortly before the onset of the peak demand), which is represented by the dash-dot line, and (iv) optimal portion ban that is imposed for the entire 4-hour simulation period of this scenario, which is shown by the solid grey line. Each of the four output curves is the average of ten simulations.

Figure 3.6 shows that banning left turns 100 mins into the simulation, when the system was already in its most congested state, was not beneficial compared to the baseline. It caused an increase in circuity due to route changes without the benefits of the shorter routes that accompany lower congestion levels. In fact, several gridlock situations even appeared during the second scenario. Starting the ban shortly before the onset of peak demand, 40 min into the simulation, achieved results almost identical to those when the ban was implemented at the very start of the simulation; i.e. the dash-dot curve and grey solid curve are almost identical. The benefits of banning left turns, including lower congestion levels and better route choices, were retained. The significance of this finding is that left-turns don't need to be banned all day. It is sufficient to ban them before the road usage demand exceed the network trip completion capacity. Scheduling the ban eliminates unnecessary control and makes more routes available during off-peak hours.

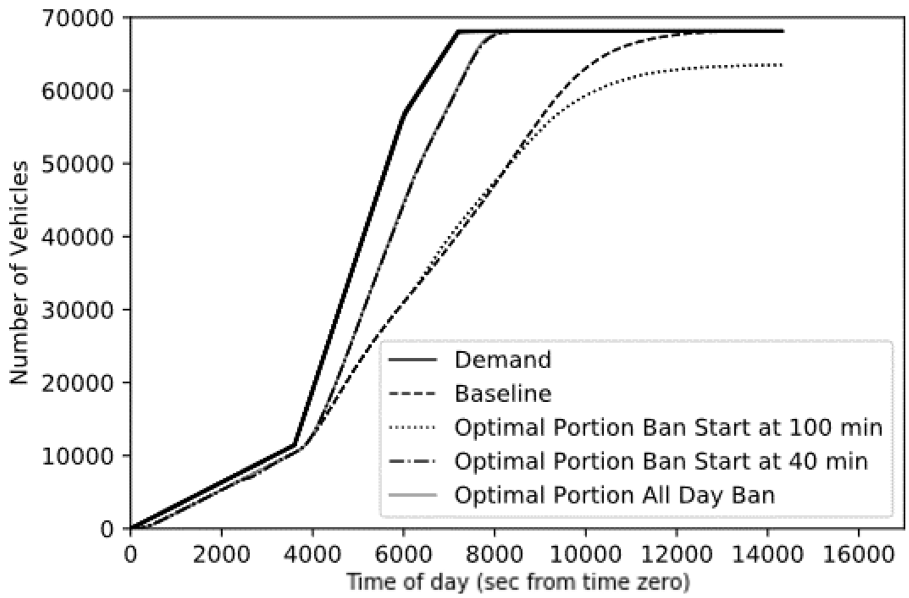


Figure 3.6: Input output diagram for different ban zone and schedule scenarios

These results show that left turns should be banned in the optimal portion of the network shortly before the onset of the morning rush. Banning left turns during off-peak times was unnecessary. Another peak in traffic appears in the network at the end of the workday, the evening rush. However, traffic patterns during the evening rush are quite different and might call for a different approach on left turns. Origins rather than destinations are concentrated at the network center. It was found that left-turn bans are not as efficient during the evening rush, see Section 3.2.4 on the effects of the time dependent change in O/D distribution. Thus, left-turn bans are only recommended for the morning rush in cities with central business districts. This finding makes the ban easier to implement logistically as agencies only need to communicate to commuters one ban zone and one timeframe.

3.2.4 Effect of O/D distribution

The distribution of origins and destination affects travel patterns. This subsection explores the effect of distinct O/D distributions on the effectiveness of left-turn bans. The previous subsections showed that an optimally sized ban is beneficial for cities with CBDs in the morning rush, and is better than a total ban. However, when these commuters leave their work during the evening rush, banning left turns was not as effective. To simulate the evening rush, the same number of morning rush commuters were considered. However, the origins and destinations were flipped. Congestion was still present mainly in the CBD. However, the level of congestion was much lower and no gridlock occurrences were observed. The same network was simulated with a total left-turn ban, and the optimal-portion ban obtained in the previous subsection. Results are presented in Table 3.1. Both the total ban and the optimal-portion ban triggered slight reductions in VHT, 2% and 3% respectively. However, these bans increased VMT and VMT. This indicates that left turn bans might not be warranted in the evening rush.

Evening Rush	VHT (h)	% Diff.	VMT (Km)	% Diff.
No Ban	15464	-	107430	-
Total Ban	15129	-2.16	107430	+12.63
Optimal Portion Ban	14969	-3.20	111136	+3.45

Table 3.1: Performance during the evening rush for different turn prohibition scenarios

Recall that for the morning rush, banning left turns at certain intersections on a network with a CBD reduced both VMT and VHT. Trips with longer distances of more than ten blocks were more favorably impacted than short-distance trips. Banning left turns increased the capacity of intersections and the availability of alternative routes for long-distance trips. These effects offset any increases in route length, and those formerly long-distance trips enjoyed shorter-distance routes at higher speeds. However, the effect of the increase in circuity was more profound for shorter-distance trips of less than six blocks of length, and were found to be at a disadvantage. To study the influence of trip distance, two scenarios were studied: one with short trip distances and another with long trip distances.

A similar network setup was used but with updated O/D distributions. In the short trip scenario, origins were spread uniformly throughout the network while the destinations for each origin were at most six blocks away. The network was loaded with vehicles until average speeds dropped below 12 km/h (less than half the average free flow speed). Traffic was also simulated with a total left-turn ban given the symmetry of the O/D distribution. Banning left turns caused both the VHT and VMT to increase by 10% and 24% respectively, see Table 3.2. The network even gridlocked in some replications. The increased circuity effect overshadowed any benefits that could be achieved from banning left turns.

To simulate a scenario with long distance trips, origins were also uniformly distributed. However, the destinations associated with each origin were at least ten blocks away. Traffic was similarly simulated with and without left-turn bans. Contrary to the previous scenario, left-turn bans led to reductions in both VHT and VMT, 7% and 8%, see Table 3.3. The reduction in VHT highlights the increase in trip completion rates and the reduction in VMT highlights the availability of better routes in a less congested network. This result confirms that left-turn bans are only effective in the presence of long-distance trips; something which should be considered before implementing this strategy in dense urban environments.

Short Trips	VHT (h)	% Diff.	VMT (Km)	% Diff.
No Ban	17875	-	270638	-
Total Ban	19728	+10.37	335212	+23.86

Table 3.2: Performance of a network with short trips and turn prohibitions

Long Trips	VHT (h)	% Diff.	VMT (Km)	% Diff.
No Ban	11232	-	183527	-
Total Ban	10409	-7.33	168787	-8.03

Table 3.3: Performance of a network with long trips and turn prohibitions

Chapter 4

Left-Turn Bans and Cordon-Based Congestion Pricing

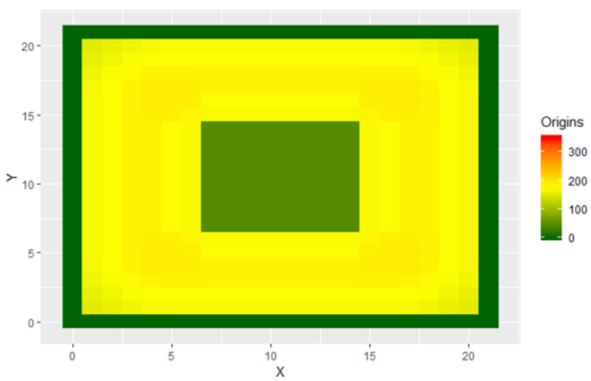
Chapter 3 focused on the effectiveness of left-turn bans, which is a supply side strategy. Congestion pricing, a demand-side strategy, works differently. It can affect: the number of commuters traveling; when they leave their homes; and how they travel. As indicated in Section 2.3, there are potential benefits of combining different congestion management strategies. This chapter discusses the benefits of combining cordon-based congestion pricing with left-turn bans in the context of Stockholm. It highlights the importance of an optimally sized ban zone when cordon-based congestion pricing is involved and the optimized zone's potential for reducing the tolls required. Section 4.1 describes the simulation setup used. Section 4.2 presents the associated findings.

