Bus Lanes with Intermittent Priority: Assessment and Design

by

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1 Introduction and Overview

1.1 Introduction

Buses that operate in mixed traffic lanes are subject to delay caused by traffic congestion, which reduces the appeal of bus transit. Alternatively, dedicated bus lanes provide excellent right-of-way to transit vehicles. However, the reduction in private vehicle capacity of a traditional bus lane can only be justified along roadways with very frequent or critical bus service. Bus Lanes with Intermittent Priority (BLIP) provide a compromise between dedicated bus lanes and buses operating in mixed traffic lanes.

Transit agencies continue to seek new ways of providing better service with limited resources. Increasing urban traffic congestion continues to decrease the effectiveness and attractiveness of bus systems. Bus Rapid Transit has been proposed as a possible remedy for increasing transit systems effectiveness. While BRT systems are less expensive than rail alternatives, they are still cost prohibitive for many transit agencies and inappropriate for many bus routes. Transit agencies need a low-cost alternative to BRT that can provide effective and efficient surface transit.

One low-cost option for transit agencies is Transit Signal Priority (TSP). TSP can decrease bus travel times by allowing buses to preempt or extend traffic signals to allow the transit vehicle to proceed through an intersection. A handful of studies have documented the benefits of TSP implementations. [Balke et al, 2000; Banerjee, 2001; Cima et al, 2000; Duerr, 2000; Furth and Muller, 2000; Garrow and Machemehl, 1998; Hunter-Zaworski et al, 1995; Janos and Furth, 2002; Kloos et al, 1995; Lin, 2002; Nash and Sylvia, 2001; Skabardonis, 2000]

Another option is an "intermittent bus lane," a bus-reserved lane that allows private vehicle traffic to use the lane when not in use by the bus. One study has proposed such an Intermittent Bus Lane (IBL) concept. [Viegas and Liu, 2001] IBL never requests traffic to leave the lane to accommodate the bus; instead it restricts traffic from changing into the bus lane. In order to guarantee that buses and private vehicles do not interact, IBL includes TSP to "flush the queues" at traffic signals ahead of the bus.

Bus Lanes with Intermittent Priority (BLIP) provide a compromise between traditional bus lanes and buses operating in mixed traffic. BLIP is similar to IBL, but it clears traffic out of the lane reserved for the bus and does not rely on TSP. Therefore, the BLIP concept is easier and less expensive to implement. With BLIP, other traffic can make use of the lane as normal. As a bus approaches, other vehicles are instructed to safely leave the lane (or are prevented from entering the lane), yielding right-of-way to the bus. Dynamic signage will communicate the status of the BLIP to other users of the roadway, potentially including overhead signalization, roadside signalization and in-pavement lights.

The BLIP concept is also related to the idea of a "queue jump lane." [Rosinbum et al, 1991; TRB, 2000; Mirabdal and Thesen, 2002] Queue jump lanes are provided by widening the roadway as it approaches an intersection. These lanes only allow buses and right-turning vehicles to enter, allowing the bus to "jump the queue" of traffic at the signal. Often, these lanes have special signalization that allows the bus to pull into the intersection before the vehicles in the other lanes, giving the bus priority as it returns to the through-traffic lane. Unlike queue jump lanes, BLIP requires no additional right-of-way and should therefore be less expensive to implement.

The purpose of this paper is to explore the design and institutional issues of BLIP. First, an overview of the BLIP concept is presented. Second, the context and precedents of BLIP are discussed. Next, the design aspects of BLIP are explored. The institutional issues surrounding BLIP implementations are presented. Then, possible criteria for implementation feasibility are discussed. Finally, the benefits and costs of a BLIP implementation are then explored, including reduced travel time and reduced travel time variability.

1.2 Conceptual Overview

Buses operating in mixed-traffic lanes experience delay due to interaction with other vehicles. Traditional bus lanes reduce this delay in two key ways: they prevent vehicles from queuing in front of the transit vehicle at signalized intersections, and they ensure that buses are not competing for roadway space with private vehicles as they leave bus stops. Bus Lanes with Intermittent Priority seek to provide the same delay reduction as traditional bus lanes by temporarily removing private vehicle traffic in the transit lane.

In order to prevent queues at intersections from blocking the right-of-way of the bus, vehicles must be removed from (or prevented from entering) sections of a lane. It is proposed that vehicles merge while discharging from intersection queues in anticipation of preventing the formation of a queue in the bus lane further downstream.

It should be reiterated here that the BLIP concept differs in some very important ways from the IBL concept discussed above. IBL relies on TSP to flush queued vehicles from the path of buses. Implementation of TSP can severely impact cross-street traffic as it changes the timing of any signal with which it interacts. This also complicates the analysis of IBL impacts by introducing additional delay to cross-street traffic. The BLIP strategy, however, does not rely on TSP. Therefore, the impacts are more localized and the necessary impact analysis is much simpler to perform.

BLIP is best suited for bus routes with headways of 10 to 15 minutes or greater on major urban and suburban multi-lane arterial roads that experience medium traffic demand during peak periods. If traffic flow is too heavy, the costs to other traffic of BLIP operation may be too great; if flow is too light, the benefits to bus passengers are minimal. This estimation is quantified in Eichler and Daganzo [2005]: the "sweet spot" for BLIP implementation depends on the size of the road. Some ranges are presented in Table 1.

Table 1: Estimated traffic demand ranges (% of capacity) for BLIP by number of lanes.

Number of Lanes	Lower Bound	Upper Bound
2	40%	45%
3	53%	60%
4	60%	68%
5	64%	72%

BLIP provides the same benefits as dedicated bus lanes. Travel time is reduced by the elimination of delay at signals. Travel time variability reduction is obtained by removing factors prone to stochastic variation from those that influence bus travel time. These benefits are discussed in detail in the following sections.

To better understand the BLIP concept, one can imagine a region of roadway that is reserved for the bus. This region or zone starts at the bumper of the bus and extends a fixed distance ahead of the bus. This zone is to be kept clear of non-bus traffic to ensure that the bus does not experience any delay caused by interacting with private vehicles. In deployment, the zone reserved for the bus will not travel continuously along the roadway, but instead travel discretely one road segment at a time.

An example of the logic behind a BLIP activation could prove instructive: A bus traveling along its route is equipped with an automatic vehicle location (AVL) system that transmits its trajectory information to a central control system. This control system then projects the trajectory of the bus forward in space and time, and determines at which intersections the bus might be queued. In order to prevent this queuing, the system then tracks back (upstream) along the roadway to determine which (and when) intersections would be discharging vehicles that would be queuing in front of the bus. The system determines when to activate the lane-restriction signals. These signals, located at intersections, instruct drivers at the appropriate time that the right-most lane should be reserved for the bus. The control system performs this logic iteratively, working its way downstream. As the bus communicates new trajectory information, the signalization plan is updated.

A variety of roadside communication technologies can be employed to provide notification of the intermittent lane's status, including in-pavement lights and changeable message signs (overhead and roadside).

It should be mentioned here what this proposed concept is not intended to do. What is proposed here will not eliminate any problems that are currently experienced with traditional bus lanes. These problems, including accommodating right turns and dealing with pedestrians blocking right-turn movements, are not in the scope of this discussion.

[Bauman, 1990] Other research is focusing on these issues. [Saint-Jacques, 1997] It is important to consider this proposed concept as a bus lane that permits non-bus use when possible. Direct comparisons to BRT should not be made.

The BLIP concept is complementary to TSP. In TSP implementations, signal cycles are changed in order to give priority to the transit vehicle. TSP reduces the delay caused to transit vehicles caused by the red signals (signal stop delay). BLIP can be effective at reducing the delay caused by the queue at an intersection (signal queue delay). In implementations where TSP and BLIP can be paired, the bus will only need to stop for passenger boarding and alighting. This will ultimately decrease travel time of the route and increase the reliability of the system by ensuring schedule adherence.

2 Context and Precedents

The concept of reserving a lane dynamically for a bus as it approaches is quite novel, and no implementation of such a concept has yet occurred. However, the BLIP concept is not without precedents. This section explores the background concepts and technologies that form the foundation of BLIP.

2.1 Advanced Public Transit Systems

The BLIP concept is the newest addition to the family of Advanced Public Transportation Systems (APTS). Other members of the APTS family include TSP, advanced traveler information systems (ATIS), and bus rapid transit (BRT). APTS itself is part of a larger group of intelligent transportation systems (ITS) concepts: APTS is joined under the ITS umbrella by its sibling, intelligent vehicle highway systems (IVHS).

The drive behind ITS to increase the efficiency of transportation networks through information technology. Much of the early research into ITS was focused exclusively on IVHS. After the passage of the Intermodal Surface Transport Efficiency Act (ISTEA) in 1991, ITS research slowly began to include the integration of advanced technology into public transportation systems.

2.2 Transportation Planning Context

BLIP will have an impact on transportation planning in several ways. The travel time benefits (reduced mean and variance) can lead to more transit riders (mode shift). Transportation infrastructure investments can often be used to leverage private sector development in the form of transit oriented development. Finally, planners must keep track of transportation technologies to ensure that their toolbox is up-to-date. This section explores the relationship between BLIP and these three aspects of transportation planning.

2.2.1 Mode Shift

Transportation planners use a four-step model to predict regional transportation demand. The four steps of this model are trip generation, trip distribution, mode choice and route assignment. The mode choice step uses logit modeling to estimate the modal split, which is the percentage of trips within an analysis zone that will be taken on each of the different modes (car, transit, bike, walk, etc.). This logit modeling is based on traveler costs, which are calculated for each mode and compared. The cost function is generally linear, and includes monetary costs, access time, waiting time and travel time. Each of these variables has unique coefficients that represent the relative importance of each of these costs to a person making a mode choice decision.

As discussed in detail later in this paper, BLIP can reduce both travel time and waiting time through reduction of travel time variation. Depending on the magnitude of these reductions, BLIP can help make bus transit a more appealing alternative to driving. The technical formulations later in the paper can assist planners in determining the magnitude of reductions in travel time and wait time.

It is commonly believed in transportation planning that time spent waiting for transit is perceived between 2 and 4 times as long as travel time. This fact should encourage planners to weigh travel time benefits with potential wait time benefits. BLIP should still be considered even if it has little effect on line-haul travel times, as transit wait time has shown to be a more highly weighted variable in the traveler cost equation.

The transportation planning goal of increasing bus transit level of service is to shift private vehicle drivers to transit. The removal of private vehicles from the roadway (initially) may have any of the following effects:

- Decreased congestion and therefore increase bus travel speeds.
- More roadway space for additional vehicles.
- Reduced air pollution from private vehicles.
- Reduced accidents between cars and cars, or cars and non-motorized modes.

In a capacity constrained corridor, travel demand is often greater than what the roadway can supply. Congestion and its associated delays influences driver behavior; many drivers may be taking secondary routes, traveling at inopportune times, or using alternative modes. If a BLIP implementation shifts some drivers to transit, it is likely that travelers shifting their travel behavior will eventually consume some if not all of the newly available roadway space. This concept is referred to as latent demand. Planners should therefore evaluate the total transportation demand for a corridor when attempting to determine the expected congestion reduction and other benefits of BLIP.

2.2.2 BLIP and Transit Oriented Development

Transit Oriented Development (TOD) is a recent trend that harkens back to pre-automobile development patterns. Generally, TOD involves the integration of residential and commercial development with transit stations. Studies of TOD have shied away from defining TOD, as many transit/development agencies have their own definitions.

One definition of TOD for a large metropolitan agency would most likely not apply to a mid-sized city with different transit infrastructure. [Cervero et al, 2004]

One general aspect of TOD is that public sector transit infrastructure investments can encourage higher density private sector development around transit nodes. This development is generally of a form that is perceived as risky for developers. The presence of public sector investment helps assuage developers' fear of new development patterns and makes private sector investments in higher density development more likely.

The TCRP report *Transit-oriented development in the United States: Experiences, Challenges and Prospects* describes over 100 examples of transit oriented developments across the United States. Among the examples and case studies provided, only 9.5% of the transit systems that had TOD experience were non-rail systems. The bus-only TOD examples consisted of development oriented around bus terminals and transfer stations. [Cervero et al, 2004] The general trend noted in these examples is that the private sector TOD investments tend to be roughly proportional to the public sector transit investments.

BLIP should not prove to be a major investment for a transit agency. In fact, BLIP is novel because it is a low-cost and mostly invisible technique for enhancing transit service. It is highly unlikely that the presence of BLIP along a bus route will make transit-oriented development along that route more likely. Cervero makes a conclusion in the TCRP report that confirms this belief: For bus transit systems, "TOD is more of a concept than a reality." [Cervero et al, 2004]

2.2.3 Transportation Planning and Transportation Technology

Finally, the relationship between transportation planning and transportation technology should be addressed. Deakin, et al, aptly summarize this relationship in a 2001 paper, *Transportation Technologies: Implications for Planners:*

> Planners need to be aware of coming technological changes so that they can integrate them or account for them in their planning and programs. Planners also need to be aware of a broader, more speculative set of technological possibilities and their implications so that they will not be caught by surprise by changes that might have been anticipated.
>
> ...
>
> As in other applications, new technologies for transportation offer the possibility of "better, cheaper, faster" transportation services. Planners will be called upon to evaluate new technologies along economic, social and environmental dimensions and to help decision-makers assess the opportunities and tradeoffs involved in the technological choices they make. [Deakin, et al, 2001]

The purpose of this paper is to do just this: to present the BLIP concept to the transportation planning world in a way such that its benefits and costs and its features and complications can be fully understood and incorporated into transportation models and methodologies.

2.3 Bus Lanes

The obvious main precedent to BLIP is the dedicated or exclusive bus lane. Bus lanes have been used in cities around the world to decrease travel time and increase schedule adherence. The benefits and issues of bus lanes are discussed by Bauman [1990] and Shalaby [1998]. Saint Jaques has performed an operational analysis on bus lanes [1997] and then performed subsequent refinement using data collected from several field tests [2000]. As discussed above, BLIP attempts to provide bus lanes dynamically and intermittently, as needed, to provide bus-lane-like performance improvements without the reduction in capacity of dedicated bus lanes.

Bus lanes provide benefit to transit vehicles by eliminating their interaction with private vehicles. Private vehicles cause buses delay in two main ways. First, buses in mixed traffic lanes can be enqueued with mixed traffic at red signals, and must therefore wait for the queue to discharge before they can continue through the intersection. This adds a non-trivial amount of delay, especially if the bus must stop again at the intersection to allow for passenger boarding and alighting. Second, buses that operate in mixed traffic lanes must merge back into these lanes after stopping at bus stops. This merging movement, as discussed below, can also add a non-trivial amount of delay to the bus.

2.4 Temporal Vehicle Regulations

BLIP has a handful of precedents in temporally-based private vehicle regulations. These precedents include school zones, high-occupancy vehicle (HOV, or carpool) lanes and priority for fire engines and other emergency vehicles. Roads adjacent to schools regularly have special speed restrictions. These restrictions are specified in one of three temporal ways: during certain times of the day as posted, when a special amber signal is flashing, or simply and somewhat ambiguously "when children are present." Section 42011 of the California Vehicle Code codifies this type of temporal regulation. [Caltrans, 2004a] These conventions are further codified in the Manual of Uniform Traffic Control Devices (MUTCD) [USDOT, 2001], as well as individual states vehicle codes.

HOV lanes are often only specified as such during peak times throughout the day. Signs indicating HOV lane status include the time of day during which the HOV regulation is in place. These are generally static signs, but examples of dynamic HOV-lane allocation are available.[1] Section 21655.5 of the California Vehicle Code codifies this type of temporal regulation. [Caltrans, 2004b] As with school zone signs, the HOV signage conventions are further codified in the MUTCD.

Emergency vehicles are another precedent of BLIP systems. These vehicles communicate with lights and sirens that the roadway should be cleared to yield priority to the emergency vehicle. This is truly dynamic lane control that provides little notice to drivers. A special challenge for emergency vehicles is that they must communicate to drivers in front of them: generally most communication between vehicles along the roadway flows upstream, via brake lights, visible openings in the roadway, etc. BLIP implementations will not experience this same challenge -- unlike emergency vehicles, buses have a lower average speed than private vehicles. Roadside signs will communicate to private vehicles from the front through roadside signs and signals, a time-tested and reliable method.

