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Publication Date
2010-05-01

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WORKING PAPER
UCB-ITS-VWP-2010-2

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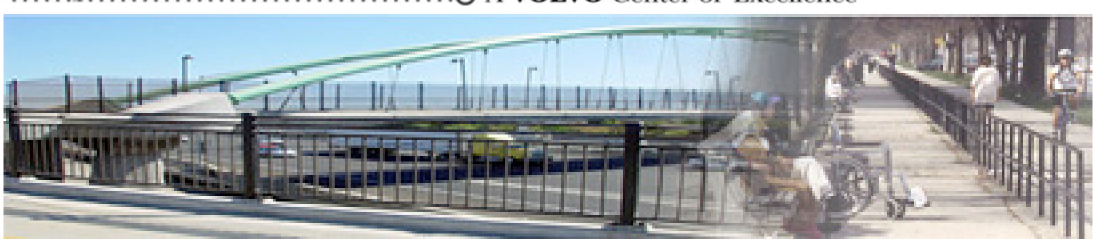

May 2010

Deploying Underutilized Bus Lanes at Key Nodes in a Road Network

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1 Introduction

Bus transport is an important tool to combat urban traffic congestion. However, the operation of buses in mixed traffic flow can be impeded by congestion, leading to unreliable and slow service. Moreover, buses that frequently stop to serve passengers can also interfere with the flow of general traffic (cars). The result of these cross-modal conflicts is reduced capacity for all vehicles. To address these issues, planners have used dedicated bus lanes to segregate buses from general traffic. These dedicated lanes provide a means for buses to bypass car queues, thereby increasing bus speeds and potentially decreasing the total person hours travelled (PHT) since buses typically carry more occupants than do cars. In cases where bus flow is low, converting a general purpose (car) lane to a bus use only lane can increase the queuing and delays to car traffic as well as the total vehicle hours travelled (VHT), since cars now discharge from one less lane, even when the bus lane is unoccupied. Additionally, the implementation of an underutilized dedicated (e.g. bus) lane leaves less queue storage space for car traffic. This will cause car queues to expand faster and longer. If an expanded queue impedes traffic at busy upstream junctions, total VHT will further increase.

The final report will explore innovative schemes for deploying bus lanes to serve low bus demand. The innovations will be deployed at key points (nodes) in a network that are either bottlenecks or that are engulfed in queues from downstream bottlenecks. Figure 1 shows a simple network with two major nodes in series and minor ingress/egress points on the intervening link. In the present work, this system will be viewed as the simplest "building block" of a road network. Strategies to deploy underutilized bus lanes will be systematically examined for this building block over a range of conditions, e.g., where the two nodes take a variety of geometries (including lane drops, curves and signalized intersections) and where either the upstream or downstream node is an active bottleneck[1]. The strategies will be developed analytically and tested through field experiments to be performed in Amman, Jordan. The extent to which the findings for the building block can be scaled up to represent a large scale, city-wide network will then be explored. The final report will include guidelines for deploying underutilized bus lanes that reduce or eliminate bus delays while minimizing the additional delay imparted to cars.

[1] An active bottleneck is characterized by a queue upstream and free flow conditions downstream (Daganzo 1997).

Section 2 reviews the literature relating to dedicated (HOV and bus only) lanes. Section 3 presents the research goals. Section 4 presents organizing principles for the analysis. Section 5 introduces the case studies located in Amman, Jordan. Section 6 discusses the field experiments to be performed at the case study locations.

2 Literature Review

Studies on underutilized high occupancy vehicle (HOV) lanes on freeways can be used to gain insights into the performance of underutilized bus lanes. Therefore, Section 2.1 will focus on the literature on HOV lanes and the impacts of implementing an underutilized HOV lane. In Section 2.2, the literature on one potential solution to underutilized bus lanes, intermittent bus lanes, will be discussed. Implications of these past findings on the current research are discussed in Section 2.3.

2.1 Implications of Dedicated HOV Lanes on General Traffic

A number of studies (e.g. Dahlgren 1998; Chen, et. al., 2005; Kwon et. al. 2008) have reported that underutilized HOV lanes cause increased delays to general non-HOV traffic. However, more recent research has shown that in many situations this may not be the case. Menendez and Daganzo (2006) theoretically predicted that an HOV lane can increase the capacities of the adjacent general traffic lanes. The authors referred to this phenomenon as the "smoothing effect" and attributed the effect to diminished vehicular lane-changing maneuvers in the general traffic lanes. Cassidy, Jang and Daganzo (2009) used empirical data from a freeway HOV lane facility to confirm that the smoothing effect exists in real traffic, and showed that diminished HOV lane flows can be compensated by increased capacities in adjacent general traffic lanes. Using queuing analysis this work concluded that even for underutilized HOV lanes it is possible to reduce both the total PHT and the VHT due to the smoothing effect.

Daganzo et. al. (2002) described how dynamic HOV lanes can be deployed at bottlenecks to increase discharge flows. To this end, a static HOV lane is terminated upstream of the bottleneck and replaced by an intermittent HOV lane that runs through the bottleneck. As long as the length of the queue in the static HOV lane does not exceed a certain length, the intermittent section is designated as a general traffic lane so that all vehicles can use it. Whenever the HOV queue exceeds the maximum length, the intermittent section is designated as "HOV only" for a period that is just long enough to discharge the queue of HOV's. With this strategy, the full capacity of the bottleneck is utilized as long as queues persist in the HOV lane.

Daganzo and Cassidy (2008) focused on long, multi-ramp freeways to analyze the queue expansions caused by underutilized HOV lanes that do not run through bottlenecks. Analysis was done to investigate the effects of expanded queues that spillover to upstream ramps. The authors concluded that even in cases when queue storage space is insufficient, implementing an underutilized HOV lane will typically only marginally increase the total VHT.

2.2 Bus Lanes

Bus lanes have been studied as early as 1973 (Levinson et. al.). Yet theoretical analysis of the roadway capacity that results from reserving a lane for buses, and solutions to underutilized bus lanes are fairly recent additions to the literature.

Cassidy, Daganzo and Jang (2009) theorized 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.