4.1 Experimental Set-up

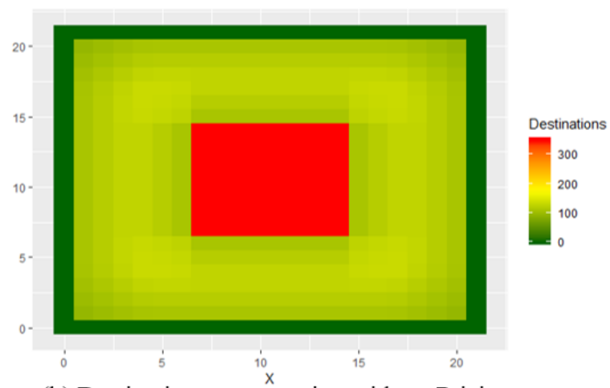
The following subsections describe the experimental set-up for a baseline scenario, the separate deployments of turn prohibitions and congestion pricing and the joint deployment of both.

4.1.1 Baseline

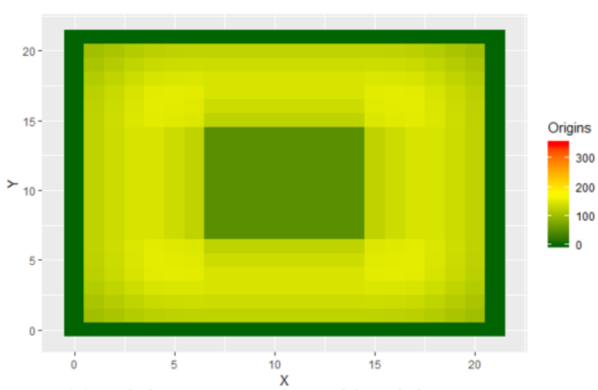
To give the experiment realism, a baseline scenario was based on the studies done of morning peak traffic in Stockholm before its cordon-based congestion pricing strategy was implemented (Eliasson, 2008; Mattsson, 2008). The same 20x20 square network introduced in Section 3.2.1 was used. An O/D distribution was created to emulate the trip distribution in Stockholm and its suburbs. The central 8x8 block zone was considered as the CBD which held the majority of destinations. The rest of the network was considered to be the suburbs which held the majority of origins. The 16% ratio of city to suburbs is in line with the size of Stockholm compared to its suburbs. The O/D distribution generated trips from the suburb to the city, from the suburb to other parts of the suburb with and without crossing into the city, inner city trips, and trips from the city to the suburbs. Figures 4.1a and 4.1b present heat maps of the origins and destinations. The resulting trip time distribution matched that of Stockholm (Mattsson, 2008). The network was then loaded with 93,668 vehicles, an amount that led to significant congestion. Ten replications of this simulation experiment were performed and the results were averaged (Casas et al., 2010).



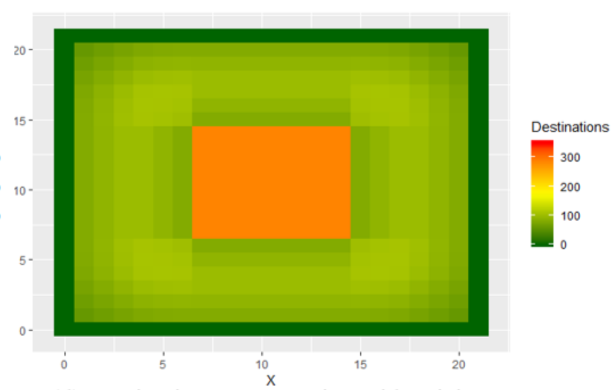
(a) Origin concentration without Pricing



(b) Destination concentration without Pricing



(c) Origin concentration with Pricing



(d) Destination concentration with Pricing

Figure 4.1: Origin and destination distributions with and without cordon-based congestion pricing

4.1.2 Separate Deployments

Left-turn bans were studied similarly to chapter 3. The same commuter trips from the baseline scenario were simulated while implementing differently-sized ban zones in the city center. The same network was also modeled with congestion pricing on its own. A cordon-based congestion pricing scheme was used because the city had a CBD and because real

-world measurement on how this scheme affected traffic in Stockholm were available. The O/D distribution was modified in accordance with what happened to the traffic demands measured in Stockholm after introducing congestion pricing (Mattsson, 2008). The 8x8 block city center was taken to be the toll zone, i.e. a cordon encased that zone. As mentioned in Section 2.2, inner city trips and suburb trips that crossed the cordon boundary decreased while suburb trips that did not cross the boundary increased. The original O/D patterns seen in Figures 4.1a and 4.1b became the ones in Figures 4.1c and 4.1d. The pricing not only led to a change in O/D distribution, but also an overall 21% decrease in demand which was also in line with the 22% reduction seen in Stockholm upon instating the cordon-based pricing (Eliasson, 2008).

4.1.3 Joint Deployment

After studying the effect of left-turn bans and cordon-based pricing separately, this subsection discusses the implications of the joint deployment of both these strategies. Each of these strategies influenced traffic in different ways. Turn prohibitions increased intersection capacity and route availability. Cordon-based congestion pricing reduced the number of trips and redistributed them. To assess the interacting effects, the two measures were analyzed in concert. The network was simulated using the O/D distribution presented in Figures 4.1c and 4.1d while applying different-sized centrally-located ban zones. Ten simulations were run for each ban zone size.

Moreover, as mentioned in Chapter 2, both of these measures face their fair share of opposition. Congestion pricing usually faces opposition due to the out-of-pocket costs it imparts to commuters. Reducing the toll has the potential to make such a strategy more acceptable to the public, but could make the strategy less effective. Optimally sizing the ban zone can lessen the concerns regarding a possible increase in VMT due to turn prohibitions, as seen in Section 3.2.4. This poses the question: If cordon-based pricing is combined with left-turn bans, can the same level of improvement be realized at a lower and more tolerable price points?

To find the answer, a set of experiments was designed to determine the ban zone that would maximally reduce required tolls without compromising network performance compared to a set goal. The goal was set to be the system performance when the original full pricing was enforced. For each size of a central ban zone, the toll was changed incrementally until the goal was reached. The change in toll was simulated by changing the O/D distribution. This change was assumed to be linear with the change in pricing. On a spectrum, Figures 4.1a and 4.1b show the O/D distribution with no pricing and Figures 4.1c and 4.1d show the distribution at 100% of the original toll. The needed change in the toll was found for ten different iterations for each ban zone size and the results were averaged.

4.2 Findings

This section presents the findings on applying left-turn bans and cordon-based congestion pricing separately and in concert. It also highlights the potential for toll reductions when both measures are deployed together.

4.2.1 Separate Deployments

The network was first simulated for the baseline, do-nothing, scenario that emulated traffic in Stockholm before tolls were introduced. Significant congestion appeared on the network. VHT was 17738 h, VMT was 211951 Km and the average vehicle delay was 470 sec/km.