2.5 Dynamic Lane Assignment

While the literature is not rich with assessments of dynamic lane assignment installations, they are indeed widespread and provide another precedent to the BLIP concept. Here,

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[1] One example of dynamic HOV-lane signage is on the HOV/bus overpass around the toll plaza of the San Francisco Bay Bridge. During both the morning and evening peak periods, vehicles with three or more occupants can bypass the toll plaza entirely and use a bypass ramp constructed for buses. A changeable message sign posted at the off ramp for the overpass indicates to drivers when the ramp is available to HOVs.

dynamic lane assignment means the ability to specify to drivers which lanes can be used at any given time. Some examples of dynamic lane assignment include reversible center lanes on capacity constrained bridges, parkways and streets, and shoulder lanes that are available only during peak periods. A specific example of an urban arterial, Connecticut Avenue in Northwest Washington, D. C., has dynamic lane assignment: during the AM peak period, four lanes are made available to southbound travelers and two northbound lanes are provided; in the PM peak, the opposite is true. The lane status is communicated to drivers by changeable message signs (CMS) that state "USE *N* LANES," where *N* is the number of available lanes. The center lanes along the reversible portion of the road are also double-striped, increasing the distance between on-coming vehicles and indicating to drivers the non-standard driving rules.

The MUTCD provides some standard devices for dynamically controlling the use of lanes. The MUTCD describes "reversible lanes" in section 2B.25 and provides standard signage for controlling the traffic flow on these lanes. The MUTCD also supports "lane control" signals in chapter 4J that specifies signals that can be used for reversible lanes or other non-reversible applications. The devices approved in the MUTCD include overhead signals that display an "X" above a lane that is not available and a downward-pointing arrow for a lane that is currently available. It should be noted that many reversible lane systems do not use the MUTCD overhead signals. The Connecticut Avenue example above uses custom roadside signs. Other examples, such as Washington's Rock Creek Parkway and San Francisco's Golden Gate Bridge provide reversible lanes manually: highway police place barriers and pylons in the roadway to indicate the status of a lane. Often in these manually controlled reversible lane systems, static roadside signs have hinged panels which, when opened, display a message indicating the traffic flow direction. In some extreme cases, moveable jersey barriers reinforce the line of separation between the lane groups. These barriers are moved from side to side by a large vehicle whose only purpose is to move them from lane to lane for the AM and PM peaks.

An exciting example of dynamic lane assignment is provided by recent article in *Traffic Technology International* [D. Panter, 2003]. This article describes a system being constructed in Brisbane, Australia, that employs dynamic lane assignment to match traffic capacity with demand along a very constrained corridor. The system includes dynamically assigned curbside bus lanes during peak periods and reversible lanes. In addition to overhead signalization similar to that documented in the MUTCD, this Brisbane experience uses in-pavement lights to act as dynamic roadway striping. That is, the lights act as pavement markings that can be changed dynamically between AM peak, PM peak and off-peak periods.

2.6 In-pavement Lighting Systems

In-pavement lighting systems can provide unprecedented levels of safe dynamic lane assignment. Currently in the United States, in-pavement lighting systems are being used to increase pedestrian safety in crosswalks. In these crosswalk systems, pedestrians activate the lights by pushing a button or tripping a microwave sensor. Once activated, lights (embedded in the pavement outlining the crosswalk) flash and draw drivers' attention to the crosswalk and pedestrians. Several studies [van Derlofske et al, 2003; Boyce and van Derlofske, 2002; Kannel and Jansen, 2004; Olsen, 2003] have shown that in-pavement lighting systems are effective at being visible to drivers. One paper proposes using in-pavement lights to increase safety at at-grade rail crossings. [Cohn, 2005] These results provide encouragement that in-pavement lighting systems can provide an effective method of dynamic lane control similar to the Brisbane example.

The MUTCD discusses the use of in-pavement lighting systems. Most of its coverage discusses their use in crosswalk-systems for pedestrian safety, but the language leaves open the possibility of additional uses.

Many vendors offer LED in-pavement lights that are both solar-powered and wirelessly controlled. Installation of these lights is very simple, fast and inexpensive, as no cables must be embedded in the roadway surface.

2.7 Conclusion

Bus Lanes with Intermittent Priority, while a novel concept in advanced public transit systems, is not without precedent. BLIP is one member of an ever-growing family of concepts that integrate transportation and technology. Systems that employ concepts similar to BLIP have been deployed throughout the world in the past, and new implementations are soon to be completed. Transportation planners can use this work to better understand how BLIP can impact travel times and mode splits. On its own, BLIP should have little effect on Transit Oriented Development.

3 Design

3.1 Technology

Many ITS components can be employed to operate a BLIP system, most of which are currently in use by transit agencies across the country. [Casey, 1999] The components required to enable BLIP are detailed in Table 2.

Table 2: Technology components required to enable a BLIP implementation.

Component	**Description**	**Use**
Automatic Vehicle Location	Hardware and communication technology that tracks the location and speed of a bus.	Provides location and speed data for bus arrival predictions.
Central control system	A centralized signal control system that manages the status of the dynamic lane-use signs and signals.	Collects vehicle location and speed data. Predicts arrival of buses at red signals. Updates dynamic lane-use signs and signals.
Changeable Message Signage	Standard roadside dynamic signs.	Conveys to drivers the status of the BLIP.
In-pavement lighting system	Standard, solar-powered and radio-controlled lights embedded in the roadway.	Acts as dynamic roadway markings, indicating the status of the BLIP.
Overhead signals	Standard, MUTCD approved lane-use signals.	Further conveys to drivers the status of the BLIP.

A wide variety of automatic vehicle location (AVL) technologies are currently available for use in advanced public transportation systems. The hardware and communication technologies differ, but the information they provide is generally the same. For the purpose of this discussion, AVL system technology will be treated as a "black box" and will not be discussed in detail. A BLIP system will require frequent updates from the AVL system in order to generate bus "trajectories," approximately every 30 seconds. These requirements should be further investigated for specific implementations. Factors that could influence the update frequency are intersection spacing, bus stop spacing, signal timing and traffic volumes.

The central control system will mostly likely be computer software that runs on a transit or traffic management center computer. The software will process the AVL data and extrapolate the location of the bus in the near future. If the system determines that the bus will queue at a signal, it will then activate the lane control communication system. This software is not unlike the intelligent TSP systems currently being researched, which predict bus arrival times at signals and proactively prepare for the bus arrival. [Balke 1999 and 2000] While software of this type is not currently available, it should not be difficult to develop.

The third technology aspect of BLIP systems is the communication system. This system communicates to private vehicle drivers the status of the BLIP, either available or reserved. As discussed above, this communication system can consist of overhead lane-use control signals, roadside changeable message signs and in-pavement lights. Static (traditional) signs can also be placed along the roadside to educate drivers of the existence of BLIP when it is not active. The dynamic communication devices are networked (wired or wireless) with the central control system, which activates the signs, signals and lights when required.

3.2 Bus Stop Design and Placement

The placement and design of the bus stops have a significant impact on the performance and benefits of a BLIP system. Bus stops generally have two designs: turn-out and in-lane. There are three options for bus stop placement: near-side, far-side or mid-block.

This typology of bus stop designs and locations is illustrated in Figure 1. The impacts of the design and placement of bus stops are explored in several articles in the literature. [Parentela et al, 1990; Rosinbum et al., 1991; Fitzpatrick and Nowlin, 2000] The relevant findings of these studies and the implications for BLIP systems are discussed in the remainder of this section.

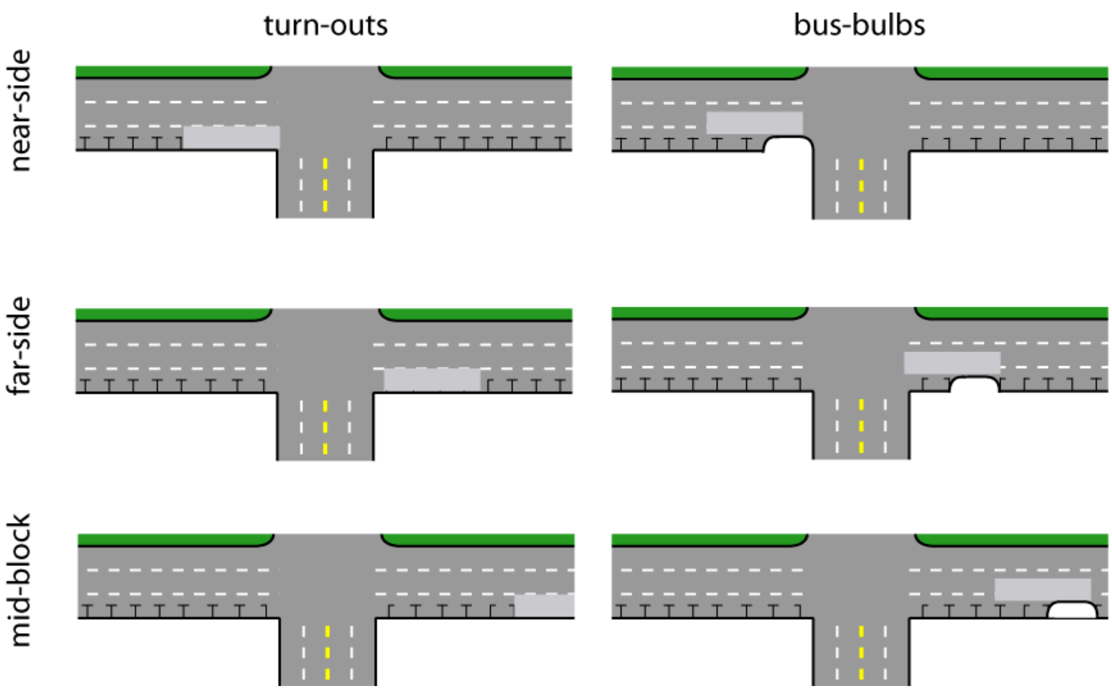

Figure 1: Typology of bus designs and locations. The gray shaded area represents the portion of the roadway reserved for the bus stop. In-lane bus stops are shown as bulb-outs.

Bus turn-outs are small sections of widened roadway that allows a bus to pull out of the traffic lane while serving bus passengers. Often, bus turn-outs use roadway space otherwise used for street parking. Turn-outs are often preferred by traffic engineers, as they prevent buses from interrupting the traffic flow. However, buses using a turn-out must reenter the traffic stream: this merge movement can often cause non-trivial delay.[2]

At an in-lane bus stop, the bus stops in the traffic lane. This occurs when the bus operates in the curb lane, or if a "bus-bulb" is constructed. Bus bulbs are sections of curb and sidewalk that reach out to the edge of the traffic lane (usually through a parking lane or shoulder). Bus bulbs provide extra space on the sidewalk for bus shelters and allow passengers to wait safely without obstructing pedestrian traffic.

Bus stop design is a factor in BLIP systems: the delay a bus encounters as it attempts to merge back into the traffic stream after a turn-out stop is eliminated by BLIP. However, no similar benefit is provided for bus stops with bulbs.

The names of bus stop placement options are mostly self-explanatory: near-side stops are situated at the upstream side of an intersection; far-side stops are located at the far- or downstream-side of an intersection; and mid-block stops are located elsewhere along the block, not near the intersection. Near-side stops dominate the bus transit world, and for obvious reason: passenger movements can occur as the bus is waiting at a red signal. However, recent implementations of TSP have included relocating bus stops to the far-side of the intersection. This is to reduce the possible delay caused by a signal being held green for the bus as it stops at a near-side bus stop for passenger movements. Mid-block bus stops are used when traffic engineers wish to ensure that buses do not reduce the

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[2] It should be noted that the author has observed many occasions where buses leave their "tails" in the traffic lane while serving bus stops at turn-outs. This is obviously to block traffic in the thru lane and reduce delay when returning to the traffic lane.

capacity of an intersection: traffic passes the bus at a mid-block stop and can then use all lanes at the intersection.

Bus stop location is also a factor in BLIP systems. Buses making use of the reserved lane approaching an intersection can pull directly up to the stop line without waiting in a queue of vehicles. Because BLIP systems can be implemented without TSP, buses may wait for signals to turn green. This time can be used for passenger movements if near-side bus stops are employed.

It should be noted that the near-side bus scenario detailed in the previous paragraph provides an added benefit over traditional bus operations. In bus operations without BLIP, buses become enqueued by private vehicles at traffic signals, often many yards away from the bus stop. When this occurs, there are two possible outcomes, both negative. The first is that the bus waits until it reaches the stop before allowing passenger movements, experiencing delay from having to stop twice -- once for the queue at the signal and once for the stop. The alternative is that the bus simply opens its doors and allows passenger movements despite its distance from the bus stop. This can compromise safety of passengers alighting and boarding the bus. Additionally, if the time needed for passenger movements is longer than the duration of the queue in front of the bus, the bus will block the traffic lane and increase delay to traffic. With BLIP, buses that must stop at signals will always stop at the stop line. This ensures safe and timely passenger movements from near-side stops without excess delay to the bus or private vehicle traffic.

3.3 Signage standards

The MUTCD [USDOT, 2001] currently provides for some signs and signals that can be used directly in a BLIP implementation. It also provides some precedents upon which other signs and signals use for BLIP can be based. Finally, the MUTCD describes the process by which new and innovative uses of traffic control devices can be approved for experimentation in section 1A.02.

3.3.1 MUTCD Standards

The most readily applicable signs and signals provided by the MUTCD are the lane-use control signals described in chapter 4J. As discussed above, these signals mark a lane with an "X" when it is not available, and a downward arrow when it is. This type of signalization may be appropriate for some semi-urban arterials and highways, but it is doubtful that overhead signalization would be considered appropriate for dense urban corridors. For these more urban environments, a more context-sensitive solution is necessary.

One option presented by the MUTCD is changeable message signs (CMS) in section 2E.21. The most general definition of a CMS is a sign whose message can vary, either changed manually, on a schedule or by remote control. One type of CMS already in use in similar situations is the roadside signage in the Connecticut Avenue example. However, in this example, the lane assignment is a regularly occurring event: the lanes are configured for AM peak, PM peak and off peak, and these assignments occur every weekday excluding holidays. This type of roadside sign is appropriate for lane use patterns that occur on a consistent and learnable schedule. A more dynamic lane use assignment scheme, like that needed to implement a BLIP system, would require more than a simple roadside sign that may be easily ignored by drivers.

Chapter 4L of the MUTCD provides support for in-roadway lights including but not limited to pedestrian safety applications. This provides encouragement that these in-pavement lighting systems can be used as dynamic roadway striping for BLIP implementation. However, such uses may require approval for experimentation from the U. S. Department of Transportation if the project is federally funded.

A BLIP system could be implemented with the above MUTCD-approved traffic control devices. However, such a system may not be appropriate for all roadway types and urban environments. The following section explores small changes or combinations of approved devices that can provide greater levels of driver safety in a broader range of urban forms.

3.3.2 New Signs and Signals

The MUTCD provides for Preferential Only Lane Signs in section 2B.26. These "preferential-only" signs specify that only a preferred vehicle type is permitted in a given lane. The preferential vehicle types specified in the MUTCD include high-occupancy vehicles, buses and inherently low emissions vehicles. The MUTCD allows for these preferential lane assignments to be on a full-time or part-time basis. For part-time preferential lane assignment, the days and times of preferential treatment are added to the signs. In order to use this type of sign in a BLIP installation, the sign would need to be paired with a flashing beacon or other dynamic signal technology, and the text "when flashing" would be added to the sign. Thus, when the lane is reserved for the bus, the dynamic signal (beacon) would be activated and the sign would communicate to drivers the meaning of the dynamic signal. Flashing beacons are provided for in the MUTCD in section 4K, and a use such as the one proposed here is within the provided standards and guidelines.