Viegas and Lu (2001, 2004) proposed Intermittent Bus Lanes (IBL) for the case of low bus demand. These operate in ways similar to dynamic HOV lanes, but are deployed on signalized arterials. The authors concluded that the use of IBLs can reduce the delays of buses while imposing only marginal extra delays on car traffic. IBLs were implemented in Lisbon, Portugal for a 6 month period in 2005 and 2006 and reportedly increased the speed of buses by 15 to 25% without significant penalty to general traffic.

Eichler and Daganzo (2005) built on the above idea and proposed Bus Lanes with Intermittent Priority (BLIP) on signalized arterials. In this strategy, one or more blocks downstream of a bus's 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 can use the intermittent lane to increase their 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 traffic density, which in congested traffic corresponds to lower speed and increased delays, as compared to using no bus lane.

While both of the prior studies focused on signalized arterials, neither study accounted for bus turning maneuvers at the intersections. Wu and Hounsell (1998) discussed how to use bus lanes and still accommodate turning buses at a signalized intersection by introducing an additional signal (called a pre-signal) upstream of the intersection. The pre-signal stops general traffic as a bus approaches the junction, allowing the bus to move into the correct lane for its turning maneuver with no conflict from other vehicles. Pre-signals have been successfully applied in London since 1993 (Transport for London, 2005), however current applications of pre-signals are limited to the accommodation of right turning bus maneuvers.

2.3 Summary of the Literature and Implications

Prior studies have shown that dedicating lanes to specific modes reduces interactions between vehicles, even in cases when the vehicles that are separated have the same physical characteristics (as is the case for HOV lanes). It is plausible that this effect will be even more pronounced when the modes being separated have different operating characteristics (as is the case for buses and cars). The ideas presented for dynamic HOV lanes can be applied to underutilized bus lanes to maximize car flows. When implementing bus lanes, it will be important to consider the potentially harmful effects of queue expansions due to the reduction in queue storage space for general traffic.

Although ideas for intermittent bus lanes have been proposed and field tested, these strategies focus solely on signalized intersections and ignore the application of underutilized bus lanes on unsignalized roadways such as expressways. The strategies also do not consider the possibility of 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, systematic study of pre-signals for all possible bus-car conflicts is absent from the literature.

3 Research Goals

The aim of this report is to systematically explore ideas for setting aside travel lanes to serve low bus demand in dedicated fashion; to do so initially for the basic building block in Figure 1, and then to explore how the ideas might be scaled-up to a city-wide road networks. This work will consider only bus priority strategies which impose little to no delay on bus traffic.

The general idea to be explored is to discontinue the bus lane near a node and replace it with either a mixed-use or intermittent bus lane. In this way all lanes will be available for car use when a bus is not present at the node. However, when a bus approaches the node, the bus will be given priority over cars. Additional traffic signals (including, but not limited to, pre-signals) can be used to resolve conflicting movements and ensure bus priority. Strategies that reduce or eliminate bus delays will then be compared to a run through lane to determine the one that will minimize total car delay. Further analysis will focus on the tradeoffs between imparting some (small) bus delay with the aim of reducing car delays. The theoretical analysis of the building block will be used to scale-up the treatments developed for city-wide implementations of underutilized bus lanes.

The local building block strategies will be tailored to specific conditions at locations in Amman, Jordan, where field experiments will be performed to confirm the effectiveness of the strategies. The knowledge obtained from the field experiments can yield insights for applying the generic strategies to other real-world locations.

4 Organizing Principles

The output flow from a node depends both on the physical properties of the node itself, and on any potential capacity constraints from downstream. Therefore, a basic building block for modeling road networks will be taken as two major nodes (locations on a roadway that present a capacity constraint) in series connected by a link with perhaps, minor access points, as shown in Figure 1. Once the impacts of the proposed strategies are understood for the building block, perhaps the building block can be tessellated to represent road networks of varying size and complexity.

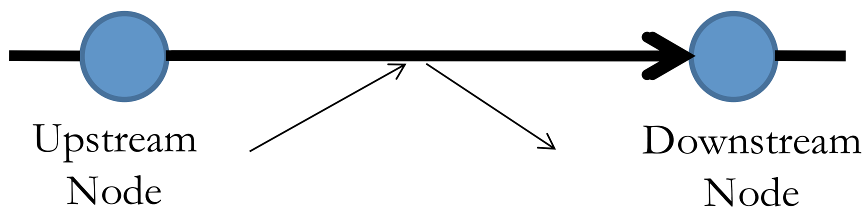

Figure 1. Basic Building Block

For a systematic analysis of the basic building block, the work will explore two cases that describe how vehicles move through the upstream node when traffic queues exist in its vicinity[2]. These two cases focus on the upstream node, and present a comprehensive list of the conditions under which converting a lane for the exclusive use of buses may eliminate bus delay for the building block. The cases are listed as follows:

Case I: Upstream node is an active bottleneck; and

Case II: Flow through the upstream node is restricted by a capacity constraint from the downstream node.

Three sets of strategies for prioritizing buses at the upstream node will be explored for the above cases. These strategies will be compared for each case, and each strategy's range of applicability (i.e. range of bus demand) will be determined. The prioritization strategies are as follows:

Strategy 1: Run through bus lane, in which a lane is reserved for buses throughout the node;

Strategies of Type 2: A set of innovative strategies to be used at the upstream node when the building block is an expressway. Two sub strategies will be used. Strategy 2.1, mixed-use lane, will be used in Case I and Strategy 2.2, intermittent lane, will be used in Case II as will be further explained; and

Strategies of Type 3: A set of innovative strategies to be used when the upstream node is a signalized intersection. For Case I, two different strategies will be considered. Strategy 3.1a involves the use of mixed-use lanes and is applied for cases when the bus does not conflict with other traffic while Strategy 3.1b entails the use of a pre-signal for those cases when the bus conflicts with other traffic. Strategy 3.2 will be used for Case II, and will build on Strategies 3.1a and 3.1b.