Left-turn bans were implemented, and different ban zone sizes were tested. As the zone size increased, the VHT decreased until the 14x14 block zone was reached. Beyond which, the VHT increases slightly and the VMT starts increasing with the increase ban zone size. The central 14x14 block zone was found to be the optimal portion of the network over which to ban left turns, as was the case in Chapter 3. Table 4 shows that the optimal portion ban reduced VHT and delay by 46% and 54%, respectively, similar to the reductions seen due to the total ban. However, the optimal portion ban only led to a slight (0.59%) increase in VMT compared to a much larger one (9.75%) that accompanied the total ban, thus making the optimal portion ban the better choice. These results are in line with the findings in Chapter 3 and confirm that banning left turns in uncongested suburban areas is counterproductive.

	VHT (h)	% Diff.	VMT (Km)	% Diff.	Average Delay (sec/Km)	% Diff.
No Ban	17738	-	211951	-	470	-
Total Ban	9806	-44.72	232612	+9.75	214	-54.38
Optimal Portion Ban	9603	-45.86	213200	+0.59	216	-54.02

Table 4.1: Performance of a network resembling Stockholm for different turn prohibition scenarios

Cordon-based congestion pricing was also successful in reducing congestion on its own. However, savings in VHT and VMT when pricing is implemented cannot be directly compared to those of other scenarios for several reasons. Pricing decreased the number of vehicles on the road making absolute VHT and VMT values incomparable. Also, the average VHT and VMT per vehicle cannot be directly compared to those of other scenarios since the O/D distribution changed. Average delay and average vehicle speed are more robust measures of system performance in this case. Table 4.2 shows that cordon-based pricing led to a 65% reduction in average delay and a 34% increase in average speed. The table also shows that pricing led to an increase in speed, just as observed in Stockholm (Mattsson, 2008).

	Average Delay (sec/Km)	% Diff.	Average Speed (Km/h)	% Diff.
Baseline	469.62	-	18.46	-
Pricing	163.51	-65.18	24.81	+34.34

Table 4.2: Performance of a network resembling Stockholm with congestion pricing

4.2.2 Joint Deployment

When turn prohibitions and congestion pricing were deployed jointly, two counteracting effects appeared. First, cordon-based pricing increased the average trip distance, which in turn increased the effectiveness of left-turn bans; as shown in Chapter 3. Second, the toll that had already reduced delay significantly, thus reduced the potential for further reductions and the need for turn prohibitions. In fact, adding a total ban to the cordon-based pricing strategy did not achieve any additional reductions in delay. However, as seen in Section 3.2.2, the total ban zone does not always yield the best results, especially when a CBD is involved. Combining the cordon-based toll with the optimal-portion ban zone showed potential to create multiple winning scenarios. Details follow.

The 65% reduction in average delay observed under the original toll without any turn bans was set as the goal. The set of experiments described in Section 4.1.3 was used to find for each ban-zone size the maximum allowable reduction, or needed increase in pricing to maintain that 65% reduction in average delay; see Figure 4.2. A small ban zone, the 4x4 block region, made congestion worse and required 10% higher tolls. The toll could be decreased as the ban zone size increased up to the 14x14 block region; i.e. the optimal-portion ban remained the same in the presence of the toll and the attendant change in O/D demand. When applying the optimal portion ban, the toll was reduced by as much as 30% without compromising network performance; see Tables 4.2 and 4.3. Not only that, but 8.5% more vehicles benefited from this 30% toll reduction and the attendant improvement in performance. From a traffic agency's financial perspective, the increased demand partially offset the decrease in pricing, such that the total toll revenue went down by only 24%. Increasing the ban zone size beyond the 14x14 block region resulted in diminishing returns. The larger ban zones generated less significant reductions in pricing. In fact, a total left-turn ban needed the same pricing as a network with no left-turn bans. These results highlight the importance of banning left turns in the optimal portion of the network, especially when cordon-based congestion pricing is involved. Further reductions in delay can be achieved by keeping the original pricing and applying the optimal portion ban in conjunction; see Table 4.3. The resulting delay savings can grow from 65% to 69%.

Thus, two possible winning scenarios became available for traffic agencies when the optimal-portion ban was introduced. Agencies can reduce the required toll by 30% and still achieve the pre-ban congestion reduction levels. Or agencies can, they could keep toll levels the same but achieve an additional 4% savings in average delay. Choosing among these two options will depend on the goals set by the agencies. However, one thing remains clear: cordon-priced networks can benefit from an optimal-portion ban.

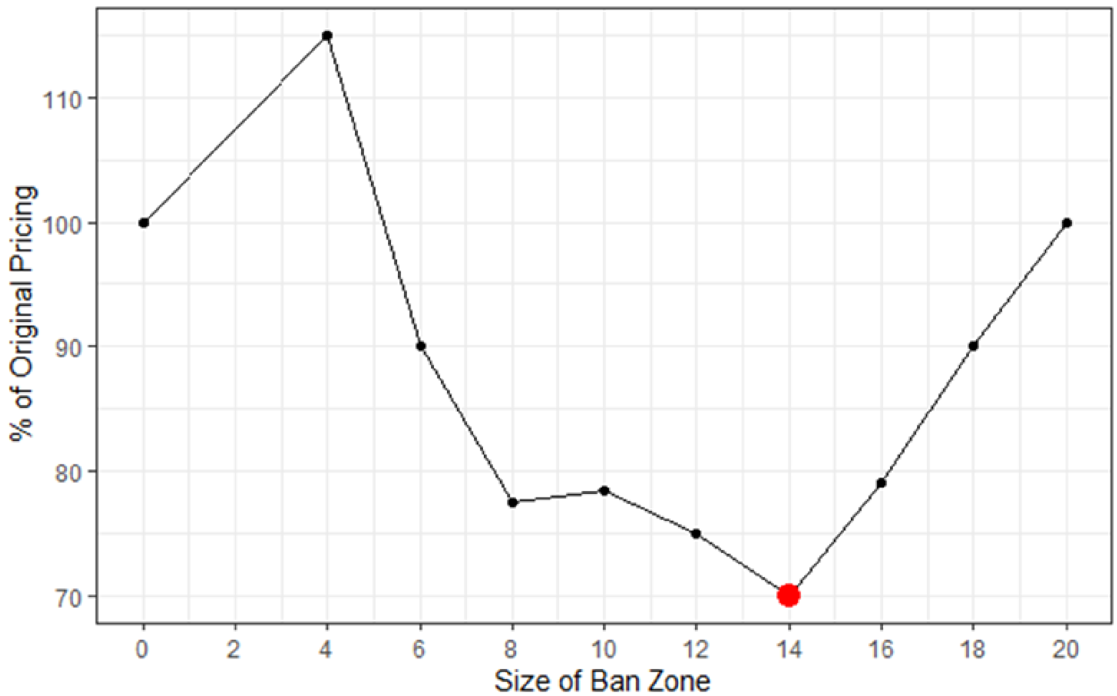


Figure 4.2: Allowable reduction in congestion pricing for different ban zone sizes

	Demand (veh)	% Diff.	Average Delay (sec/Km)	% Diff.	Average Speed (Km/h)	% Diff.
Baseline	93668	-	469.62	-	18.46	-
Reduced Pricing & Optimal Left-Turn Ban	79653	-44.72	162.24	-65.45	25.89	+40.20
Original Pricing & Optimal Left-Turn Ban	73633	-44.72	143.09	-69.53	26.32	+42.58

Table 4.3: Performance of a network resembling Stockholm with congestion pricing and turn prohibitions

Chapter 5

Left-Turn Bans and VMT-Based Congestion Pricing

Chapter 4 showed that applying turn prohibitions to a network with cordon-based congestion pricing in a city with a CBD can be beneficial. In that case, only the commuters who cross the cordon boundary paid tolls and these tolls were not affected by the introduction of turn prohibitions. The benefit was solely due to the increase in network productivity. The real potential for combining turn prohibitions with congestion pricing appeared when the toll amounts were affected. For cordon-based strategies, toll reductions became possible without sacrificing system performance. For VMT-based strategies, all commuters pay tolls, and these time- and distance-based tolls are more sensitive to the change in productivity and trip lengths brought by turn prohibitions. The effect on toll amounts is more direct, and this has the potential for significant improvements in system performance. For this reason, this chapter shows that, in a city with uniformly distributed destinations in space, the joint deployment of VMT-based congestion pricing and turn prohibitions can lead to synergistic benefits beyond the sum of those from each strategy separately. Section 5.1 describes the simulation set-up, the equilibrium model and the cost equations used. Section 5.2 presents the findings for a parametric analysis and a case study of downtown Los Angeles. [1]

5.1 Experimental Set-up

This section discusses the set-up of a microsimulation experiment used to obtain network speed-accumulation relationships for downtown Los Angeles. The relationships are used in an agent-based time-of-day travel model in which commuters evaluate their travel costs from day to day. Equations to calculate each commuter's travel costs with and without VMT-based congestion pricing are presented.

