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**Strategies for Sharing Bottleneck Capacity among Buses and Cars**

by

Sukran Ilgin Guler

A dissertation submitted in partial satisfaction of the  
requirements for the degree of

Doctor of Philosophy  
in

Engineering – Civil and Environmental Engineering

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA, BERKELEY

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Strategies for Sharing Bottleneck Capacity among Buses and Cars

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Sukran Ilgin Guler

## Abstract

Strategies for Sharing Bottleneck Capacity among Buses and Cars

by

Sukran Ilgin Guler

Doctor of Philosophy in Engineering – Civil and Environmental Engineering

University of California, Berkeley

Michael J. Cassidy, Chair

In urban settings where space is at a premium, bus lanes can often only be created via the conversion of existing general-use lanes. This can be politically infeasible in cities where bus flows are low, because the converted lanes would be under-utilized and thereby squander road space. The roadway bottlenecks would then as a result create even greater delays and queuing for car traffic.

The present thesis explores novel ways in which buses and cars might share lanes within select bottlenecks. Details of these shared-lane strategies vary, depending upon a bottleneck's local operating conditions. In all cases, cars would be inserted into a shared lane in ways that impart few delays to the buses. These insertions would allow for the unused space between buses to be used, lessening the damage otherwise incurred by car traffic at bottlenecks. Hence, by reducing the car delay at bottlenecks it may become feasible to deploy ordinary bus-lane conversions elsewhere throughout a city's road network. The ordinary lane conversions would enable buses to bypass the car queues that still form at bottlenecks.

Analytical assessments unveil the wide range of bus flows for which these strategies increase a bottleneck's car-carrying capacity, in comparison to reserving one of its lanes for buses only. Simulations of a real case study indicate that significant reductions in car delays can result while increasing bus speeds as much as ordinary conversions.

To  
my family.

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# Chapter 1

## Introduction

Bus agencies have long sought ways to provide better service to customers in a cost efficient way. To this end, dedicated bus lanes have often been used to enable buses to bypass car queues. This priority treatment can reduce the person hours traveled on a road network, since buses typically have higher on-board occupancies than do cars. And bus lanes can also help reduce variation in bus travel times which leads to higher utility for bus users. Overall, prioritizing buses may induce modal shifts from cars to buses which can reduce roadway congestion, the network's total vehicle hours traveled, total greenhouse gas emissions and perhaps even the number of traffic accidents.

In urban settings where unused space is in short supply, a bus-lane installation often entails the conversion of a general-use lane. If the converted lane is thereafter fully or near-fully utilized by buses, cars as well as buses can benefit. This is because segregating distinct vehicle classes into their own lanes can have a “smoothing effect” on traffic by reducing the disruptive conflicts that would otherwise occur between these classes. The network's capacity to serve all of its vehicles can increase as a result (Cassidy *et al.*, 2009, 2010).

However, if the converted bus lane is underused due to low bus flows, then road space that was formerly available to cars is now wasted. The converted lane will invariably run through one or more roadway bottlenecks, and the under-used lane will reduce the capacities of these bottlenecks to serve cars. The result will be greater delays and queuing for those cars, and this unfavorable outcome can render a lane conversion politically infeasible.

### 1.1 Dissertation Overview

In light of this, this thesis explores novel ways of converting lanes for bus use when bus flows are low. The ideas entail ordinary bus-lane conversions over much of the city's road network. The ideas are novel in that the special treatments proposed would link to these ordinary conversions, and would be deployed only at what we shall call “critical bottlenecks”. Within a bottleneck of this kind, buses and cars

would share a lane in ways that preclude bus delays, while squandering little if any of the bottleneck's capacity to serve its cars. The sharing strategies would therefore prioritize bus travel while limiting the resulting damage (i.e., the added delays and queues) to car traffic. The details of how this sharing would occur depend upon a bottleneck's local operating conditions. Two types of operating conditions can be accommodated.

Conditions of the first type arise when a bottleneck is active, meaning that it is not itself affected by car queues from any other bottleneck further downstream. The bottleneck may exist prior to the bus lane's deployment, or arise only thereafter. Either way, it is proposed that one of the bottleneck's lanes be shared continuously among cars and buses, as will be described in Section 3.1.

Conditions of the second type arise when a bottleneck that would otherwise be engulfed in a queue from downstream instead becomes active when one of its lanes is converted for bus-use only. In these cases, it is proposed that a bottleneck lane be shared intermittently, as described in Section 3.2

Examples of locations where the strategies can be applied include: road intersections, including signalized intersections; short-distance reductions in lanes, as can occur at narrow bridges and tunnels; and bottlenecks that are formed by changes in horizontal or vertical road alignments.

Excluded from the set of feasible locations are arterials with closely-spaced signalized intersections in series. This exclusion is not as serious as it may seem at first, since bus-car sharing strategies for facilities of this kind have already been developed (Viegas & Lu, 2001; Eichler & Daganzo, 2006).

### **1.1.1 Research Contributions**

The first contribution of this dissertation is the identification of bus priority strategies for low bus flows on isolated roadway bottlenecks. While strategies of this kind have been developed for signalized arterials, this dissertation presents unique ideas for facilities with bottlenecks that are sparse (such as expressways or arterials with few, widely-spread signals). The dissertation also presents an evaluation method to determine whether shared lanes or ordinary lane conversions should be used at critical locations on these facilities.

The second contribution of this thesis is a systematic analysis of shared lane strategies for isolated signalized intersections. While some of the ideas presented in this thesis have been used at different sites, no systematic categorization of strategies or analysis of the conditions under which these strategies are applicable has been conducted.

This dissertation also provides recommendations on how to implement shared lane strategies along a bus route. A methodology is developed that can be used to systematically deploy shared lanes and ordinary bus lanes along the route. This allows for a complete design of a proposed bus priority route with minimum negative impacts on cars, regardless of different roadway facilities that it may run through.

Finally, this dissertation provides a proof of concept through a case study demonstrating the potential benefits of these strategies and their applicability to the real world. This case study also unveils how site specific details can be included in the design.

### **1.1.2 Organization**

The references mentioned in Section 1.1 and other relevant literature are described in the following chapter. Details on how the proposed shared lane treatments would work in real settings are given in Chapter 3. The conditions under which these treatments are less damaging to cars than are ordinary lane conversions are theoretically explored in Chapter 4. Practical considerations for deploying these ideas, and the outcomes from a case study are presented in Chapter 5. Brief discussion on the need for field experiments and future directions is offered in Chapter 6.

# Chapter 2

## Literature Review

The goal of bus priority strategies is to induce modal shifts from cars to buses by increasing the attractiveness of buses. This shift means that more people are carried using less road space, which can make urban transportation systems more efficient and environmentally friendly. Treatments that provide bus priority are often less expensive to implement than other investments in public transportation systems, such as building rail systems. Bus priority strategies can be divided into two categories: those targeted to links (i.e., road segments) and those targeted to nodes (e.g., intersections). These strategies intend to decrease bus delays and increase on-time performance of buses. It has been shown (e.g., Murray & Wu, 2003) that such improvements can significantly increase the perceived quality and attractiveness of bus service. This chapter offers an overview of different bus priority strategies that have been proposed by researchers and used by agencies, and describe how the strategies can improve bus service. Section 2.1 describes strategies that are targeted at links and Section 2.2 describes strategies that are targeted at nodes. A review of the present gaps in the literature is provided in Section 2.3

### 2.1 Bus Priority Strategies Targeted to Links

The most common way of providing priority to buses on links is to designate a lane for bus use only. In urban environments, where space is limited, this is typically done by converting an existing general-use lane to bus-use only. When bus flows are high, removing buses from the general stream of traffic can reduce the number of conflicting maneuvers between cars and buses, which in turn can improve the travel speeds of both modes. Also, the resulting induced modal shifts from cars to buses may further decrease traffic congestion.

Dedicating a lane for buses is often combined with other features such as longer stop spacing and stations with level access and prepayment to further decrease bus travel times. Implementation of these strategies as a bundle is referred to as a bus rapid transit (BRT) system. BRT strategies can vary in direction of flow of buses (with- or contra- car flow), placement of the bus-lane (median or outside) and mix

of traffic allowed to use the bus-lane. A summary of different types of BRT systems can be found in Miller *et al.* (2009) and Levinson *et al.* (2002, 2003).

BRT systems have been studied as early as 1975 (Levinson *et al.*, 1975). That work provides guidelines on efficient bus operation on streets by examining implementation of different BRT systems that exist around the world. Early studies focused on quantifying the increase in bus speeds and decrease in bus travel times that result from dedicating a lane for bus use only. Typically, these studies were conducted using a mix of data from field experiments or simulations (e.g., Tanaboriboon & Toonim, 1983; Roupail, 1984; Shalaby & Soberman, 1994; Surprenant-Legault & El-Geneidy, 2011). While these studies verify that BRT systems can decrease bus travel times, the magnitude of these benefits and the conditions for which these benefits are realized varies greatly. Tanaboriboon & Toonim (1983) theoretically analyzed four different bus route options for implementation of a BRT system and observed that bus travel times decreased on all routes. The authors also observed that the coefficient of variation of the bus travel times decreased as well, implying that the reliability of bus service increases by implementing dedicated lanes. A similar result was found in Surprenant-Legault & El-Geneidy (2011) which evaluated changes in bus speeds using data from a field implementation of a BRT corridor in Montreal, Canada collected with automated vehicle location systems. Additionally this study found that the increase in bus speeds leads to an increase in user satisfaction with buses. Roupail (1984) evaluated different bus priority strategies, including dedicated bus lanes using data from a simulation model of Chicago, and also conducted a field experiment to verify the findings. The author concluded that the simulated increase in bus speeds was comparable to the field test, verifying the evaluative power of the simulation tool. Lastly, in a field experiment conducted in Toronto, Canada, Shalaby & Soberman (1994) assessed the changes in bus travel times on different segments of an arterial on which a BRT system was implemented. The authors observed that travel times decreased for buses only on previously congested segments of the roadway, and there were no travel time benefits to buses on other segments.

Later studies focused on the effects of BRT systems on both cars and buses (i.e., Shalaby, 1999; Japson & Ferreira, 2000; Currie *et al.*, 2007; Arasan & Vedagiri, 2010; Cassidy *et al.*, 2010). Using various methods (such as simulation or theoretical evaluation), these studies often conclude that it is difficult to justify the implementation of BRT systems if the effects on car traffic are also considered. Using a simulation of Toronto, Canada, Shalaby (1999) analyzed the changes in car and bus speeds after a BRT system (including a dedicated lane for buses) was implemented. The work found that the BRT system increased bus speeds and reduced the car speeds. Even though the reduction in car speeds is more than the increase in bus speeds, the overall bus travel times still exceed that of cars due to buses having lower cruising speeds and long dwell times at stops. However, a mode shift from buses to cars was still observed after the implementation of the BRT lane. Japson & Ferreira (2000) used a combination of theoretical analysis and simulation to identify the minimum flow of buses needed to justify dedicated bus lanes in terms of reducing total person hours



traveled. Depending on the occupancy of the bus and the car demand, these values ranged between 17 buses/hour to 300 buses/hour. Currie *et al.* (2007) developed an theoretical methodology to evaluate optimal road space allocation for cars and buses. This study also included a simulation to assess changes in travel time and reliability for buses, and changes in travel time for cars along with models to predict mode shifts and economic impacts. Based on a small-scale example, the authors concluded that often priority for buses is hard to justify when car demands are high (greater than 500 vph/lane) and bus headways are large (greater than 5 minutes). Arasan & Vedagiri (2010) developed a simulation of Chennai, India to study the effects of a BRT system on heterogeneous traffic. The authors determined that for cars to remain operating at an acceptable level of service (C), a volume to capacity ratio of approximately 0.55 and a road space allocation of 34% (for a 3 lane roadway) for buses would be needed. Finally, theoretical analysis conducted in Cassidy *et al.* (2010) showed that it is possible to reduce total VHT by segregating bus and car traffic on circular beltways when the smoothing effect is considered. However the analysis assumed that bus demand is fairly high and was further idealized in that it ignored many complications of real-world traffic such as driver behaviour.

Several other studies evaluated the effects of dedicated bus lanes at a network-wide level, as compared to only evaluating changes on a BRT route. Waterson *et al.* (2003) created a theoretical methodology to evaluate the effect of bus priority on a network. This methodology included determination of an order in which travelers respond to the changes on the roadway (e.g., modal shifts, rerouting etc.) and using these assumptions to develop a simulation framework. Testing this on a small network, the authors confirmed that the findings of this framework followed intuition that as the length of the dedicated bus lane becomes longer, the penalty to cars increases. However, the authors also found unexpected results, including that after a certain initial bus route length (around 3 kms) traffic congestion outside of the dedicated bus lane region becomes so severe that bus service also becomes slower as compared to there being no priority treatment. Liu *et al.* (2006) integrated demand and supply side transportation simulation models, and simulated this combined model on a real life network to evaluate the effects of dedicated bus lanes. The authors concluded that even after accounting for route changes among cars that may result from the implementation of dedicated bus lanes, the total travel times in the network increase due to the reduction of car capacity on the BRT route. Mesbah *et al.* (2008) combined an optimization model, a traffic assignment model and a mode share model to develop a methodology for optimally assigning road space to buses. That work found that only when there exists high car demands can dedicating a lane for buses help decrease total travel times on the network. This phenomena occurs by inducing mode shifts from cars to buses, which in turn can also reduce car congestion.