For the remainder of this section, the upstream node of length ℓ will be visualized as shown in Figure 2. Let x_i denote the location on the roadway section. Location x_1 is near the point where the permanent bus lane is discontinued upstream of the node; x_2 is the entrance to the

[2] When there is no queuing at the node, there is no need for a bus lane.

node; x_3 is the node's exit; and x_4 is the location immediately after the permanent bus lane is re-introduced downstream of the node. The roadway upstream of location x_1 and downstream of location x_4 is assumed to be homogeneous, and have L number of lanes, each of capacity c [vehicles/hour/lane]. The node itself (between location x_2 and x_3) is assumed to have L_n number of lanes, each of capacity c_n [vehicles/hour/lane] (where $c_n \leq c$ and $L_n \leq L$). A reduced capacity at the node can occur for many reasons, including a lane drop, a curved or uphill section of the expressway, a traffic signal etc.[3]. Lanes are numbered 1 through 4 as shown in Figure 2.

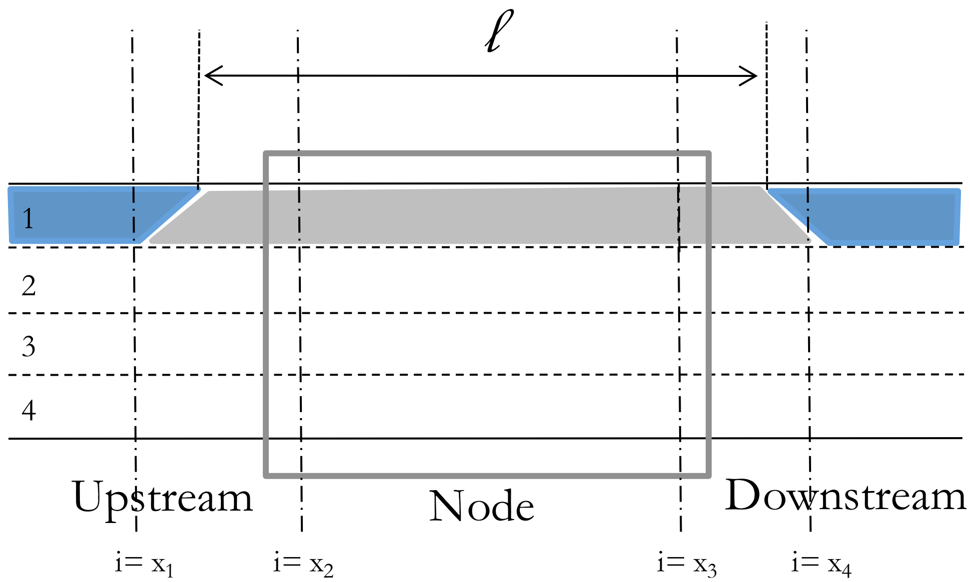

Figure 2. Geometry of the Upstream Node

Analysis will estimate and compare the queue discharge flows (i.e. capacities) across all lanes at locations x_1 through x_4, denoted $Q(x_i)$. The flow of buses, q_b [buses/hour] (assuming a car equivalence of a bus is p ≅ 2.5), will be used to determined different bounds on the applicability of the different bus priority strategies.

For each priority strategy, the flow that would discharge from the node will be determined. The resulting delays to general traffic will be estimated using queuing theory, and the queue expansions will be estimated as in Daganzo and Cassidy (2008).

Section 4.1 will focus on Case I (when the upstream node is an active bottleneck and the building block is an expressway), and Section 4.2 will focus on Case II (when the upstream node is constrained from downstream and again is an expressway). Section 4.3 will introduce some ideas when the upstream node is a signalized intersection for both Cases I and II.

[3] Initially the smoothing effect will be ignored and per lane capacity at the node will be assumed to remain constant, independent of the bus lane strategy to be used.

4.1 Building Block is an Expressway – Case I

Consider a flow approaching the upstream node of d [vehicles/hour], the upstream node will be an active bottleneck when:

$$d > c_n \times L_n$$

In this case, a run through bus lane (Strategy 1) will result in a limiting capacity at location x_2. Thus,

$$Q(x_2) = c_n \times (L_n - 1) + q_b \times p \tag{1}$$

To increase this output flow, a mixed-use bus lane (Strategy 2.1) will be considered[4]. In this strategy, the permanent bus lane will be discontinued some distance upstream and downstream of the node and a mixed-use lane (for both cars and buses) will replace it through the node as shown by the lightly shaded region in Figure 1. The length of the mixed-use lane is denoted as ℓ. Whenever a bus is not present, cars can use all L_n lanes to discharge through the node. When a bus approaches the node, the flow of cars on lane 2 will be stopped with the use of a signal at location x_3. Cars discharging from lane 1 during this period will do so at free flow speed, v_f, without encountering any conflict from cars in lane 2. The bus that approaches the node in its dedicated lane will then mix with cars in lane 1 for a distance ℓ. Therefore, the bus can also pass through the bottleneck at its free flow speed, and experience no delay. Once the bus has re-entered the permanent bus lane downstream of the node, the signal at location x_3 will turn green to allow vehicles in lane 2 to discharge through the node again. The queue discharge flows at each location x_i for this case are:

$$Q(x_1) = Q(x_4) = c \times (L - 1) + q_b \times p$$

$$Q(x_2) = c_n \times L_n$$

$$Q(x_3) = c_n \times (L_n - R)$$

where R is the fraction of time that lane 2 has a red signal at location x_3, and can be expressed as:

$$R = \frac{\ell \times q_b}{v_f}$$

The values of $Q(x_2)$ and $Q(x_3)$ include the flow of buses since buses and cars are mixed in the median lane at the node.

[4] An intermittent bus lane strategy is not chosen because of the queue storage benefits of a mixed-use bus lane as will be explained in Section 4.2

In order for the proposed strategies to succeed, the head of the queue should reside at location x_3, which will occur if $Q(x_3)$ is smaller than $Q(x_1)$. This will only be true if the following inequality holds (i.e., the node will remain an active bottleneck).

$$q_b > \frac{c_n \times L_n - c \times (L-1)}{p + \frac{\ell \times c_n}{v_f}} \tag{2}$$

In cases where condition (2) holds, the discharge flow that can be achieved through the node is:

$$\min\{Q(x_1), Q(x_2), Q(x_3)\} = Q(x_3) \tag{3}$$

Since in the latter case queuing begins upstream of location x_3, the entire length of the bottleneck can be used for queue storage purposes and the probability of a queue spillover to an upstream location will be reduced compared to the run through bus lane scenario (where queuing will begin at location x_2).