[1]The work presented in this chapter is adapted from a recently published work by (Itani et al.) (2021).

5.1.1 Simulation Set-up

The network of major streets in downtown Los Angeles (encased by a rectangle in Figure 5.1) was idealized as the homogeneous square grid of 20 N-S and 20 E-W streets as previously presented in Section 3.2.1. Trip origins and destinations were uniformly distributed over the network. The physical length of each trip was obtained by randomly generating its origin and destination, and determining the shortest-distance path connecting that O-D pair. For baseline, do-nothing cases, average trip length turned out to be 2.9 km, with a standard deviation of 1.5 km[2]. Demand was studied parametrically, such that the fixed number of car-trips in each simulation ranged from 10,000 to 100,000. All these travelers were assumed to be captive commuters, meaning that their numbers were independent of travel conditions on the network. It was further assumed that all commuters wished to arrive at work at a common time, which was set to zero without loss of generality.

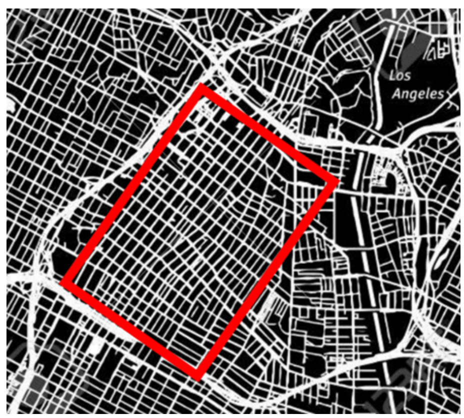


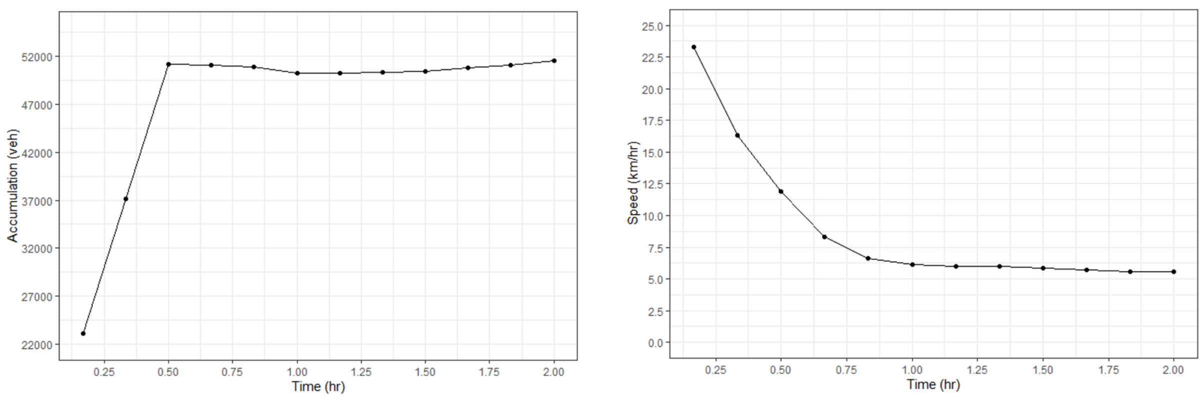
Figure 5.1: Street map of downtown Los Angeles. Study site is an idealization of area enclosed in box

As in Vickrey (1969), penalties were imposed for exiting the network (i.e. arriving at a workplace) earlier or later than wished. Earliness and lateness penalties are denoted e and L, respectively and expressed in units of in-vehicle travel time. They describe how our commuters trade unpunctuality for travel time. (Tolls will also be expressed in units of travel time.) The penalties were set at e = 0.5 and L = 2, as suggested in Small (1982).

An agent-based model to be described in Section 5.1.2 relied upon network-wide relations between vehicle accumulation and average speed. Two such relations were required, to separately reflect baseline (do-nothing) conditions and supply-side changes to the network when left turns were prohibited; see Daganzo (2007). A total left-turn ban was considered due to the homogeneity in congestion throughout the network caused by the uniform distribution of destinations in space. Both were estimated using the AIMSUN platform (Casas

[2]When left turns were prohibited, average trip length increased to 3.4 km, again with a standard deviation of 1.5 km.

et al., 2010) to simulate network conditions under parametrically-varying demands. Twenty distinct demands were examined in this fashion, such that network conditions ranged from free-flow to gridlocked. Each demand level was simulated until reaching steady state, and accumulation and speed were jointly extracted over the 60-min period that followed. Figures 5.2a and 5.2b present the accumulations and associated speeds obtained from one of those experiments. Ten simulations were performed for each demand level. Curves were fit to the values thus obtained in piecewise fashion using least-squares regression. Resulting curves are shown in Figure 5.3. Note the effect of turn prohibitions on the relationship.



(a) Vehicle Accumulation (b) Network Speed

Figure 5.2: Vehicle accumulation and speed maintained over time

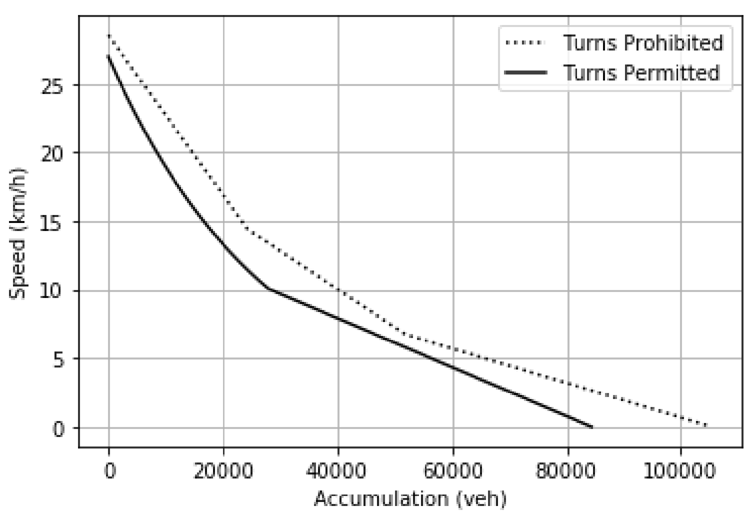


Figure 5.3: Speed accumulation relationship for a network with and without turn prohibitions

5.1.2 Equilibrium Model

Conditions on the network were simulated using the agent-based, multichannel model in Daganzo and Lehe (2015). The model was coded in-house and is described by the diagram in Figure 5.4. It functions in iterative fashion to emulate equilibriums that might occur over the passage of days. Each iteration simulated commuter decision-making in regard to scheduling trips over a single day's morning rush. For each scenario tested, the system was simulated for many days until an approximate equilibrium was reached and maintained for an extended period. The results were then recorded. Details follow.

