CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Enhanced Transit Strategies: Bus Lanes with Intermittent Priority and ITS Technology Architectures for TOD Enhancement

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California PATH Research Report
UCB-ITS-PRR-2006-2

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration.

Final Report for Task Order 5103

February 2006

ISSN 1055-1425

CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS

Enhanced Transit Strategies: Bus Lanes with Intermittent Priority and ITS Technology Architectures for TOD Enhancement

California PATH MOU 5103 Final Report

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Abstract

Due to increases in congestion, transportation costs, and associated environmental impacts, a variety of new enhanced transit strategies are being investigated worldwide. The transit-oriented development (TOD) concept is a key area where several enhanced transit strategies can be implemented. TODs integrate transit, residential, retail and/or commercial entities into a compact, pedestrian-friendly community, thereby reducing private car usage and increasing transit use. This research report addresses two enhanced strategies within the TOD framework: 1) using Bus Lanes with Intermittent Priorities (BLIPs) to enhance bus transit; and 2) addressing how and what Intelligent Transportation System (ITS) technology can be used within TOD system architectures. With respect to 1), it has been shown that the implementation of BLIPs for bus rapid transit can greatly increase system efficiencies without compromising the level of service for other facility users. The basic analysis in this report shows that both conservative and liberal approaches have similar impacts to traffic and identical benefits. The macroscopic analysis illustrates that traffic disturbances caused by BLIP activation will not slow down subsequent buses, and that roads with medium traffic demand can easily support a BLIP implementation. The microscopic analysis provides some quantitative equations that can help decision makers determine whether a given intersection can be outfitted with a BLIP implementation within predefined parameters. A framework for cost-benefit analysis was provided for BLIP implementation. With respect to 2), it has been shown that transportation efficiency and effectiveness within a TOD can certainly be enhanced with the integration of ITS technology. This project report has identified technology bundles and architectures that have the greatest potential for increasing mobility. Further, it has demonstrated that ITS technologies implemented in a well-integrated fashion will promote transit efficiency and convenience and lead to transit usage beyond levels currently observed.

Summary

Increases in congestion, transportation costs, and associated environmental impacts continue to promote the research, planning, and development of enhanced transit strategies. The transit-oriented development (TOD) concept, often synonymous with “transit village”, integrates transit, residential, retail and/or commercial entities into a compact, pedestrian-friendly community. The ultimate transportation objective relative to a TOD is to reduce private car usage with an associated increase in transit ridership. Previous research indicates that residents living in developments near stations are five to six times more likely to commute via transit than other residents in a region. Additionally, a proportional relationship has been found between urban density and transit use. Relative to bus transit, ridership associated with buses can promote greater efficiencies through the implementation of bus rapid transit (BRT) strategies. One of the most promising areas of BRT enhancements is Bus Lanes with Intermittent Priorities (BLIPs). Successfully transitioning individuals from private vehicle usage to transit ridership is a complex transition involving an array of socio-economic variables. This study focuses on strategies, such as BLIPs, and ITS implementation architectures within TODs to promote the adoption of transit.

Private vehicle users must perceive significant benefits for adopting transit in place of a personal vehicle. These often include: economic, time, convenience, or environmental benefits. While the environmental, economic, and travel-time benefits associated with transit are quantifiable, user convenience and system efficiency are more variable due to user perception. With other factors being fairly equivalent, individuals will choose the transportation option with the most consistent convenience. Those who own automobiles will compare the convenience of private vehicle use relative to the level of convenience obtained through transit. Significant transit improvements are desirable in the area of perceived convenience and associated time savings. Enhanced transit strategies are continuing to expand mobility options, system efficiencies, and level of convenience associated with transit. These improvements are increasingly being achieved through a variety of ITS implementations.

Ever expanding ITS technology improvements related to communications and electronics continue to create exciting options for TODs and BRT. These improvements include BLIPs, smart parking, electronic payment services, innovative mobility modes, enhanced traffic management, vehicle monitoring and control, carsharing, and driver and traveler services. The following enhanced strategies have been evaluated:

> ***Bus Lanes with Intermittent Priorities—***uses changeable message signs, traffic signal priority, automatic vehicle location, and in-pavement lights to yield right-of-way to the bus. Such a system would ultimately decrease route travel times and increase system reliability by ensuring schedule adherence. Ideal system configurations and operational methods are discussed.
>
> ***Implementation of TOD System Architectures—***this analysis focuses on: 1) the integration of compatible ITS strategies into an open architecture structure; 2) the evaluation of suitable TOD architectures that integrate common ITS components into a single modular networked system; 3) the integration of specific advanced personal vehicle services within a TOD for improved personal mobility; and 4) modular synthesis

of advanced personal vehicle services (APVS) into a TOD environment including: low-speed modes, carsharing, smart parking, and Elockers.

As transportation networks become overburdened with increases in travel demand, system efficiency requirements must also increase to maintain an acceptable level of service. Transportation systems are continually being augmented with ITS technologies to maintain these needed system efficiencies. The analysis of BLIPs has proven the system effectiveness associated with combining specific ITS strategies with BRT scenarios. A well-integrated BRT system utilizing a BLIP configuration can increase bus transit efficiencies, while not compromising the level of service for other users of the facility.

The modular synthesis of multiple ITS strategies into a networked system requires the strategic development of individual technology components. Through the exploration of multiple TOD architecture scenarios for advanced personalized vehicle services, the inter-system communication techniques and compatibility becomes the foremost issue. Utilizing an open architecture Internet-based backbone allows for individual ITS components to be melded into a single TOD servicing system. Users of the TOD perceive and access a single system to service all their associated transit needs.

This study presents new and exciting ITS technology solutions for enhancing transit deployments. The ITS strategies have demonstrated the potential to provide transit users with increased mobility while limiting the dependence on the private vehicle. It has been shown that transportation efficiency and effectiveness within a TOD can certainly be enhanced with ITS synthesis. Additionally, implementation of BLIPs for BRT can greatly increase system efficiencies without compromising the level of service for other facility users. The goal of this report has been to identify technology bundles and architectures that have the greatest potential for increasing mobility. This study has demonstrated that ITS technologies implemented in a well-integrated fashion will promote transit efficiency and convenience and lead to transit usage beyond levels currently observed.