The bus demand necessary to ensure that the mixed-use bus lane strategy achieves higher discharge flows through the bottleneck than does a run through bus lane is determined by comparing (1) and (3):

$$(3) > (1)$$

$$c_n \times (L_n - R) > c_n \times (L_n - 1) + q_b \times p$$

$$q_b < \frac{c_n}{p + \frac{\ell \times c_n}{v_f}}$$

The range of bus flows for which the mixed-use bus lane is superior to a run through bus lane is therefore:

$$\frac{c_n \times L_n - c \times (L-1)}{p + \frac{\ell \times c_n}{v_f}} < q_b < \frac{c_n}{p + \frac{\ell \times c_n}{v_f}}$$

Under these conditions, the mixed-use lane will promote higher discharge flows for cars and provide the additional queue storage space of length ℓ, while ensuring that there is no bus delay.

4.2 Building Block is an Expressway – Case II

Here the case where flow from the upstream node is constrained by a queue from downstream is examined. The output flow per lane from the node is therefore equal to some downstream queued flow, q_d [vehicles/hour/lane] (where $q_d < c$) .

In this case, the problem that may arise when implementing a run through bus lane at the upstream node is that the node can potentially become a more restrictive bottleneck and starve the downstream node of flow. The queue discharge flows from each location x_i when a run through bus lane is present are:

$$Q(x_1) = c \times (L - 1) + q_b \times p$$

$$Q(x_2) = Q(x_3) = c_n \times (L_n - 1) + q_b \times p$$

$$Q(x_4) = q_d \times (L - 1) + q_b \times p$$

If the minimum of the above is $Q(x_4)$ (as opposed to $Q(x_3)$) , then a run through lane at the node will not starve the downstream bottleneck of flow. Therefore, the output flow of cars from the node will be the same as the capacity of the downstream bottleneck:

$$q_d \times (L - 1) + q_b \times p \quad (4)$$

This output flow will only be achieved when the restricted flow from the downstream bottleneck meets the following condition:

$$q_d < \frac{c_n \times (L_n - 1)}{(L - 1)} \quad (5)$$

However, if (5) does not hold, the upstream node will become an active bottleneck with a lower discharge flow than the downstream bottleneck, effectively starving it. In this case, the queue discharge flow that can be achieved through the upstream node is:

$$c_n \times (L_n - 1) + q_b \times p \quad (6)$$

To increase this output flow and not starve the downstream bottleneck, the bus lane can be discontinued upstream and downstream of the node and an intermittent bus lane can be implemented on the intervening segment of length ℓ (See Figure 2). A mixed-use bus lane as described in Section 4.1 is not suitable in this case, since the node's output flow is constrained, vehicles cannot discharge from lane 1 at free flow speed. When an intermittent bus lane is implemented, whenever a bus is not present, cars can use all L_n lanes to discharge from the node. A certain time before the bus arrives at the node, cars will be banned from entering lane 1 at location x_2. Additionally, no lane changing will be allowed between lanes 1 and 2 over the stretch of x_1 to x_4 during this time period. The aim is to clear lane 1 of cars as the bus arrives at the node, allowing the bus to pass through at free flow speed. The duration of the intermittent application can be set to achieve this aim (and impart no delay to the bus), while wasting no capacity in lane 1. Immediately after the bus enters the intermittent lane, cars will be allowed to re-enter lane 1. The queue discharge flows at each location x_i for the intermittent bus lane case are:

$$Q(x_1) = c \times (L - 1) + q_b \times p$$

$$Q(x_2) = c_n \times (L_n - R) + q_b \times p$$

$$Q(x_3) = c_n \times L_n$$

$$Q(x_4) = q_d \times (L - 1) + q_b \times p$$

where R is the fraction of time that cars are banned from entering lane 1 from location x_2.

The time required for lane 1 to empty itself of cars can be found using kinematic wave theory. Assuming a density of d_d for a constrained flow of q_d, R can be calculated as:

$$R = \frac{\ell \times d_d \times q_b}{q_d}$$

Note when determining $Q(x_2)$, since the bus enters the node while cars are banned from entering lane 1, the flow of buses has to be added to the flow of cars. However at location x_3, since there is always output flow from lane 1 and cars follow the bus, the flow of buses is included in $Q(x_3)$.

The maximum flow that can be achieved through the node is:

$$min\{Q(x_2), Q(x_4)\}$$

When $Q(x_4)$ is the minimum, the node is no longer an active bottleneck and the downstream bottleneck will not be starved of flow. When $Q(x_2)$ is the minimum, the upstream node will still starve the downstream bottleneck, but the flow of cars through the downstream bottleneck will be increased by $c_n \times (1 - R)$ as compared to a run through bus lane[5].

Since the benefit is a function of R, additional capacity can be achieved using a value of R that does not allow the intermittent lane portion to completely clear of cars upon the arrival of a bus. This will result in some delay to the bus since it must wait for cars to clear before it can proceed to the downstream bus lane. A future step in this analysis will be to explore the tradeoff between car and bus delays as R is changed. R can be decreased, imparting some delay to buses, but increasing flow from the total system in cases when the upstream node starves the downstream bottleneck; or to limit the growth of queues so that egress points on the intermediate link are not blocked (hence delay imparted to cars bound for the egress point is reduced while no extra delays are imposed on cars bound for the downstream node).

4.3 Upstream Node is a Signalized Intersection – Preliminary Analysis

This section provides a framework for analysis when the upstream node is an isolated signalized intersection (i.e. unaffected by nearby intersections).

[5] When the node is an active bottleneck as in Section 4.1, the minimum flow will occur at location x_2, and the queue storage space of the node cannot be used. Therefore a mixed-use lane has queue storage benefits.

Since at a signalized intersection multiple approaches can serve the same destination, the analysis will differ slightly from before. The total queue discharge flow through location x_2 in Figure 2 will be the sum of all the approaches that have the same destination as the bus. This value will be compared to the total queue discharge flow through location x_3, where x_3 is the approach to which the bus is destined. By comparing these two flows, the actual output flow through the node can be determined. These flows for Strategy 1 will be compared against those for the set of Strategies 3.