The network's time-varying travel conditions were estimated during each rush by stepping through time in 1-min increments. Each minute, the number of vehicles with entry times that had already occurred, but that still remained on the network (i.e. the accumulation) was determined. This accumulation dictated the network's average speed during that minute, as per a multi-channel model following the relations in Figure 5.3. This, in turn, determined the distance traveled by each accumulated vehicle over the minute. A vehicle arrived at its destination upon reaching the travel distance assigned to it from the beginning, and was thereupon removed from the network.

The resulting travel cost to each ith commuter, C_i , was then evaluated. It was expressed in units of time, and is the sum of i's time spent traveling on the network, and the penalties incurred, P_i. The latter include an unpunctuality penalty for arriving early or late to work, plus a monetary penalty due to the toll. All these values were dynamic and depended upon entry and exit times. The formulas are given in the next subsection.

Once all simulated trips during a rush were completed and all C_i determined, a random sample of 10% of the commuters was assumed to evaluate their C_i vis-a-vis those of other entry times. The sampled commuters shifted their entry times on the following day to the best times possible for each. It is assumed that these commuters have perfect knowledge of costs associated with each trip start time. The simulation was then repeated for the next day; and for ensuing days in this iterative fashion until reaching a quasi-equilibrium in which similar conditions thereafter persisted on the network for 100 days or more[3].

5.1.3 Cost Formulas

Formulas for C_i are given below. Let $t_{e,i}$ and $t_{a,i}$ be the exit and entry times of commuter i. Then, the commuter's in-vehicle travel time is $max\{et_{e,i}, Lt_{a,i}\}$, and the schedule penalty is $max\{et_{e,i}, Lt_{a,i}\}$. If τ_i denotes the toll paid (in units of in-vehicle time), the commuter's total cost becomes:

$$C_i = t_{e,i} - t_{a,i} + \tau_i + max\{et_{e,i}, Lt_{a,i}\}.$$

The more complex VMT-based toll was chosen because it is more appropriate for a uniformly distributed network. The toll, τ_i, depends dynamically on $t_{e,i}$, and the formula for the toll

[3]Those scenarios that did not result in gridlock were found to reach a quasi-equilibrium state within roughly 50 days.

is given below. It allows a commuter to arrive at work close to the ideal time by paying a higher toll, or paying less by arriving further from the ideal. The formula is:

$$\tau_i = \frac{eW_i}{(e+L)V_r} - max\{et_{e,i}, Lt_{a,i}, 0\},$$

where W_i and V_r are known constants. The former is the cumulative distance collectively traveled by all vehicles with trip distances less than that of commuter i. It is calculated by sorting all trips by their physical lengths, and summing the values that are less than that of i. The V_r is the maximum rate at which the network processes vehicle-miles. It can be calculated by finding the maximum product of accumulation and the corresponding speed given by Figure 5.3; see Daganzo and Lehe (2015) for further explanation.

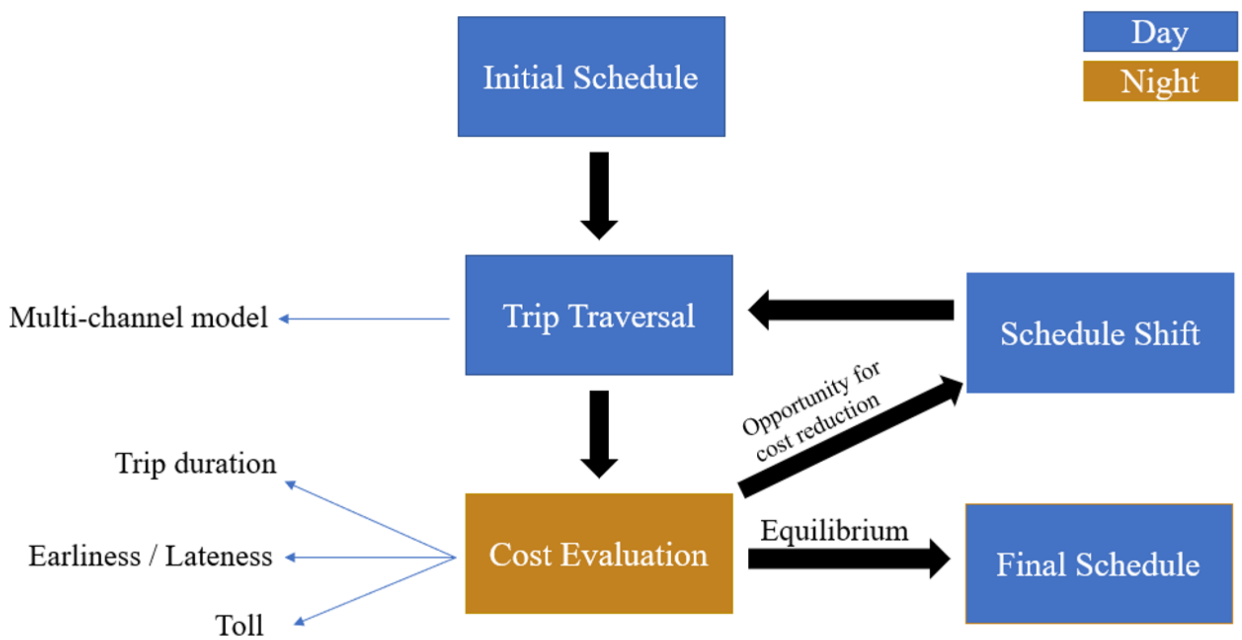


Figure 5.4: Agent-based simulation model

5.2 Findings

The morning commute was modeled under four control measures: (i) a baseline, do-nothing case; (ii) a global left-turn ban; (iii) the tolling scheme just described; and (iv) measures (ii) and (iii) together. Synergies are unveiled in sec. 5.2.1 by varying demand parametrically and observing the resulting total travel costs in each scenario. Causal mechanisms are uncovered in sec. 5.2.2 by examining the components of total cost under conditions roughly akin to those in downtown Los Angeles.

5.2.1 Parametric Analysis

Total costs of travel for each scenario are determined as functions of demand[4]. Demand for car-trips were varied from 10,000 to 100,000 in increments of 10,000. For each scenario and demand level, 25 separate equilibrium analyses of the kind described in Section 5.1.2 were performed. Each of these analyses entailed a distinct set of commuters with a distinct set of origins and destinations. Figure 5.5 presents the results for one of these experiments at a demand of 40,000 vehicles without tolling and turn prohibitions. Notice how the total travel cost drops from day to day until an equilibrium is reached. The average equilibrium cost associated with each demand level and scenario is shown in Figure 5.6. The upward-bending trend in each curve reveals that marginal costs increase with increasing demand.

The figure's bold, solid curve shows that travel costs are virtually always highest by doing nothing. The bold, dotted curve unveils how turn prohibitions (alone) tended to produce only modest cost savings, even when demands were high and the network was congested. The light, solid curve shows that substantially greater savings came via sole deployment of congestion tolling once demand reached about 50,000 car-trips, an amount that severely congested the network and dropped speeds to as low as 9 Km/h. Not surprisingly perhaps, the light, dotted curve shows that cost savings were greatest when the two measures were implemented jointly.

Further note from Figure 5.6 that the vertical displacements between the light, solid curve and the light, dotted one are appreciably larger than the displacements between the two remaining (dark) curves. Consideration shows that these pairwise features of the curves unveil the synergies at play when the demand- and supply-side measures were deployed in combination. The differences in vertical displacements were more than double for demands in the range of 70,000 to 90,000. Thus, we see that for this range of demands, the effectiveness of turn prohibitions more than doubled when deployed in combination with tolling.