Contents

1. Introduction

Travel demand in California continues to steadily increase, due primarily to California's expanding population growth. Most of California's current travel demand is satisfied with the automobile traveling on an expansive roadway system, often as single occupant vehicles. However, the roadway system is no longer expanding with increased travel demand; as a result, congestion has become a serious problem in terms of cost, safety, energy, and the environment. It is clear that the state's transportation system will need to provide for more efficient and flexible mobility options beyond the standard use of automobiles. Transit can play a major role in alleviating these problems; however, the majority of current transit systems are not very flexible nor reliable. What is needed are innovative ideas that can provide integrated door-to-door services to reduce travel times and increase ridership.

Transit agencies are seeking new ways to increase ridership and to provide better service with limited resources. In recent years, many transit agencies have investigated several options, including non-fixed-rail systems, such as Bus Rapid Transit (BRT) as well as promoting Transit-Oriented Developments (TOD). In general, TODs promote transit use through the integration of multiple transit options in high-density developments consisting of residential, commercial, and retail entities. TODs have been demonstrated to increase transit usage, elevate the pedestrian mode, and reduce private vehicle use [Arrington, 2003].

Crucial to any transit option (including BRT and TODs) is the use of Intelligent Transportation System (ITS) technologies. New technology expands the different transportation possibilities and allows for significant improvements in mobility. Through the use of advanced transit modes, innovative feeder options, integrated ITS technologies, shared-use vehicle systems (i.e., short-term vehicle rentals), and intelligent parking services, TODs have the potential to improve personal mobility while enhancing the livability within a community. Further, BRT systems can be enhanced through the application of ITS and new operational concepts, resulting in enhanced mobility for bus riders in and around the transit community.

In 2004, this study was initiated to explore two key options which combine technological advancements, operational improvements, and flexible approaches that could lower travel times, enhance reliability, connectivity, and system appeal; and ultimately lead to increased transit ridership. These two options include:

> ***Bus Lanes with Intermittent Priority—***this innovative concept employs changeable message signs, traffic signal priority, automatic vehicle location, and in-pavement lights. During hours of Intermittent Bus Priority operation, other vehicles can also make use of the lanes. As a bus approaches, however, other vehicles are instructed to leave the lane, yielding right-of-way to the bus. Other vehicles are instructed to maneuver to the other lanes through a variety of methods: overhead and roadside signalization, in-pavement lights, etc. Additionally, the bus would receive signal priority at intersections. Under optimal conditions, the bus would only need to stop at bus stops, regardless of roadway traffic conditions. Such a system would ultimately decrease route travel times and increase system reliability by ensuring schedule adherence.

> ***Advanced Personalized Vehicle Services*—**these services combine several innovative mobility solutions, including: shared-use vehicle systems, linkages to transit, small electric vehicles, and advanced electronic and wireless communication devices. ITS technology is used to facilitate reservations, billing, vehicle access, and traveler information; as well as smart parking management services.

The results of this research are described in detail in this report. It is expected that these results could take California closer to its goal of making transit a more competitive mobility option to the single occupancy vehicle, particularly in congested corridors and regions, such as the Bay Area. As part of this report, the two innovative mobility options are examined in terms of cost-effectiveness, impacts on travel times, reliability and/or flexibility, and how these strategies could be bundled to offer greater benefits.

As part of this research program, specific project tasks were carried out:

Task 1: Detailed literature reviews were conducted on several topics, including (but not limited to) bus rapid transit, traffic signal priority, automatic vehicle location systems, changeable message signs, in-pavement lights, shared-use vehicle systems, wireless communications technology, and a variety of transportation system architectures;

Task 2: Based on the results of the literature review, a new Bus Lane with Intermittent Priority (BLIP) concept was developed, as well as new system architectures that can be used for integrated technology applicable to transit-oriented developments;

Task 3: These innovative concepts were then analyzed in detail, examining the cost-effectiveness and the impacts on travel times, reliability, and flexibility; and

Task 4: Finally, proposed next steps were examined for these innovative options.

These research tasks were carried out by two research teams, one from UC Berkeley (focusing on bus lanes with intermittent priority) and the other from UC Riverside (focusing on new system architectures for TODs). In Chapter 2, the authors provide a brief overview of several key transportation concepts to this study. Next, Chapter 3 describes the results of the technology evaluation, describing different ITS components that are applicable to bus operations and TODs. Chapter 4 then describes the BLIP concept in detail and provides a detailed analysis. Chapter 5 describes the integrated architectures for TOD development and associated analysis. In Chapter 6, the authors discuss proposed next steps with recommendations on how the technologies can be implemented. Finally, Chapter 7 provides a summary and conclusions. The report also contains two appendices, including detailed annotated bibliographies from the literature review.

2. Background

This section of the report includes a brief overview of innovative transit bus concepts and advanced personalized vehicle services.

2.1. INNOVATIVE TRANSIT BUS CONCEPTS

Buses that operate in mixed traffic lanes are subject to delays caused by traffic congestion, reducing the appeal of bus transit. On the other hand, 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, such as a BRT system. As a compromise between dedicated bus lanes and buses operating in mixed traffic lanes, the concept of Bus Lanes with Intermittent Priority or BLIPs can be implemented. With BLIP, other traffic can make use of the lane as normal. However, as a bus approaches, other vehicles are instructed to safely leave the lane (or are prevented from entering the lane), yielding the right-of-way to the bus. Dynamic signage can communicate the status of the BLIP to other users of the roadway (e.g., overhead signalization, roadside signalization, in-pavement lights, etc.).

BRT systems often incorporate a variety of features to improve overall service. One feature that is often employed is Transit Signal Priority (TSP). In general, 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, such as [Balke et al, 2000; Banerjee, 2001; Cima et al, 2000; Duerr, 2000; Furth et al, 2000; Garrow et al, 1998; Hunter-Zaworski et al, 1995; Janos et al, 2002; Kloos et al, 1995; Lin, 2002; Nash et al, 2001; and Skabardonis, 2000]. These and other references are cited in the annotated bibliography in Appendix A.

Another option for BRT (or other enhanced bus service) is the concept of an Intermittent Bus Lane (IBL): in this case, a lane is reserved for bus use, but it also allows private vehicle traffic to use the lane when not in use by the bus. One study has proposed an IBL strategy: [Viegas et al, 2001]. This IBL strategy never requests traffic to leave the lane to accommodate the bus; instead, it restricts traffic from changing into the bus lane and relies on TSP to “flush the queues” at traffic signals. The BLIP concept proposed here is similar to this IBL concept; however, it clears traffic out of the lane reserved for the bus when necessary, not relying on TSP. As a result, the BLIP concept is easier and less expensive to implement.