The MUTCD also provides warning signs for lane reductions. These static signs illustrate a lane being removed from the roadway, suggesting to drivers that they prepare to merge. A dynamic version of this sign could be useful in a BLIP implementation. One option would be to place a similar combination of flashing beacons and "when flashing" text that would indicate when the merge movements were required. Another option would be a wholly dynamic version of this sign that lights up with the familiar icon when merging is required. This sign would be similar to the dynamic "no left turn" sign proposed by James Misener for his Intersection Decision Support project. [Misener, 2003]

In-pavement lighting systems provide the most exciting possibilities for lane use control. In-pavement lights can be seen as the first step towards truly dynamic road markings. Considering in-pavement lighting systems in this way opens up a whole new chapter (MUTCD Chapter 3B) of possibilities: any symbol or word that is approved for pavement marking with paint could be come dynamic and only activated as needed. This would provide a wide array of communication techniques for BLIP systems. The words BUS ONLY in the pavement could light up at the appropriate time, or the "diamond lane" symbol could light up or flash. The standard lane reduction "arrow" pavement marking could become dynamic as well, encouraging drivers to merge at the appropriate time.

One possible precedent for the use of in-pavement lights for dynamic pavement markings is displayed in Figure 3B-21e of the MUTCD. This figure shows in-pavement reflectors being used to illuminate a "wrong-way" arrow. This example definitely encourages potential use of in-pavement lights to dynamically illuminate formerly static pavement markings.

3.4 BLIP and TSP

Special attention should be given to the potential synergy between BLIP and TSP. As discussed in more detail in section 6.1.1.1, a BLIP system reduces or eliminates what here is defined as "signal queue delay." This is the delay caused by other vehicles queued in front of the bus at the signal. TSP is a technique that tries to reduce what is defined here as "signal stop delay." This is the delay caused by the red signal itself, isolated from the delay caused by other vehicles. When added, the signal stop delay and the signal queue delay equal the total delay caused to a bus (or any vehicle) by a signalized intersection. Pairing BLIP and TSP means that they can, together, eliminate all delay due to signals. This would result in a bus's travel time being only a function of the route distance, bus travel speed and stopping for passenger alighting and boarding.

TSP systems most often supply priority by triggering the green signal early (called red-truncation), or extending the green signal (called green-extension)[3]. Many TSP implementations currently rely on stationary detectors to trigger transit priority at intersections. This works well for buses approaching a green signal that is about to change; the bus cruises past the detector, requests priority, and then continues through

[3] Other techniques, such as phase insertion, have a much larger impact on cross-street traffic.

the intersection. However, stationary detectors cause problems for red-truncation priority calls if traffic queues prevent buses from reaching the stationary detectors. [Balke 2000] When paired with BLIP, TSP systems can effectively provide both red-truncation and green-extension priority to buses, as there will never be traffic queues in front of buses blocking the detector loops.

Some TSP implementations use wireless communication technologies that do not rely on stationary detectors. These wireless-enabled TSP systems often provide "intelligent priority" algorithms [Balke 1999 and 2000] that can predict bus arrival times at intersections without detection near the intersections. These intelligent priority systems, in their calculation of bus trajectories and arrival time predictions, are perfectly suited for augmentation to support BLIP.

It should be reiterated that BLIP and TSP are perfect partners: complementary systems that, when combined, can eliminate all delay to buses due to traffic signals. Accordingly this dynamic duo, in eliminating signal delay, also eliminates all variability associated with it. This pairing has the potential to drastically reduce bus travel times and bus travel variability on roadways with moderate levels of traffic congestion. Eichler and Daganzo [2005] provide a rough estimate of the capacity ranges where BLIP and TSP are appropriate. These ranges are displayed in Table 3, where "demand" is a percent of the roadway operating with one fewer lane. Pairing BLIP and TSP can result in great savings for transit agencies, and potentially allow the reduction of bus fleet size.

Table 3: Rough traffic demand ranges for different traffic management strategies.

Demand	**Transit Management Strategies**
Less than 80%	Dedicated bus lanes.
80 to 120%	BLIP or BLIP with TSP.
120% or greater	TSP only, with physical queue jump lanes if possible.

3.5 Conclusion

The design of a BLIP system consists of three major technology components: automatic vehicle location, a centralized control system and roadside signs and signals. The design and location of bus stops can have an influence on the benefits of BLIP: Bus routes with near-side bus stop turn-outs have the most to gain. Signs and signals currently provided by the MUTCD can be used to implement BLIP using all-approved traffic control devices. However, bus routes through dense urban areas may wish to consider proposing new devices or novel uses of existing technologies to implement context-sensitive BLIP installations. In-pavement lights hold promise for being used as dynamic pavement markings for purposes including and beyond BLIP. Finally, BLIP and TSP are very different concepts that can work together in a complementary fashion to drastically decrease bus delay and increase reliability.

4 Institutional Issues

When considering a new engineering solution, planners need to fully understand all of the non-engineering aspects of the solution. One aspect of that is system design, discussed above. Another aspect, potentially more important, is that of institutional issues. Planners need to explore issues of liability, enforcement, coordination, user acceptance and funding among others.

BLIP is a completely new concept. As such, no literature exists that addresses the specific institutional issues of BLIP. However, concepts related to BLIP have been studied, and insights can be drawn from them. This section begins with the general institutional issues involved with any ITS/APTS implementation. It then explores institutional issues specific to BLIP system implementation.

4.1 General Institutional Issues

The first step in implementing any ITS system is to understand the institutional structures within which the planning, engineering and implementation must be performed. The literature contains some discussion of institutional structures surrounding transit planning. [Kons, 1990; Peyrebrune, 1999] The literature is rich with guideline documents and institutional assessments for ITS, APTS, and systems institutionally similar to BLIP. These are reviewed in detail below.

The articles, papers and books providing ITS-deployment guidelines cover many institutional aspects of the deployment process. These include attaining stakeholder acceptance, use of standards, planning for long-term operations and maintenance and documenting policies, procedures and decisions. [Collura, 2004; DeBlasio et al., 1999; FHWA, 1997; Stough, 2001; Stough and Yang, 2001]

Many studies in the literature have assessed institutional aspects of specific APTS implementations through direct studies or surveys of transit agencies and related stakeholders. Dinning and Collura's study [1995] determined that user acceptance and technology were major issues. Horan et al [1995] conducted a literature review and in-depth interviews and determined that major institutional challenges to ITS/APTS were research collaboration, regional management and stakeholder acceptance.

Miller's work [2000] identified nine broad dimensions of Bus Rapid Transit institutional aspects: intergovernmental and inter-organizational, intra-transit agency, political, public relations and marketing; funding and finance; labor; safety and liability; planning and land use; and the physical environment. His subsequent work [2001, 2002, 2003, 2004] continued to explore the institutional concerns, including providing a deployment framework and investigating issues of transit operations including multiple agencies. His 2001 paper summarized survey results on institutional issues of BRT:

> The most frequently sighted (sic) issues about which the survey respondents were unsure included issues of insurance, liability, differing responsibilities between BRT and non-BRT routes, the changing role of drivers, new vehicle procurement, and the use of AVL in monitoring.

Conroy [2003] concluded that traditional transportation projects differ from ITS implementations in three key ways: the use of advanced technology and its interoperability and maintenance; system approaches at the planning and operational levels; and private industry products and services working together with publicly provided services and infrastructure. Further, he focused on five institutional aspects; the planning and financial process; decision support tools; characteristics (structure and competencies) of the agency performing the deployment; arrangements with technology partners; and incorporation of 3rd party technology and services. He heavily stresses the importance of fully considering operations and maintenance funding and responsibilities for ITS projects. In his 2002 study of international ITS deployments, he found the following unique or interesting aspects of the transit case he studied: perceived mutual benefit from stakeholders; proprietary systems and lack of standards; and support and/or concern from transit labor unions on safety and efficiency aspects of the project. He also noted the following major institutional issues: resource gaps for technology (including human resources, expertise and funding); traditional decision support systems and funding mechanisms did not adequately capture the benefits and costs of ITS, particularly in the realm of operations and maintenance; the complexity of the ITS solutions often confused the public and stakeholder officials as to the values and needs of the project. [Conroy, 2002]

Schweiger [2001] explored the specifics of gaining stakeholder acceptance in transit ITS deployment. She stressed the following stakeholder aspects of advanced public transit systems deployment: stakeholders must be fully educated; the consensus process can be time-consuming and contentious, and may change the direction of the project; a consultant experienced with ITS deployment can help stakeholders reach consensus; and strong project management must be supplied either by the transit agency or by a select group of stakeholder representatives.

Cashin [2002] determined four potential barriers to advanced public transit systems deployments: system integration and connectivity; coordination and cooperation between overlapping or abutting jurisdictions, funding from multiple sources (federal, state and local); operations and maintenance responsibilities and funding.

Gifford et al [2001] explored the requirements of stakeholders in providing priority to transit vehicles and signal preemption to emergency vehicles. The analysis determined the following six requirements of their APTS deployment:

1. The system should be set up such that vehicles are tracked to provide accountability.

2. The system should be as interoperable as possible.
3. Flexibility and adjustability should be built into the system.
4. The system should be easy to maintain.
5. Responsibilities for operations and maintenance should be clearly defined.
6. Transit operators should have minimal interaction with the technology.

Finally, a few articles described methods for assessing stakeholder preferences. [Khattak and Kanafani, 1996; Levine et al., 1999; Levine and Underwood, 1996] These papers used multivariate analysis, analytic hierarchy process and case-based reasoning to resolve conflicts and inconstancies in stakeholders desires and expectations from ITS projects. Levine [1999] defined five steps to preference measurement:

1. Identify participants in the decision-making process, including decision makers, stakeholders, users and other groups affected by the decision.
2. Identify the dimensions, criteria or goals that will characterize the alternatives.
3. Generate preference-based weighting schemes.
4. Develop measures by which each of the alternatives is assessed along each of the relevant dimensions.
5. Rank or rate the alternatives based on measured outcomes and group preferences.

Levine also identified eight stakeholder groups in advanced public transportation systems implementation: transit agency, customer, local/regional public administration, federal officials, agencies, business people, citizen groups and non-profile regional organizations.

4.2 Liability

A major factor in the provision of public services is liability. Stough and Yang [2001] accurately summarized the need for concern for legal liability and the provision of ITS services:

> As in-vehicle and infrastructure based ITS technologies are developed and deployed the driver of the vehicle becomes less of an autonomous agent. Travel and driving behavior including, for example, route selection, signal perception, crash avoidance, vehicle maintenance, speed and navigation all become actions that are in part supported by technology. In a litigious society like the U.S., this creates the opportunity to attribute or spread the blame and costs of driving accidents beyond the driver to others, including governments. For example, when a crash occurs is it only the responsibility of the driver, or is it also the responsibility of the manufacturers of some in-vehicle technology that was supporting the driver or the vehicle at the time of the crash, or perhaps the technically enhanced infrastructure?

A 1996 FTA report defines tort liability within the context of public transit systems as the obligation to make payments for a civil (not criminal) wrong. Torts include negligent acts and other acts for which one can be held strictly liable, even in the absence of negligence. A tort is defined by the presence of four conditions: there is a duty to act, a breach of that duty, the breach of duty caused the incident, the incident resulted in the presence of damage(s). [FTA, 1996]

An example of liability in a transportation-institutional context is the responsibility for a department of transportation to maintain their traffic control signs. If a stop sign is damaged, removed or otherwise rendered unnoticeable to drivers, and a driver, in failing to stop at the intersection, is involved in an accident, the DOT can be held liable for the damages caused by the incident. [Crawford, 1999] The duty to act in this example is the transportation agency's responsibility to maintain all proper signage. The failure of this duty is obvious, as is the cause of the incident and the subsequent damages.

Miller, in his 2000 technical report on the institutional aspects of bus rapid transit, highlighted the following legal and liability concerns:

- Insurance industry-initiated changes in assignment of risk and responsibility for bus transport.
- Potential changes in liability associated with technological and/or operational malfunctions of BRT systems.
- Safety issues arising from changing interaction of pedestrians and motorists with new technologies and/or strategies.
- Safety concerns of residents along BRT corridors.

An article by Ford, et al, [2002] discusses the liability issues associated with traffic calming. The article begins by stating that liability issues associated with traffic calming are the same as any other transportation improvement, and provides five recommendations to avoid being held liable for damages that may be caused by transportation infrastructure improvements:

1. Use proper design standards, including use of devices that have been tested and seek the advice of a licensed professional.
2. Develop a standardized procedure for evaluating a project.
3. To reduce possible incidents during construction, advise the construction process appropriately and provide proper protection of traffic during construction.
4. Supervise the installation.
5. Monitor the results.

The article identified three types of claims that can be brought by the public: a tort challenge (as described above), a challenge of the authority to implement the improvements and a takings claim. (A takings claim arises when an individual or corporation feels it has experienced damage to property rights or values.) The article recommends that the legislation enabling the transportation improvement should fully describe the purpose of the improvement within its preamble.

A BLIP implementation could potentially cause incidents; drivers unfamiliar with the concept of BLIP could react in unexpected ways when the dynamic signage and signals activate. This is especially true if these signs and signals are completely unfamiliar to the drivers. This could result in a possible tort claim. In a BLIP implementation, the failure to act could be the failure to provide adequate information to drivers.

Using only signs and signals already approved by the MUTCD to implement a BLIP system would increase drivers' familiarity with the traffic control devices and therefore reduce potential liability. As discussed above, the use of devices as described by the MUTCD may not be desirable in some locations where BLIP system benefits are desired. In that case, an agency wishing to implement a BLIP system should consider the following recommendations to shield itself from liability:

- Propose combining elements of MUTCD signs and signals, to reduce unfamiliarity with the new signs and signals.
- Place informational signs along the roadway well in advance of BLIP implementation, educating drivers about future changes to the roadway.
- Acquire approval from the US DOT for experimentation with traffic control devices, in accordance with the MUTCD section 1A.02.

A BLIP implementation is unlikely to give rise to an authority challenge. State and municipal departments of transportation have the right to control traffic on their roadways. And the transit system benefiting from the BLIP system would surely work with the appropriate authorities to ensure that the appropriate enabling legislation would be in place before implementation.

All of the technology components that would enable BLIP along a bus route would be installed on public property. AVL transponders and associated hardware would be installed directly on buses. The AVL detectors would be either installed on utility poles or embedded in the pavement. The central control system would be housed at the traffic management center and all signage would be installed in public rights of way. It is unlikely that a takings claim could be successfully brought against a public agency because of a BLIP implementation.

4.3 Enforcement

It is commonly known that rules and regulations, signals and signs are not enough to ensure that drivers obey traffic laws, policies and conventions -- enforcement is necessary. Enforcement systems for dedicated bus lanes can also be used for BLIP implementations. The literature contains many articles discussing enforcement techniques for bus lanes.

The most promising enforcement technique for intermittent bus lanes is bus-mounted cameras linked to image processing and ticketing systems. Many articles describe bus lane enforcement systems that use bus-mounted cameras: Catling and Warner, 1996; Eastman et al., 1996; Ellis, 1998; TEC, 2004a; TEC 2004b; Turner and Monger, 1996; Wiggins, 1998. Bus-mounted enforcement cameras provide several benefits to dedicated bus lanes, all of which also apply to BLIP implementations:

- Bus-mounted cameras ensure that offense is only recorded when delay is caused to the bus.
- Drivers cannot learn the location of the cameras.
- Bus-mounted cameras pick up stationary vehicles parked or double-parked in the bus lane.

Many of the bus-lane enforcement strategies reviewed described roadside changeable message signs that activate when a bus-lane offense has been recorded. This is motivated by an interest to ensure that all drivers (offenders and non-offenders) are aware that the enforcement system is working. Some of the systems reviewed did not include a ticketing mechanism at all, but simply used the roadside CMS as "shock tactics," to let the offenders know they are being watched. [TEC, 2004b]

The articles discussed some legal and institutional issues of bus lane enforcement cameras. Turner and Monger [1996] advised that additions to the vehicle code might be required to ensure that bus lane offences are indeed enforceable and to set fines. They also suggest that a two-camera system proves most effective; the first camera captures photos of license tags, second continuously records the street traffic in front of the bus. The second camera's recordings can be used as evidence in court to provide more context than the still photograph. Ellis [1998] raised the issue that the technology needs to be approved by the local traffic law enforcement body, so that prosecution and fines can be legal. All articles reviewed stated that some political wrangling was necessary to get the enforcement schemes off the ground.