To decrease the negative effects that dedicated bus lanes have on cars, other bus priority strategies on links have allowed buses and cars to share a lane. One proposed treatment, termed queue jumper lanes, allows buses to use right turn bays at signalized intersections to bypass car queues. Nowlin & Fitzpatrick (1997) used

simulation to predict that, when combined with signal priority for buses, queue jumper lanes can be effective in increasing bus speeds by 5 to 15 km/hr. Zhou & Gan (2005) also theoretically evaluated different signal priority options, bus stop locations and car congestion levels using simulation and found that queue jumper lanes alone were not as effective in increasing bus speeds as if signal priority was also provided.

In one proposed treatment for an arterial with possibly many signalized intersections, cars would be periodically prohibited from entering lane segments in advance of an arriving bus (Viegas & Lu, 2001, 2004). The restricted segments might span several blocks at any one time; and the span would move forward with the bus as it progresses along its route. Car drivers are alerted to these intermittent restrictions by means of electronic signs, signals and other devices. Cars already occupying the lane at the time of its intermittent restriction may remain in that lane, and the lane segments are re-opened to all cars in the immediate wake of a passing bus. Field experiments in Lisbon, Portugal showed that the strategy increased bus speeds by 15 to 25%, as compared to the mixing of buses and cars (Viegas *et al.*, 2007). A variation of intermittent bus lanes was also field tested in Melbourne, Australia in 2001 (Currie & Lai, 2008). Even though travel time improvements to buses were observed in Melbourne as well, the authors found that these improvements were not as significant as in the case of Lisbon. Both Viegas *et al.* (2007) and Currie & Lai (2008) concluded that driver compliance with the intermittent bus lane restrictions was high and also that intermittent sharing strategies improved bus service without significantly degrading car traffic. Sakamoto *et al.* (2007) also field tested the idea of allowing cars to use a bus priority lane when buses are not present in Shizuoka, Japan. These authors not only observed reduced travel times for buses, but also a reduction in car congestion. This phenomenon was explained by an induced mode shift from cars to buses, shifting of departure times to out of the peak period and changes in car routes that arise. Yang & Wang (2009) conducted a simulation analysis of intermittent bus lanes. The authors found that intermittent or dedicated bus lanes both decrease bus travel times. However, the negative effects on adjacent car traffic is lower for intermittent bus lanes and this effect is more pronounced when bus headways are large.

In a variation on intermittent bus lanes termed Bus Lanes with Intermittent Priority (BLIPs), cars are required to vacate an intermittently restricted lane segment in advance of the approaching bus (Eichler & Daganzo, 2006). In this strategy, one or more blocks downstream of a bus current location are designated for bus use only, essentially creating a “cocoon” of empty space that travels with the bus as it moves along the arterial. On blocks where no bus is present, cars are allowed to use the intermittent lane, which can increase the total discharge flow through signalized intersections. Theoretical study found that the application of BLIPs reduces the interaction between buses and cars which can significantly reduce delays to buses. However, this comes at the cost of increasing average car density, which in congested traffic corresponds to lower speed and increased delays, as compared to using no bus lane. More recently, Chiabaut *et al.* (2012) theoretically analyzed the capacity of BLIPs

while also taking into account capacity drops that might arise at the first signalized intersection of an arterial where BLIPs are implemented. This capacity drop arises due to merging and acceleration of lane-changing vehicles. Even after taking into account the reduced capacities, the authors conclude that this activation effect can be negated if the signalized arterial on which BLIPs are implemented is long enough (6 or more intersections). Beyond this length, travel time benefits to buses will be observed with the implementation of BLIPs.

## 2.2 Bus Priority Strategies Targeted to Nodes

Buses that travel through signalized arterials often experience significant additional delays at those intersections. A common solution to give priority to buses at these locations is to use transit signal priority (TSP) strategies. This can be done either passively (on a pre-determined schedule) or actively (in real time). Passive priority is achieved typically by changing the signal settings, such as cycle length, green time and offsets, on a pre-determined schedule so to improve bus operations. This is typically achieved by having shorter cycle lengths to minimize bus delays at intersections, longer green times for bus travel directions and offsets between consecutive signals which are optimized for the speed of buses (instead of the speed of cars). Skabardonis (2000) developed theoretical formulations for optimizing passive transit priority strategies and confirmed through simulation that these strategies decreased bus travel times, especially when bus headways were small and predictable. However, passive strategies are often not effective because it is difficult to accurately predict traffic conditions and bus arrival times at a signalized intersection.

Active strategies, on the other hand, require that real-time bus arrival times to a signalized intersection be known or predicted with high accuracy. Based on when the bus will arrive to a given intersection, different strategies such as phase extension, phase advance, phase insertion or phase rotation can be used to minimize the bus delay (FHWA, 2008). These strategies change the signal phase in the advance of an arriving bus to ensure that the bus has a higher probability of encountering a green phase. Various studies have analyzed the impacts of transit signal priority on the performance of buses and cars (Al-Sahili & Taylor, 1996; Balke *et al.*, 2000; Skabardonis, 2000; Mcleod & Hounsell, 2003; Ahn & Rakha, 2006). This research was often conducted through simulation, and only a few present results from field experiments. Overall, the reported level of benefit to buses under this type of priority varies. However, these studies tend to be site specific, and often the benefits to buses are observed only when these strategies are used along with BRT systems with dedicated bus lanes, which also could include longer stop spacing and stations with level access and prepayment. These studies also evaluated the effects of transit signal priority on car queues and delays. These results often show that when providing priority to buses cars experience additional queuing and delays.

The studies mentioned above (whether or not they are combined with BRT systems) assume that buses travel the entire length of the arterial without exiting at an

intermediate intersection. When this is not the case, bus delays can occur if buses maneuver into car lanes to perform their exit maneuvers due to conflicts that arise between the buses and cars. This problem has been addressed by means of mid-block pre-signals. These devices halt cars in their lanes when an approaching bus needs to maneuver through those lanes (Wu & Hounsell, 1998). Wu & Hounsell (1998) also developed analytical formulas to quantify the bus delay savings when pre-signals are used. Other uses of pre-signals also exist in the literature. Stein (1961) analyzed the use of pre-signals to negate the time lost at signalized intersections due to the bounded acceleration of vehicles. That work shows that if there are only cars in a traffic stream, approximately 4 seconds of additional green time can be gained at intersections with the use of this type of pre-signals. More recent work has explored the use of pre-signals to increase intersection capacity by resolving these and other types of vehicular conflicts that would otherwise occur at the signalized intersection downstream (Xuan *et al.*, 2011).

## 2.3 Gaps in the Literature: Moving to Shared Lanes on Bottlenecks

Although ideas for intermittent bus lanes have been proposed and field tested for low bus flows, these strategies focus solely on signalized arterial streets and not on the application of shared lanes on unsignalized roadways such as expressways. The strategies also do not address bus turning maneuvers and instead assume that buses travel straight through the arterial. While pre-signals have been used to solve some bus turning conflicts, a systematic study of pre-signals for all possible bus-car conflicts is absent from the literature.

The present ideas borrow from the above studies. For example, some of the treatments proposed herein entail the use of intermittent lane-use restrictions and pre-signals. Yet the ideas presented in this dissertation are distinct, in part because they are exclusively targeted to select bottlenecks in a road network. The ideas are therefore well suited to networks where bottlenecks are relatively infrequent, as compared to signalized arterials with bottlenecks (intersections) at short block lengths. Suitable facilities include urban or suburban expressways, as well as the sparse road networks that are common in cities throughout the developing world. Or, the ideas might be deployed at a limited number of especially problematic bottlenecks in a dense urban network.<sup>1</sup>

By targeting the proposed treatments to bottlenecks, I argue that it is often possible to eliminate, or nearly eliminate bus delays while maintaining high discharge

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<sup>1</sup>As cases in point, the present ideas were born of efforts to design a next-generation bus rapid transit system for the developing city of Amman, Jordan (Guler & Cassidy, 2010). In addition, it was surprising to learn that one of the ideas (see Figure 4.3(a)) is presently deployed at a single signalized intersection near downtown London (see the citation for GoogleMaps (n.d.) in the reference section of this manuscript).

flows for car traffic. Higher car flows will, of course, limit the delays to cars (e.g. Wattleworth & Berry, 1965; Banks, 1991; Newell, 1993; Cassidy, 2003; Daganzo & Geroliminis, 2008). Moreover, the ideas can be deployed at relatively modest cost because information and control technologies are needed only at the select bottlenecks and not throughout the city's road network.

On the downside, the ordinary lane conversions that are located away from the bottlenecks which allow buses to jump the queues formed at the bottlenecks (see again Chapter 1) will still be under-utilized. The resulting waste of road space will cause car queues to expand faster and further over the network. This can become problematic if the expanded queues spill-over to junctions upstream and impede access or egress at those locations (see Daganzo, 2007). This should be considered when deploying special-use lanes of any kind. Fortunately, analysis techniques have been developed for this purpose (see Daganzo & Cassidy, 2008).

# Chapter 3

## Shared Lane Strategies

The proposed shared-lane treatments for bottlenecks are explored here. To fix ideas, first bottlenecks of fixed capacities will be examined. Bottlenecks with time varying capacities (e.g., signalized intersections) require additional considerations that will be described later in Chapter 4.

Without loss of generality, it will be assumed that vehicles travel on the right-hand-side of the road, as in the U.S., for example; and that the median lane is to be converted: for shared use within critical bottlenecks; and for the exclusive use of buses elsewhere in the network.

### 3.1 Type 1 Conditions: Active Bottleneck

This corresponds to situations where the bottleneck is either active even before the provision of a special lane for buses, or becomes active after this provision. Consider the middle link of length  $\ell$  shown in Figure 3.1(a). It has  $L_n$  lanes and an average queue discharge flow in each (i.e., an average capacity per lane) of  $s_n$ . For simplicity, assume that the upstream and downstream links each have  $L$  lanes with queue discharge flow  $s$  in each. Suppose that  $L \cdot s > L_n \cdot s_n$  and that car demand for the middle link exceeds  $L_n \cdot s_n$  as well. Thus in the absence of any queue that has spilled-over from a downstream bottleneck, the middle link is an active bottleneck, and this could be true whether or not  $L = L_n$ .

It is proposed that the link upstream of the bottleneck include a converted lane for the exclusive use of buses, shown with dark shading in Figure 3.1(a). The exclusivity of that lane would end near the bottleneck's entrance. The portion of the lane downstream would be continuously shared by both buses and cars over the bottleneck's length,  $\ell$ , as shown with light shading in the figure. Buses may thereafter enter an exclusive lane downstream: an ordinary conversion could be resumed somewhere on the downstream link if car queues arise there due to other bottlenecks, as shown by the resumption of dark shading in the figure. (The figure depicts a worst-case scenario in that the link immediately downstream of the critical bottleneck: presumably holds a car queue that spills-over from a further downstream bottleneck so that it is

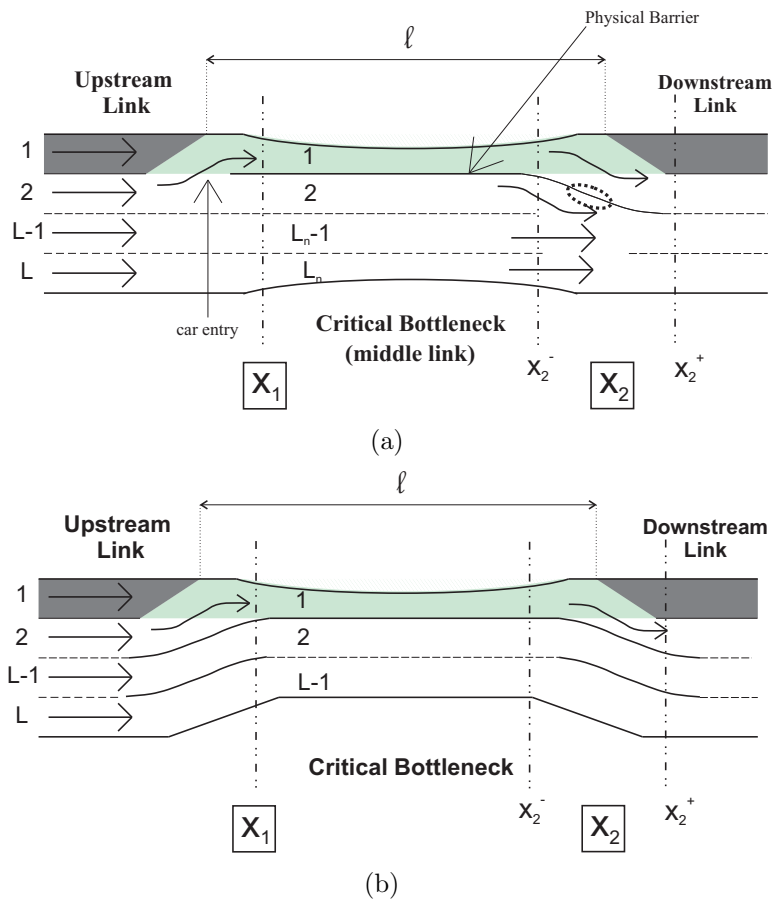


Figure 3.1. Shared lane conversions at a critical bottleneck when: (a)  $L = L_n$ ; and (b)  $L > L_n$ .

necessary to re-install an ordinary lane conversion; and does not itself widen, e.g. to  $L + 1$  lanes.) In contrast, cars in the bottleneck's shared lane would diverge into lane 2, also as shown in Figure 3.1(a). In many instances, this shared-lane treatment can increase the discharge flows of cars through a bottleneck without delaying buses, as explained below.