The BLIP concept is also related to the idea of a *queue jump lane* [Rosinbum et al, 1991; TRB, 2000; Mirabdal et al, 2002]. Widening the roadway near key intersections provides queue jump lanes. These lanes only allow buses and right-turning vehicles to enter, enabling the bus to “jump the queue” of traffic at the signal. These lanes often 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, BLIPs require no additional right-of-way and again should be less expensive to implement.

2.2. TRANSIT-ORIENTED DEVELOPMENT (TOD) AND COMPONENTS

Many transit organizations and communities are participating in the creation of commercial, retail, and residential developments proximal to transit facilities. While a variety of configurations and definitions can be found for a TOD, there is general consensus among transit professionals that a TOD consists of “a pattern of dense, diverse, pedestrian-friendly land uses near transit nodes that, under the right conditions, translates into higher patronage” [TCRP, 2004]. There are multiple types of transit-related developments that are often discussed in close association with TODs. These include:

- Transit Adjacent Development (TAD),
- Transit Village, and
- Transit Joint Development (TJD).

TADs are proximal to a transit station and lack significant integration, while TJDs primarily describe the development relationship between transit authorities, governmental bodies, and business organizations [Cervero, 2002]. Transit joint development is considered a sub-set of transit-oriented development in which the development occurs on or adjacent to land owned by the transit agency; the transit agency shares in some of the revenue generated by the project or where there is some physical alteration made to the transit station as a result of the project [TCRP, 2004]. Developments that occur next to a transit location and do not fully integrate transit into the development are often referred to as TADs. TADs often lack key pedestrian-friendly components and are frequently smaller developments compared to TODs [Arrington, 2003]. The TJD terminology is frequently used to describe multiple interests involved in the development versus the transportation modes being promoted. *Transit Village* definitions are generally synonymous with TOD definitions as discussed on a transit village-dedicated website (www.transitvillages.org), as well as the Federal Highway Administration’s case study of the Fruitvale Transit Village in Oakland California [FHWA, 2005].

A review of TOD definitions has revealed some common similarities among most TOD descriptions [Cervero, 2002]. These include:

- Mixed-use development,
- Development that is close to and well served by transit, and
- Development that is conducive to transit ridership.

The potential success of transit is strongly correlated to how well the community design promotes transit use. Mass transit designs inherently have significant distance between locations (stations) where users can enter or exit the transit mode. This transit characteristic often requires users to utilize another mode of transportation at either end of their transit-based trip leg. This implies that an individual’s origin and/or destination is often beyond the preferred walking distance of a transit stop (i.e., greater than one-quarter mile). This indicates that an overall transit system must integrate effective mass transit services (e.g., bus, bus rapid transit, train, subway, shuttle) as well as convenient feeder options (e.g., bike access, taxi, low-speed vehicles, personal vehicle parking, etc.).

TOD development is a complex process typically involving a multitude of stakeholders, including: transit agencies, private developers, environmental groups, alternative transportation advocates, residential developers, private retailers, and private transportation service providers. Most interest groups agree that, if successful, TODs can yield many benefits, including increases in transit ridership and profits to public and private partners [TCRP, 2004]. The same TCRP report states the top five transit agency motivations for engaging in TODs are:

1. Increasing ridership,
2. Promoting economic development,
3. Raising revenues,
4. Enhancing livability, and
5. Expanding housing choices.

In this section, a brief review is provided of several components that can play an important role in transit-oriented developments. These include shared-use vehicle systems (i.e., short-term vehicle rentals, such as carsharing), smart parking management, and low-speed modes.

2.2.1. Shared-Use Vehicle Systems

There has been significant interest in shared-use vehicle systems over the last decade as an innovative mobility alternative. The general principle of shared-use vehicle systems is that individuals can access a fleet of shared vehicles (ranging from cars to bikes and scooters) on an as-needed basis, rather than using their personal vehicles for all trips. There are many potential advantages of shared-use vehicle systems, including better vehicle use (leading to higher transportation efficiency), cost savings to the user, energy/emissions benefits, and improved access to established transit operations. For further information on the history and benefits of shared-used vehicle system, see [Shaheen et al., 1998; Britton et al., 2000].

Over the last several years, numerous shared-use vehicle services have developed that reflect different operational models (or market segments) and purposes. A classification system for categorizing different shared-use vehicle system models, ranging from neighborhood carsharing to station car systems (i.e., shared vehicles directly linked to transit), was developed in 2002 [Barth & Shaheen, 2002]. The predominant shared-use vehicle model is neighborhood carsharing, where individuals in dense metropolitan areas access shared-use vehicles distributed throughout neighborhood lots. Indeed, this is the prevailing approach in Europe and commercial shared-use services in North America. Station car systems are another model, where vehicles are closely linked to transit stations to enhance access. Station cars are often shared, although not always. Some of the more innovative shared-use vehicle service providers today are combining elements of both traditional carsharing and station cars, forming what are called “hybrid” models [Barth & Shaheen, 2002]. As of July 2005, U.S. carsharing programs collectively claimed 76,420 members and operated 1,192 vehicles [Shaheen et al., 2005a].

When integrated within a TOD, shared-use vehicle systems can enhance mobility significantly. The shared-use vehicle system can provide transit users with convenient personalized transportation to their final destination. For many transit riders, the TOD transit station will likely not provide the door-to-door convenience associated with privately owned vehicles. A carefully designed shared-use vehicle system integrated within a TOD can get the transit user closer to the personal mobility associated with private vehicle ownership. To achieve the optimum level of convenience, well integrated ITS technologies should be integrated with the shared vehicle system and corresponding transit modes.

One of the key elements of modern-day shared-use vehicle systems is the application of ITS technologies. These technologies can enhance shared-use vehicle services by improving their overall efficiency, user-friendliness, and operational manageability. Several ITS technology user services [U.S. DOT, 2005] can be applied: 1) *dispatching and reservation systems* so that users can obtain system information, check-out vehicles, and make reservations over the web, by phone, kiosk, etc.; 2) *smartcard technology* to assist with vehicle access control; 3) *on-board navigation and travel information* to assist system users; and 4) *intelligent communication and tracking systems* to provide vehicle location/identification, emergency messaging, and electronic debiting. Much of this advanced technology has been developed and applied in shared-use vehicle research programs, such as the University of California-Riverside IntelliShare testbed [Barth et al., 2000] and the Carlink II program [Shaheen et al., 2000].