Two different sub-strategies will be used when the upstream node is an active bottleneck, since the implementation of a bus lane at a signalized intersection depends both on the specific movement that the bus makes at the intersection (through, right or left turn) and the signal phasing (i.e. left turns are permitted or protected). These two sub-strategies will be explained below. All combinations of possible signal plans and bus movements, and the sub-strategy to be applied for each combination can be seen in Table 1. Strategy 3.1a is applied to cases where the bus movement will not conflict with the movement of other vehicles at the intersection. Strategy 3.1b is applied to cases where the opposite is true.

Table 1. Combinations of Bus Movements and Left Turn Phases and the Strategy Used

Left Turn Phase	Bus Movement		
	Left Turn	Through	Right Turn
Permitted	Strategy 3.1b	Strategy 3.1b	Strategy 3.1b
Protected	Strategy 3.1a	Strategy 3.1b	Strategy 3.1b

4.3.1 Strategy 3.1a

When the bus movement is not in conflict with the movements of other vehicles, specifically for the case of a left-turning bus when (*i*) there is a protected left-turn phase, and (*ii*) the intersection is an active bottleneck, a mixed-use lane can be deployed there. As before, the permanent dedicated lane will be discontinued upstream and downstream of the bottleneck and the "opened" lane segments will be designated for mixed-use by all vehicles making a left turn. Upon exiting their permanent lane, left-turning buses will mix with left-turning car traffic to discharge through the intersection. Cars will use all left turning lanes (including the mixed-use lane) but will discharge into separate receiving lanes from the buses (See Figure 5b). This will eliminate merging conflicts at the location where the mixed-use lane ends and the permanent bus lane begins downstream.

This strategy does not eliminate delays for buses since a bus can arrive to the intersection at the beginning of the red phase and will have to wait for an entire cycle. However, this strategy will provide additional left turning capacity (and less delay) for cars compared to using a run through bus lane.

For certain lane configurations at the intersection, other movements discharging into the median lane may experience delays at the location where the permanent bus lane begins downstream (See again Figure 5b). Thus while this strategy will eliminate delays for cars making the same left turning movement as buses, the delays of other movements will need to be considered. This strategy will be illustrated in greater detail in Section 5.2.2.

4.3.2 Strategy 3.1b

When the bus movement conflicts with the movements of other vehicles, a pre-signal can be installed upstream of the junction to allow buses to move to the front of the car queue. For the sake of simplicity, it will initially be assumed that the geometry at the intersection is homogeneous (i.e. on each approach the number of lanes at the intersection is equal to the number of lanes upstream).

Several issues regarding these pre-signals will be addressed. When buses must make a left turn during a permitted phase, it will be advantageous to allow the bus to jump to the front of the queue so that they may proceed through the first suitable gap in opposing traffic. However, when the previous cycle's queue does not fully discharge (resulting in a residual car queue) the bus will be unable to move to the front of the queue and will experience additional delay. A comprehensive list of these problems and their solutions (including solutions involving signal designs) will be enumerated in the final report.

4.4 Modeling Large-Scale Networks

In the final report, the comprehensive knowledge obtained about a single building block will be used to analyze how to join these building blocks into larger networks. The idea of scaling up the knowledge from a building block to a macroscopic network was done by Daganzo (2008). Similar ideas will be explored for modeling networks with bus lanes.

5 Case Studies

The city of Amman Jordan plans to convert many kilometers of existing general use lanes (typically median lanes) to bus use only. Bus headways will initially be very low (with headways of several minutes or more). Case studies are drawn from Amman, and field experiments are expected to be performed at these locations.

Site visits along the planned bus lane deployments, preliminary data collection at some locations on these routes, and meetings with Amman officials all occurred in summer 2009. As a result, two sites suitable for testing the proposed ideas have been identified. The geometries of these locations, the specific solutions proposed for each, and some initial analysis will be discussed in this section.

5.1 Expressway Bottleneck – Press Tunnel

The first location is a tunnel on a roadway that operates like an expressway (with high vehicle free flow speeds, and few access and egress points). The existing geometry for this location is shown in Fig 3a and is symmetric for northbound and southbound travel. The three travel lanes approaching the tunnel branch-out into four lanes: two lanes proceed into the tunnel, and the other two connect to an over-pass. The four lanes re-converge into three lanes downstream of the tunnel. The bus lane in each direction will run on the median lane as shown by the shading in the figure.

The site operates under both Cases I and II; sometimes during the rush, the site is an active bottleneck and at other times a downstream queue from a downstream bottleneck (i.e. Sports City Circle) spills over to constrain the tunnel's output flow. The initial analysis described in this report will look at Case I, and thus a mixed-use lane is proposed (intermittent bus lanes can be deployed for those periods when the downstream queue spills over to the site).

5.1.1 The Problem

Reserving one of the tunnel's lanes for bus only (Strategy 1) use would create a very restrictive bottleneck and generate excessive queues and delays for car traffic. Measurements taken during the summer site visits indicate that the tunnel's two lanes (in each direction) furnish a capacity of approximately 3,700 vehicles/hour. Converting one lane for bus use would, of course, diminish this capacity by about one half (to less than 1,900 vehicles/hour). This reduced capacity would be significantly lower than the traffic demand that arises during a rush[6].

5.1.2 Proposed Solution

The above concerns could be remedied by mixed-use lanes (Strategy 2.1) as shown in Fig 3b. Given the site's symmetry, the ideas are illustrated for a single (northbound) travel direction, though these would apply to the other travel direction as well. The strategy will provide more capacity than a run through bus lane and could provide sufficient capacity to serve present day car demands.

[6] For example, traffic counts (collected by Amman officials in April 2007) indicate that during the morning rush, northbound demand for the tunnel is as high as 3,000 vehicles/hour. This high demand (comprised almost entirely of cars) could not be served via a single tunnel lane without creating significant delays, together with long queues that could spill-over and disrupt traffic at other locations.