When  $L = L_n$  as in Figure 3.1(a), and when car demand is sufficiently high, car queues will form in the lanes labeled 2 through  $L$  starting at the bottleneck's downstream end, labeled  $x_2$ . The queue forms there because cars in the bottleneck's  $L_n - 1$  regular lanes are required to merge into  $L - 2$  lanes; see again Figure 3.1(a). Once that queue expands upstream, and assuming that  $\ell$  is of appreciable length, car drivers approaching the bottleneck in lane 2 will be motivated to use the (lightly-shaded) continuously shared lane to improve their speeds: notice that speeds in the continuously shared lane will be relatively high, commensurate with un-queued, capacity flows.<sup>1</sup> Thus, the occasional arriving bus would join the stream of un-queued cars and traverse the bottleneck in the continuously shared lane without encountering delay. An additional benefit of this shared-lane treatment is that the bottleneck's  $L_n - 1$  regular lanes can be used for queue storage over length  $\ell$ . This reduces the chance of queues spilling over to other bottlenecks upstream, especially if  $\ell$  is large as might be the case for a bridge or a tunnel.

When  $L_n < L$ , the treatment would be slightly different, as shown in Figure 3.1(b). Traffic would be freely-flowing through the length of the bottleneck,  $\ell$ , since the queue would now form at the bottleneck's upstream end near the location labeled  $x_1$ . Since car drivers would therefore not enjoy a speed advantage by entering the continuously shared lane, they would likely leave that lane underutilized. The resulting waste of bottleneck capacity would exacerbate car queuing and delay. It is therefore proposed that cars arriving in lane 2 be fed into the shared lane (e.g. via pavement markings) as in Figure 3.1(b). These cars would be fed back into lane 2 after having traversed the bottleneck.

## 3.2 Type 2 Conditions: Congested Bottlenecks

This corresponds to the case when the bottleneck is engulfed in a queue from downstream. Suppose now that the bottlenecks in Figures 3.1(a) and 3.1(b) were engulfed in car queues that had spilled-over from locations downstream. Converting a bottleneck lane for the exclusive use of buses would be ill-advised if such action would constrain car flows to the point of starving the downstream queues. (This could further diminish car flows through the network.) Sharing a lane continuously, as previously described, could also be objectionable if that would mean that buses are delayed by traversing the shared-lane segment at slow, queued speeds. However, if

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<sup>1</sup>If the bottleneck's length,  $\ell$ , is short, drivers might lack motivation to travel in the shared lane. The lane could be underused as a result. In these cases, a policeman could be stationed at  $x_1$  and direct suitable traffic quantities into the shared lane.



$\ell$  is short, these delays could be small and judged to be acceptable.<sup>2</sup> In this case, a continuously shared lane as described above can be used.

When  $\ell$  is large, it is proposed that the lightly-shaded lane segments of Figures 3.1(a) and 3.1(b) be made available to cars on an intermittent basis, and only when no bus is on the scene. The lane would be closed to cars in advance of each arriving bus by means of electronic signs, signals and possibly mast arms. Each periodic restriction could be activated at such time that a bus would arrive to the intermittent shared-lane segment when its car queues had nearly vanished. The bus would then traverse the intermittently shared lane and enter the exclusive bus lane downstream, free of delay. Cars would be re-admitted to the shared-lane in the immediate wake of the passing bus.

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<sup>2</sup>Discussion on the magnitude of the bus delays that might result from this treatment can be found in Section 4.2

# Chapter 4

## Domains of Application

In this Chapter the bottleneck capacities for serving car traffic via the use of shared lanes is compared against the car-carrying capacities when a bottleneck's lane is converted for the exclusive use of buses. Car-carrying capacity is of major concern since the bus demand would be fully served by the bottleneck when either treatment option is used there. The comparisons will now also include cases in which the bottleneck is formed by a signalized intersection. Outcomes unveil the broad range of conditions under which a shared lane is the superior treatment option.

### 4.1 Active Bottlenecks: Continuous Sharing versus Exclusive Bus Lane

Consider first an active bottleneck with  $L = L_n$  lanes, as previously shown in Figure 3.1(a) is considered. Suppose for now that one of the bottleneck lanes were to be turned-over to buses exclusively. (see Figure 4.1) In this case, the head of the car queue would reside at the location labeled  $x_1$  in the figure. The car-carrying capacity there,  $Q(x_1)$ , would be given by:

$$Q(x_1) = (L_n - 1) \cdot s_n. \quad (4.1)$$

Suppose now instead that the bottleneck were to operate with a continuously shared lane. In this second case, the head of the car queue would now form at the downstream end of the bottleneck, either at location  $x_2^-$  or  $x_2^+$ , as labeled in Figure 3.1(a). Whether the queue's head resides at one location or the other will depend upon the magnitude of the capacity available to cars as they perform their merging maneuvers at the bottleneck's downstream end. If we assume that cars take up all the capacity of the shared lane unused by buses, the flow cars on that lane will

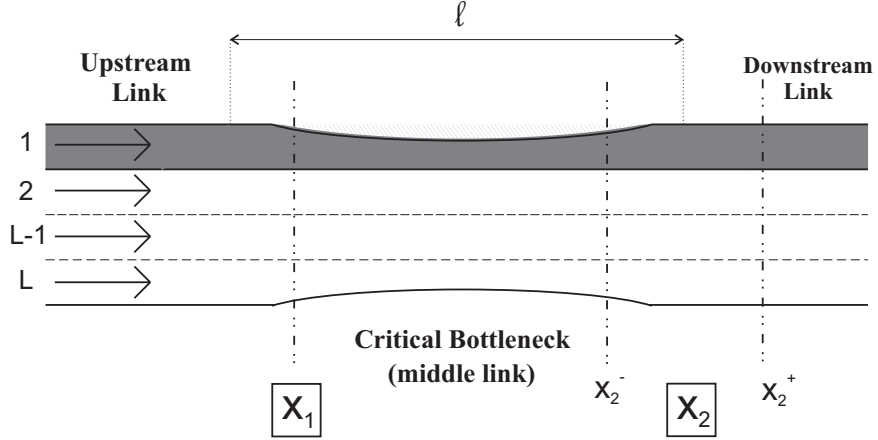


Figure 4.1. Exclusive Bus Lane Conversion at a Critical Bottleneck when  $L = L_n$

be  $s_n - q_b \cdot p$ , where  $q_b$  is the flow (demand) of buses,  $p$  is the car equivalence of a bus ( $p \approx 2$ ).<sup>1</sup> Therefore the bottleneck's car-carrying capacity can be expressed as:

$$Q(x_2) = s_n - q_b \cdot p + \min[\alpha \cdot (L_n - 1) \cdot s_n; (L - 2) \cdot s], \quad (4.2)$$

where  $\alpha$  is the percentage of the flow that can be sent from  $x_2^-$  retained on the critical bottleneck's outer lanes ( $2-L_n$ ) when cars merge into one less lane ( $L - 2$ ) at location  $x_2^-$ ,  $0 < \alpha \leq 1$ .

Consideration of Figure 3.1(a) shows that the last terms of (4.2) recognize that the constraint on this flow in the remaining (i.e., car) lanes is the smaller of what can be sent from  $x_2^-$ , or received at  $x_2^+$ .<sup>2</sup>

From (4.1) and (4.2), the upper bounds on bus flow,  $q_b$ , for which a bottleneck's car-carrying capacity is greater with a shared lane than with an exclusive lane conversion is found. These bounds can be expressed as:

$$q_b < \frac{s_n \cdot [1 - (L_n - 1) \cdot (1 - \alpha)]}{p} \quad \text{if } 1 - \frac{1}{L_n - 1} < \alpha \leq \frac{(L - 2) \cdot s}{(L_n - 1) \cdot s_n} \quad (4.3a)$$

$$q_b < \frac{(L - 2) \cdot s - (L_n - 2) \cdot s_n}{p} \quad \text{if } \alpha > \frac{(L - 2) \cdot s}{(L_n - 1) \cdot s_n}. \quad (4.3b)$$

<sup>1</sup>One could consider sending even higher car flow to  $x_2^+$  by allowing some cars to merge with the stream of cars diverging from Lane 1, i.e., by sending the merging cars through the dotted oval in Figure 3.1(a). This merging would have to be controlled so that car queues in Lane 1 are kept small. Expanded queues in Lane 1 would not only delay buses, but could disincentivize car drivers from entering the lane near location  $x_1$ . Furthermore, drivers might have to be coerced into merging through the dotted oval in the figure, since they may have little incentive to do so on their own. Though this kind of control might be feasible, the benefits may be modest when weighed against the complexities of the strategy required to realize any gains. Benefits would be especially small for  $s_n$  close to  $s$ .

<sup>2</sup>Further consideration of (4.2) and Figure 3.1(a) shows that the car-carrying capacity at location  $x_1$ ,  $L_n \cdot s_n$ , will not constrain car flows in cases when  $\alpha < 1$ .

Note that (4.3a) holds for cases when  $\alpha$  is relatively small (as specified by its limits shown above), and that (4.3b) holds otherwise.

For illustration, (4.3a) is analyzed parametrically for a range of  $s_n$  and several choices of (relatively small)  $\alpha$ . The resulting upper bounds on  $q_b$  are shown in Figure 4.2(a) for the fixed values of  $L = L_n$ ,  $s$  and  $p$  specified in the figure's caption. Note how the bounds increase with increasing  $s_n$ . This is because higher lane capacities in the bottleneck make it possible to insert more cars into the shared lane, even as  $q_b$  increases. Note too how these bounds exhibit comparatively large jumps when  $\alpha$  increases. When merging maneuvers in the vicinity of  $x_2$  are less damaging to capacity (see again Figure 3.1(a)), the shared-lane treatment enjoys greater domain of application. Control technologies to smooth-out merging (e.g., metering lights) might therefore be worth considering in certain instances.

The curves in Figure 4.2(a) also highlight the limits on  $\alpha$  for which (4.3a) is valid. The limits arise because  $\alpha$  is a function of  $s_n$ . For example, the dashed, upper curve in the figure reveals that for the inputs used in this assessment,  $\alpha$  must exceed 0.75 when  $s_n > 1550$  cars/hour/lane.

Figure 4.2(b) displays the upper bounds on  $q_b$  when  $\alpha$  is large enough to satisfy the inequality in (4.3a). The figure shows that the upper bound: is high for small  $s_n$ , and diminishes as  $s_n$  increases. Thus it is seen that when the capacity of bottleneck lanes  $2 - L_n$  is already high, allowing cars to share the remaining lane makes sense only when that lane would otherwise be substantially under-used by buses.

Overall, the analysis indicates that a shared lane enjoys a broad domain of application. Consider even the case when  $\alpha$  is large and when  $s_n \approx 1700$  cars/hour/lane, meaning that the lane capacity in the bottleneck is only about 6% lower than that of the link downstream. In this case, Figure 4.2(b) shows that the continuously shared lane is still beneficial to cars when  $q_b \approx 100$  buses/hour. Bus flows greater than this typically occur only in the larger cities of the world.