4.4 Funding

A BLIP implementation will require funding to cover the installation, operations and maintenance costs, as outlined in section 6.2.2 below. Briefly, the installation costs will consist of the AVL system, the central control system and the roadside traffic control devices described above in section 3.1. Additional funds will be required for operations and maintenance of the system. Finally, marketing funds should be acquired to support the transit agency's advertising of the enhanced transit system.

There exists a wide variety of funding sources for transportation projects, and all of these sources apply to BLIP systems specifically and ITS projects in general. Henk et al [2004a, 2004b] provide a resource for locating sources of funding for intelligent transportation projects. Other sources of funding specific to BLIP installations are discussed below.

The most reliable source of funding for a BLIP installation would be from the cost savings from the transit agency. As discussed in section 6.1, if the roundtrip time savings of a bus route are equal to or greater than one bus headway, a vehicle can be eliminated from the bus fleet and one fewer driver will be required to operate the route. The transit agency can use this cost saving to offset the installation and operating costs of a BLIP system.

Another source of funding is from the fines collected from bus lane enforcement. It is not possible to determine up front whether this will be a consistent and reliable source of income. Drivers may become aware of the enforcement system and change their behavior to avoid getting tickets: Obviously, this is the desired result, as fewer tickets means less delay to the bus. An agreement would need to be reached between the jurisdictions through which the BLIP route runs and the agencies experiencing the costs of BLIP implementation to ensure that violation fines are redirected from the enforcement agency to the agency experiencing the operating and maintenance costs.

4.5 Marketing

Public relations and marketing of BLIP-enhanced bus lanes will raise awareness of new benefits. DeBlasio et al [1999] state that one of the nine key approaches to successful ITS deployment is to "make ITS visible." Miller [2000] describes that BRT projects need to be "sold" to stakeholders: passengers and general motorists as well as the general public, employees and decision-makers. It is recommended that high and achievable goals be set for the project and communicated to the public. Options for increasing BLIP visibility would include using distinctively colored buses, TV and radio advertisements, bus shelter advertisements and fliers at park-and-ride lots. A website describing the BLIP system's benefits would also be useful.

4.6 Inter-jurisdictional Coordination

BLIP implementations will require coordination between technical components that are installed all along the bus route receiving BLIP treatment. If this bus route crosses jurisdictional lines, some level of inter-jurisdictional coordination will be required to ensure success. Cities usually have jurisdiction over their transportation infrastructure. As such, they have control over their traffic signals, roadside signs, etc. (However, this jurisdiction often does not extend to state highways and US highways.) Establishing coordination between the jurisdictions along a bus route is necessary, as the AVL system needs to work in all areas along the BLIP route. If the transit agency agrees to provide installation and maintenance of the roadside signs and signals, very little coordination between jurisdictions will be needed. It could be as simple as power and communication cables to the roadside signals.

One way to ensure inter-jurisdictional coordination would be to work with a regional transportation agency or the state department of transportation. First, these levels of governance may have fiscal oversight over the city and county transportation agencies. This fiscal oversight can be used as a carrot to encourage coordination between local jurisdictions. Also, if the BLIP route is along a state or US highway, the state will have jurisdiction over the roadway and can ensure the AVL, signs and signals required for BLIP are installed seamlessly along the roadway.

One thing to be noted is that BLIP does not interact directly with traffic signals. This means that the inter-jurisdictional aspects of BLIP are easier to work with than those of TSP. TSP, by its very nature, requires modification of the traffic signal algorithms, and real-time access to signal controllers. Acquiring this type of access from a series of cities along a BLIP route could prove challenging. However, implementations pairing BLIP and TSP will require such inter-jurisdictional cooperation.

Finally, fiscal coordination should be considered. The agencies spending the money to establish, operate and maintain the BLIP system may not be the same agencies reaping the financial benefits. A high level of understanding of the fiscal inflows and outflows should be established during the planning period of the project, and some system to match costs and benefits across agencies should be decided upon.

4.7 User Acceptance & Human Factors

The users of the system must also be considered when discussing the institutional impacts of BLIP, which will have impacts on bus drivers, passengers, private vehicle drivers and residents along a BLIP route. This section explores the possible impacts on these populations.

Bus drivers may experience the biggest impact. BLIP will function without any driver interaction: therefore, there is no change in the responsibilities of the driver along the route. However, since the bus will operate with less delay, there is the possibility of reduced driver fatigue due to shorter trips and less stopping along the route. On the contrary, the reduction in travel time variation will result in bus routes with less slack time: bus drivers may no longer be required to wait at specific time-points. Drivers may perceive these time-points as small breaks [Bailey and Hall, 1997], and may perceive their subsequent reduction as reduced en-route rest time. Miller [2001] states that bus drivers may have the following concerns when working with BRT technologies: drivers may not get the support they need from transit managers; the role of drivers will change with the adoption of new technology; the AVL system could be used to monitor driver performance and schedule adherence; and drivers may become confused when switching from high-tech to low-tech routes. Additionally, video cameras installed for enforcement may also be perceived as spying by "Big Brother" and may cause come concern or stress for bus drivers.

It is to be expected that BLIP may cause private vehicle drivers some frustration. Drivers in a queue at a signal may become annoyed as they watch the bus pull up past them. Also, drivers will be required to react to the newly installed dynamic signs and signals.

This may be a cause for concern and potential incidents. For example, a car might react too quickly to the roadside sign and/or pavement lights and collide with a vehicle in a neighboring lane while merging. However, it is likely that these new warnings could decrease drivers sense of safety, resulting in them driving more slowly and safely. [Beaubein, 2002]

One interesting experience that may have some relevance is an example from Sweden referred to as "Dagen-H". On September 3, 1967, traffic in all of Sweden switched from driving on the left side of the road to driving on the right. A common expectation is that traffic accidents would increase after such a drastic change. On the contrary, the accident rate dropped significantly and remained lower for the next two years. One possible explanation for this is the change in driving conditions made drivers more aware of their surroundings and therefore more cautious while driving. [Wikipedia, 2005].

Passengers of bus systems will also experience a change. As discussed above, reductions in travel time and increases in reliability should shift some riders to the BLIP-enabled route. One example of ridership changes resulting from a comparable ITS/APTS implementation is the impact that TSP had on the Los Angeles MetroRapid bus lines. Results from before and after surveys showed increased rider satisfaction, increased ridership and changes in rider demographics. Specifically, the results indicated:

- Customers perceived an unprecedented increase in reliability and quality.
- The MetroRapid system drew non-traditional users, and had higher new ridership than local lines.

- 13% of the riders on the MetroRapid had income over $50,000, versus only 6% on local buses.
- MetroRapid buses had a higher percentage of male riders. [MTA, 2002]

BLIP implementations will have little impact on pedestrian populations, local residents and employees, etc. The signage necessary will not disrupt the pedestrian environment. No additional noise or odor will be generated by the implementation. Because buses may be braking and accelerating less often, a BLIP implementation might improve ambient air quality by reducing diesel emissions and brake dust. Air quality impacts due to increased private vehicle congestion should be considered. However, it is likely that the impact on private vehicles of a BLIP system will be similar to that of buses operating in mixed traffic lanes.

4.8 Equity

Transportation planners have realized the need to evaluate transportation projects for the equitable distribution of benefits. Equity in this context means that the benefits do not unintentionally favor one particular group at the expense of another group. An equitable transportation project is a Pareto improvement: many experience benefits while none experience disbenefits. As hinted above, certain transportation projects may intentionally provide benefit to a particular group, usually one already disadvantaged. And this benefit might come at a cost to another group, usually one better off. The essence of an equity evaluation is to ensure that there are no unintended consequences in the benefit distribution of a transportation project.

With BLIP, there are two opportunities for equity evaluation. The first is the potential benefit to bus riders at the expense of drivers of private vehicles. While benefit in this case is going to one group at the expense of another, it is an intended benefit shift, and the decision to benefit bus riders at the expense of private vehicle drivers is one that a jurisdiction must make when deciding whether to implement BLIP along transit routes. That jurisdiction should ensure that a BLIP route has high enough ridership to warrant special treatment for the bus: the disbenefit to drivers cannot be outweighed by empty buses moving quickly. As discussed later in this paper, the benefits to individual bus riders can be significant, and the cost to individual drivers trivial.

The second case where benefit distribution must be evaluated is among bus riders. Is any group of riders being disadvantaged because of the benefits being gained by others? At first blush, it seems that all bus riders will benefit from BLIP: the bus simply travels with less delay and greater schedule adherence. If a transit agency decided to install BLIP only along certain routes, an equity evaluation should be performed to assess whether resources are being diverted from other routes to provide benefit to the BLIP route. And if so, is this transfer of benefit intentional and are the benefits being reaped by those more well off at the expense of those less well off? Rider surveys can help answer these questions.

One possible example of such an equity issue in bus transit is from the MetroRapid final report mentioned above. The survey results show that the MetroRapid TSP-enhanced bus lines had higher percentages of higher-income and male riders. [MTA, 2002] Survey results have shown that the MetroRapid system is attracting non-traditional bus riders. Another possibility is that affluent males are best suited to benefit from the MetroRapid service enhancements (fewer stops and no schedule). Are these benefits being conveyed to affluent male riders at the expense of lower income and female riders? Are disadvantaged riders no longer well served by buses along this route? In this case, rider surveys have answered these questions, showing that the MetroRapid project does not have negative equity impacts.

Another equity issue that should be raised comes from possible scheduling changes associated with APTS. Many TSP systems have abandoned traditional schedules in favor of headway-based schedules. With headway-based schedules, buses aim to arrive at a stop a set number of minutes (one headway) after the previous bus instead of at a particular time. The end goal is to ensure that riders waiting at a bus stop will wait no more than a set time for a bus, and that buses will not waste time and fuel idling at time-points. In doing so, they eliminate the concept of schedule adherence by eliminating the schedule. These systems are often augmented with real-time bus tracking systems (AVL) that allow riders to look up arrival times online, via wireless internet or through digital displays at the bus stops.

The potential equity issue with these systems is that they remove set schedules that are printed on paper and accessible to all, and replace them with dynamic schedules that many people may not have the technology to access. In simple terms, more affluent riders who can afford access to the Internet via personal computers or advanced wireless phone technology are the only real beneficiaries of the new headway-based schedules. Those less fortunate, who do not have access to information technology, must arrive at the bus stop before learning when the bus will arrive. Once a rider has reached the bus stop, that information is of little use.

4.9 Conclusion

Institutional issues that apply to ITS and APTS implementations also apply to BLIP systems. BLIP also has some unique issues that must be considered. The merging movements required of private vehicle traffic may cause accidents; therefore BLIP implementers should take care to shield themselves from liability. Bus-mounted cameras can provide a reliable method of BLIP enforcement. In addition to other funding sources, traffic fines and cost savings from BLIP delay reduction can be used to finance a BLIP implementation.

The use of ITS should be made visible, and the benefits may need to be "sold" to stakeholders. The transit agency should work with the jurisdictions through which the BLIP route runs to ensure that common technologies are in place to facilitate the entirety of the bus route. Also, jurisdictional coordination is necessary to ensure that those organizations reaping the benefits of BLIP are compensating the organizations experiencing the BLIP costs. Many different populations will be affected by a BLIP implementation, and care must be taken to ensure that no one group is disproportionately burdened or benefited.

5 Feasibility Discussion

5.1 Overview

The implementation of BLIP will have an effect on the traffic capacity of the roadway. The severity of that impact depends on a series of factors, such as traffic demand, number of lanes, headway (frequency) of the bus, percent of right-turning vehicles and pedestrian volumes. If both traffic demand and bus frequency are high, the private vehicles may experience serious delay.

Eichler and Daganzo [2005] provide a macroscopic analysis of BLIP impacts, determining expected capacity reduction due to BLIP. In this analysis, it is shown that under BLIP, buses act as moving bottlenecks and can be modeled using the traditional analytical methods of transportation engineering. It is also shown that, on roads of three or more lanes, BLIP does increase delay to traffic but does not significantly decrease the capacity of the roadway. Finally, it is posited that BLIP is most appropriate for roads where demand is about 80 to 90% of the capacity the road with one fewer lane. [Eichler and Daganzo, 2005] Discussion of microscopic feasibility criteria is presented below.

It may be of interest to decision makers to impose constraints on the impacts of a BLIP implementation. Decision makers may be interested in setting limits for the maximum duration of a traffic queue caused by BLIP activation. Or perhaps they may wish to set a rule that queues caused by BLIP cannot extend back beyond a certain distance (perhaps the distance between intersections, to prevent traffic queues from blocking intersections). The following discussion explores boundary conditions for feasibility of a BLIP system given such self-imposed level of service (LOS) constraints.

This discussion considers that traffic merges upstream of potential bus interaction while discharging from a queue. Once the queue has cleared, traffic is no longer instructed to merge. This queue clearance time is a function of the offset between the signal and the next upstream signal.

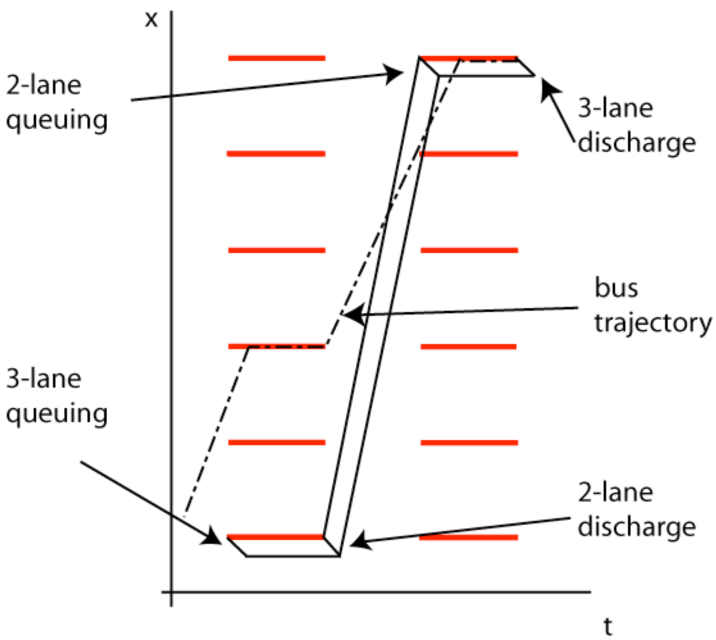

Figure 2: Example of BLIP activation. Traffic merges from 3 lanes to 2 lanes while discharging from an upstream signal in anticipation of queuing in 2 lanes downstream. The broken line represents the trajectory of the bus, and the solid lines represent the first and last vehicle that will queue at intersection where a bus is expected.

Figure 2 displays a time-space diagram that provides an example for a three-lane roadway. The vehicles denoted by the solid trajectories are the first and last to queue at the intersection where the bus is expected. These vehicles and any in between will queue at the upstream signal as normal, but will discharge from that queue in only two lanes. This will ensure that the vehicles at the downstream intersection queue in only two lanes. This leaves a lane open for the bus which, represented by the broken line, can jump the queue and pull up to the stop line.

Again, in this scenario, once the queue at the upstream intersection has dissipated, vehicles arriving at the intersection are permitted to use all lanes. If the vehicles arriving after the queue has dissipated are anticipated to interact with the bus, they will have already merged at an intersection even further upstream. If not, they will either arrive to the downstream intersection after the bus has passed, or they will be stopped at an intermediate intersection.

A series of simple calculations can be performed on an intersection-by-intersection basis to determine whether a BLIP implementation is feasible along a given roadway segment. The criteria for feasibility include:

- Impacts constrained in time: Implementation will not create a prolonged disturbance over time.

- Impacts constrained in space: Implementation will not cause queues that spill back beyond a predefined distance.

These self-imposed constraints are discussed in detail in the following sections.