Commercial carsharing organizations in North America have increasingly added technology to their systems, where 70 percent of U.S. shared-use vehicle organizations have advanced operations; 24 percent provide partially automated services; and six percent offer manual services (as of 2005, see [Shaheen et al., 2005a]). In Canada, 73 percent of the carsharing organizations have partial automation and 18 percent manual operations [Shaheen et al., 2005a]. In Shaheen et al.’s (2005a) technology analysis, manual operations include operator phone services and in-vehicle trip logs; partially automated systems are automated reservations via touch-tone telephone or Internet or both; and advanced operations involve smartcard access, reservations, billing, automated vehicle location, and cellular/radio frequency communications. As shared-use vehicle systems continue to expand and multiply, the penetration of ITS technology use will only increase as manually managing larger fleets and more diverse user markets (e.g., one-way trip rentals) becomes more difficult with increased scale.

The integration of shared-use vehicle systems into TODs has been slow to develop. Nevertheless, emerging ITS technology developments are allowing shared-use vehicle systems to be more feasible and economically viable for TOD integration.

2.2.2. Smart Parking Management

It is well known that parking is costly and limited in almost every major U.S. city, contributing to increased congestion, air pollution, driver frustration, and safety problems. Furthermore, limited parking can also constrain transit ridership in dense regions. As a potential solution to many of these parking problems, *smart parking management* can be applied as an ITS solution and is crucial for a TOD to succeed. Smart parking management is the use of advanced technologies to help direct drivers efficiently to available parking spaces at transit stations (and other high-activity locations), encouraging transit ridership, lessening driver frustration, and reducing congestion on highways and arterial streets. Smart parking approaches range from dynamic displays on roadway signs informing drivers of location and parking lot capacity, to providing space availability, location, and pricing information through the Internet and/or cell phones.

In Europe, there are several smart parking systems that are replacing traditional paid parking with real-time communications and payment systems via mobile phone. Recently, European cities have integrated ITS technologies into intermodal transportation centers, such as transit park-n-ride lots, to provide real-time information to motorists regarding availability and electronic/wireless parking payment services. This includes dynamic message signs (DMS) and changeable message signs (CMS) that provide motorists real-time parking information (see, e.g., [Cervero, 1998]). According to a mobile company in Ireland, 70 percent of individuals in most western European countries have mobile phones, and penetration rates increase among motorists. Many European companies and municipalities use a smart paid parking platform that works on normal mobile phones via the Internet. Advantages for customers include no coins/exchange, a lower chance of parking tickets, and a reduction in overfed meters (as demonstrated in Easy Park in Oslo, Norway; see www.easypark.net). In the U.S., intermodal transportation parking (also known as “commuter lot parking”) began at gas stations along a Detroit transit line in the 1930s [Maccubbin & Hoel, 2002]. It is now common for cities and states to have transportation demand management (TDM) programs that include such commuter facilities or “park-n-ride” lots to better manage travel demand [Maccubbin and Hoel, 2002]. Beyond park-n-ride lots and transit station lots, little innovation has been attempted to better manage parking resources at critical rail and bus lots in dense urban regions in U.S. cities. Only recently have researchers begun to investigate smart parking management, such as smart parking field operational test linked to transit. This test involves communication technologies to help manage existing parking spaces at and around a BART station to increase space availability and transit access [Shaheen et al., 2005b].

As previously described, TODs must accommodate the individuals whom use a personal automobile for some percentage of their transportation. Therefore, having an efficient and convenient transition of individuals from their personal vehicle to transit is of utmost importance. The transition of individuals from their personal vehicle to transit can be enhanced through smart parking technology.

Many variations of smart parking have been implemented. These include autonomous parking garages to reserved parking spaces. There are a few defining characteristics associated with smart parking at a TOD:

1) The land area in and around the TOD is of high value, and therefore, some type of efficient parking structure is nearly always a design preference;

2) The location upon which the driver departs from their vehicle needs to be within a convenient distance to the transit stop or feeder service (e.g., shuttle); and,

3) Each vehicle consumes a significant amount of space that is not easily used for any other purpose while the vehicle is present.

Autonomous garages provide the optimum convenience to users while making the most efficient use of land area (see www.roboticparking.com). Unfortunately, the cost of autonomous garage implementation is typically prohibitively expensive.

Other smart parking options include intelligent parking space management, automated fee payment, and driver information services. These ITS technologies aid to improve the traditional method of utilizing a parking structure. The integration characteristics of various smart parking options will be discussed in detail in later sections.

2.2.3. Low-Speed Transportation Modes

In recent years, a number of low-speed transportation modes have become very popular for a variety of applications. These include small Neighborhood Electric Vehicles (NEVs), electric bicycles, scooters, CyberCars (see www.cybercars.org), and the Segway Human Transporter (HT). All of these modes can provide a high degree of mobility in constrained areas (e.g., university campuses).

While transportation in the U.S. is dominated by automobiles, there are numerous other transportation modes and products that are relatively new in the marketplace. While some of the technology and vehicles have been available for many years, regulations, policies and manufacturing characteristics have made these mobility options new to the TOD market.

NEVs are an example of vehicles that have a long history in the golf industry, but they are relatively new to the transportation market as a mobility option (see examples of NEVs in Figure 2.1). Recent legislation in California has allowed low-speed vehicles to travel on roads within California as long as the posted speed limit is at or below 35 mph (many other states have similar legislation).

Figure 2.1. a) A four-seat neighborhood electric vehicle; b) a two-seat NEV; and c) a utility NEV.

Electric bicycles and/or electric scooters are certainly not a new technology, but recent advancements in technology allow them to be considered as an innovative mobility mode that can be made part of a TOD development. These transportation modes have received limited attention in previous years due to their relatively low performance. In recent years, their improved power/weight ratios have allowed for increased performance and market acceptance. Figure 2.2 (below) displays several electric bike/scooter options currently being marketed. The electric bikes are power assisted at speeds up to 18 mph and last approximately one hour. The three-wheeled scooter offered by ZAP has a top speed of 12.5 and a maximum range of 15 miles. The folding two-wheeled scooter has a maximum speed of 13 mph and maximum range of 8 miles (www.zapworld.com).

Figure 2.2. a) electric bicycle; b) electric 3-wheel scooter; and c) electric 2-wheel scooter.