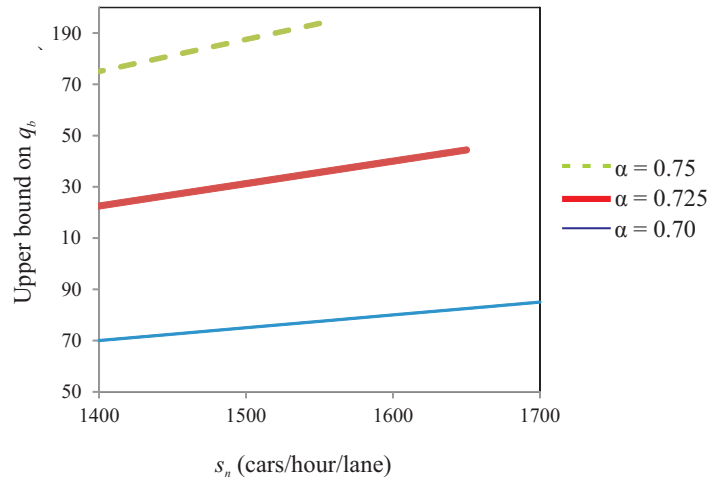
Consider now the subcase with  $L_n < L$ , as in Figure 3.1(b). In this scenario there seem to be numerous situations in which a continuously shared lane can bring higher bottleneck capacities for cars. Since in this case  $\alpha = 1$  (i.e, there is no merging at the bottleneck's downstream end), from (4.2) and (4.1) it is found that:

$$q_b < \frac{s_n}{p}. \quad (4.4)$$

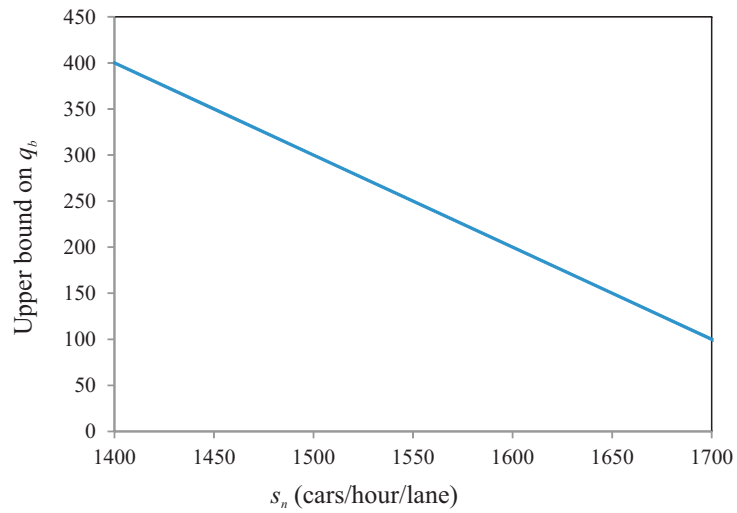
Equation 4.4 confirms that greater opportunities exist to fill a shared lane with cars when its  $s_n$  is large, even in the presence of relatively high bus flows.

#### 4.1.1 Special Case: Signalized Intersections with Type 1 Conditions

Consider the homogeneous intersection approach labeled 1 in Figure 4.3(a). Assume for now that all buses on that approach execute left turn movements at the intersection and therefore traverse the entire approach in their own (median) lane. Accommodating buses that perform other movements will be considered momentarily. It is further



(a)



(b)

Figure 4.2. Upper bounds on  $q_b$ , such that higher car-carrying capacity is achieved by continuously shared lanes for Type 1 conditions when: (a) capacity is constrained at  $x_2^-$ ; and (b) capacity is constrained at  $x_2^+$  ( $L_n = L = 4$ ,  $s = 1800$  and  $p = 2$ ).

assumed that the approach is controlled by a so-called split phase, so that in every cycle all of the approach's movements are served in a single, unopposed phase (i.e., split from the opposing approach). The equations to follow can be readily altered to accommodate other signal designs.

As a further starting point, assume for now that the median lane on Approach 1 is converted for the exclusive use of buses over its entire length (see Figure 4.4). The approach's car-carrying capacity (measured at the location labeled  $x_1^+$  in the figure) would be:

$$Q(x_1^+) = \frac{G_1}{C} \cdot (L_1 - 1) \cdot s, \quad (4.5)$$

where  $C$  is the fixed cycle length of the intersection's traffic signal,  $G_1$  is its fixed green time displayed to approach 1, and  $L_1$  is the number of general use (i.e., car) lanes on that approach. This car-carrying capacity can be achieved only if the bus demand does not exceed what could be served by one exclusive bus lane; i.e.,  $q_b \cdot p \leq \frac{G_1}{C} \cdot s$ .

Suppose now instead that the lightly-shaded lane segment in Figure 4.3(a) is to be continuously shared by both buses and cars on Approach 1. This shared segment would extend for a distance,  $\ell_1$ , such that  $G_1$  can be saturated by buses and cars when demand for either is sufficiently high. Once again, each arriving bus would mix with cars in the lightly-shaded segment. After passing through the intersection, left-turning buses and cars would enter their designated lanes on the receiving approach, labeled Approach 2 in the figure. Note that the darkly-shaded exclusive bus lane could resume on Approach 2, should the need arise.<sup>3</sup>

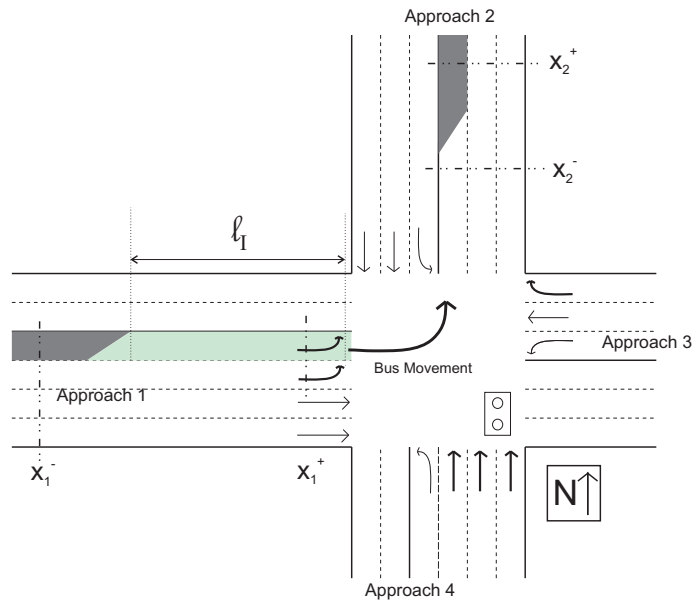
By terminating the median lane's exclusivity short of the intersection, bus delays will increase modestly because buses stopped during a red phase may find themselves queued behind cars. Though this would postpone bus entries into the intersection, each entry will occur during the very next green, much as it would had the exclusive lane spanned the entire approach.

Now the case in which some buses moving on Approach 1 travel straight through or turn right at the intersection, while others turn left will be considered. Buses still arrive in their (darkly-shaded) exclusive lane, but near the intersection some move into other lanes conducive to their impending movements.

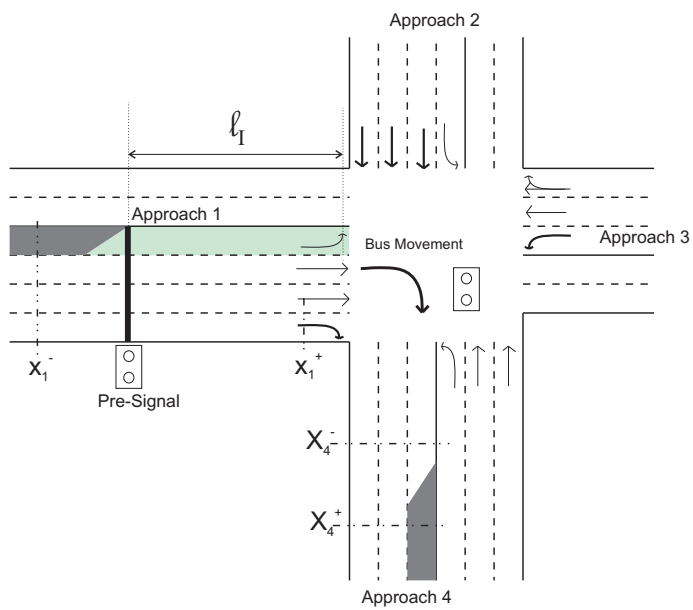
Pre-signals can be used to eliminate the vehicular conflicts that would otherwise arise as these buses maneuver through streams of cars; see Figure 4.3(b). Cars would be periodically halted at the pre-signal to enable each arriving bus to maneuver into a suitable lane. The approach's car-carrying capacity with the set-up shown in the figure becomes the minimum of the car flow that be discharged by: the pre-signal at the location labeled  $x_1^-$ ; and the intersection's traffic signal at the location  $x_1^+$ . These flows are given by:

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<sup>3</sup>The converted lane should resume a sufficient distance downstream of the intersection so that Approach 2 can hold the queue sent from another approach (e.g., Approach 4) while that queue is served by the diminished number of lanes at around  $x_2^+$ ; see Figure 4.3(a). In some circumstances, there may be need to re-order the sequence of signal phases so that queues sent from distinct approaches do not collide in a single cycle.



(a)



(b)

Figure 4.3. Geometry for signalized intersection with: (a) left-turning buses; and (b) through-moving or right-turning buses.

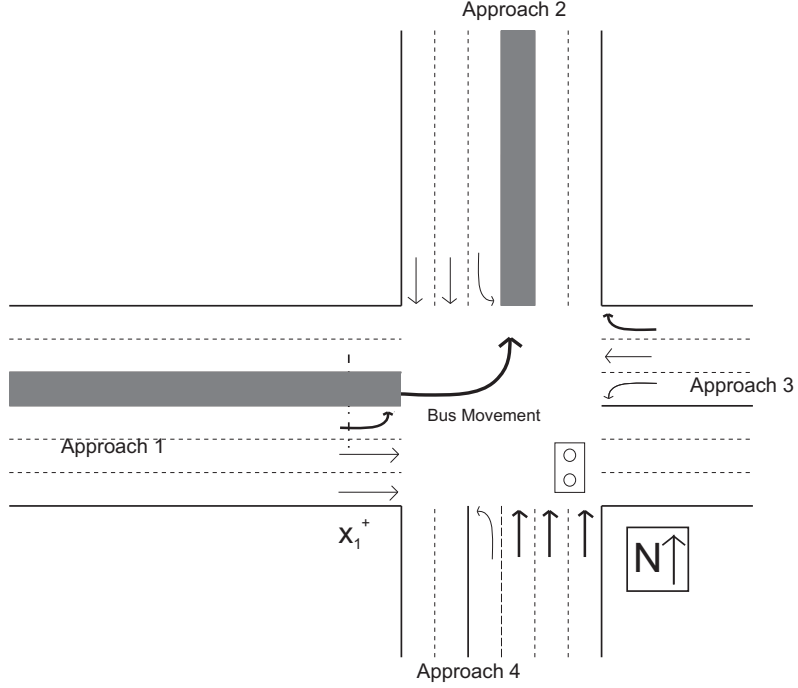


Figure 4.4. Exclusive bus lane conversion at a signalized intersection

$$Q(x_1^-) = (1 - q_b \cdot R_{PS}) \cdot (L_1 - 1) \cdot s \quad \text{where } q_b \cdot R_{PS} \leq 1 \quad (4.6a)$$

$$Q(x_1^+) = \frac{G_1}{C} \cdot L_1 \cdot s - q_b \cdot p, \quad (4.6b)$$

where  $R_{PS}$  is the duration that cars are stopped by the pre-signal for each arrival of a through-moving or right-turning bus.<sup>4</sup>

Equation 4.6b is idealized in that the rate,  $Q(x_1^+)$ , would not be achieved if the voids in car traffic created by the pre-signal were to propagate through the intersection. This state of affairs might arise when the pre-signal interrupts car flows while at the same time the intersection's traffic signal downstream displays a green for those cars. In these instances, it might be advisable to use the pre-signal to first halt buses instead, until the intersection's signal turns red. The pre-signal would then halt the cars, thereby enabling the bus(es) to maneuver into suitable lanes without conflicts. Buses impeded in this fashion would experience a delay equal to about one-half the

<sup>4</sup>It is conservatively assumed that bus arrival is deterministic and that cars are stopped for each individually arriving bus. Fluctuations in bus arrivals can increase the capacity at the pre-signal if multiple buses can be made to pass the pre-signal in batched fashion.



signal cycle length, but the capacity given in (4.6b) could then be realized in more cases.<sup>5</sup>

Of the two equations above, (4.6a) becomes the more constraining when cars are halted frequently by arriving buses. An upper bound on  $q_b$  that precludes this constraint from occurring is found by setting  $Q(x_1^+)$  in (4.6b) less than  $Q(x_1^-)$  in (4.6a). It is thus found that:

$$q_b < \frac{s \cdot (L_1 \cdot (1 - \frac{G_1}{C}) - 1)}{s \cdot (L_1 - 1) \cdot R_{PS} - p}. \quad (4.7)$$

There are cases when the continuously shared lane shown in Figures 4.3(a) and (b) is still the superior option, even when the pre-signal starves the downstream intersection of car flow, such that  $Q(x_1^+) > Q(x_1^-)$ . An upper bound on  $q_b$  for these cases is found by comparing (4.6a) to (4.5), giving:

$$q_b < \frac{1 - \frac{G_1}{C}}{R_{PS}}. \quad (4.8)$$

It is further required that  $q_b$  not exceed the capacity of a single lane, giving an upper bound of:

$$q_b < \frac{G_1}{C} \cdot \frac{s}{p}. \quad (4.9)$$

The bounds given by (4.7)-(4.9) are displayed in Figure 4.5 for a range of  $\frac{G_1}{C}$  and the fixed inputs specified in the figure's caption.<sup>6</sup> The figure's lightly shaded region denotes the combinations of  $q_b$  and  $\frac{G_1}{C}$  for which car flow is constrained by the intersection's traffic signal; i.e., the approach's car-carrying capacity is  $Q(x_1^+)$ , as given in (4.6b). As  $\frac{G_1}{C}$  increases, the pre-signal becomes more prone to starving the downstream intersection of car flow, meaning that the constraint on this flow can become  $Q(x_1^-)$  as given in (4.6a). Cases in which a shared lane is still preferred to running an exclusive bus lane over the entire approach lie in the figure's darkly shaded region. In these cases, one can reduce the  $\frac{G_1}{C}$  so that  $Q(x_1^+) = Q(x_1^-)$  and the extra green at the intersection can be given to other approaches without penalizing cars on Approach 1. Therefore, both the light and darkly shaded regions denote the domains of application of pre-signals.