5.2 Basic Analysis

This basic analysis uses a simplified scenario for evaluating the impacts of the bus on through traffic. First, the discussion ignores turning traffic. It will be noted below when non-trivial turning traffic will impact the formulations. Second, it is assumed that all signals have the same cycle length and same percentage of green time. Third, it is assumed that the signals are coordinated such that there is no offset between intersections: all signals turn green at the same time. The scenario uses a free-flow speed of 60 km/hr, and the intersections are spaced 100 meters apart. As such, the first vehicle leaving a green signal will be the first vehicle to queue at a red signal five intersections (500 meters) downstream. This analysis also assumes that the traffic demand is at capacity. These assumptions only pertain to this section.

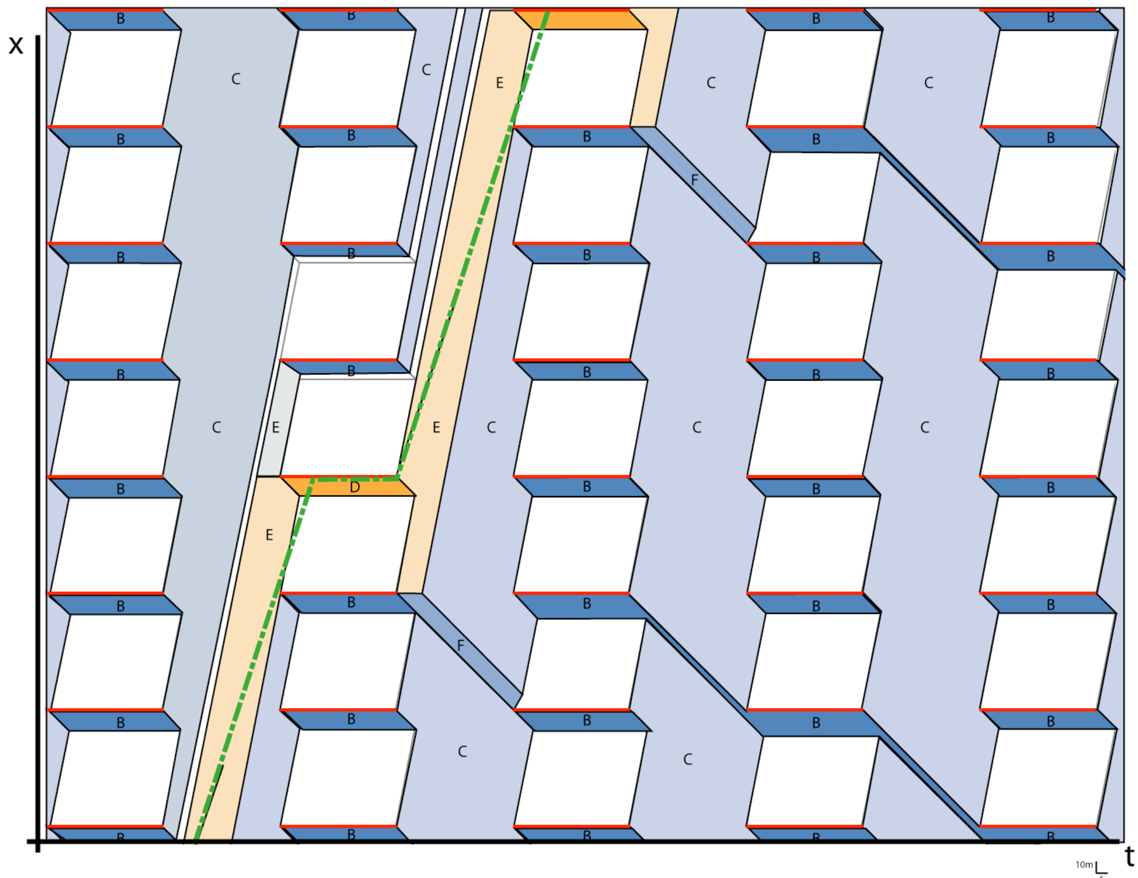

Figure 3: Basic time-space diagram showing a BLIP activation. See Figure 7 in the appendix for descriptions of traffic states.

The approach, illustrated in Figure 3, restricts the right lane from private traffic only long enough to ensure that private vehicles do not queue in front of the bus. This is accomplished by requiring discharging queues to leave the rightmost lane when deemed necessary by the algorithm. This creates a "slanted" restricted region that is roughly a parallelogram. The sides of the region are defined by the trajectories of the first and last vehicle in the restricted region, and the slope of these trajectories is free flow speed.

Because all vehicles within and neighboring the restricted region are traveling at free flow speed, vehicles only enter the region at the "bottom". Notification of roadway status is communicated to drivers at the intersection signals.

It is clear from Figure 3 that the merging movements created by BLIP activation create ribbons of congestion that travel backwards along the roadway. It should be noted that these ribbons would dissipate if the demand were less than capacity. It should also be noted that matching ribbons of low flow are generated in front of the bus. It can be shown (and is demonstrated in Eichler and Daganzo [2005]) that the forward-moving ribbons of low flow cancel out the backward-moving ribbons of congestion. As such, the traffic disruption caused by the first bus is cancelled out before it reaches the second bus.

5.3 Impacts Constrained in Time

The duration of the disturbance caused by reserving a lane for traffic is localized to the merge movements of private vehicles as they vacate the lane reserved for the bus. As stated above, this discussion recommends that these merge movements are performed as an intersection queue discharges. It can be easily imagined that a three-lane queue discharging into only two lanes would have some non-trivial impact on traffic flow on the roadway. The section *Relaxation Time Constraint* Calculation describes the calculation of the duration of that impact.

The impacts in time of the disturbance caused by the activation of BLIP can help determine the feasibility of implementing this architecture on a given bus route/roadway segment.

5.4 Impacts Constrained in Space

Any disturbance in traffic flow not only persists in time, but also exists in space: traffic queues take up physical roadway space. It might be desirable to ensure that queues caused by a BLIP implementation do not grow beyond a certain length: for example, one may wish that a queue does not back up into the previous upstream intersection.

Decision makers can use the technical discussion in the section *Queue Length Constraint* below to determine the length of a queue caused by a BLIP activation. Alternatively, formulas are presented that can determine an upper-bound for the traffic demand flow such that a BLIP-caused queue does not grow beyond a fixed length.

6 Benefits & Costs

6.1 Benefits

The direct benefits of a BLIP implementation fall into two categories: reduced mean travel time and reduced travel time variation. These are explored below. However, it must be noted that reductions in bus roundtrip time mean and variance have a compounding benefit: if the amount of running time and slack time saved by BLIP is equal to or greater than one headway, a bus can be removed from the fleet. [Callas, 2002] It is here, in the decreased capital costs, that real cost savings can be reaped.

6.1.1 Reduced Mean Travel Time

Transit vehicle travel time is usually estimated using three factors. The first is the distance traveled divided by the free-flow speed of the bus. The second, signal delay, is time spent waiting at traffic signals. The third, stop delay, is the stop time required for the discharge and boarding of passengers. Bus Lanes with Intermittent Priority can help reduce the signal delay and stop delay components of bus travel times. BLIP can reduce signal delay by allowing buses to jump the queues at traffic signals. Additionally, they reduce stop delay by allowing buses to easily merge back into the traffic stream. These benefits are explored in detail below.

6.1.1.1 Reduced Signal Delay

Signal delay for a transit vehicle is defined as the delay experienced at signalized intersections. This delay can be broken down into two components: signal stop delay and signal queue delay. The signal stop delay is the delay caused by the red stop signal. The signal queue delay is component of the delay caused by the existence of other vehicles in the queue ahead of the bus. As discussed above, TSP has been proposed to help reduce signal stop delay by modifying the green time of a given cycle period to give priority treatment to the bus. In contrast to this, a BLIP proposal attempts to eliminate the signal queue delay portion of signal delay.

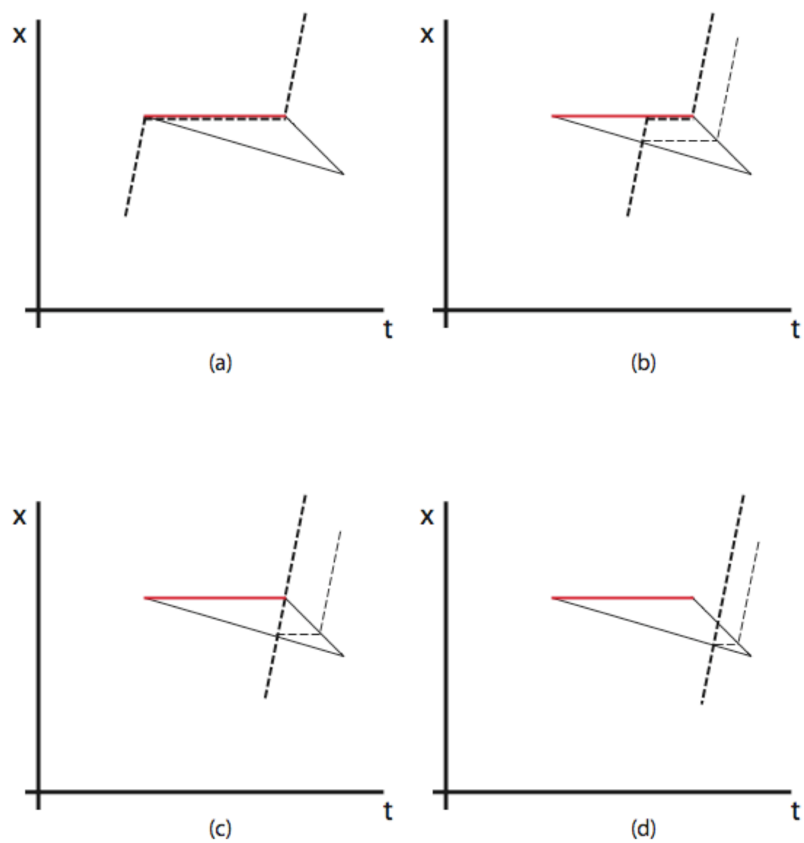

Figure 4: Delay reduction benefits as a function of bus arrival time. The thick dashed line represents a bus trajectory that uses a BLIP, and thin dashed line represents trajectory of bus without priority treatment. a) Bus arrives at onset of red signal and receives no benefit. b) Bus arrives near middle of red and receives some benefit and experiences some signal delay. c) Bus arrives at end of signal and receives maximum benefit. d) Bus arrives after signal has turned green, and receives benefit by jumping the residual queue.

Under a BLIP implementation, the reservation of the lane allows a bus to "jump the queue." The amount of delay saved by a bus as it jumps the queue at an intersection is highly variable, and depends on the traffic volume as well as the bus's arrival time at the intersection in relation to the cycle. Figure 4 shows examples of time-savings as a function of bus arrival time. If the bus arrives just as the signal turns red, as in Figure 4a, there is no queue-jumping savings; there would be no queue in front of the bus and the entire signal delay is all due to the red signal. (In this situation, traffic signal priority would provide much benefit, holding the signal green until the bus passed.) However, a bus with a trajectory such that, if there were no queue at all it would reach the stop line of the intersection the instant the signal turns green as in Figure 4c, will gain much benefit from jumping the queue. (And in this situation, TSP would provide little benefit.)

The section *Reduced Signal Delay* in the appendix explores the calculation of signal delay reduction due to a BLIP installation. The formulation represents the time savings per intersection at which the bus would normally have queued. However, this doesn't portray the full time-savings of a bus: saving time at one intersection could result in a bus avoiding a red signal further downstream, yielding even more time-savings. This potential encourages the development of a generalized model.

An additional time saving bonus can be reaped when near-side bus stops are used. The bus, as it jumps the queue, can use the time waiting at the stop line for passenger movement. Depending on when the bus arrives in the signal cycle and the existence of pedestrian-blocked right turns, this can result in a 100% overlap of signal stop time and bus stop time, resulting in even further time savings.

6.1.1.2 Reduced Stop Delay

Stop delay is defined as the delay experienced by a transit vehicle due to stops for passenger movements. This delay can be decomposed into the following parts: acceleration/deceleration time, passenger alighting and boarding time and merge delay. The merge delay component is delay experienced by the bus as it attempts to merge back into the traffic stream. Because a traffic lane is reserved for the bus, BLIP systems eliminate merge delay and therefore reduce stop delay. Merge delay is roughly explored in the literature without consideration of traffic flow theory. [Emelinda et al, 1990] The mathematical exploration of the calculation of this merge delay is presented in *Reduced Stop Delay* of the appendix.

Depending on the bus stop design, this delay can be deterministically zero (in the case of in-line bus stops or bus bulbs), or non-zero (in the case of bus bays). Bus stop location also has an influence on merge delay: near-side bus stops have the effect of allowing the bus to use the intersection as an acceleration lane [Tod et al, 1991], reducing merge delay, where as far side and mid-block intersections do not have this benefit.

6.1.2 Reduced Travel Time Variation

Perhaps more important than reduced travel time is reduced travel time variation. Variation in bus round trip time reduces reliability and increases transit agency costs. As discussed above, the round trip travel time of a bus is a function of many factors. All of these factors except for travel distance are subject to variation.

A BLIP implementation reduces travel time variation either by reducing the variation in one of the above-described variables or removing the variable entirely. In the case of signal delay, a bus that arrives at any time of a red signal will leave the signal as it turns green. In effect, regardless of when the bus arrives at the red signal, it will leave at the same time. This has a consolidation effect on bus trajectories, acting as a built-in check on variation in travel time. Some or all of the delay (variation from the mean travel time) incurred between signals is erased as the bus jumps the queue at the red signal.

Figure 5 illustrates this graphically: The solid line represents the scheduled bus trajectory, with an average running speed (including stop delay) of v_1 and an overall average speed (including signal delay) of $\bar{v}$, represented by the double-dashed line. The two other dark dashed lines represent other possible bus trajectories with lower average running speeds (v_2 and v_3) due to unexpected conditions, such as traffic accident, pedestrians blocking right turns, or the boarding of a wheelchair-bound passenger. The grey dashed lines represent the trajectories of the slower buses operating without BLIP.

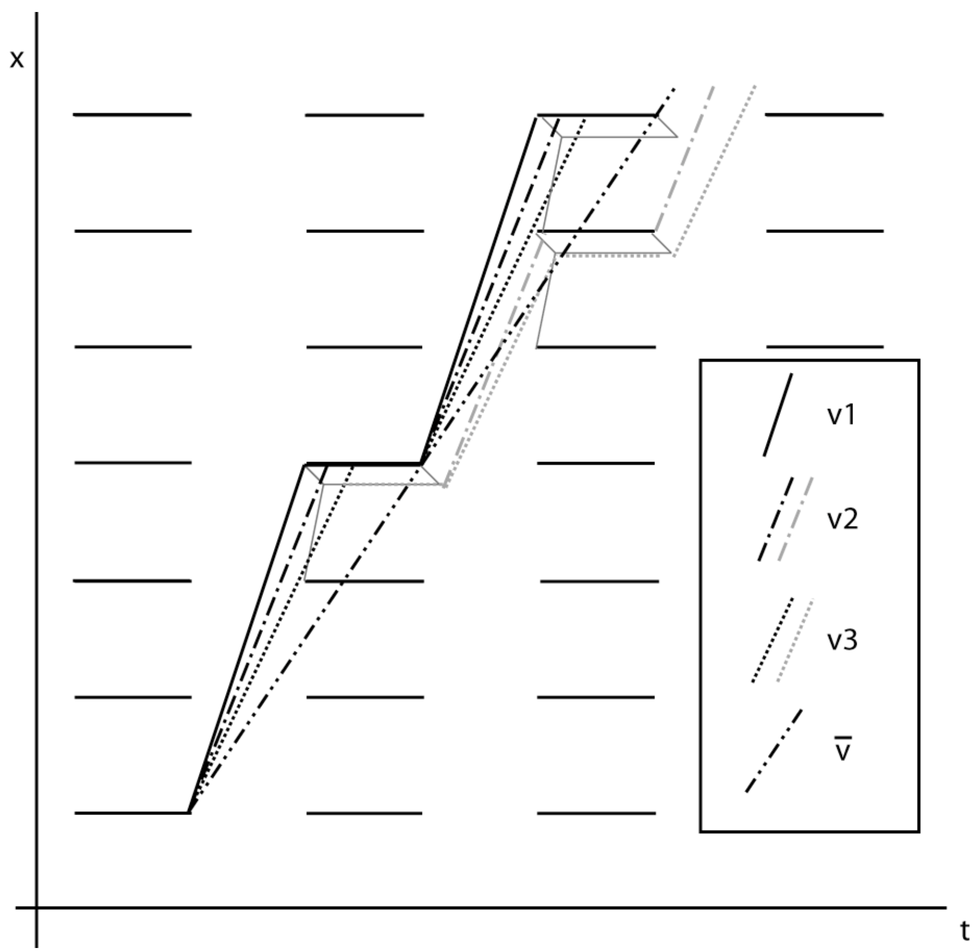

Figure 5: Illustration of various bus trajectories with speeds v_1, v_2, v_3, all of which under BLIP have the same average speed $\bar{\mathbf{v}}$. The gray lines represent the v_2 and v_3 trajectories without BLIP treatment.