One of the most innovative and interesting new mobility modes is the Segway Human Transporter (HT). The gyroscopic-balanced, two-wheeled electric scooter platform allows for quiet and efficient personal mobility in pedestrian-oriented areas. The Segway HT mode is the closest power-assisted mobility option to walking that is currently available. The footprint of the Segway HT is approximately two square feet. This is nearly equivalent to the amount of space occupied by a standing individual. Figure 2.3 (below) shows the Segway HT with a maximum speed of 12.5 mph and a maximum range of 24 miles (www.segway.com).

Figure 2.3. Segway HT operating on a city sidewalk.

The use of these “new” transportation modes on sidewalks, pathways, and public areas has been an issue of much discussion. The Segway HT has received significant attention and is the topic of many city and state regulations [Rodier et al, 2004; Shaheen, 2003].

It is important to note that the types of vehicles used can play a significant role in marketing a transit-oriented development. If the vehicles are unique, new, and fun-to-drive, this can be used as a valuable marketing tool. When the vehicles are incorporated within a TOD, there are also potential increases to transit use.

3. ITS Technology and Deployment

Prior to describing the intelligent bus priority lane concept and analysis, as well as the TOD architecture analysis, a variety of ITS technology has been investigated (along with several deployments) with a focus on its applicability to enhancing transit-oriented development. Much of the technology investigation was directed on specific data communications and constraints. Results from this technology investigation are described below.

3.1. NATIONAL STANDARDS AND GUIDELINES

As interest grew in intelligent transportation system technology in the late 1980s and 1990s, national standards and guidelines were developed for current and future ITS applications [US DOT, 2005]. An overall ITS "architecture" was defined and has been incrementally revised throughout the years. The ITS architecture (defined by the U.S. Department of Transportation) categorizes and groups the wide variety of technology and their applications. The following *user services* are of particular interest for TOD development:

- Travel and Traffic Management:
    - Pre-trip Travel Information,
    - En-route Driver Information,
    - Route Guidance,
    - Ride Matching and Reservation, and
    - Traveler Services Information.
- Public Transportation Management:
    - En-route Transit Information,
    - Public Transportation Management, and
    - Personalized Public Transit.
- Electronic Payments.

The Travel and Traffic Management *user service bundle* focuses on *user services* that convey vehicle and/or travel information to end user locations. These services typically employ technology that gathers information associated with the transportation facility(s), transfers the information to a suitable end point, and displays the information to the end user. The information may be relative to a specific vehicle (route guidance), facility (en-route driver information), or a region (traveler services information). The end user may be a transportation user or a transportation provider/manager (e.g., traffic operations center).

The *user service bundle* Public Transportation Management targets ITS solutions in the transit arena. Similar to the previously discussed services, these *user service bundles* primarily promote the transfer of transit operational data to the user. The user may be the transit rider, the transit operator, or transportation management body.

Many transportation systems and transportation alternatives are provided at a cost to the user of the facility, vehicle, or system. Collecting a fare from the end user is often a time consuming task. Traditional bus systems are often slowed by the fare collection procedures involved with individuals entering the bus. In an effort to improve the efficiency of fare collection, electronic payments have been implemented in many transportation applications. These applications range from electronic toll booths (electronic toll collection) to smart cards for electronic fare collection in transit systems.

The technology bundles associated with these user services possess many similarities. The need for database management, data transfer, and real-time data access exists for nearly every potential application of ITS within a TOD. The flexibility, manageability, and increasing portability of Internet-connected devices have made the Internet the primary means of data sharing for the majority of these applications. Web-based applications are increasingly being used to provide transit users and operators with transit system information.

3.2. SPECIFIC TECHNOLOGY

3.2.1. Wireless Communications

Critical to many ITS applications is the ability to communicate between different devices and/or users. A high degree of development in the mobile wireless communication arena has occurred in recent years with the proliferation of cellular phones, personal digital assistants (PDAs), and other mobile computing platforms. Much of this development has been associated with the information needs of consumers, such as messaging, sending and receiving emails, and downloading information from the Internet. There has also been a good deal of activity in the communications arena of ITS. Five general types of communications linkages have been defined for ITS, which include:

- Wide Area Broadcast Communications,
- Wide Area Two-Way Wireless Communications (e.g., cellular),
- Dedicated Short Range Communications,
- Vehicle-to-Vehicle communications; and
- Wireline communications [US DOT, 2005].

These communication linkages are being developed for a variety ITS applications for a range of purposes, such as safety, remote diagnostics, maintenance, and entertainment. In general, ITS applications have different communication requirements in terms of bandwidth, latency, and quality of service (QoS). For example, vehicle-to-vehicle communications in an automated highway system scenario will require local high bandwidth communications, while applications such as remote emergency diagnostics will need a low-bandwidth, highly available connection. It is important to note that the wireless network architecture developed for personal data communication needs (e.g., internet-capable mobile phones) will not necessarily be able to satisfy all ITS communication requirements. As a result, specific wireless communication architectures and methods are being developed and tailored for various ITS applications (e.g., see [Bana & Varaiya, 2002], [Lee et al., 2001], [Punnoose et al., 2001], and [Munaka, 2001]).

Wireless communications will play a significant role in transit-oriented developments, particularly in communicating information between users, the system, and vehicles. Much of the communications needs make use of the Internet, since it is often widely available and a variety of communication protocols have already been established. A variety of architectures are applicable for TODs, using the Internet as the backbone for communications. For example, an architecture for generic local communications between a "system" and vehicles is shown in Figure 3.1 (below). This architecture is useful for vehicle (or any other shared resource) access control, as well as for uploading and downloading vehicle information. This architecture is not well suited for real-time applications unless the resources (vehicles in this case) do not travel far from a local short-range communications unit.