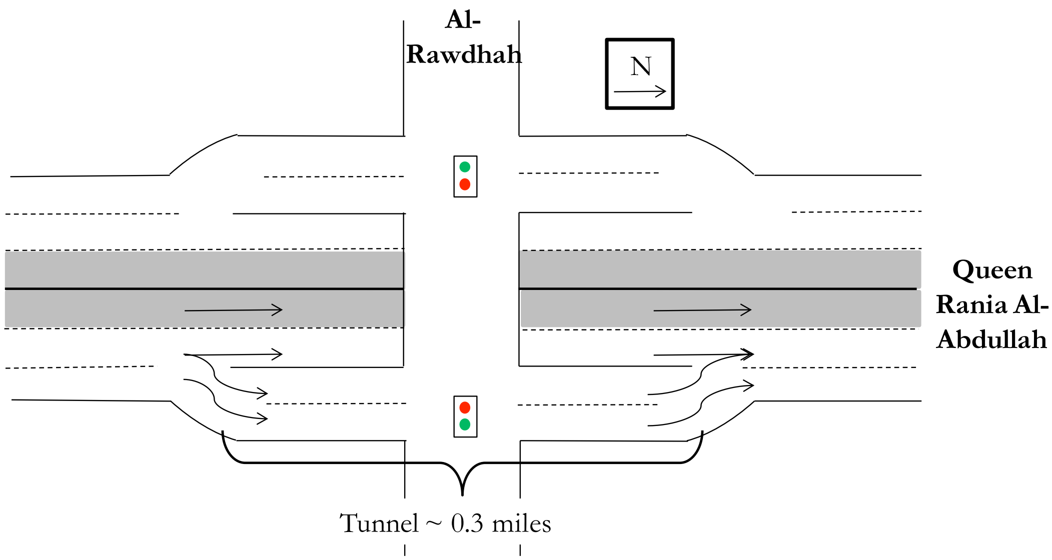

Figure 3a. Geometry of Press Tunnel

The operation would proceed as described in Section 4.1. Immediately prior to each bus arrival at the tunnel, a traffic signal located at the tunnel's downstream end (Location A in the figure) would turn red to stop traffic in the lane adjacent to the median lane. The arriving bus then mixes with cars in the median lane, and the entire stream proceeds through the tunnel with full priority; i.e. without sharing the tunnel's limited downstream capacity with the traffic in the adjacent lane. Thus, the median lane's vehicles (cars and the bus) travel at high speed and high flow. When the bus exits the tunnel, it proceeds directly into the bus lane that is re-introduced downstream; the red signal turns green for the adjacent traffic stream and it too now proceeds forward.

Buses are expected to encounter only minor delays as a consequence of temporarily mixing with cars. Although the operation would periodically reduce the tunnel's car carrying capacity by roughly half, this reduction would persist only for the time required for a bus to traverse the tunnel. Thus, when bus headways are large (several minutes or so), the strategy would result in significantly higher car capacities and lower car delays than for the case of a run through bus lane.

The strategy would require a barrier to separate tunnel lanes so that when forced by the signal (at Location A) to stop, cars in the adjacent lane could not maneuver into the mixed-use median lane and disrupt traffic there. The barrier could be composed of retractable traffic cones so that if the adjacent lane were to be blocked by an incident, queued cars in that lane could slowly cross-over the barrier and not become entrapped in the tunnel.

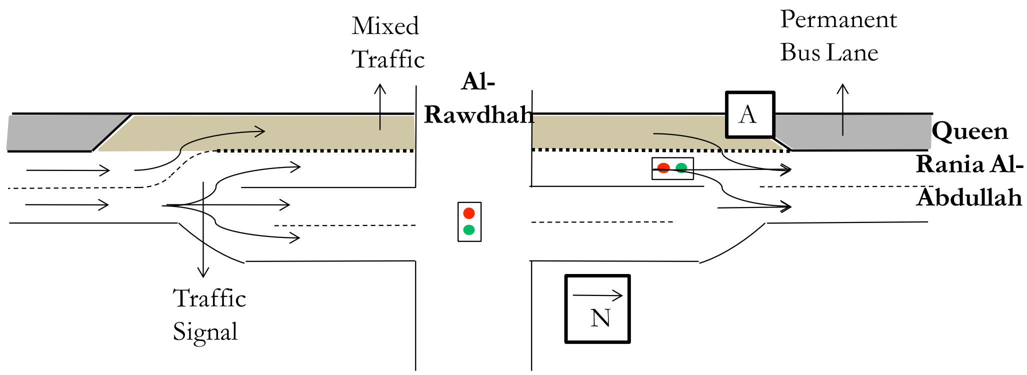

Figure 3b. Proposed Strategies for Active Expressway Bottleneck

5.1.3 Some Preliminary Analysis

The queuing analysis that follows furnishes some preliminary idea of the impacts of the proposed solutions. Analysis was performed for a range of rush-hour demand. After 1 hour, the demand was assumed to drop (to 1,000 vehicles/hour) and remain at this low value. The capacity of the tunnel was taken to be 3,700 vehicles/hour for those periods when both lanes served traffic, and was reduced by half during those brief periods when a bus traversed the tunnel. A bus was assumed to arrive at the tunnel every 2 minutes, and predicted outcomes turn out to be fairly insensitive to small changes in the choice of bus headway.