It is obvious from the diagram that, despite the possible delays incurred along their routes, all of the trajectories "collapse" to a single average speed. The greater meaning of this is that a BLIP implementation has the potential to reduce the infinite variety of possible average speeds down to a finite set of average speeds. Given known traffic conditions, signal spacings and offsets, average passenger volumes, etc., a transit agency can use BLIP technology to effectively render highly variable bus travel times into deterministic and known travel times.

6.1.3 Qualitative Benefits

The benefits of a BLIP implementation are not restricted only to travel time savings. Many other quantitative benefits exist and should be considered when evaluating the merits of implementation. The social benefits of a faster and more reliable system and increased ridership should be one of the driving factors behind considering a BLIP implementation. There is a possibility of private vehicle drivers switching to transit use, which can result in either less congestion on the roadway or allowing latent demand to take the roadway space vacated by the new transit riders. Either way, person miles traveled increases without an increase in vehicle miles traveled.

6.2 Costs

6.2.1 Increased travel time for traffic

The delay to other vehicles can be easily evaluated using the input-output diagram displayed in Figure 6. In this example, it is clear that the delayed departures catch up to the desired departures after one cycle. From the data used to derive this queuing diagram, one can easily derive delay caused by the bottleneck: the delay is the area between the two departure curves. This delay can be calculated geometrically or through analytical methods with a spreadsheet. This delay is one of the costs that should be considered when evaluating a potential BLIP implementation.

This delay should be averaged over a bus headway to provide an accurate portrait of the actual effects. Additionally, the delay can be averaged over the number of vehicles in a bus headway, resulting in an average delay per vehicle due to providing the bus priority at intersections and stops.

It should be noted that this delay might not be newly created, as the interaction between buses and private vehicles often causes delay. The delay calculated here could simply be a representation of normal interaction delay. This depends highly on characteristics of the roadway, including the bus stop configuration. It is possible that the delay described above could be less than that which would occur due to normal bus-vehicle interaction.

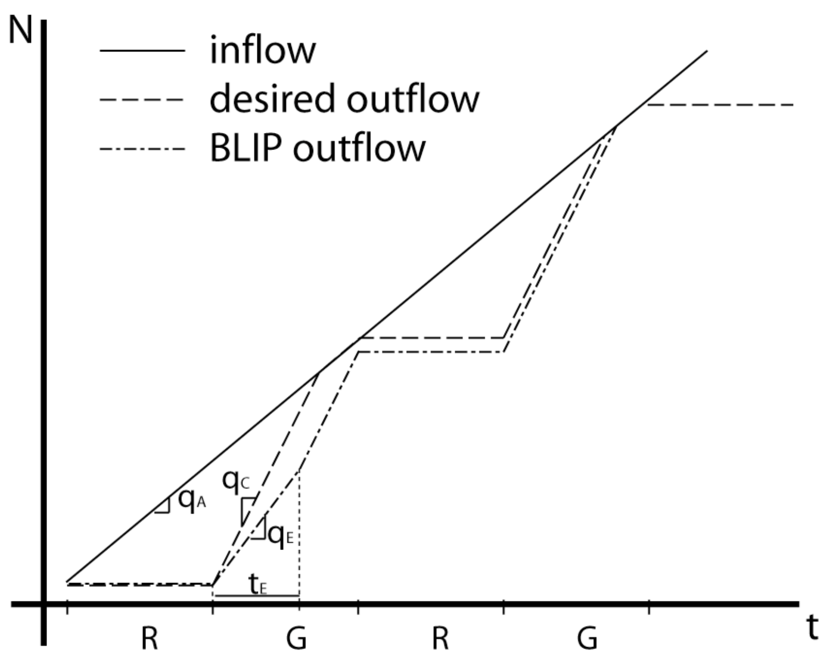

Figure 6: Queuing diagram showing the dissipation of the disturbance caused by the BLIP activation.

6.2.2 Installation and operating costs

As discussed above, it may be possible to implement a BLIP with pre-approved signals available in the MUTCD. However, it may be necessary to propose new signs and signals. Transit agencies should be able to work with vendors of traffic signs, signal and signal controllers to determine the implementation cost of a BLIP.

Operating costs of BLIP systems should prove trivial, as the only costs are power supply and communications costs. However, maintenance costs should be considered and budgeted for.

7 Conclusion

The above discussion of Bus Lanes with Intermittent Priority (BLIP) has presented a cost effective method of increasing bus transit system speed and reliability without creating excessive delays to private vehicle traffic.

BLIP is not without precedent, and the concept exists within a larger family of Advanced Public Transit Systems technologies. The design of a BLIP system includes consideration of technology, the design and placement of bus stops, and standards for signs and signals. BLIP is fully compatible and even symbiotic with TSP.

Institutional issues abound with all ITS and APTS system implementations. Special consideration should be taken when considering BLIP in regards to liability, enforcement, funding, marketing, inter-jurisdictional coordination, user acceptance and equity.

BLIP systems can be deemed feasible based on a variety of criteria, including the duration of the disturbance caused by merge movements and the length of the queues that grow due to these merges. The benefits of decreased travel time and decreased travel time variation are compelling, and can potentially offset the installation and operation costs and potential delay to private vehicle drivers.

With the current trend of increasing traffic congestion and decreasing bus transit ridership, transit agencies need an efficient and effective way to reduce delays to transit vehicles. Bus Lanes with Intermittent Priority are an exciting new concept in surface transit and have the opportunity to solve the problems of slow and irregular transit service.

7.1 Recommendations for Implementation

- Use near-side bus stops to maximize overlap between signal delay and passenger movement time.
- Use MUTCD-approved signs when appropriate. Submit requests to have experimental uses of traffic control devices approved.
- If possible, pair BLIP with TSP for maximum benefits.
- Use bus-mounted cameras to provide an enforcement mechanism.
- Include enforcement cameras, bus lane violations and policy statements in enabling legislation.
- If necessary, use regional public-private partnerships to span jurisdictions and include technology standards and funding agreements.
- Advertise BLIP-enhanced bus lines to stakeholders and the general public.
- Assess bus drivers' opinions about BLIP and address any concerns they raise.
- Perform surveys before and after implementation to assess riders' attitudes and potential issues of inequitable benefit distribution.
- Implement BLIP as a technique to enhance schedule adherence, maintaining fixed and published schedules.

7.2 Recommendations for Further Research

- Development of a generalized model for predicting BLIP benefits and the extent of disruptions to traffic.

- Incorporation of BLIP into traffic modeling tools.
- Incorporation of BLIP-enabling signs and signals into the MUTCD.
- Investigation of in-pavement lighting technology and similar technologies that can enable "dynamic" pavement markings.

Appendix: Technical Formulations

The above institutional assessment and design discussion intentionally avoided the introduction of complicated technical concepts, equations or figures. The technical analysis of BLIP has been divided into two parts. The first part is a macroscopic assessment of BLIP capacity performed by Eichler and Daganzo [2005]. The second part, a microscopic technical assessment, is briefly discussed above and presented below in more detail. First, the system inputs and supporting concepts are discussed. Then the equations from the feasibility discussion are presented: relaxation time and maximum queue length. Finally, the benefits of reduced signal delay and reduced stop delay are explored mathematically.

System Inputs

The following variables will be used throughout the following technical formulations.

q_X	Flow at traffic state X
g	Green time
c	Cycle length
t	Time. Used to illustrate "specific" times (t_1, t_i, t_{i+1}, etc.)
t_X	Time of interest in traffic state X
O	Offsets, expressed in time units.
L	Length of roadway segment, usually the distance between intersections.
v_F	Free flow speed.

Supporting Concepts

Kinematic Wave Theory

This technical discussion uses concepts of the kinematic wave theory, also known as the Lighthill-Whitham/Richards (LWR) theory. [Lighthill and Whitham, 1955; Richards, 1956] This theory provides tested techniques for modeling traffic flow and queuing. The LWR theory covers stationary traffic states, queue formation and discharge speeds, traffic response to bottlenecks, etc.

Fundamental Diagram

One component of the LWR theory is the concept of the fundamental diagram. The following sections assume a triangular fundamental (flow/density) relationship for all lanes combined as displayed in the diagram in Figure 7. The flow at any given point on the diagram will be expressed as a q with a subscript matching the label of the point on this diagram. For example, the flow at point E will be expressed as q_E. The diagram illustrates two "curves." The first, larger curve represents the roadway at "full" capacity. The smaller of the curves represents "reduced" capacity roadway conditions, when one of the lanes has been reserved for the bus and is therefore no longer available to private vehicles.

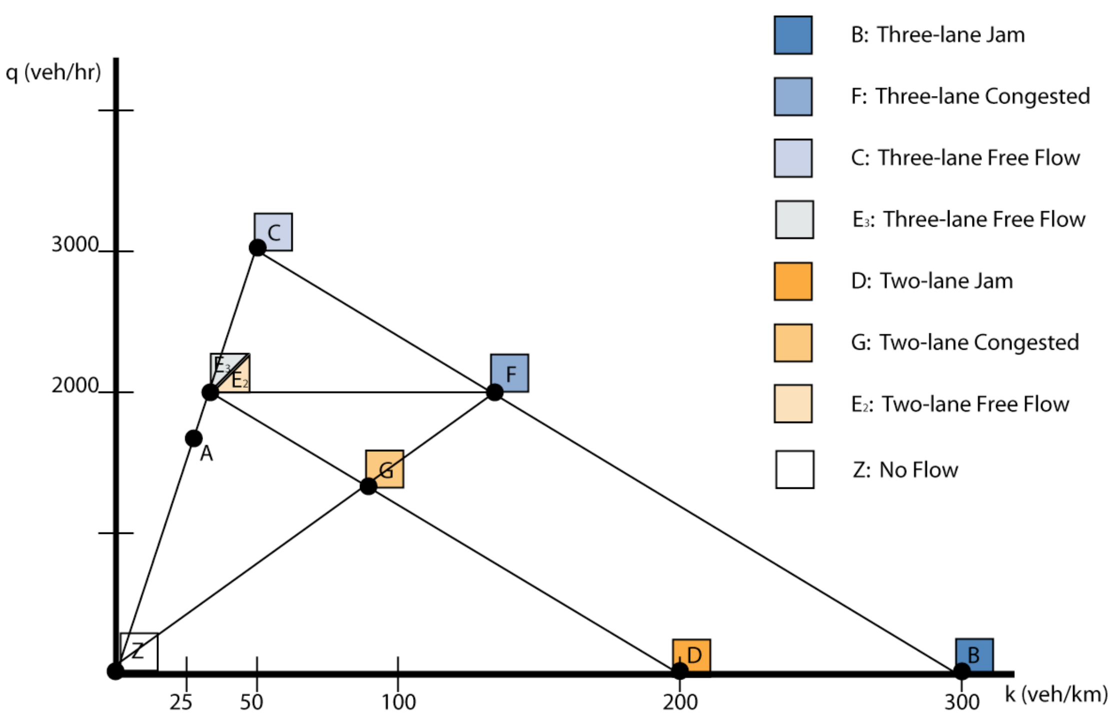

Figure 7: Flow/Density diagram. This specific diagram represents a three-lane roadway being reduced to a two-lane roadway.

The diagram illustrates the following traffic states of interest:

A	Uncongested free-flow
B	Full roadway jam density
C	Full roadway capacity
D	Reduced roadway jam density
E	Reduced roadway capacity
F	Congested full roadway conditions with same flow as state E
G	Congested reduced roadway with same speed as F

Offsets

An offset is time difference between signal cycles at subsequent intersections. Offsets can be expressed as absolute, relative or effective. An absolute offset (O_A) is the actual time difference between initiations of the green phases of two signals. A relative offset (O_R) is the absolute offset adjusted by the free-flow travel time between intersections. Relative offsets can be positive or negative, and are always between *-c/2* and *c/2*.

$$O_R = O_A - \frac{L}{v_f}$$

The effective offset (O_E) is the amount of time the red signal of an intersection is exposed to traffic from the upstream signal.

Actual and effective offsets are illustrated in Figure 8. The basic equation for the effective offset is simply the absolute value difference of the relative offset:

$$O_{E\,basic} = \left|O_R\right|$$

The absolute value is necessary here due to the fact that the effective offset's sign does not have an effect on the queue length: whether the vehicles arrive at the start of the red or towards the end, the queue length does not change. All that matters is the amount of time that the red signal is exposed to oncoming traffic from the previous signal.

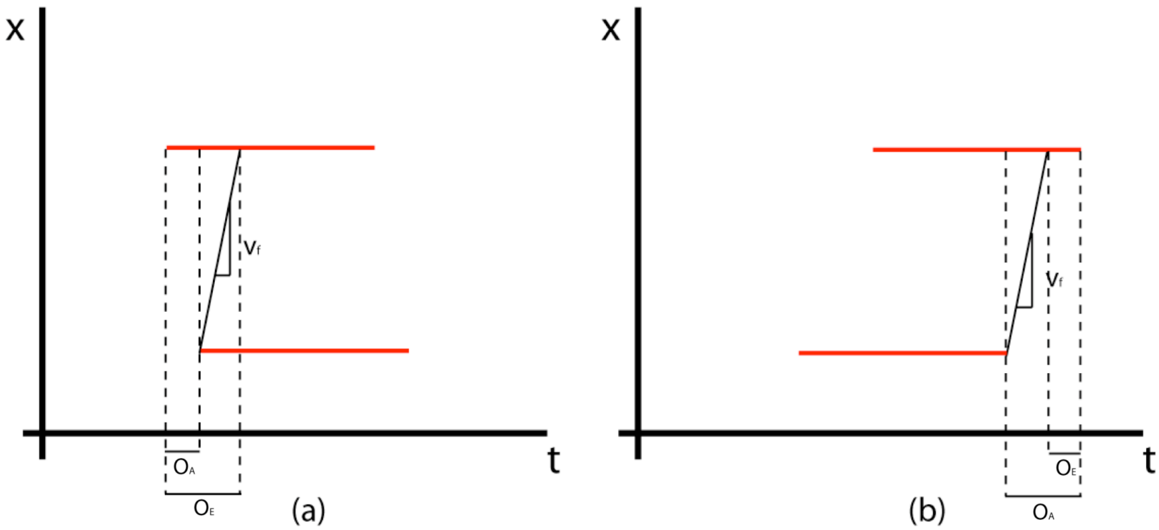

Figure 8: Comparison between actual and effective offset. The actual offset is represented by t_a and the effective offset is represented by t_O. Part a shows a negative actual offset, part b shows a positive actual offset.

Due to the cyclical nature of traffic signals, this basic formulation must be further refined to accommodate the situation where the signals are anti-coordinated. In other words, if the basic effective offset is greater than the green time provided by the signal:

$$O_E = \begin{cases} O_{E\,basic} & O_{E\,basic} < g \\ \min(g, c - O_{E\,basic}) & g < O_{E\,basic} \end{cases}$$

This expression captures the fact that if the basic effective offset is greater than the green time provided by the signal, the effective offset will be equal to the green time of the upstream signal.