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<sup>5</sup>Delaying select buses as described above could still, in some instances, produce voids in car traffic that pass through the intersection and thereby waste capacity. However, this would only occur if the green time for the approach (e.g., Approach 1) is long. Kinematic wave analysis (Lighthill & Whitham, 1955) shows that the problem need not arise for  $\frac{G_1}{C} \lesssim 0.45$ .

<sup>6</sup>Note that the value of  $R_{PS}$  is conservative and includes the start-up lost time of cars at the pre-signal.

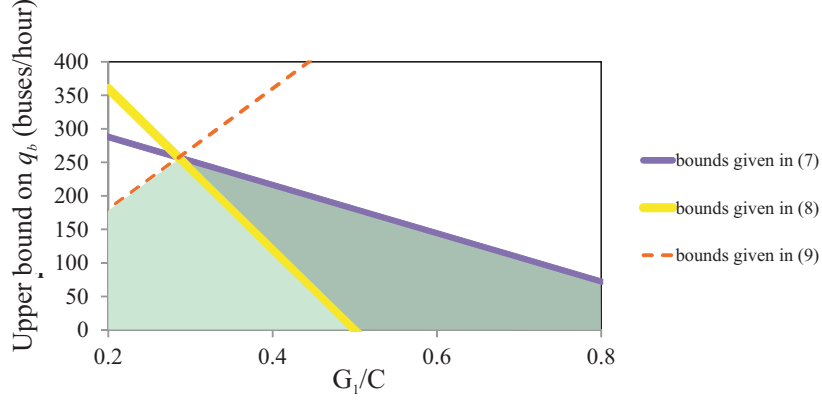


Figure 4.5. Upper bounds on  $q_b$ , such that higher car-carrying capacity is achieved by continuously shared lanes with pre-signals ( $L_1 = 2$ ,  $s = 1800$  cars/hour,  $R_{PS} = 10$  sec and  $p = 2$ )

## 4.2 Congested Bottlenecks: Intermittent Sharing versus Exclusive Bus Lane

Consider now a congested bottleneck, such that the middle link in Figure 3.1(a) or 3.1(b) is engulfed in a queue from downstream. Suppose first that the link's median lane is given over for the exclusive use of buses. The queued (i.e., constrained) flow downstream of the link is  $q_d$  per lane. With its exclusive bus lane, the middle link could become a critical bottleneck, such that the head of a new car queue would form at location  $x_1$ . The downstream queue would therefore be starved of flow, which would diminish car flow through the system. The capacity of what would now be a critical bottleneck is given by (4.1).

However, it is also possible that an exclusive bus-lane conversion would not constrain the middle link's flow below  $q_d$  per lane (e.g., if  $q_d$  is small). In that case, the constrained flow that departs the middle link would simply be:

$$Q(x_2^+) = (L - 1) \cdot q_d. \quad (4.10)$$

From (4.1) and (4.10) the upper bound on  $q_d$  for which (4.10) governs and the exclusive conversion does not starve the downstream queue can be determined:

$$q_d < \frac{(L_n - 1) \cdot s_n}{L - 1}. \quad (4.11)$$

If (4.11) holds, the exclusive conversion does no damage. Otherwise, the damage by the conversion can be lessened by instead sharing the middle link's median lane between cars and buses. Recall that this sharing could be done continuously if  $\ell$  is short. Assuming that the fundamental diagram for a lane of the critical bottleneck

is as in Figure 4.6 and a geometry of the critical bottleneck as in Figure 3.1(a), the average delay that a bus would encounter ( $d_b$ ) from traveling on the median lane mixed with cars can be found using kinematic wave theory:

$$d_b = \ell \cdot \left( \frac{w \cdot k_j - q_d \cdot (L - 1)}{w \cdot q_d \cdot (L - 1)} - \frac{1}{v} \right). \quad (4.12)$$

where  $k_j$ ,  $w$  and  $v$  are as shown in the figure. The bus delay for a critical bottleneck's geometry as shown in Figure 3.1(b) can be found in a similar manner, again by using kinematic wave theory.

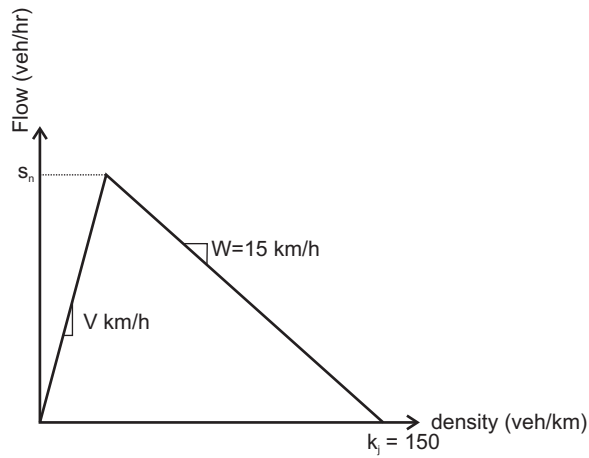


Figure 4.6. Fundamental diagram for the critical bottleneck

For illustration, Figure 4.7 shows the bus delay as found in (4.12) versus the length of the critical bottleneck for three different values of  $q_d$ . Using a figure of this kind, city officials can decide whether to use continuous or intermittent sharing on a congested bottleneck, depending on the level of bus delay they deem acceptable.

If judged necessary, the sharing in the middle link could be done in intermittent fashion. With this intermittent treatment, the middle link's flow would be:

$$Q(x_2^+) = (L - 1) \cdot q_d - \frac{q_b \cdot p}{s_n} \cdot q_d, \quad (4.13)$$

where the second term represents the fraction of the shared lane's capacity that is unavailable for car flow. Thus from (4.13) and (4.1), the upper bound on  $q_b$  for which intermittent sharing makes sense is obtained:

$$q_b < \frac{s_n \cdot (q_d \cdot (L - 1) - s_n \cdot (L_n - 1))}{q_d \cdot p}. \quad (4.14)$$

For illustration, Figure 4.8 displays these bounds for a range of  $q_d$  and with other inputs specified in the figure's caption. Note how the bounds increase with increasing  $q_d$ . This is because lower flow constraints from downstream enable more cars to discharge from the critical bottleneck with an intermittently shared lane.

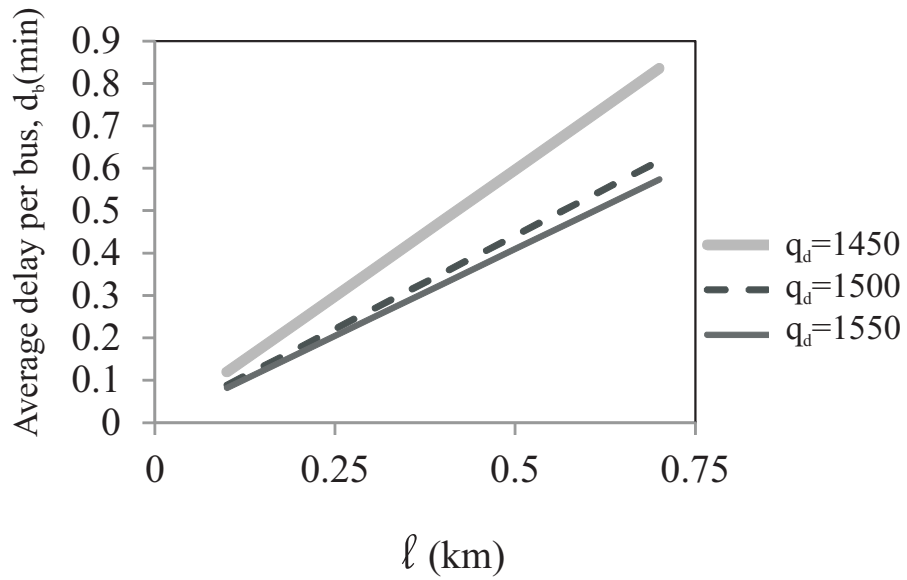


Figure 4.7. Average bus delay for continuous sharing on a Type 2 bottleneck ( $L = 4$ ,  $L_n = 4$ ,  $s_n = 1300$  cars/hour,  $w = 15$  km/hour and  $k_j = 150$  cars/km.)

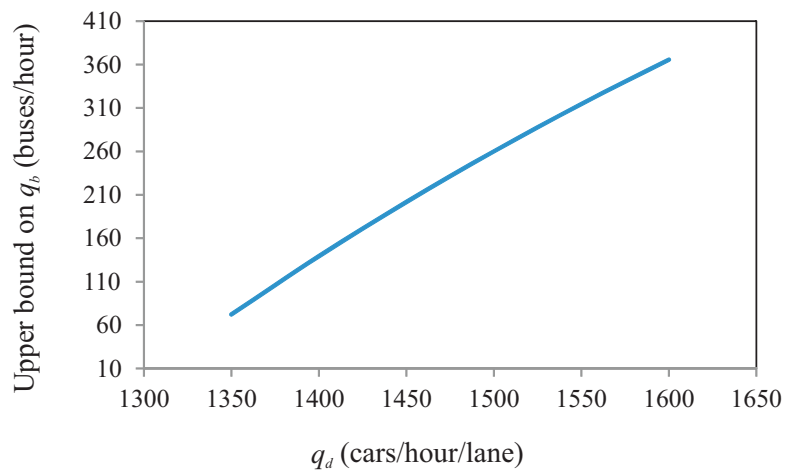


Figure 4.8. Upper bounds on  $q_b$ , such that higher car-carrying capacity is achieved by intermittently shared lanes ( $L = 4$ ,  $L_n = 4$ ,  $s_n = 1300$  cars/hour and  $p = 2$ .)

### 4.2.1 Special Case: Signalized Intersections with Type II Conditions

Intermittent lanes along with pre-signals can be readily applied to intersection approaches. For illustration, refer to Figure 4.3(a) and imagine that its northbound lanes on Approach 2 are engulfed by queues from downstream. Further suppose that the lightly-shaded lane segment on Approach 1 is intermittently shared. Car queues would therefore be cleared of that lightly-shaded segment prior to any bus entering it. These periodic restrictions could diminish the car-carrying capacity of Approach 4 since cars in its three through-moving lanes have to merge into 2 lanes on Approach 2. The car-carrying capacity of Approach 4 would then be given in equations comparable to those of (4.6). The upper bounds on  $q_b$  for Approach 1 would again be defined by (4.7)-(4.9).

# Chapter 5

## Implementation Issues

So far the work has focused on theoretical analysis of shared lanes implemented at isolated locations. Discussion in Section 5.1 will relax the assumption of isolated locations and focus on the deployment of shared lanes at the level of an entire bus route. Simulation is used in Section 5.2 to assess the savings in car delays that would be realized by deploying shared lanes in select bottlenecks of a real highway network. Further practical issues are discussed in Section 5.3.

### 5.1 Route-Level Considerations

Consider a bus route that passes through a series of  $N$  critical bottlenecks, like the one shown in Figure 5.1. The strategies of Section 4 can be applied to all the bottlenecks of the route as its bottlenecks become active or engulfed in queues. An operator needs to know which lane-sharing strategies are to be deployed at each bottleneck, so that each bottleneck is equipped with the suitable instrumentation, lane striping, etc. To this end, the following discussion presents an example of how to make these determinations.

At the start of a rush, a continuously shared bus lane could be deployed within each of these bottlenecks to maximize their car-carrying capacities. Car queues that form at any of the bottlenecks would initially be small, local affairs. However, the queues could grow long at a rapid pace because a lane on each of the route's  $N$  links would have been converted to bus-use only. Since these converted lanes would be underutilized (the  $q_b$  is small), the road loses space for storing queued cars (see Daganzo & Cassidy, 2008).

Hence, the goal is to determine which critical bottlenecks become engulfed in queues from downstream. These would have to be equipped with suitable infrastructure (e.g. control and information technologies) to facilitate other bus-lane treatments during their engulfment periods. It is not essential to predict these periods precisely. These would surely vary from one day to the next due to random variations, and would therefore be determined each day via real-time measurements. Coarse predictions using kinematic wave theory (Lighthill & Whitham, 1955; Richard, 1956; Newell, 1993;

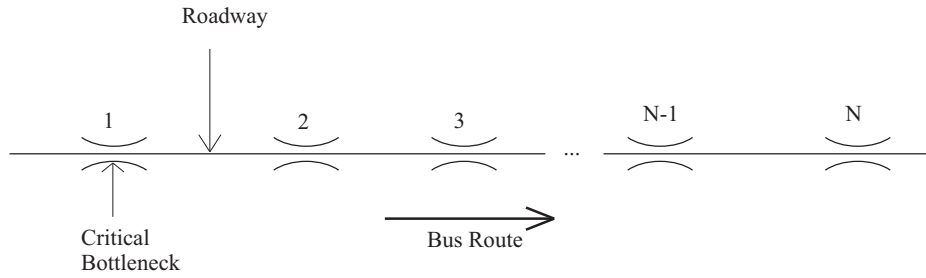


Figure 5.1. Roadway with multiple critical bottlenecks

Daganzo, 1995; Daganzo & Cassidy, 2008) would therefore suffice. For simplicity, one might assume that the physical length of each bottleneck,  $\ell$ , is negligible relative to that of the total route.