These synergies are made more evident in Figures 5.7 and 5.8. Their curves display the absolute and relative differences in travel costs incurred relative to the baseline, do-nothing cases. Note that each of these figures provides: two curves that reflect separate deployments of each measure; a third curve that sums the two; and a fourth curve reflecting joint deployments of both measures combined. Visual inspection of Figure 5.8 shows that for demands greater than about 50,000 car-trips, the travel costs saved by combining both measures exceed the savings summed across the separate deployments of each; i.e. the whole is greater than the sum of its parts. The synergistic savings are substantially large in absolute terms at high demands. Note from Figure 5.8 how the synergy was highest for a demand of roughly 70,000. In that case, the synergistic gain over the sum of separate deployments is 30%; see Table 5.1. This synergy and the turn prohibition were responsible for a 64% increase in benefits as compared to tolling (alone). Table 5.1 shows that turn prohibitions were successful in increasing the effectiveness of the VMT-based toll at different demand levels, by as much as 66% in certain cases.

[4]Total costs to commuters entail only travel time, unpunctuality penalties and tolls, as per sec. 5.1.3.

Turn prohibitions allow traffic to follow the more efficient speed-accumulation relationship presented in Figure 5.3 at higher accumulations levels. On the other hand, congestion pricing allows traffic to operate at lower accumulations on the baseline relationship. When these strategies are combined, traffic follows the more efficient relationship at lower accumulations; thus, leading to the best outcome.

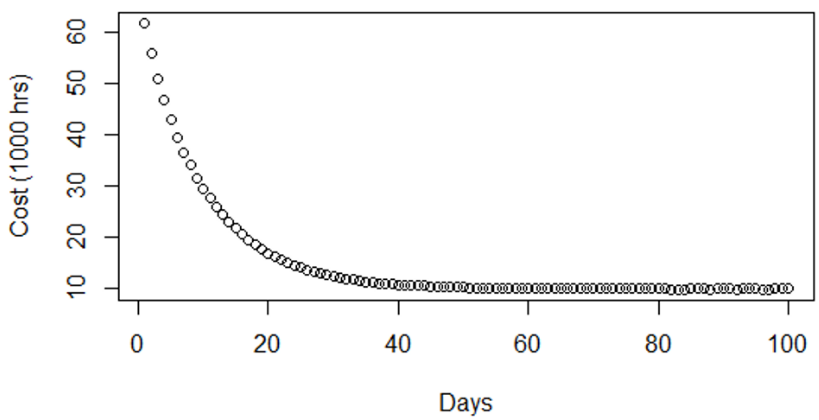


Figure 5.5: Cost evolution over time for a network with 40,000 vehicles

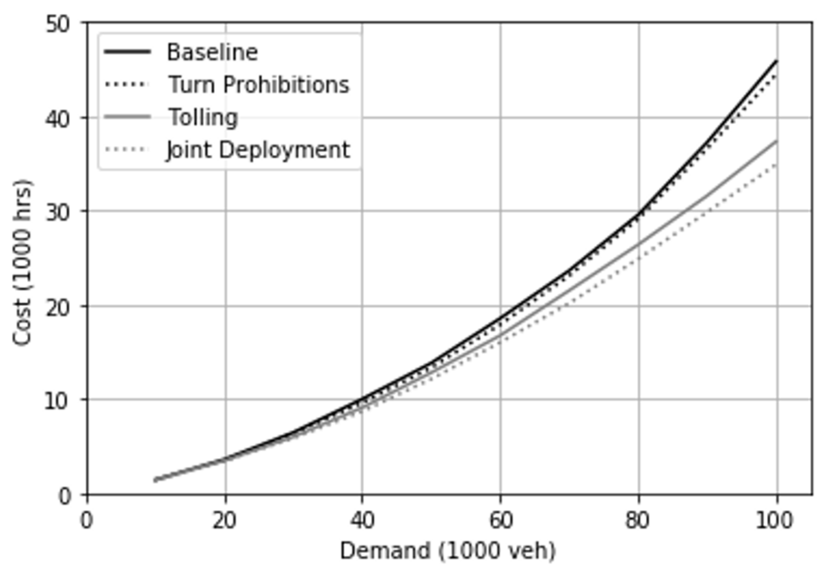


Figure 5.6: Travel costs as a function of demand for different congestion management scenarios

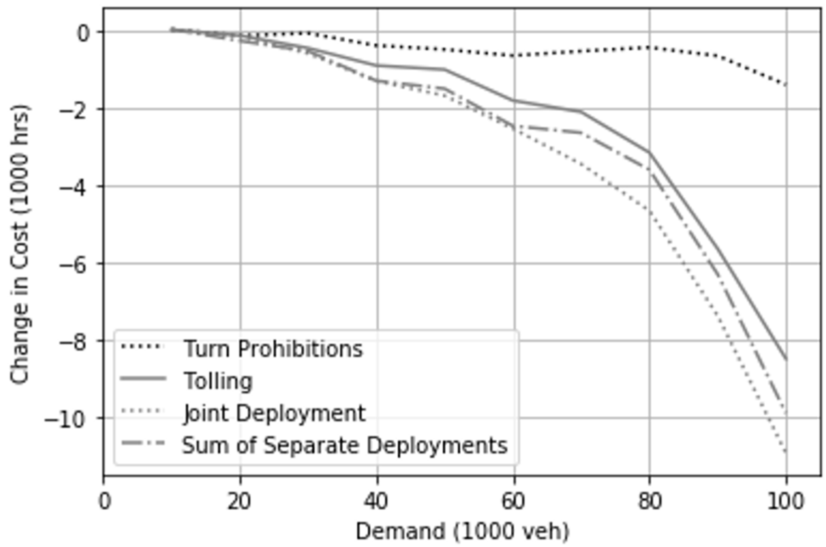


Figure 5.7: Costs saved by different congestion management scenarios

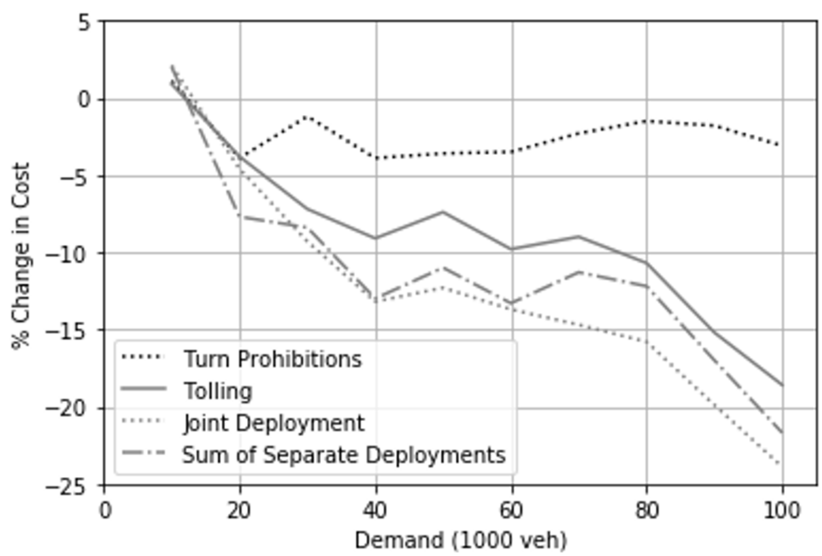


Figure 5.8: Costs saved relative to baseline by different congestion management scenarios

Demand (1000 veh)	10	20	30	40	50	60	70	80	90	100
% Increase in benefits from adding turn prohibitions	126	22	30	44	66	40	64	48	31	29
% Synergy	4	-40	12	1	12	3	30	29	17	10

Table 5.1: Increase in benefits and synergies caused by combining left turn prohibition and VMT-based congestion pricing at different demand levels

5.2.2 Case Study of Downtown Los Angeles

We next explore the mechanisms that gave rise to the above findings. To add a touch of realism, the network was loaded with a demand of 100,000 car-trips. This produced congestion that persisted on the network for nearly 2 hours, which is roughly commensurate with what occurs each weekday morning in downtown Los Angeles (Burger and Kaffine, 2009). Los Angeles ranks as the 6th worse urban area in the United States in terms of average traffic delay (INRIX, 2021).