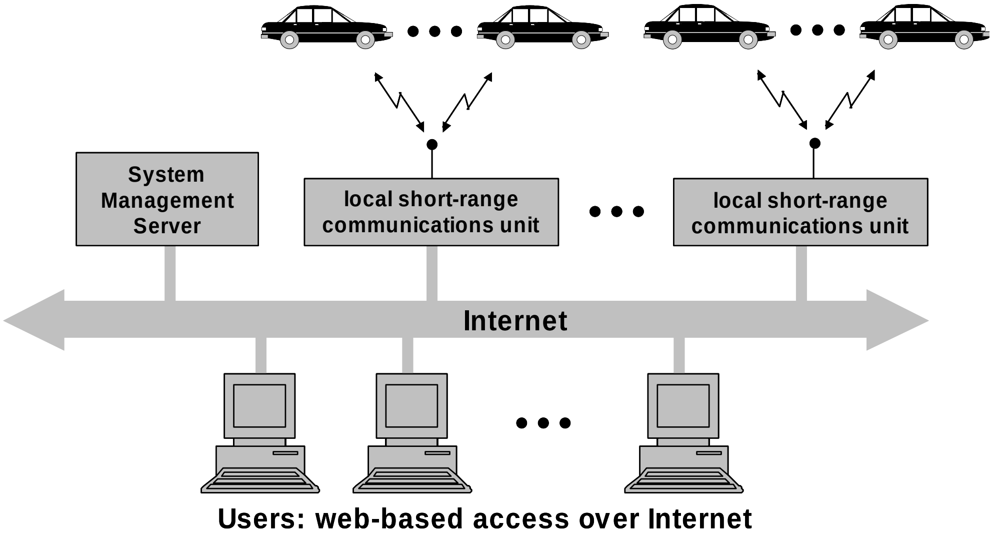

Figure 3.1. Generic local communication architecture.

Another example communications architecture is shown in Figure 3.2 (below). In this figure, a generic, wide-area communication architecture is illustrated. In this case, resources (e.g., vehicles) are not required to be at a designated location to communicate with the system. Instead, cellular based communications can be used to send messages between the system and the resources. Cellular Digital Packet Data (CDPD) and General Packet Radio Service (GPRS) communications, considered as wireless Internet protocol (IP) networks, are now widely accepted standards in North America. They primarily provide packet data service for mobile users by automatically using idle cellular phone channels to send packet data traffic. As such, CDPD and GPRS have been the primary target of ITS applications that require wide-area data communications. A mobile-end system communicates with the CDPD or GPRS network via a 19.2 kilobits per second or greater raw duplex wireless link, which is shared by several mobile end systems. Packets from network to end systems are broadcast, thus establishing a connectionless downlink. For the reverse direction or uplink, CDPD follows a traditional slotted, non-persistent Digital Sense Multiple Access protocol (DSMA/CA). Additional intelligent wireless techniques, such as frequency hopping, radio service (RS) code, roaming, and dynamic channel relocation are used to provide a fairly robust data channel [Lin, 1997]. When implementing such a wide-area communication architecture, a monthly subscription fee must be paid. Further, a wide-area cellular system will always have a certain degree of data packet loss and data packet latency, which might affect shared-use vehicle system operations (see [Barth et al., 2002]).

Hybrid communication architectures are also possible, as shown in Figure 3.3. This type of architecture is particularly well suited for the multi-nodal systems where short-range communications is used for resource access control, and wide-area communications is used for relaying resource status information. Data packet loss and latency issues become less important in this architecture since there is redundant communications at the different nodes.

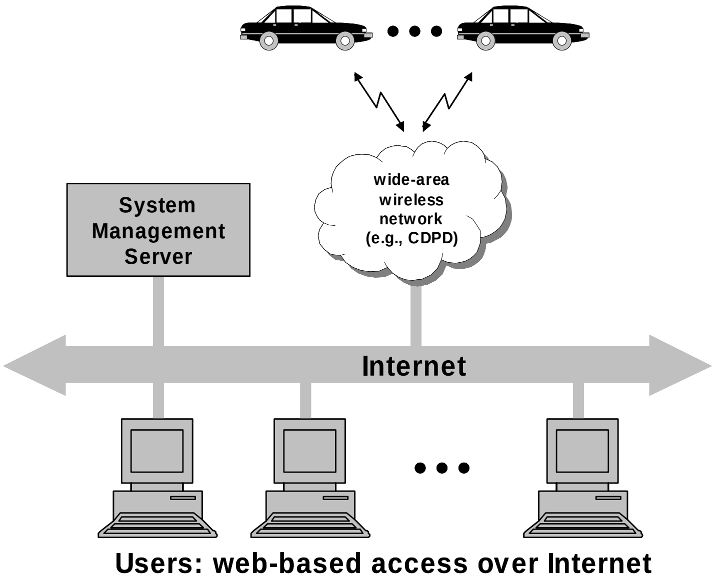

Figure 3.2. Generic wide-area communication architecture.

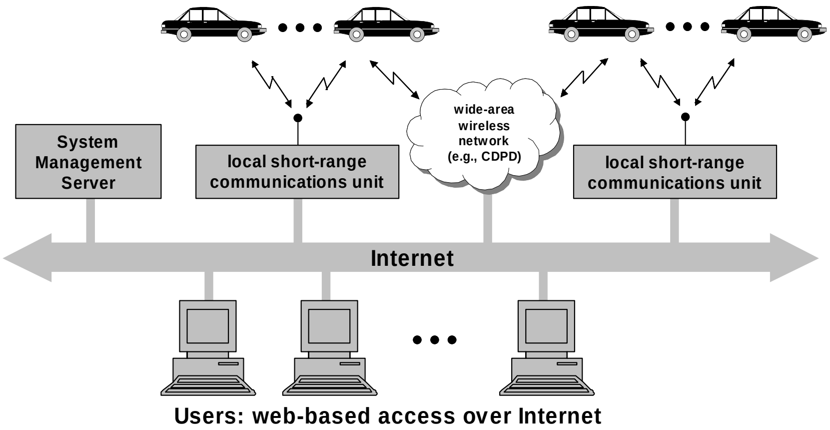

Figure 3.3. Generic hybrid communication architecture.

There can be many variations of the generic communication architecture examples given above. In general, the pros and cons of these architectures are given in Table 3.1 (below).

Communication Architecture	Advantages	Disadvantages
Local, Dedicated Short-Range Communications (Figure 3.1)	• Low cost • Low data packet loss • Low latency • High bandwidth	• Resources (vehicles) can only communicate at stations • Automated Vehicle Location (AVL) and system messaging are not possible
Wide Area, Cellular Communications (Figure 3.2)	• Communications over large areas • AVL and system messaging are possible	• Monthly subscription fee required • Non-trivial data packet loss • Non-trivial data latency • Low bandwidth
Hybrid Communication Architecture (Figure 3.3)	• Communications over large areas • AVL and system messaging are possible • Redundant communications at stations	• Monthly subscription fee required.