The analysis would proceed through time. Each time a downstream queue is predicted to engulf a bottleneck, its capacity would be assessed under other bus lane treatment options in the ways previously described. Thus, comparison of (4.1) and (4.10) would determine the suitability of replacing the bottleneck's continuously shared lane with an exclusive conversion. If this replacement would starve the downstream queue of flow, the suitability of instead using an intermittently shared lane for the engulfment period would be determined by comparing (4.13). Once the type(s) of treatment for the bottleneck are selected and its resulting capacity estimated, the kinematic wave analysis would continue. Assessments would end when all bottleneck queues dissipate at the end of the rush.

## 5.2 Case Study

The implementation of these strategies on a planned bus rapid transit network in Amman, Jordan is now discussed. This planned BRT route goes through many major bottleneck locations within the urban core of the city. While at some of these locations the city is looking to invest in new infrastructure (e.g. building new lanes) to give priority to buses, at many others priority will be given by converting an existing car lane for the exclusive use of buses. The case study location reflects the latter case.

Consider the portion of road network in Amman shown in Figure 5.2(a). The bus route labeled 1 (shown with solid arrows) runs through Junction II, where the two median lanes pass beneath a traffic circle, while the two outside lanes form an at-grade junction with that circle. The route continues through a signalized intersection, labeled Junction I, where buses turn left. Route 2 on the network runs in the opposite directions, as shown by dashed arrows in the figure.

If an existing car lane is converted for the exclusive use of buses southbound cars on Route 1 will be forced to use only one lane at junction II, see Figure 5.2(b). When demand is high this will cause the queues to grow and potentially spillover to a nearby signalized intersection that exists just to the north of junction II. At junction

I, dedicating a lane for bus use only will force left-turning cars to discharge from the signal using only one lane (since only one lane will be available to receive left-turning cars downstream). This is especially problematic since field observations at this site show that the southbound car demand is greater for left-turning movements than for through-moving or right-turning movements. If the left-turn queue grows long, it can also block through-moving cars at junction I, further reducing car discharge from the signal.

The proposed treatment for Route 1 is shown in Figure 5.3(a). It is proposed that the bus lane's exclusivity be terminated at the location labeled "A". The lightly-shaded downstream portion of the median lane would operate as an intermittently shared lane, such that cars turning left at Junction I would enjoy periodic access to that segment. The intermittently shared lane will be terminated at location "B", allowing cars from the traffic circle at Junction II to merge into the median lane. Left-turning buses and cars would eventually enter their designated lanes at the location labeled "C". Transient car queues may form at this location each cycle as cars merge into their single designated lane, and buses would incur modest additional delays as a result.

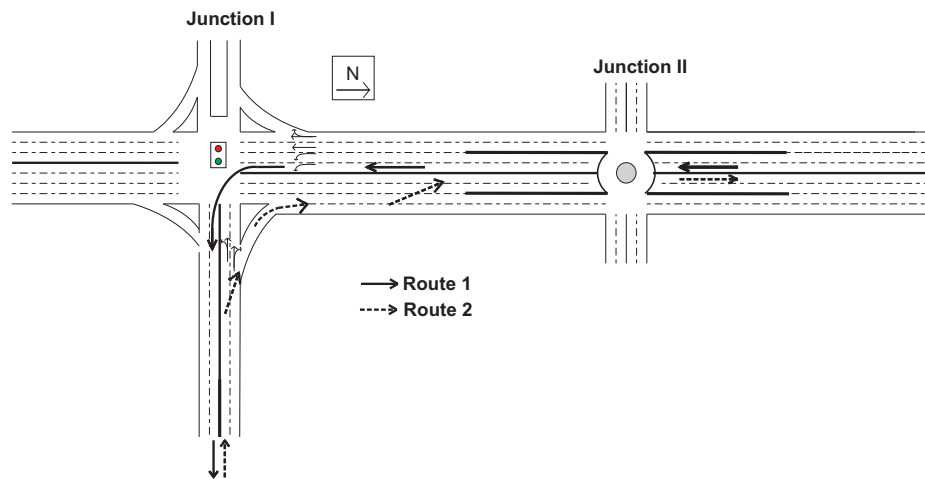
On Route 2, converting an existing car lane for the exclusive use of buses will reduce car capacities by 50% for westbound through-moving and left-turning cars at junction I leading to longer queues, see Figure 5.2(b). The queue of cars formed as a result could also block the free right-turn lane, reducing the flow of right-turning cars. Hence all cars travelling through junction I will experience increased delays. If a car lane is converted to an exclusive bus lane at junction II, only one lane will remain available for through-moving cars, halving the capacity for that movement. This could cause queues to grow and spill over to junction I, further inhibiting car operations also at the latter location.

The proposed treatment for Route 2 is shown in Figure 5.3(b). It does not entail the use of shared lanes. Rather, a pre-signal accompanies the termination of an exclusive bus lane at the location labeled "D", and the exclusive bus lane is resumed at location "E". Though this treatment is not novel (i.e., it is akin to those already used in London), its impacts on cars is assessed nonetheless, since this kind of analysis appears to be absent from the literature.

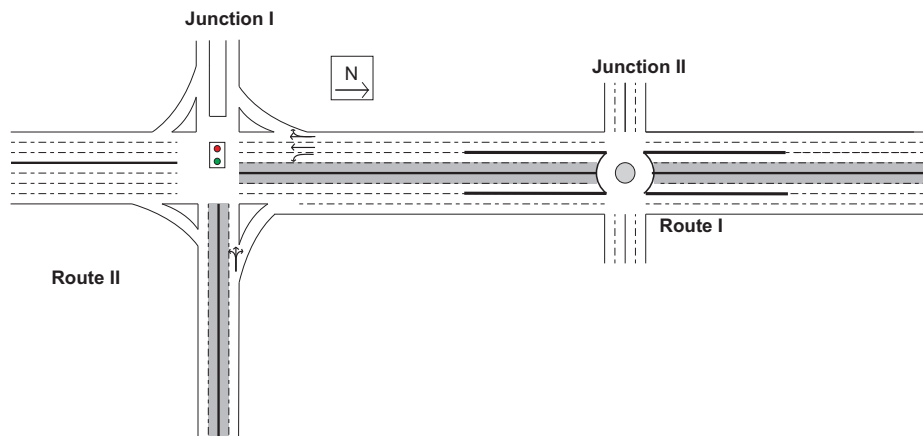
### 5.2.1 Simulation Models and Inputs

The benefits of the proposed strategies were measured as the average delay savings to cars when compared to using exclusive bus lanes that would run through the entire case-study site. Since the lane-changing behavior of drivers can lead to lower discharge flows from the bottlenecks than theoretically predicted, the benefits of these strategies may be over predicted if obtained via deterministic models. The predictions were therefore generated using the Aimsun microscopic, stochastic simulation model (AIMSUN, 2010.) in an effort to realistically represent car lane-changing behavior on the network. The existing geometry of the case-study site and the car speeds were



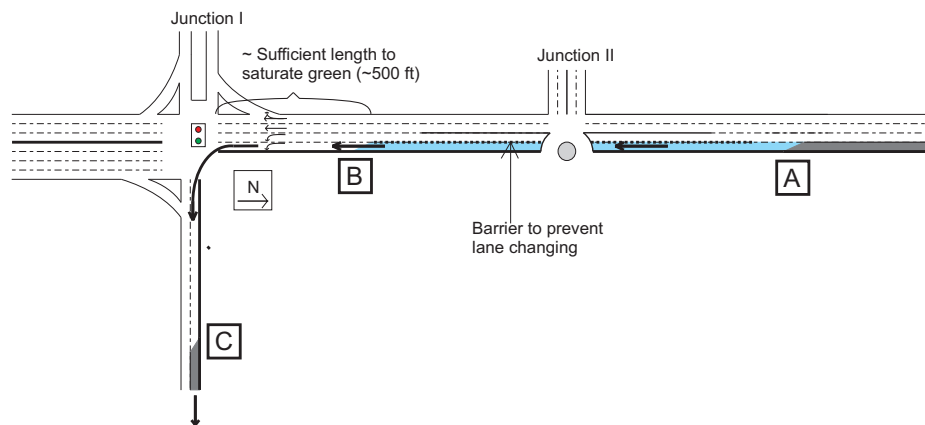


(a)

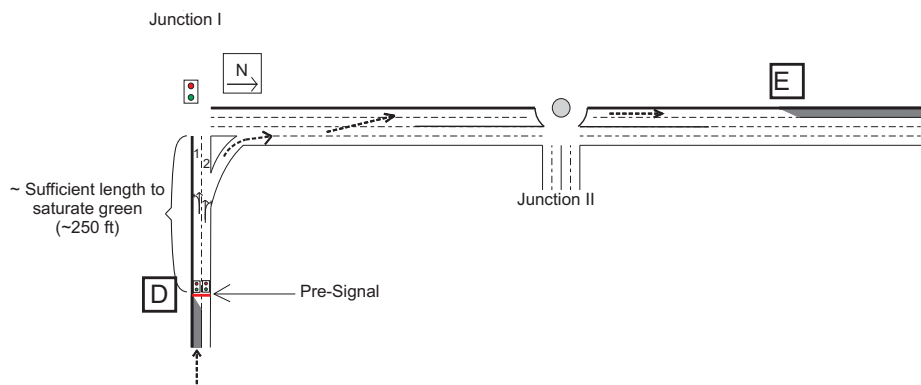


(b)

Figure 5.2. Amman network: (a) Existing geometry; and (b) Conversion of the median lane for exclusive use of buses.



(a)



(b)

Figure 5.3. Shared bus lanes on the Amman network: (a) On route 1; and (b) On route 2.

known. Assumptions were made in regard to driver behavior (e.g., acceleration rate, reaction time, etc.). The predictions of the Aimsun model were compared against the macroscopic and deterministic Cell Transmission Model (CTM) (Daganzo, 1995) which is a good approximation of kinematic wave theory (Lighthill & Whitham, 1955). This CTM model is easier to build, and requires less input data. As will be shown, the two simulation models predict delays that are qualitatively similar, though the numeric values predicted by each simulation model differ somewhat. Also, it is important to note that when the CTM model predicts that a benefit will be gained from using shared lanes, the Aimsun model predicts this as well. This suggests that when impacts cannot be determined directly from field experiments and when creating a detailed microscopic simulation is too costly, the CTM method can be used to provide insights into operation. For example, the CTM can still unveil cases in which it would be beneficial to implement shared lanes instead of exclusive bus lanes.

Table 5.1. Inputs to the simulation models

Peak southbound demand from the overpass on Route 1 (cars/hour)	500
Off-peak southbound demand from the overpass on Route 1 (cars/hour)	300
Percentage of southbound cars on route 1 turning left at junction I	66
Cycle length for signal at junction I (sec)	120
Green time for southbound left-turning cars on Route 1 at junction I signal (sec)	42
Green time for westbound cars on Route 2 at junction I signal (sec)	20

Simulations were performed for an array of scenarios. Each simulation was composed of a 1-hour peak (of varying demand for southbound and westbound cars on Routes 1 and 2, respectively) followed by 4 hours of off-peak traffic (with a fixed demand of 500 southbound cars/hour for Route 1 and 400 westbound cars/hour for Route 2 which are commensurate with present-day levels). Other inputs to the analysis are listed in Table 5.1. Even though the signal at junction I is currently actuated, it was observed that during peak hours the duration of the green times and cycle lengths were very nearly constant. Therefore, the signal was modeled as a pre-timed one.

For each set of inputs, a simulation was run for the treatments shown in Figure 5.3 and again for a treatment in which the median lane is given over for the exclusive use of buses throughout the network (Figure 5.2(b)) using both the Aimsun and CTM simulation methods. In both methods, the small car delay caused due to merging at location C on Route 1 (Figure 5.3(a)) and due to merging at location E on Route 2 (Figure 5.3(b)) were assumed to be negligible.

The schematic of the CTM for both Route 1 and Route 2 are shown in Figure 5.4, and the assumed triangular fundamental diagram for the CTM is shown in Figure 5.5. A bus demand of  $q_b = 12$  buses/hour was used for all routes, which is the bus flows that are initially expected to be seen in the Amman BRT network. Also, to observe

how an increase in bus demand would affect the predicted benefits, a bus demand of  $q_b = 20$  buses/hour was simulated. As a result, it was seen that the findings of the case study is robust to a small increase in bus demand.