The bar graph in Figure 5.9 presents cost components for: the baseline, do-nothing case; separate deployments of each measure; and joint deployment of both[5]. Note how in this realistic case, the best result was still obtained when combining both measures. Also note from the cost reductions relative to the baseline that there continued to be significant synergies. These reductions were: 1,410 h for turn prohibitions alone; 8,510 h for pricing alone; and 10,955 h for the deployment of both measures combined. The rest of this section examines how the various components of generalized cost varied across strategies.

We start with turn prohibitions. These caused speeds to increase on the network, as previously shown in Figure 5.3. The network's free-flow speed rose from 27 Km/h for the baseline case, to 28.5 Km/h under the turn ban. Average trip distance also rose, however, by 16%. The net effect of these two changes: free-flow travel time on the network grew by 1000 h. This was treated as an increase in delay. Nevertheless, the higher speeds achieved under the turn ban had the net effect of diminishing network-wide delay by a modest 200 h. Moreover, the lowest speed measured over the network rose from 5.4 Km/h for the baseline, to 6 Km/h with turn prohibitions.

The higher speeds motivated commuters to schedule trips closer to workplace start time. This had the perverse effect of raising network accumulations, which drove down speeds; along with the favorable effect of lowering unpunctuality costs, which fell by roughly 1,200 h from the baseline.

For its part, tolling alone reduced baseline total cost by a more substantial 8,510 h. This came via a reduction in delay of 49.5% (10,740 h), coupled with a partially-offsetting rise in unpunctuality cost (of 1,480 h) and the initiation of tolls (collectively equivalent to 750

[5]Average cost per user can be obtained by dividing total costs in Figure 19 by the demand (100,000 car trips).

h). All this was because tolling brought about the pattern of trip scheduling shown by the dark-shaded data in Figure 5.9. These collectively denote each commuter's toll-induced equilibrium values of workplace arrival time and trip distance in a single rush. Note from Figure 5.10 how long-distance trips occurred further from the work start time than did short-distance trips. The rearrangement of trips caused the lowest-measured speed on the network to rise from the baseline rate of 5.4 Km/h to 8.5 Km/h. Unpunctuality rose by 20% for commuters with trip distances greater than the mean; and dropped for commuters with shorter trip distances. Though both long- and short-distance commuters saw reductions in total cost, the reductions were greater for those with shorter trips.

Returning to the bar chart in Figure 5.9, we turn attention to the joint deployment of both measures. Total travel cost in this case fell by 10,955 h from the baseline, an additional cost savings of 29%, compared to what was achieved by tolling alone. The sum of the total cost reductions separately achieved from each measure (1,410 h + 8,510 h) can account for 9,920h of this drop. The remaining savings of 1,035 h (10%) is the synergistic effect of combining the two measures together.

This synergy was manifest as a reduction in baseline delay. It fell by approx. 12,400h (56.4%). The value exceeds the sum of the delay reductions separately achieved from each measure (200 h + 10,800 h) by 1,400 h. This extra savings was partially offset by tolling and unpunctuality costs associated with joint deployment. Additionally, the lowest speed measured over the network rose to 11.3 Km/h, an increase greater than the sum of those achieved by each measure separately (0.6 Km/h + 3.1 Km/h = 3.7 Km/h).

Inspection of the two right-most bars in Figure 5.9 reveals how joint deployment of both measures changed things relative to tolling alone. On the downside, tolls slightly increased (collectively by an equivalent of just 20 h) when accompanied by turn prohibitions. The rise is so small as to be barely visible in the figure, and tolls still only comprised about 3% of total travel cost. The small rise occurred because joint deployment of both measures motivated commuters to schedule trips closer to their work start time; refer again to Figure 5.10 and compare its lightly-shaded data (for joint deployment) with the dark-shaded data (for tolling alone). On the upside, Figure 5.9 reveals that delay under joint deployment diminished by 1,600h relative to tolling alone, a reduction of more than 14%. Unpunctuality fell by 900 h, a reduction of just over 6%. This reduction offset the increase in unpunctuality due to tolling by more than 40%. These favorable outcomes were again due to the change in trip scheduling noted above with the aid of Figure 5.10.

Finally, we note that the average times when commuters departed from home varied little across cases. For example, joint deployment of both measures enabled commuters to leave their homes later than did tolling alone. Yet, the average difference was little more than 1 min in duration, and likely too small to be noticed by most commuters.

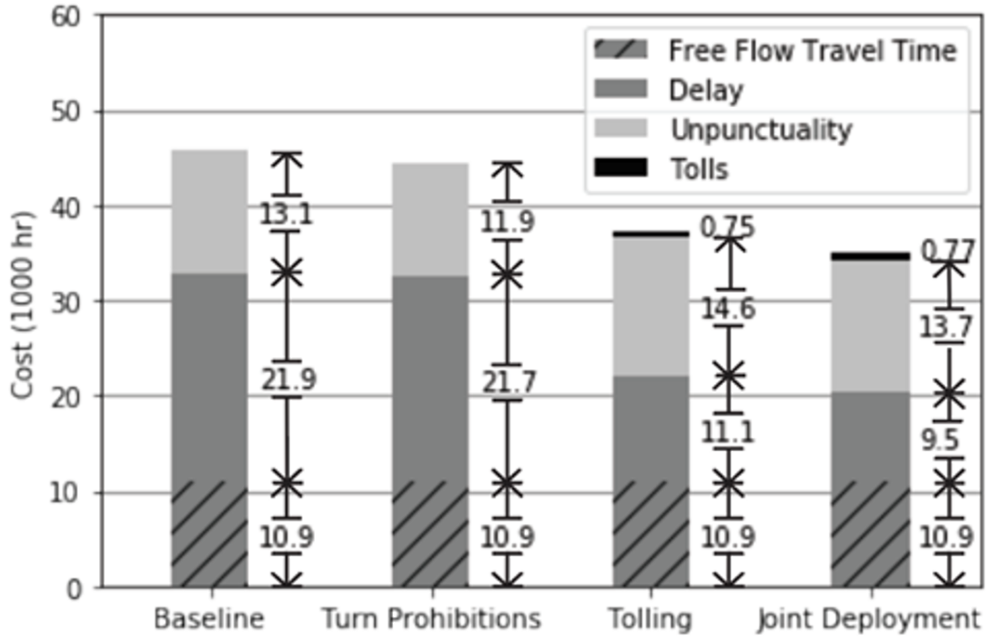


Figure 5.9: Cost breakdown under four scenarios

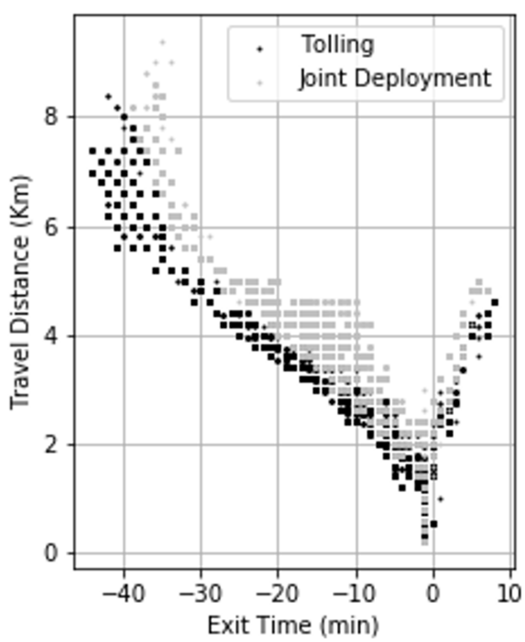


Figure 5.10: Workplace arrival times and trip distances

Chapter 6

Conclusion

This chapter summarizes the findings of this research effort and provides an outlook on future work that it inspired.