Table 3.1. Advantages and Disadvantages of Shared-Use Vehicle System Communication Architectures

3.2.2. Resource Access Control

When applying intelligent transportation system technology to shared resources (e.g., vehicles, lockers, seats, etc.), much can be gained by equipping the resources with on-board electronics, especially if they are mobile. There are four primary functions that on-board electronics can provide, namely: 1) resource access control, 2) resource data acquisition, 3) automated location capability if the resource is mobile, and 4) on-board navigation and user/system messaging. In general, each of these functions can be integrated into a single black “box” that is installed and interfaced in the resource.

It is important to note that in many cases, installing these type of electronics may be “overkill” for the resource at hand. For example, it does not make sense to install elaborate electronic devices that are more costly than the resource itself. More detail on this issue is provided in Section 5.

That being said, having some type of resource access control improves user convenience and system security (potentially leading to lower insurance premiums). Minimum hardware elements that are required for smartcard-based resource access control include a card reader (e.g., applied wireless identification (or AWID)) system, which is used by several of the largest U.S. carsharing organizations) and an interface to the vehicle’s door lock circuitry. When a user waves his/her smartcard by the reader, and the card is recognized as valid, the user is granted access. That simple functionality can be implemented with discrete hardware components, not requiring any processor. However, if a smartcard-exclusive-access methodology is used, then the sophistication of the hardware increases. In this case, user codes must be transmitted between the system and resources so that only valid users can access the resource at the proper times. With that added level of sophistication, typically a microcontroller or microprocessor is required to store code variables and carry out preprogrammed state machines to implement proper sequencing. Adding a keypad system for PIN entry does not significantly complicate the microcontroller system, other than adding an additional hardware component to the overall on-board electronics.

Coupled with reservations and/or on-demand check-out procedures, there are several different ways to control resource access:

Lockbox: All users of the resource can carry a single key that allows access to a lockbox located at the resource location. In the lockbox, the keys of the different resources are available. Many systems have taken this a step further by using common smartcards to access the lockboxes.

Common Key: In this scenario, all of the shared resources are keyed so that a single key can be used for all resources. All users then have a copy of the same key and can access any of the resources.

Smartcard Open Access to All Resources: Instead of a common key, on-board electronics (i.e., card reader secured to a lock mechanism) can be used to read smartcards issued to the users. In this scenario, all resources would unlock using any system smartcard. This method, along with the common key and lockbox methods, depends on users following an honor system to enforce reservations, since any user can access the resource at any time.

Smartcard Exclusive Access for Specific Users: Similar to above, smartcards are issued to users. Each smartcard has a specific code, and when resource access is requested, only the designated smartcard (with the associated PIN code) can release the requested resource for use. This resource access control requires that the smartcard code be transmitted to the resource prior to the time of access for that user.

Smartcard Exclusive Access for Specific User with PIN Confirmation: This method is similar to the above, where smartcard codes are used to enable specific user access. However, an additional step is required in that once the user is at the resource, he/she has to enter a personal identification number (PIN) on an input device (e.g., message display terminal) to enable the resource. This is similar to bank automated teller machines to help prevent fraudulent use of lost or stolen cards.

In all of the smartcard options, key “fobs” (i.e., small devices that can hang from a key chain) can also be used. Furthermore, PDAs or other wireless devices could be used for keyless access by performing short-range communication (e.g., infrared) with the resource.

All of these resource access solutions have tradeoffs in convenience, security, and cost. Figure 3.4 (below) illustrates qualitatively how each access method compares in terms of security and cost. The lockbox technique provides a small amount of security in that users have to go through an extra step to gain access to the resource keys. The common key method is the least secure method, since any lost key could be found and used. The smartcard-open-access method provides a small increase in security since a person who finds a lost card would not necessarily know how to use it. The smartcard-exclusive-access method provides significantly more security but at the cost of requiring the ability to communicate smartcard codes to the resource. The smartcard-exclusive-access-with-PIN provides the most security and has the added cost of requiring a PIN input device.

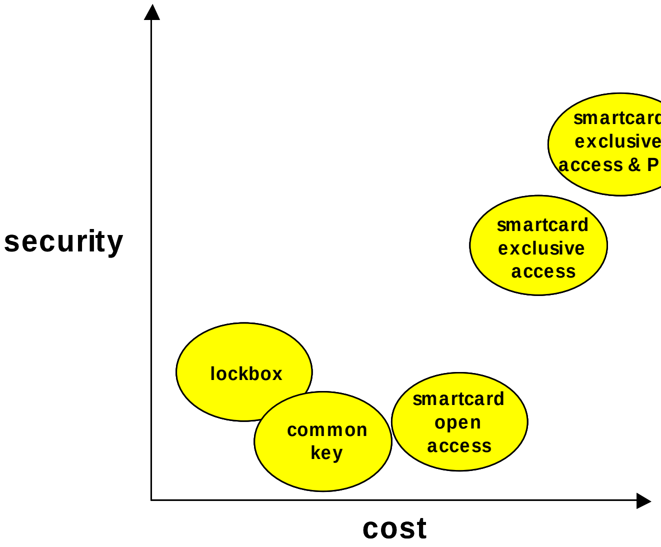

Figure 3.4. Cost and security comparison for various ITS resource access technologies.

Figure 3.5 (below) illustrates the tradeoff between user convenience and cost. The lockbox method detracts from user convenience in that participants must perform the step of accessing a lockbox that may be inconveniently located. The common key method is very convenient for the user, but there is some cost involved in having all resources keyed the same. The smartcard-open-access and exclusive-access are equally convenient to the user. The smartcard exclusive access-with-PIN requires an extra step prior to gaining full access to the resource and is therefore somewhat less convenient.

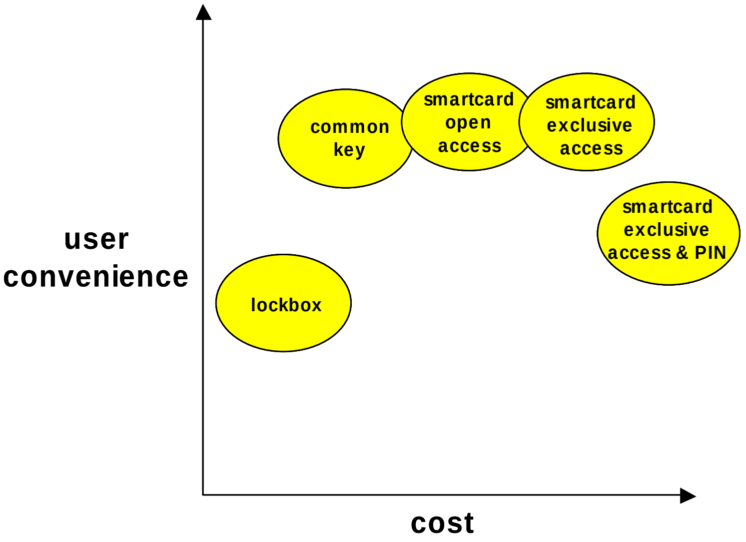

Figure 3.5. Cost and convenience comparison for various resource access technologies.