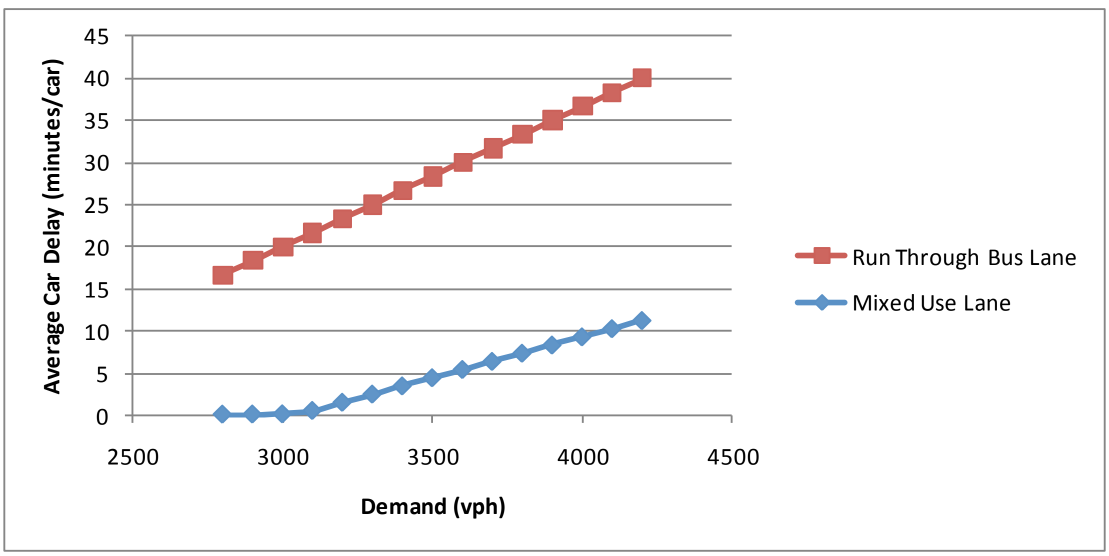

Figure 4. Analysis of Mixed-use Lanes

The lower of the two curves in Figure 4 shows the average car delay predicted when a mixed-use lane (Strategy 2.1) is deployed at the tunnel for a range of rush hour car demand. (Note that when these demands are fairly low, the delays are on the order of seconds). Under the higher demands, the rush-hour car queue adjacent to the median lane does not dissipate prior to the next bus arrival (2 minutes later).

The upper curve in Figure 4 shows the average delay to cars when a run through bus lane (Strategy 1) is implemented for the tunnel. The vertical displacements between the two curves show the delay savings of the proposed strategy.

This analysis assumes that there is no queue spillover to the tunnel from some downstream bottleneck. For the case when the tunnel is engulfed by queues from a downstream bottleneck, the application of intermittent bus lanes will be both theoretically analyzed and field tested.

5.2 Signalized Intersection – Wadi Saqrah

The second case study location is a signalized intersection. The representative geometry and the bus movements through this intersection are shown in Figure 5a. The traffic signal at this location is isolated and displays "split phasing;" i.e. each approach receives its own green phase to serve its through-moving and turning traffic simultaneously. The signal is vehicle actuated, such that cycle lengths and green times vary over the day. This location behaves as an isolated signal, and therefore operates as described in Case I.

Note from the figure that buses are required to perform certain turn maneuvers at the intersection. The routes of the bus lanes are shown with shading in the figure.

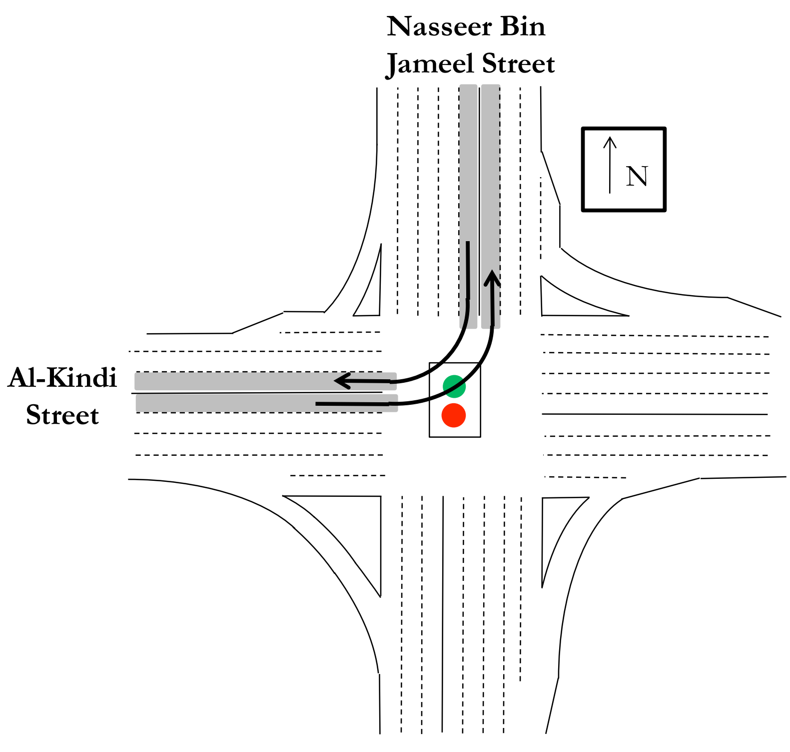

Figure 5a. Geometry of Wadi Saqrah Intersection

5.2.1 The Problems

Run through bus lanes at the intersection (Strategy 1) would make the location a more restrictive bottleneck, because taking lanes from cars would reduce their queue discharge flows. The longer cycle lengths thus required to keep the intersection under-saturated would cause car delays and queue lengths to increase markedly.

The bus route running southbound to westbound introduces a special challenge: how to accommodate right-turning buses without imparting further delays to cars.

5.2.2 Proposed Solutions

The details of Strategy 3.1a, mixed-use lanes in the intersections immediate vicinity, for the eastbound to northbound route, and Strategy 3.1b, mixed-use lanes with pre-signals, for the southbound to westbound route are described below.

Eastbound to Northbound Route

The strategy for this case will be described with the aid of Figure 5b. On the eastbound approach, the bus lane would discontinue some distance upstream of the intersection. The segment of median lane directly feeding the intersection would be mixed use. Upon receiving the green, any bus present on the eastbound approach would turn left into the intersection and proceed directly to the northbound median lane, while left-turning cars would be directed (via pavement markings) to the adjacent lanes, as shown in the figure with arrows. The mixed-use lane segment on the eastbound approach should be of sufficient physical length to enable a queue of left-turning vehicles to fully saturate the green phase. Any bus that joins a left-turning car queue would wait no more than one cycle length before proceeding into the intersection.