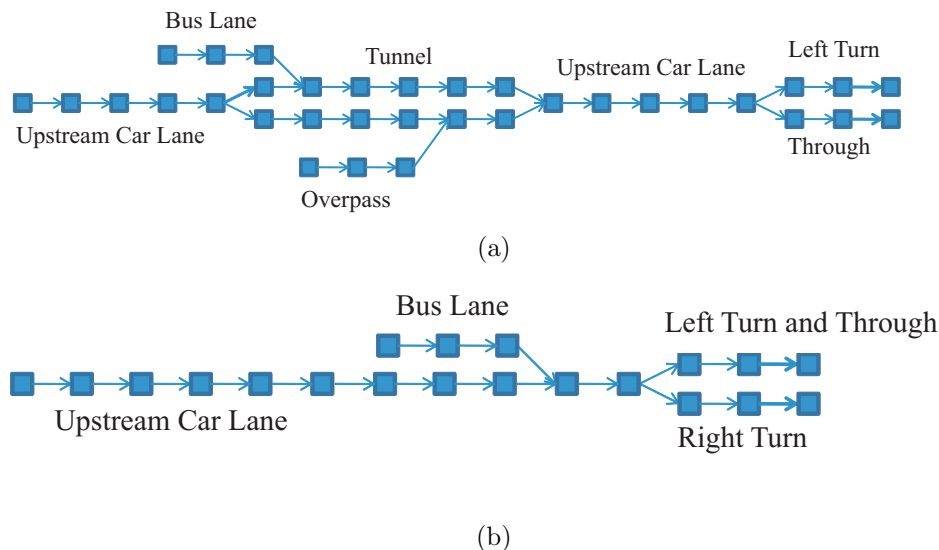


Figure 5.4. Schematic of cell transmission model (not to scale) on (a)Route 1 ; and (b) Route 2

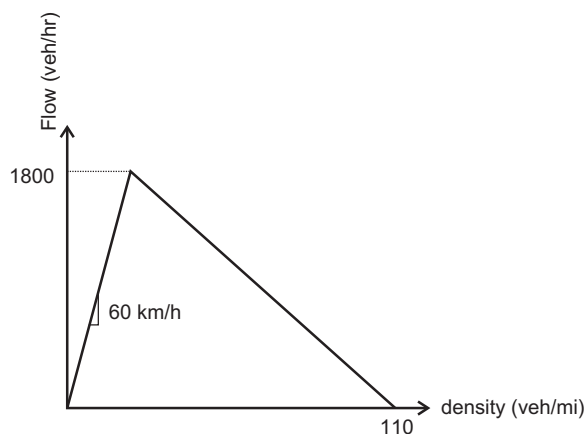


Figure 5.5. Fundamental Diagram used for Cell Transmission Model

### 5.2.2 Predictions for Route 1

Figures 5.6(a) and (b) shows the delay savings for Route 1 by using shared lanes as predicted by Aimsun and CTM, respectively. These results are averages across all cars over the entire 5-hour simulation period and are given for various peak-hour demands. The delay savings are significant. For example, for present-day peak-hour

car demand, (900/hour) and for  $q_b$  projected in the short run (12 buses/hour) the average savings is predicted to be 5 min/cars while bus delays are nearly eliminated. Of course the average savings to those cars that travel during the peak is much larger than the value given above.

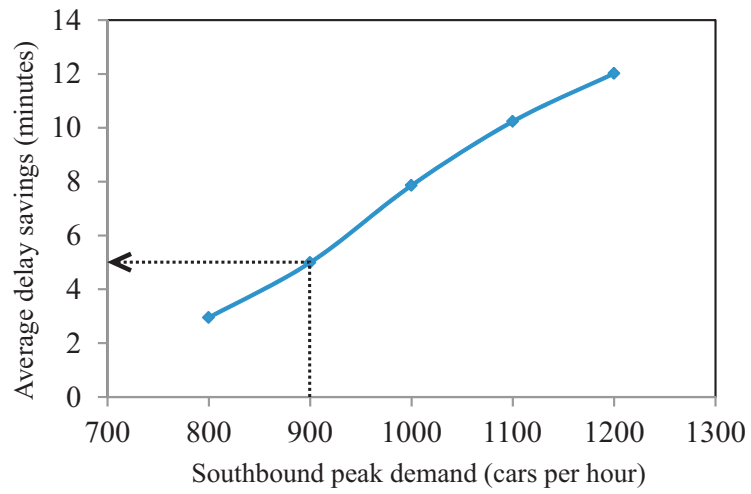
Significant savings in car delays would persist even if bus flows were to increase in the future. For example, a curve that is nearly identical to the one shown Figure 5.6 applies for  $q_b = 20$  buses/hour.

The average delay savings of shared lanes increase as car demand increases with both methods of assessment. At lower car demand values, when the system is not much congested, the average delay savings predicted by both methods are very close to each other. As congestion in the system increases, the microscopic simulation still predicts high delays, but not as high as the CTM. In the microscopic simulation when the system is very congested, some of the cars that arrive from the overpass and that wish to turn left at junction I cannot easily find acceptable gaps to merge into the left-turning lane. These cars end up queuing in the left-hand through lane, very near to the intersection, until an acceptable gap becomes available. Through-moving cars maneuver around these queued cars and discharge through the intersection (with minimal delay) using the right-hand through lane. However, in the CTM these left-turning cars force their way into the left-turn lane; this leads to increased queue lengths which block the through-moving cars. Also, in the microscopic simulation, when left-turning cars cannot merge into the left-turn lane after a reasonable amount of time they simply abandon their left-turn maneuver and continue through the intersection, further reducing the average delays that are recorded (These cars may still have great delays). This causes the CTM to predict slightly higher delays than the microscopic simulation at these high demands.

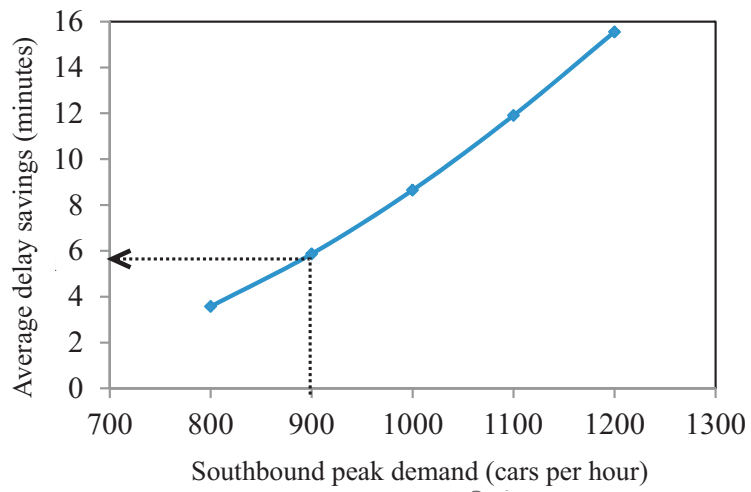
### 5.2.3 Predictions for Route 2

Predicted outcomes for Route 2 are shown in Figures 5.7(a) and (b). Their curves present the car delay savings versus the fraction of westbound cars that turn right at Junction I. The bold curve presents predictions for the present-day rush hour car demand of 1500 northbound cars/hour. For the present-day turning percentage (0.7), both simulations predict that implementing the ideas will save cars an average delay of about 2 minutes/vehicle while nearly eliminating bus delays. The second route did not afford opportunity to reduce car delays via shared lanes. The savings obtained via the proposed treatments are substantial nonetheless. It is predicted that cars would continue to enjoy delay savings, though more modest, even if peak-hour car demand were to diminish in the future. Once again it is found that if bus flows were to increase to  $q_b = 20$  buses/hour, the savings would be almost identical to those shown in Figure 5.7.

From Figure 5.7 it can be seen that with both simulation methods the benefits of using shared lanes grow as demand increases and shrinks as the right-turn percentage of cars increases. This makes, sense since increasing right-turn cars decreases the



(a)



(b)

Figure 5.6. Average delay savings on Route 1 ( $q_b=12, 20$  buses/hour) (a)Using Aim-sun ; and (b) Using Cell Transmission Model

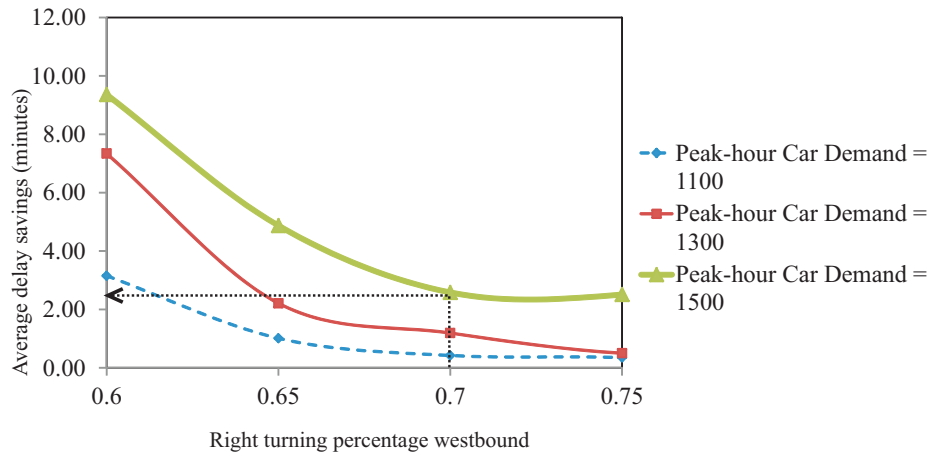
left-turn and through-moving car demand which in turn reduces the delay of left-turn and through-moving cars, especially in the case when exclusive bus lanes are used. However as the right-turn percentage of cars gets too high, demand of right-turning cars exceeds the right-turn lane's capacity. In turn, the right-turning car queue grows longer and blocks the left-turning and through-moving cars as well. Therefore, with either exclusive bus lanes or shared bus lanes the predicted average delays start to increase at high right-turn percentages. Microscopic simulation predicts that the increase in average car delays when shared lanes are implemented is less than when exclusive bus lanes are implemented. Hence with the Aimsun model, the average delay savings level off generally at values slightly higher than zero at high right-turn percentages. However, the CTM predicts that the increase in average car delays at high right-turn percentages is similar for exclusive bus lane or shared bus lane implementations. Therefore in the CTM model the average car delay savings stay at zero. It is also interesting to note that the shared lanes never perform worse than exclusive bus lanes in terms of car delays, and hence during off-peak periods shared lane strategies could still be used.

### 5.3 Technical Details

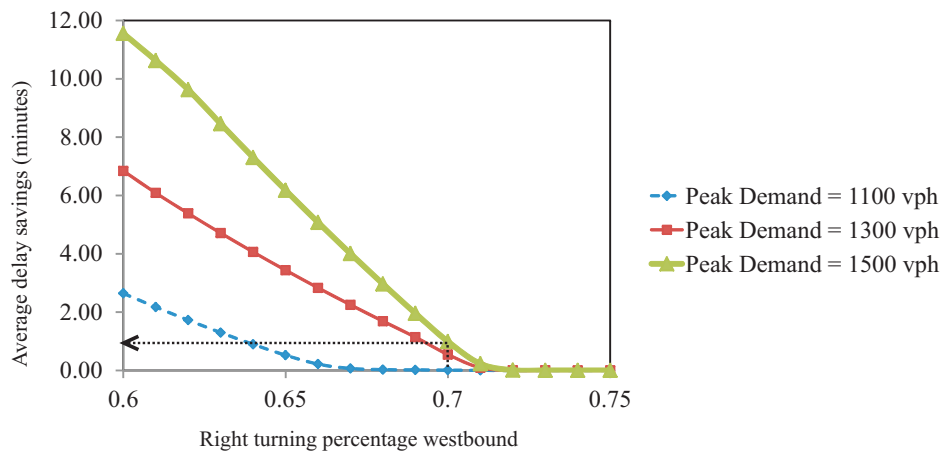
The technology requirements for deploying shared lanes would be relatively modest. The technologies used for pre-signals have long been developed and proven in the field. Continuously shared lanes would need similarly small levels of investment. Perhaps little more would be needed than suitable signing and pavement markings along with retractable traffic cones for separating the shared lane from its adjacent regular-use ones. One might additionally consider the use of semaphores to meter merging near the upstream and downstream ends of the bottleneck; see again Figure 3.1(a).

Intermittently shared lanes would likely require greater investments in infrastructure. For example, to restrain cars from entering the shared lane at suitable times, the system would rely on estimates of bus arrival times (e.g., using on-board GPS) and the durations required to flush the shared lane of its car queue (e.g., based upon real-time measurements of the congested flow downstream). Car entries might be restrained via changeable message signs and traffic signals. Or, automated mast arms and even police presence might be required to ensure driver compliance.

Compliance is an important issue. It would influence not only the required levels of investment in technologies, but also the very efficacy of the ideas. The matter is therefore discussed further in Chapter 6.



(a)



(b)

Figure 5.7. Average delay savings on Route 2 ( $q_b=12, 20$  buses/hour) (a)Using Aim-sun ; and (b) Using Cell Transmission Model



# Chapter 6

## Conclusions

This section presents a summary of the major findings of this dissertation and provides thoughts on possible future research directions.

### 6.1 Dissertation Findings

This dissertation has presented ideas for providing priority travel to buses while limiting any resulting damage to car traffic. The treatments are deployed only at key capacity constrained locations, called critical bottlenecks, which limits both the costs of deployment and the complexities of operation. Specific details depend in part on the bottleneck's local operating conditions, but all treatment options seek to seamlessly insert cars between buses to minimize waste of bottleneck capacity. The models indicate that the treatments can produce higher car-carrying capacities for wide ranges of bus demand. This thesis also looks at applying these theoretical ideas to real transportation networks. An exact recipe for implementing shared lanes at a case study location in Amman, Jordan was designed. Simulation analyses conducted on this case study site unveiled the benefits of these strategies in terms of delay savings to cars.