The effective offset is useful when determining the amount of queuing at an intersection given the coordination (or lack there of) between a signal and other upstream signals. More specifically, the effective offset is the time during which a red signal could be exposed to saturation flow traffic from an upstream intersection. For example, if the actual offset is equal to the free flow travel time between intersections, the downstream signal will turn green as the first vehicle discharging from the upstream queue reaches the intersection, resulting in an effective offset of zero and no queuing at the intersection.

Queue Clearance Time

Mentioned above, the BLIP restriction will be activated at an intersection for the amount of time that it takes the queue to clear at that intersection. As displayed in Figure 9, this "queue clearance time" is defined as the elapsed time between the initiation of the green phase and the time the last queued vehicle crosses the stop line. (It should be noted that this last vehicle might not have been queued when the signal turned green.) The queue clearance time is a function of the size of the queue at an intersection, and that queue size is subsequently a function of the traffic flow from the upstream signal, the offset between the signals and the queue discharge rate. This clearance time can be determined analytically. The size of the queue by definition is the flow that is stopped at the signal.

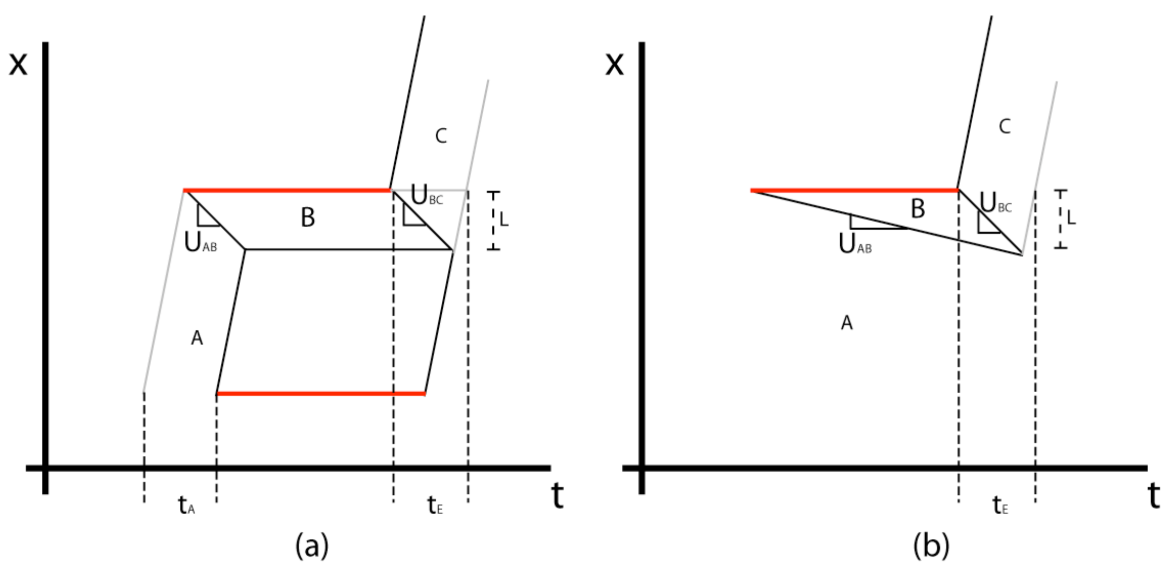

Figure 9: Queue clearance time for non-isolated (a) and isolated (b) intersections.

For an intersection in a series, as illustrated in Figure 9a, the red signal is only exposed to flow for the duration of the effective offset, $t_A = O_E$. (Here t_A represents the time the signal is exposed to traffic state A, which is equal to the effective offset (O_E) calculated above.) As such, the queue clearance time, t_E, for a non-isolated intersection can be calculated easily using queuing concepts. The queue size, N_q, will simply be the flow arriving at the intersection times the effective offset, $N_q = q_C \cdot O_E$. Here, q_C is the saturation flow of the discharging upstream signal. The same will apply to the discharge of the queue, $N_q = q_E \cdot t_E$, where q_E is the saturation flow of the signal under inspection. Setting the right-hand sides of these equations equal to each other and solving for t_E results in the following equation for the queue clearance time of a non-isolated signal:

$$t_E = \frac{q_C}{q_E} t_A$$

For an isolated intersection with an assumed constant flow less than saturation, as illustrated in Figure 9b, vehicles will be interrupted not only by the red signal but also by the tail end of the dissipating queue, resulting in vehicles queuing for a duration of $(c-g) + t_E$. Using the same method used above, the following equation can be derived for the queue clearance time for an isolated intersection:

$$t_E = \frac{q_A (c-g)}{(q_E - q_A)}$$

If traffic turning on to the arterial is considered, a factor will need to be added to the arrival flow quantity.

Relaxation Time Constraint Calculation

Figure 10 displays a time-space diagram of the situation where a base traffic flow (state A) queues at an intersection in three lanes (state B) and then discharges at a two-lane free flow (state E). This merge process creates a new traffic state (state F): the removal of a lane at the intersection can be seen as a stationary bottleneck, and the discharging queue results in different states on either side of the bottleneck: uncongested downstream (state E) and congested upstream (state F).

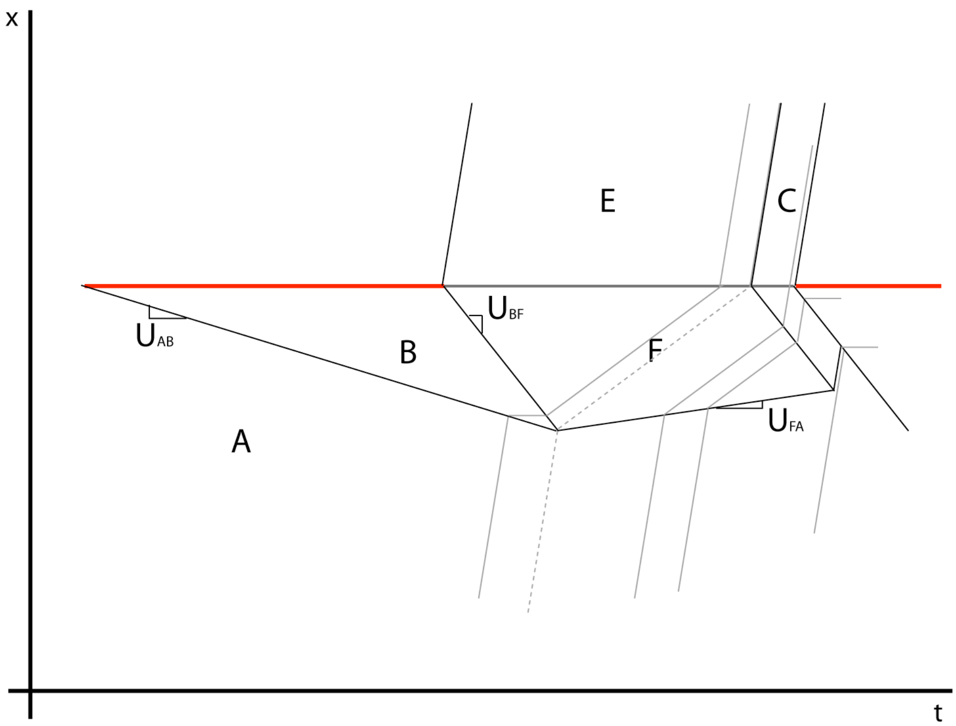

Figure 10: Time-space diagram illustrating merge during the activation of the priority lane.

The demand for the intersection in question is simply desired flow during the relaxation time:

$$q_A nc$$

where q_A is the "base" flow or demand, n is the number of cycles that the disturbance persists and c is the cycle length.

The supplied capacity of the intersection is made up of three parts:

$$q_E t_E + q_C(g - t_E) + q_C g(n-1)$$

The first part ($q_E t_E$) gives the flow capacity available during activation of the BLIP at the intersection, where q_E is the reduced saturation flow and t_E is the queue clearance time.

The second part gives the number of vehicles that can clear the intersection during the remainder of the green time after the queue has cleared, where q_C is the saturation flow and g is the cycle green time. The third part gives the number of vehicles that can depart at saturation flow q_C for the remaining *n-1* cycles.

Setting the supply equal to the demand and solving for n results in the relaxation time, given in number of cycles.

$$q_A nc = q_E t_E + q_C(g - t_E) + q_C g(n-1) \Rightarrow n = \frac{t_E(q_C - q_E)}{(gq_C - cq_A)}$$

Using this equation, decision makers can set limits on the relaxation time and determine whether a given roadway/bus route can support a BLIP implementation. Since the saturation flow (q_C) is known to be greater than the reduced outflow provided under bus lane activation (q_E), the numerator of this equation will be positive. From this formulation, it can be seen that the number of cycles will approach infinity as the denominator approaches zero. From this, we can determine another criterion for feasibility:

$$gq_C - cq_A > 0 \Rightarrow q_A < \frac{g}{c} q_C$$

That is, the demanded flow must be less than the flow capacity provided by the intersection. If they are equal, infinite queuing will occur until traffic conditions change.

Queue Length Constraint Calculation

The length of a queue caused by BLIP or otherwise, is a function of the red time and the arrival flow rate. As discussed above, it is of interest to limit the queue caused by BLIP activation. For isolated intersections, the calculation of this queue length is straightforward. For intersections in series, the vehicle arrivals depend on the offset of the upstream signal. (For example, if the signals are perfectly coordinated, no vehicles will arrive during the red phase of the signal.)

Figure 11 illustrates queues growing and dissipating at isolated and networked intersections. For isolated intersections, as shown in Figure 11a, vehicles arrives in stationary traffic state A, and the speed at which the back of the queue grows is U_{AB}.

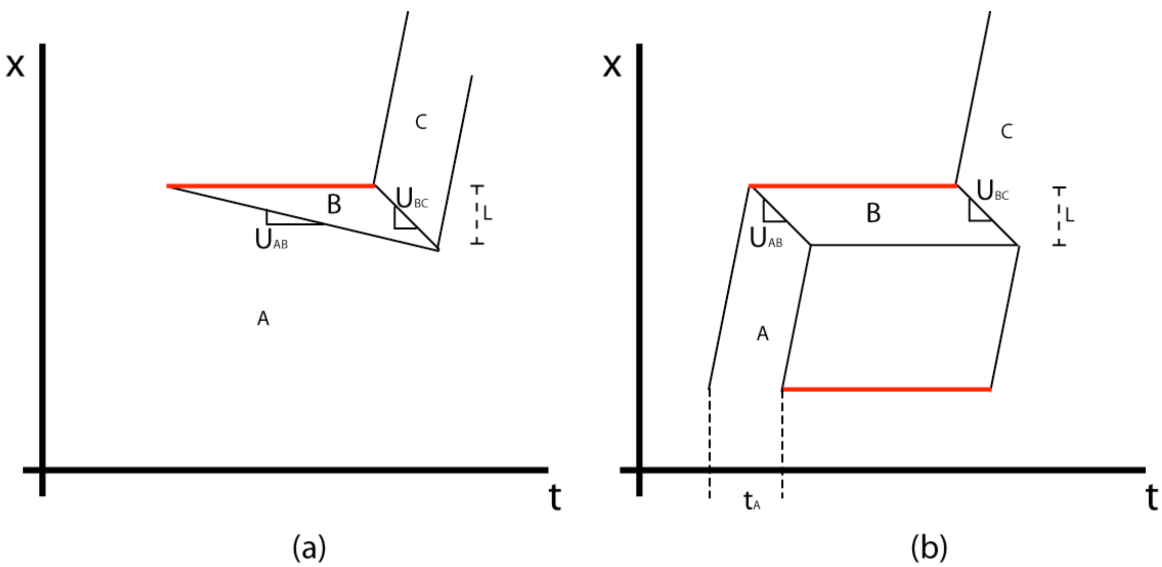

Figure 11: Graphic illustration of impacts in space for isolated and non-isolated intersections. a) The queue length (L) at an isolated intersection is a function of the arrival and discharge traffic states (A and C respectively). b) The queue length (L) at a non-isolated intersection is a function of the traffic state (A) and the offset from the previous signal.

Given that vehicles will leave the queue in a different traffic state than they arrive, traffic state E, the speed at which the front of the queue dissipates can be represented by U_{BE}. The location of the back of the queue growing for time t_1 can be expressed as $t_1 U_{AB}$. The location of the front of the queue after discharging for a time t_2 can be represented by $t_2 U_{BE}$. Since the queue is fully discharged when the front of the queue meets the back, the maximum queue length occurs where the two meet:

$L = t_1 U_{AB} = t_2 U_{BE}$

Additionally, we know the queue begins forming when the signal turns red, and begins discharging when it turns green. Therefore, $t_1 = t_2 + R$, where R is the red time of the cycle. Solving these equations for t_2 and then for L results in the following equation for the maximum queue length of an isolated intersection:

$$L = \frac{U_{AB} U_{BE}}{U_{BE} - U_{AB}} R$$

Since the goal here is to ensure that the queue caused by reduced queue discharge rate does not extend beyond a certain length, L, it is desirable to determine an upper bound for the demand flow, q_A. This can be derived from the above equation by substituting the definition for the "interface" speeds, i.e. $U_{AB} = (q_B - q_A)/(k_B - k_A)$, and then solving for q_A. This results in the following expression for the maximum flow q_A given self-imposed constraints on L:

$$q_{A_{MAX}} = q_E \cdot \frac{(k_A - k_E)}{\frac{R}{L} q_E + k_E - k_B}$$

In the case of intersections in series (non-isolated), the queue length is a function of the arrival flow rate and the offset from the previous signal, as discussed above and illustrated in Figure 11b. The queue will grow at the rate U_{AB} while the red signal is exposed to flow from an upstream signal, the effective offset time $t_A = t_O$.

$$L = t_A U_{AB}$$

Substituting the definition for the interface speed (as discussed above) and solving for q_A will result in the maximum flow q_{Amax} that can arrive at the red signal without the queue spilling beyond our pre-defined distance L.

$$q_{A_{\max}} = \frac{L(k_B - k_A)}{t_A}$$

Since this formulation is for signals in a series, the $q_{A\max}$ may be the saturation flow from an upstream intersection, coming to the current intersection in platoons with flow q_A, but having an average flow significantly lower than q_A. If this is the case, the average flow can be given by

$$\overline{q}_{A_{\max}} = \frac{c}{g} \cdot q_{A_{\max}}$$

where c and g are the cycle length and green time of the upstream signal.

It should be noted that, depending on the cycle offsets and the overall traffic demand on the arterial, the flow arriving at the signal during the red phase may or may not be saturation flow. If this analysis predicts queues that grow to unacceptable lengths, the signal offset should be adjusted in an attempt to ensure that the signal is exposed to a flow at a level below the saturation flow. However, if the system is at or near capacity, this may not be possible.