6.1 Summary of Findings

This dissertation contributes to the understanding of how certain congestion management strategies work. Left turn prohibitions are not fully optimized and the effects they can have on congestion pricing strategies are not considered.

Chapter 3 provided simulation-based evidence that an optimal spatiotemporal left-turn ban zone exists for a congested city with a central business district in the morning peak. Findings showed that in a 20x20 block city with a CBD, the optimal portion within which to ban left-turns was the central 14x14 block zone. Banning left turns in wholesale fashion, in that context, managed to reduce VHT by 43%. However, better results could be achieved with the optimal potion ban; it led to an additional 29% in VHT reductions. Not only that, but the optimal portion ban also managed to reduce VMT by as much as 12%. This finding was contrary to the popular belief that left-turn bans always increase VMT and a valuable addition to the literature. This also confirmed that the improved intersection capacity and increase in route availability can overcome the effects of increased circuity associated with turn prohibitions in certain cases. Chapter 3 also showed that while the optimal portion ban was successful in curbing congestion in the morning peak for a city with a CBD, applying this ban for the wrong period of time can lead to negative effects on the network. The optimal time to start the ban is slightly before the onset of morning congestion. The optimal time to end the ban is when the congestion subsides. Delaying the start of the ban led to undesirable results and even gridlock in certain simulation scenarios. Extending the ban into the evening peak also led to undesirable results. This chapter also showed that turn prohibitions favor longer-distance trips over their shorter-distance counterparts.

Chapter 4 showed that, for a city with a CBD like Stockholm, combining optimal portion ban with cordon-based congestion pricing can lead to multiple winning scenarios. The effects of cordon-based pricing were simulated by changing traffic demands to correspond with what was observed in Stockholm when the tolls were implemented. These demands along with the left-turn bans were modeled in microsimulation environment. The results highlighted the importance of banning left turns in the optimal portion on a network with a CBD. They showed that while banning left turns in a wholesale fashion in a network with cordon-based congestion pricing did not improve performance, the optimal portion ban opens the door for additional improvements in performance and allowable reductions in cost. The optimal portion ban for the network modelled after Stockholm was found to improve the effectiveness of the cordon-based congestion pricing scheme by 4%. However, if the system performance due to pricing on its own was satisfactory, implementing the optimal portion ban would allow for a 30% reduction in tolls without sacrificing performance.

Chapter 5 proved potential for synergistic benefits that can be gained by combining turn prohibitions with VMT-based congestion pricing in the context of a city with uniformly distributed destinations in space like downtown Los Angeles. The deployment of each measure separately and jointly was compared to the baseline do-nothing case. The effects of a distance- and time-based congestion toll were simulated using an agent-based decision-making model of captive commuters integrated with a simulation generated multichannel model. Tolls affected the cost functions used in the decision-making tradeoff while banning left turns affected trip distances and network performance functions. The joint deployment of both measures led to synergistic benefits that exceeded the sum of each measure's individual benefits. The synergies accounted for 30% of the total cost reduction in certain cases. Moreover, the VMT-based tolls reorganized trips which increases unpunctuality costs but reduced delay significantly, leading to an overall reduction. Adding turn prohibitions not only increased the delay benefits, but also, mitigated the increase in unpunctuality.

6.2 Future Work

The work presented in this dissertation prompted new avenues of research that can be pursued in the future. One such avenue is evaluating the effect of combining supply- and demand-side strategies in the context of a bottleneck rather than a multichannel city. Consider the cumulative arrival departure curves, presented in Figure 6.1a, for a bottleneck with capacity μ_1 with a total demand of N_D vehicles that wish to depart following the wish curve $W(t)$. Commuters arrive as described by the (virtual) arrival curve, $V(t)$, and depart as per the departure curve, $D(t)$. Commuter costs consist of delay and penalties for being early or late. They shift their arrival times until they reach an equilibrium, presented in Figure 6.1a (Vickrey, 1969). Supply-side strategies like infrastructure improvements increase the capacity of the intersection and change the arrival and departure curves; see Figure 6.1b. This change has a significant effect because it changes the delay at each moment in time, and thus, would change the effectiveness of tolling strategies. Congestion pricing strategies at bottlenecks usually work by replacing delay costs with tolls, which removes the incentive of arriving at a rate higher than the bottleneck capacity (Arnott et al., 1990). Additionally, the reduction in delay caused by supply-side measures can create an induced demand (Hymel et al., 2010). Both these effects can make tolls calculations based on the original arrival pattern and demand obsolete. However, at higher capacities, reductions in delay can be achieved by lower tolls. For these reasons, studying the interactions due to combining capacity improving measures with congestion pricing is a possible avenue of research worth looking into.

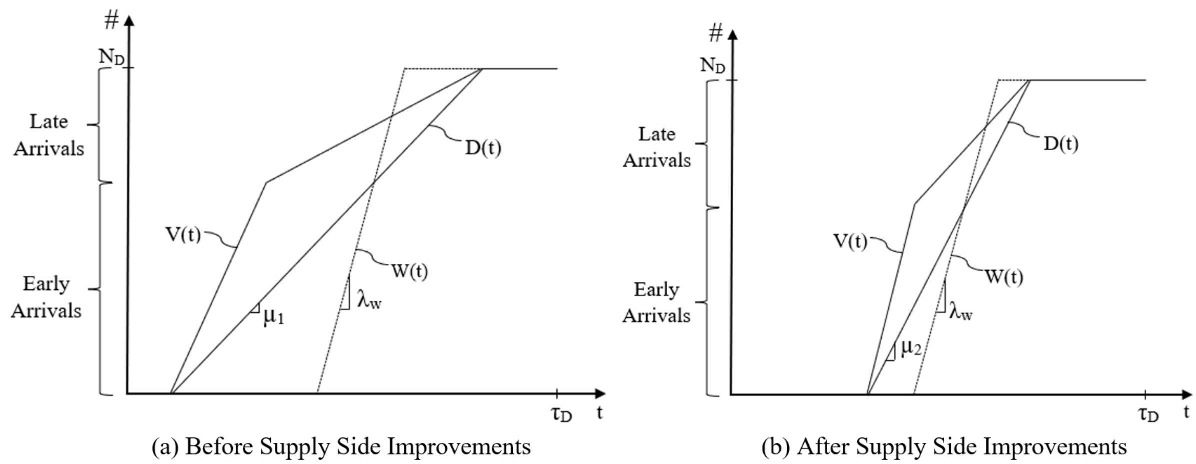


Figure 6.1: Arrivals to and departures from a bottleneck at equilibrium

Moreover, in simulating these models two things are assumed. The first being that traffic agencies know commuters' preferences in terms of earliness and lateness aversions, wished arrival times, and values of time; all of which is expensive information to collect. The second being that commuters have perfect information and make rational decisions. Moving forward, this dissertation prompted work into making inferences on commuter behavior using easily available data. The work examines the slopes of the arrival curves obtained from detector data and uses those curves to infer earliness/lateness penalties and wished arrival times. These inferences can be used to design a congestion pricing strategy for bottlenecks. Moreover, work has also started on changing the agent-based simulation model presented on section 5.1.2 to make the decision-making process more realistic. The current model assumes that people have perfect knowledge and act accordingly; however, in reality, commutes have limited access to information through applications and other services. The model being developed incorporates the limited access to information with each commuter's experiences to create a more realistic commuter knowledge of travel times. Moreover, commuters do not always change the time they leave their homes based purely on this information. The new model incorporates a more realistic decision making process that accounts for past experiences commuters had with shifting the time leave their homes and their willingness to adapt.

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