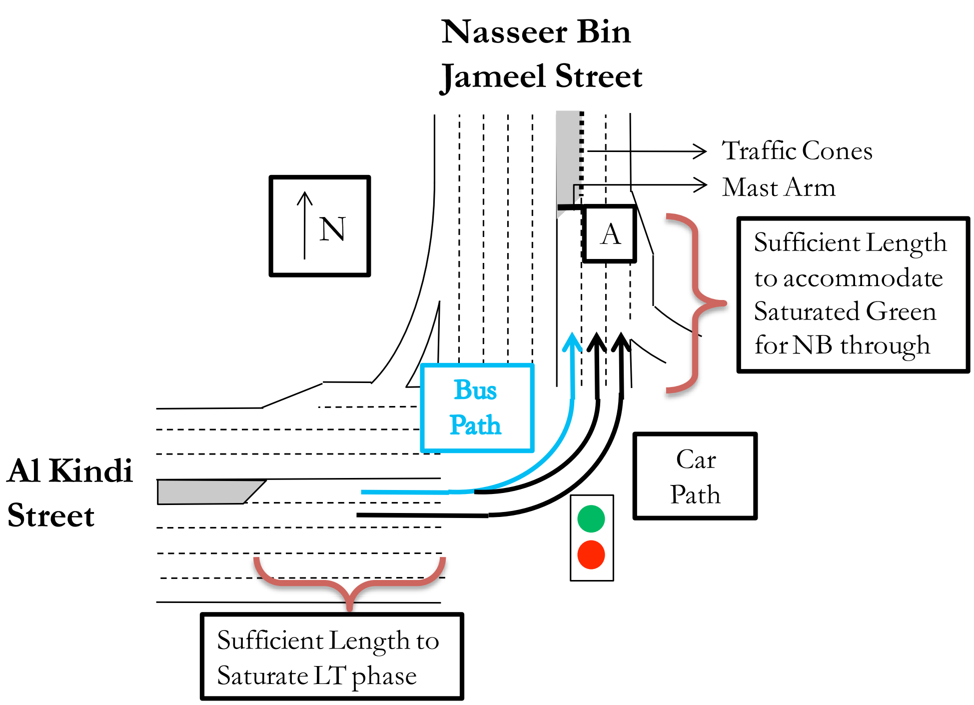

Figure 5b. Eastbound to Northbound Route

The bus lane would re-start on the northbound approach at some location downstream of the intersection (labeled Location A in the figure). The mixed-use segment of lane immediately upstream of Location A would act as a buffer for storing the queues that form during each cycle when through-moving northbound cars pass through the intersection. The physical length of this buffer would be designed to accommodate rush-period demands so that the cyclic northbound car queues never spill-over into the intersection. It may also be a good idea to physically block cars from entering the northbound bus lane. This could be done, for example, by means of a mast arm and (permanent) traffic cones, also as shown in Figure 5b.

Southbound to Westbound Route

This case will be described with the aid of Figure 5c. Mixed-use lanes would be deployed at the intersection, for the reasons already discussed. In addition, pre-signals would be deployed at the discontinuation point of the southbound bus lane (Location B in the figure). These pre-signals would mitigate disruptions created by right-turning buses by enabling them to maneuver more easily from the bus (median) lane to the shoulder lane; i.e. from Location B to C in the figure. Once a southbound bus reaches Location B, the pre-signal's display would (eventually) turn green for the bus and red for the adjacent cars. This change in the pre-signal display might best occur while southbound vehicles are receiving a green at the intersection – and more specifically, when the green time remaining for that phase roughly equals the bus trip time from Location B to C. In this way, a bus could proceed into the intersection at the very end of that green (i.e. without waiting for the next green display). Moreover, only a small number of cars that are stopped by the pre-signal would have otherwise reached the intersection without encountering a red phase there: only these cars are subjected to extra delays.

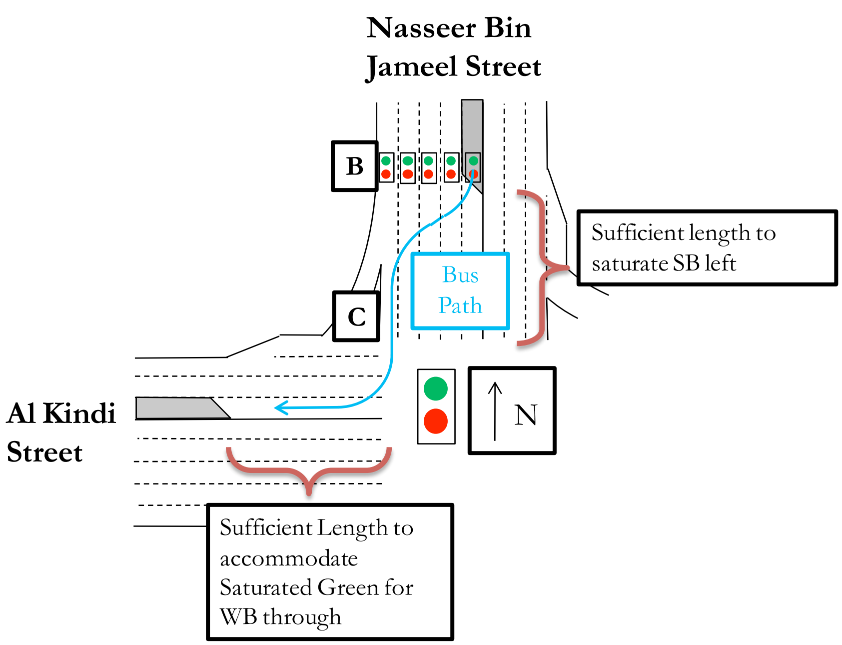

Figure 5c. Southbound to Westbound Route

5.2.3 Analysis

A queuing analysis, similar to that in Section 5.1.3, will be done to analyze the delay savings of a mixed lane with bus priority when compared to permanent bus lanes.

6 Field Experiments

Field experiments will be performed on the two case studies to quantify the benefits achieved by the proposed strategies in real settings. These benefits depend on external factors including driver behavior in Amman. During the experiments, the necessary data, especially output flows from the sites will be collected. These data will be used to compare against the theoretical findings.

The field experiments can be done with the help of policemen, without need for any costly infrastructure. Whenever the expressway bottleneck is active, it may be possible to have a police officer enact Strategy 2.1. The officer would stop traffic in the tunnel's adjacent lane whenever a bus approaches it. When the downstream queue spills over, again a police officer can enact Strategy 2.2 by stopping cars from entering lane 1 at appropriate times. Experiments at the signalized intersection could also be conducted inexpensively with the aid of policemen. For the eastbound to northbound route, a police officer could direct left-turning cars from the eastbound approach into the appropriate lanes on the northbound approach (as shown in Figure 5b). For the southbound to westbound route, police could act as the pre-signals whenever a bus arrives to Location B in Figure 5c.

In two consecutive sections in the final report, results obtained from the field experiments will be presented for expressway active bottleneck and signalized intersection. The benefits of the proposed strategy will be analyzed and conclusions will be drawn.

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