Reduced Signal Delay

The fundamental diagram in Figure 7 applies to this analysis, and signal queue delay of a bus trajectory at an intersection can be calculated, given the following parameters:

c	cycle length
g	effective green time
A	initial traffic state
B	traffic state of queued vehicles
C	traffic state of discharging vehicles
U_{AB}	Speed of interface between A and B
U_{BC}	Speed of interface between B and C
v_f	Freeflow speed of bus
t_0	Time the signal turns red

x_0 Location of the signal
x_B location of bus at t_0

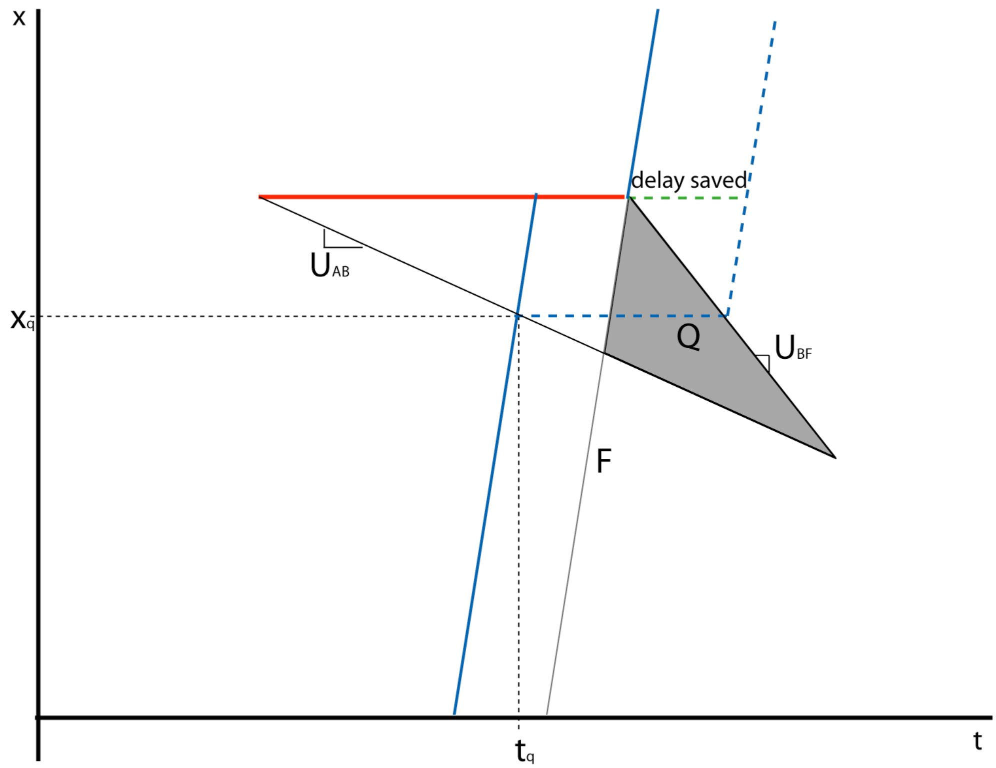

Figure 12: Time-space diagram illustrating signal stop delay and signal queue delay. Trajectories crossing through the shaded triangle Q experience delay due to other vehicles at the signal. The delay of any vehicle trajectory stopped at the signal can be decomposed into signal stop delay and signal queue delay, however vehicles arriving at the back of the queue after the signal has changed experience only queue delay. The bold trajectory illustrates the path of a bus receiving priority treatment at the intersection. The dashed trajectory illustrates it's path without priority treatment. The horizontal component of the dashed line through the shaded triangle Q represents the delay saved by the priority treatment.

Figure 12 shows a time-space diagram representation of an isolated intersection. The trajectory of the bus arrives at the back of the queue at t_q but proceeds to the stop line[4].

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[4] Actually, the time t_q represents the time the bus would have hit the back of the queue if the priority lane had not been activated. Because in this example the vehicles are queuing in N-1 lanes, the vehicles actually queue in state D and the back of the state-D queue grows at the rate $U_{AD} > U_{AB}$. Also, it should be noted that vehicles could be allowed to fill in the vacant lane space behind the bus. This would effectively return the queue to state B and reduce the queue discharge time. However, due to buses' frequent stops, this might never be advantageous to drivers. But this thought experiment does show how traffic disruptions due to the presence of the BLIP are not very different from existing disruption caused by buses in mixed traffic lanes.

The delay that would have been experienced by the bus is represented by the horizontal dashed line at x_q, and is bisected by line F into signal stop delay and signal queue delay. The signal stop delay is to the right of line F and signal queue delay is to the left.

From this diagram, it should be visible that the signal queue delay of a bus reaching the back of the queue at location x_q is represented by the corresponding horizontal slice of the shaded triangle labeled Q. The length of that slice is the difference between the line BC and the maximum t value of either line F or line AB. Using geometry, the equations of all the lines of interest can be determined:

line	point-slope form	solved for t
AB	$x - x_0 = U_{AB}(t - t_0)$	$t_{AB} = \dfrac{x - x_0}{U_{AB}} + t_0$
BC	$x - x_0 = U_{BC}(t - (t_0 + c - g))$	$t_{BC} = \dfrac{x - x_0}{U_{BC}} + t_0 + c - g$
F	$x - x_0 = v_f(t - (t_0 + c - g))$	$t_F = \dfrac{x - x_0}{v_f} + t_0 + c - g$
B	$x - x_B = v_f(t - t_0)$	

The first step towards the solution is to determine where the bus would have hit the queue, x_q. This can be easily accomplished by placing the expression for t_{AB} into the point-slope form for the line B and solving for x. This results in the following equation:

$$x_q = \frac{U_{AB}x - v_f x_0}{U_{AB} - v_f}$$

Using the convention $t_i(x_q)$ to represent the time function i evaluated at x_q, the expression for the delay saved (signal queue delay) for the bus can be written as the following:

$$\omega_{saved} = \max(t_{BC}(x_q) - \max(t_f(x_q), t_{AB}(x_q)), 0)$$

If we define ω_R as signal queue delay experienced by vehicles who also experience signal stop delay (if not queued, they would arrive at the stop line during the red phase) and ω_G as the signal queue delay of those vehicles who, but for the queue, would not need to stop, we can determine components of the expression for the signal queue delay as a function of intersection arrival time:

$$\omega_R = t_{BC} - t_F = \frac{U_{AB} v_f (t_0 - t^*)}{U_{AB} - v_f}\left(\frac{1}{U_{BC}} - \frac{1}{v_f}\right)$$

$$\omega_G = t_{BC} - t_{AB} = \frac{U_{AB} v_f (t_0 - t^*)}{U_{AB} - v_f}\left(\frac{1}{U_{BC}} - \frac{1}{U_{AB}}\right) + (c - g)$$

where t^* is the number of seconds after the signal turns red that the vehicle in question arrives (or would have arrived, if queued) at the stop line. These expressions can then be used to express the delay saved as a function of bus arrival time at the intersection:

$$\omega_{saved} = \max\left(\min\left(\omega_R, \omega_G\right), 0\right)$$

Figure 13 graphically displays the relationship between arrival time of a bus at a signal and the delay saved (signal queue delay) by the BLIP.

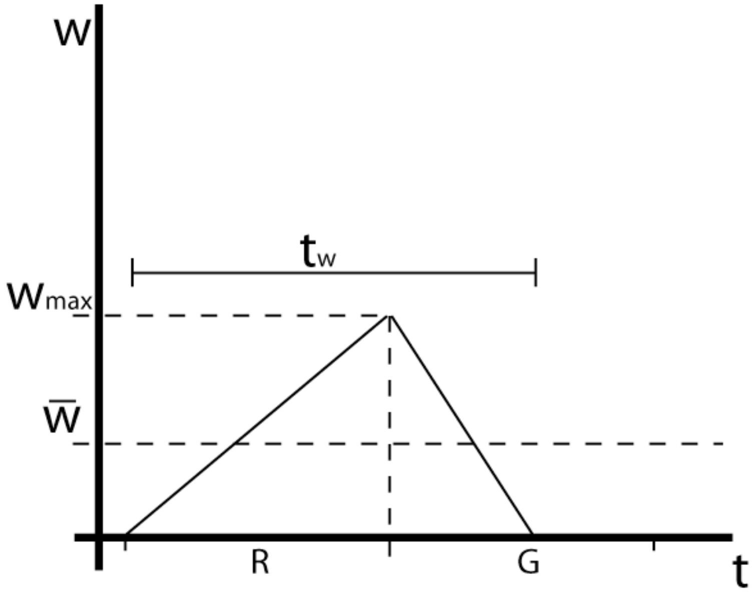

Figure 13: Diagrammatic illustration of signal stop delay as a function of arrival time at an intersection.

Figure 13 illustrates that the maximum benefit will be reaped by the bus with a trajectory such that it will arrive just as the signal turns green. The maximum delay (benefit) value can be calculated by determining the signal queue delay at *c-g* (the effective red time):

$$\omega_{\max} = \omega_R(c-g) = \left(\frac{1}{U_{BC}} - \frac{1}{v_f}\right) \cdot \frac{U_{AB} v_f (t_0 - (c-g))}{U_{AB} - v_f}$$

Because of the triangular nature of the signal queue delay function, the average delay for any bus that joins the queue is simply $\omega_{\max}/2$. If t_w is defined as the maximum t^* such that a vehicle arriving at t_w will experience delay, we can express it as a function of our parameters by evaluating the expression for ω_G where the delay is zero:

$$t_w = (c-g) \cdot \frac{\left(\frac{1}{v_f} - \frac{1}{U_{AB}}\right)}{\left(\frac{1}{U_{BC}} - \frac{1}{U_{AB}}\right)} - t_0$$

Subsequently, the expected (average) delay of a randomly arriving vehicle at the intersection can be given by:

$$\overline{\omega} = \left[\frac{c - t_w}{c} \cdot 0 + \frac{t_w}{c} \cdot \frac{\omega_{\max}}{2}\right] = \frac{t_w \omega_{\max}}{2c}$$

This expression can be used to determine the average BLIP benefit to a bus randomly arriving at a signalized intersection. Figure 14 shows the graphical result of a numerical analysis implementing the equations defined above. It illustrates the same shape as the diagram in Figure 13 and validates the above formulations.

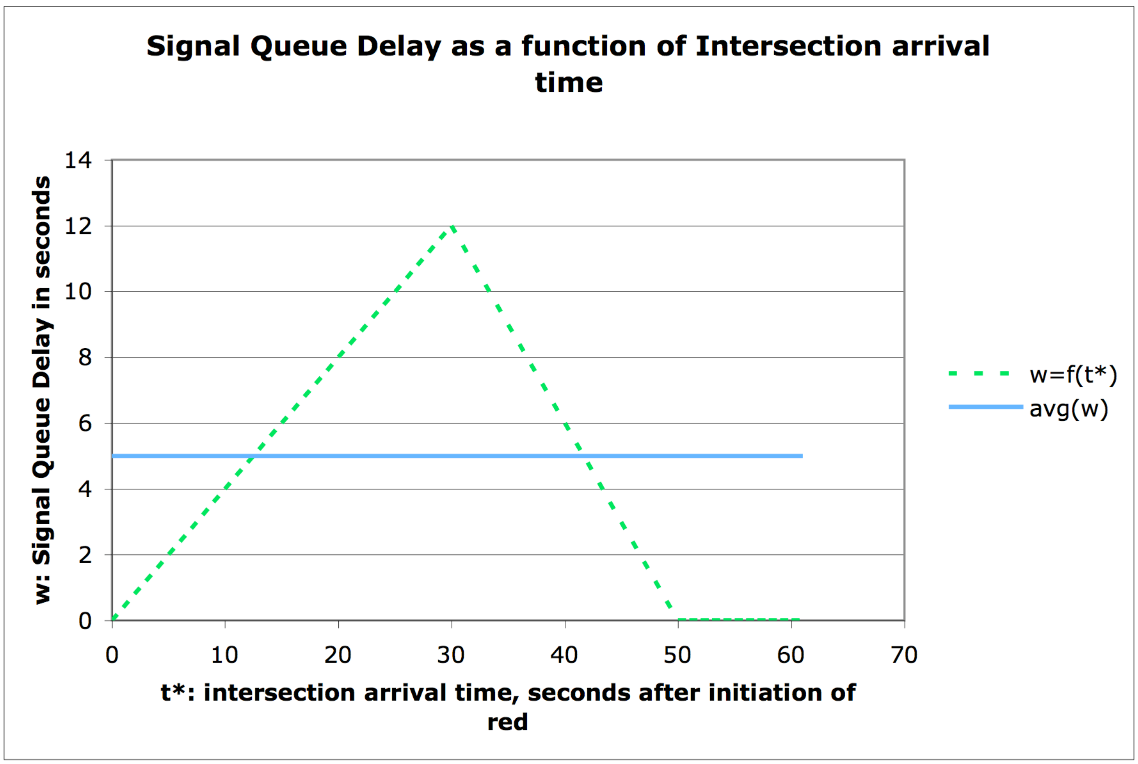

Figure 14: Signal queue delay as a function of intersection arrival time, calculated under the following conditions: C=60s, G=30s, q_A=1200 vph, q_C=3000 vph, v_f=60 kmph, U_{AB}=-12 kmph.

For non-isolated intersections that are somewhat coordinated, the calculation of delay saved is not as straight-forward. Signalized intersections are more likely to experience higher flows due to concentrated platoons of vehicles arriving from upstream intersections. Additionally, signal coordination can greatly effect how much of the traffic leaving an upstream intersection queues at a given signal. Figure 15 illustrates possible situations where signals have positive and negative actual offsets, and the potential for time-savings. The problem of non-isolated intersections can be solved, however, by modifying the effective red and green times for a signal. These offsets have the effect of extending the effective red time by the absolute value of the actual offset. This procedure is discussed in detail in Skabardonis and Geroliminis, 2005.

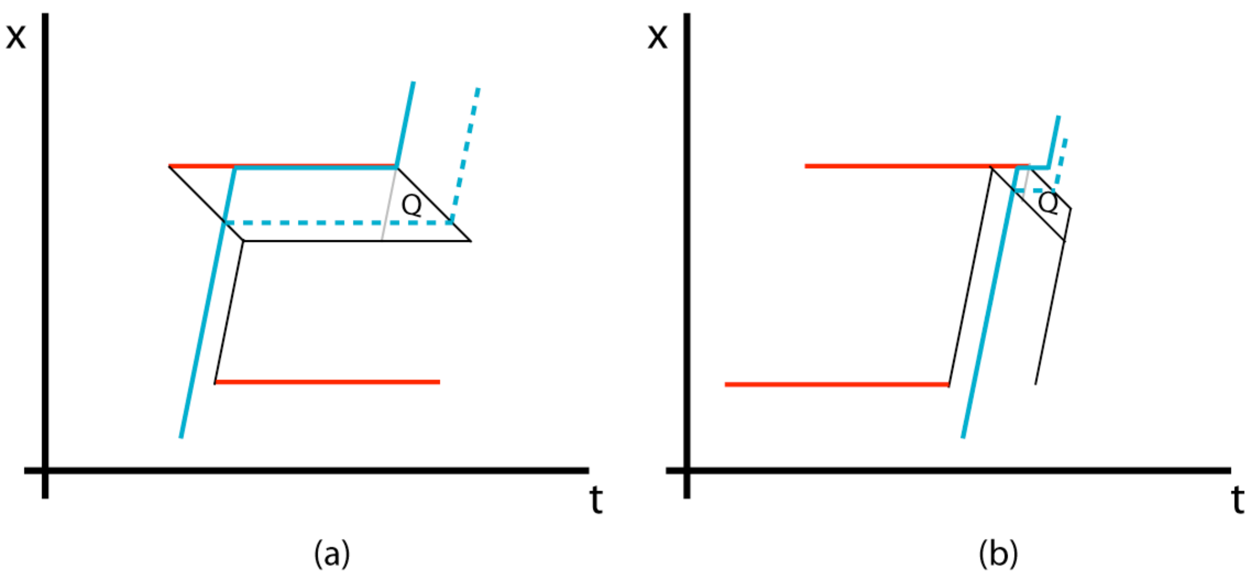

Figure 15: Time-savings benefits for non-isolated intersections; a) illustrates a negative actual offset, and b) illustrates a positive actual offset.

Reduced Stop Delay

BLIP reduces stop delay by eliminating merge delay experienced by the bus. In traditional bus travel time calculations, this merge delay not separated from the acceleration time.

Merge delay is a function of the traffic flow in the adjacent lane. If the traffic in the adjacent lane is stationary, the following equation can be used to estimate merge delay:

$$t_{merge} = 0.00001175 q_{adj}^{2} + 0.0019 q_{adj} + 0.05.$$

In this equation, t_{merge} is the merge delay in seconds and q_{adj} is the stationary flow in the adjacent lane in vehicles per hour. This equation is formulated from a linear regression of tabular data presented in the HCM. If vehicles arrive randomly or in platoons from upstream intersections, the merge delay is much harder to calculate. [TRB, 2000]

As noted above, the merge delay experienced by a bus is a function of many factors. As such, it is extremely difficult to derive a deterministic model to calculate the stop delay time-savings from a potential BLIP implementation. However, the Highway Capacity Manual [TRB, 2000] discusses estimating merge delay from empirical data in chapter 27. When considering a BLIP implementation, a transit agency can use the guidelines provided by the HCM to determine the time-savings that can be accrued at each bus stop.

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