This dissertation has shown that even if low bus flows are expected, which often arises in developing areas with limited public transportation service, it is possible to provide priority to buses without imparting large disbenefits to cars. These strategies can be implemented with very little additional infrastructure investment. However the effectiveness of the strategies depend on driver compliance. Lack of driver compliance not only could deem these strategies infeasible, but could also lead to concerns about the safety of their operation. Drivers changing lanes where they should not, or not yielding for buses at the shared lane entrance points could lead to confusion, or even crashes. However, Currie & Lai (2008) reported that during the field experiments conducted for intermittent lanes in Melbourne, Australia no increase in accidents was observed. While reporting some initial confusion among drivers in the field experiment of intermittent lanes in Shizuoka, Japan, Sakamoto *et al.* (2007) stated that the drivers were behaving as expected by the end of the experiment (which

lasted 5 days). The authors also reported that as a result of a survey conducted on residents who live close to field experiment site, the dissatisfaction rate was only 10%. The findings of these two field experiments that test ideas similar to those presented here give the author hope that the proposed ideas could be made to work without increasing the number of accidents and with high public acceptance rates. Therefore, the author believes that these strategies can help improve the political feasibility of bus rapid transit systems in many urban environments.

## 6.2 Future Research Directions

There are several assumptions made in this dissertation which could be relaxed in the future to provide more accurate insights into the use of shared lanes. These assumptions will be explained and proposals for relaxing them will be presented in the following sections.

### 6.2.1 Perfect Driver Compliance

All of the models and analyses assume that drivers perfectly comply with the regulations required for sharing lanes. Thus, the outcomes presented here may be viewed as upper bounds on what the shared-lane treatments can achieve. In cities characterized by undisciplined drivers, compliance might be achieved through coercion; e.g., signals might be augmented with retractable mast arms, enforcement could be stringent and fines for violations steep. It is therefore suspected that the ideas could be made to work in most any city. Still, verification of this conjecture is sorely needed.

This could come via field experiments. It might suffice, at least initially, to conduct these experiments on small portions of networks, like the portion analyzed via simulation in the case study. Lessons learned might dictate that the treatments be modified or that the prescribed domains of application be scaled downward. In any event, success in small-scale tests might be leveraged to eventually realize broader, city-scale deployments. Appendix A presents an example of how these ideas could be tested in the field without permanent changes to the roadway, including the minimum amount of data that needs to be collected. In this way, the benefits of these strategies could be verified before investing in costly infrastructure.

The author remains hopeful that cities can be found where decision-makers are amenable to field tests of the proposed ideas. The world's rapid urbanization and the attendant problems of congestion dictate that these ideas and others like them receive a chance to succeed.

### 6.2.2 Merging

This work assumes that the percentage of capacity retained after cars merge into one less lane with shared-lanes is unknown, and this value is used as a parameter ( $\alpha$ ) in the determination of the domains of application in Section 4. However there is need

to estimate realistic values for this input. While a site specific value for  $\alpha$  can be estimated through field experiments, theoretical merging models currently present in the literature can also be used to determine a feasible range for this parameter. One such approach can be found in Leclercq *et al.* (2012) which estimates the capacity drop at merges. Even if the actual value for  $\alpha$  cannot be estimated, a tighter bound on the value can be determined, which would lead to tighter domains of application of shared lanes.

### 6.2.3 Transit Signal Priority at Signalized Intersections

The current work assumes that buses are not provided additional priority at signalized intersections above that provided by shared lanes (with or without pre-signals). However, the addition of priority schemes (such as active transit signal priority) could significantly change the analysis. Along with improving average bus speeds, TSP could also benefit cars traveling in the same direction as the bus since they will be mixed with buses. A detailed analysis could determine how the addition of TSP can affect both shared lanes and ordinary bus conversion strategies, and if it would lead to a larger or smaller domain of application of shared lanes.

Also, in some cases providing transit signal priority could negatively affect the operation of the pre-signal since coordination is necessary between the pre-signal and the main signal to ensure that green time for cars is not wasted at the main signal. This would require constraints in the operation of the main signal which ensures that while providing priority to the bus, the car operation is not made worst off. Ideas from Christofa & Skabardonis (2011); Xuan *et al.* (2011) can be used and synthesized to develop such transit signal priority strategies at consecutive signals that minimize the negative effects on cars.

### 6.2.4 Demand

The analysis assumes that the demand for buses and cars is fixed. However, especially with the improvement in the bus service, mode shifts from cars to buses are likely to occur. This could lead to reduced car congestion, which would result in lower car delays. However, the higher bus demands might lead to more frequent bus service. If these effects are included, the domains of application of shared bus lanes could be much different than predicted in this paper. An algorithm to systematically analyze these conflicting effects could make the results of this dissertation more accurate.

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# Appendix A

## Future Work: Description of Field Experiments

Here an overview of field tests that can be conducted on the case study site are presented. The goal of this appendix is to provide readers with ideas on how shared lanes can be tested in simple and relatively inexpensive ways without posing risks to travelers. These experiments would enable quantification of the effectiveness of the proposed strategies in real settings. This knowledge could then guide decision-makers in their ultimate choices of bus-lane design.

How experiments could be carried on Route 1 is described first. The experimental design for Route 2 is described thereafter. The experiments could be conducted for both routes simultaneously. Or, the tests could be separately conducted for each route on separate days. In either case, experiments for each route would ideally be performed over multiple days during the peak hours. A single bus (or similarly large vehicle) would be needed for these experiments. This vehicle would cycle through the test site at 5-minute headways.

### A.1 Route 1

The car demand is highest for this route during the afternoon rush from 5:00 to 6:00 pm, meaning that experiments should be conducted during periods that span this hour. Traffic cones could be used at the locations shown in Figure A.1(a) to emulate the presence of an exclusive bus lane on the southbound approach to junction II. The physical length of this faux bus-lane could be relatively small; 300 ft or so would suffice. Only the bus would be permitted entry into this faux lane (at its upstream end). Entry could be controlled by means of a mast arm, perhaps operated by the bus driver via an on-board remote or manually by a police officer.

Traffic cones starting a short distance (100 ft or so) downstream of location A would be used along the length of the intermittent bus lane to separate it from adjacent car lanes. The cones would continue until location B, for a distance of approximately 1200 feet. The periodic prohibition for cars at location A could be



emulated with the aid of a police officer. Whenever the officer sees an approaching southbound bus, the officer would stop cars from entering the median lane until the end of the next green for southbound left turning cars<sup>1</sup>. Once the bus enters the intermittent bus lane, the police officer would allow left turning cars (only) to follow behind the bus. Signage designating the intermittent lane for left turning cars only would be required; and the control enacted by the police officer could easily be automated if the strategy were to be adopted permanently.

The resumption of the exclusive bus lane downstream of junction I in the east-bound direction would again be emulated with the use of traffic cones. This faux bus lane would be started a short distance downstream of the junction I, at a distance of approximately 200 feet, and continue for a nominal distance of 300 ft or so. Once again, only the bus would be permitted entry into this faux lane (at its upstream end), perhaps via a mast arm and an on-board remote.

### **A.1.1 Data to be Collected During the Experiment**

The queue discharge flows of southbound cars at both junction I and junction II would be collected using video cameras. The sampled discharge rates would be compared against those that presently occur at the junctions in the absence of any bus priority strategies. Again, it is expected that these comparisons will unveil only small differences. It would also be useful to measure the discharge rates at both locations- at least for a few cycles - that occur when the median lane is completely closed; again to verify the damage that would be done to cars by extending the bus lane over the entire westbound approach.

An observer on-board the bus will measure the time it takes to travel from the downstream end of the faux bus lane to junction I during each trip to verify that only modest bus delays would arise from these strategies.

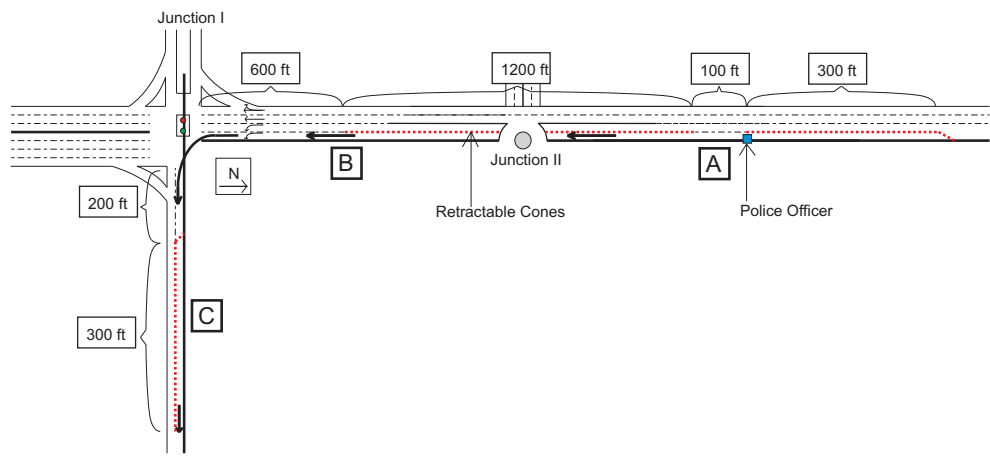
## **A.2 Route2**

The car demand is highest for this route during the morning rush from 7:30 to 8:30 am. Thus, experiments for this route would occur during these times (and possibly others). Traffic cones could be used at the locations shown in Figure A.1(b) to emulate the presence of a static bus lane on the westbound approach to junction I. The physical length of this faux bus lane and its other features could be as described in Section A.1.

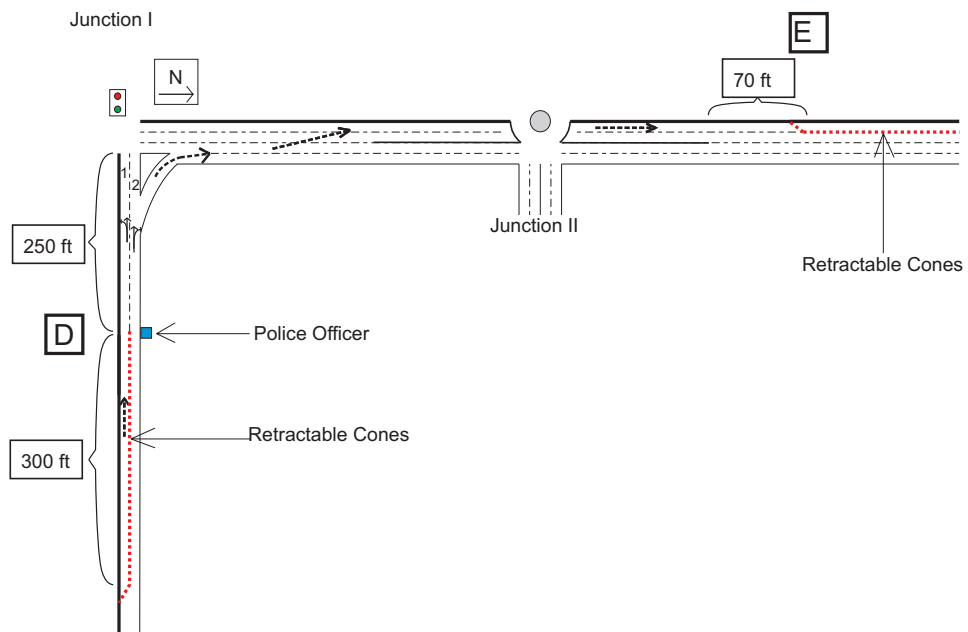
The pre-signal at location D in Figure A.1(b) could be emulated with the aid of a police officer. The bus driver would voluntarily halt upon arriving to that location (via the faux bus lane). In the presence of the stopped bus, the police officer would wait for the traffic signal at junction I to turn green for westbound traffic. The officer

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<sup>1</sup>This is approximately how long it will take for the car queue in the intermittent lane to clear



(a)



(b)

Figure A.1. Field experiment design for the Amman network: (a) Route 1; and (b) Route 2.

would then instruct the cars stuck in the upstream portion of the queue to remain stopped - but just long enough to allow the bus to move forward undisturbed.

### **A.2.1 Data to be Collected During the Experiment**

The queue discharge flows of westbound cars at junction I could be collected using video cameras. (Car delays for any demand levels can be assessed once these discharge rates are field-estimated). The sampled discharge rates would be compared against those that presently occur at junction I in the absence of any bus priority strategies. It is expected that these comparisons will unveil only small differences. It would also be useful to measure the westbound discharge rates - at least for a few cycles - that occur when the median lane is closed at junction I. This would verify the extreme damage that would be done to cars by extending the bus lane over the entire westbound approach.

Finally, an observer on-board the bus (possibly the driver) would measure the time required for the bus to travel from the pre-signal to junction I during each trip. It is expected that these data will confirm that the proposed strategy of using a pre-signal will impart only modest delays to buses.

Videos would also be taken of queued cars to estimate both: i) the speed of kinematic waves that travel through car queues; and ii) the jam density of stopped cars. These estimates would further assist in predicting the physical extents of car queues once some lanes have been given over to buses.