3.2.3. Trip and/or Resource Performance Data Acquisition

Another important function that on-board vehicle electronics can provide on any transportation mode is the ability to automatically record trip data. These data can then be used at a minimum for billing purposes and resource allocation analysis. In many low-technology solutions (e.g., such as those used for shared-use vehicle systems), users are typically asked to complete a trip log or diary, recording the time when the resource was checked-out and checked-in along with the trip mileage (if applicable). Collecting and entering these data can be time consuming for operations. Further, this system also relies on a customer honor system. On-board electronics can be programmed to automatically record the same parameters by interfacing with the resource (e.g., if it is a vehicle, then we can detect usage) and using an on-board real-time clock. These data can simply be stored and downloaded at a later time by system management personnel (e.g., once every several weeks).

Alternatively, this resource usage information can be transmitted back to the system using wireless communications. If electronics are attached to a shared resource for gathering a minimal set of use parameters (i.e., in a car: trip duration and trip distance), it is relatively straightforward to extend this data set to include other useful pieces of information. Additional parameters may include energy use, and for a vehicle, door open/close signals, gear selection, etc. Another valuable data parameter for mobile resources is location information, described below. It should be noted that in the early stages of any system deployment, it is often desirable to collect a wide range of data to document net system benefits.

3.2.4. Navigation Systems and Automated Vehicle Location Capability

In the last decade there has been a significant amount of progress in developing in-vehicle navigation systems that help drivers efficiently reach their intended destinations. These systems rely on electronic maps in conjunction with sensor systems (e.g., Global Positioning System (GPS) receivers) and associated navigation algorithms. In-vehicle navigation systems began as a novelty offered only in rental cars and high-end luxury vehicles. However, the technology has improved and associated costs have fallen, resulting in a wide range of vehicle navigation systems that can be purchased separately or as part of an option package, which are increasingly available to new car buyers. Similar progress has been made in the transit and fleet management arena, where many Automated Vehicle Location (AVL) systems are employed to track and manage fleets such as buses, taxis, and delivery vehicles.

In general, vehicle navigation and AVL tasks can be broken into three scales: 1) macroscale, 2) microscale, and 3) mesoscale.

> ***Macroscale—***the macroscale level generally considers a large roadway network as consisting of links (roadways) and nodes (e.g., intersections). Specific link and node attributes define how the network is connected together and what the general features are of the different links/nodes (e.g., position, length, number of lanes, capacity, speed limit, etc.). Macroscale navigation usually consists of finding a particular path between two nodes in the network. This path is usually based on some optimality, such as shortest distance or shortest traverse time. Dijkstra’s algorithm [Chabini and Lan, 2002] is a prime example of a solution to the macroscale route-planning problem.

> ***Microscale*—**the microscale level typically considers navigation at the vehicle level and is concerned with tasks such as lane-keeping, as well as detecting and avoiding obstacles. At this level, there is no consideration of the ultimate or intermediate goal on the route. The driver generally carries out these tasks; however, there has been a significant amount of research in automating many of the navigational tasks at this level, such as the work performed for automated highway systems (see, e.g., [Connolly & Hedrick, 1999; Hatipoglu et al., 2003; and Lu & Tomizuka, 2002]).
>
> ***Mesoscale*—**the mesoscale level is a level in-between the micro- and macro-scales and considers vehicle operation at the link-level. A particular link may have a variety of features: multiple lanes, turn pockets, off-ramps, etc. From a navigational point of view, mesoscale route planning is generally concerned with vehicle maneuvers, such as passing, pulling off to the side of the roadway, moving out of the way of emergency vehicles, merging in and out of specialty lanes (e.g., high occupancy toll lanes), and choosing the correct lane to exit. A link-based planning algorithm may be concerned with when, where, and how lane changes are made with respect to a planned course change (e.g. turn, freeway exit) or the current traffic situation.

Most of the navigational and AVL research to date has been at the macroscale and the microscale. For in-vehicle navigation and AVL at the macroscale, sensors with positional accuracy of approximately 10-20 meters are sufficient. For automated microscale operations, higher resolution sensors and actuators currently exist, but they are costly and have only been proven in controlled environments (e.g., automated highway systems, see [Hedrick et al., 1994; Horowitz & Varaiya, 2000]).

To date, very little research has been performed on mesoscale navigation tasks. Two of the primary reasons for this are:

1) Only recently has low-cost sensor technology become available with positional accuracy to 1-3 meters (e.g., differential GPS (DGPS) receivers); and

2) Today’s digital road network data have sufficient accuracy and features for macroscale navigation; however, they are insufficient for many mesoscale navigation tasks.

Now that it is possible to obtain sensors that have improved spatial resolution (e.g., 1-3 meters using DGPS) at a reasonable cost for a vehicle, newer mesoscale navigation and AVL systems are being developed.

For many transportation modes, it is very useful to have location information. For example, in multi-nodal, shared-use vehicle systems where there are many one-way trips, having knowledge of vehicle locations at any time as well as past trajectories is valuable for keeping the number of vehicles balanced across multiple stations. Further, recording errand destination location information can be valuable in determining where new stations should be placed. Location information can be acquired using GPS receivers described above or by using other techniques, such as land-based radio triangulation. The location and trajectory data need not necessarily be transmitted in real time, it may be sufficient to record the data to be downloaded at a later time (e.g., ignition on-and-off). AVL systems are often used on buses to help manage the fleet. However, there are certainly privacy issues associated with AVL systems installed on (semi-)

private vehicles, i.e., those that are part of a shared-use system. Care must be taken to separate private user data from vehicle location data in any type of analysis.

3.2.5. System Messaging

Additional functionality can be added to on-board electronics, such as integrating on-board navigational aids that assist passengers with directions to their destinations or other information. Also, it can also be beneficial to have system messaging capabilities so users can send/receive messages to the system for both emergency and non-emergency related reasons. This added functionality can be beneficial for users and overall system operations.

3.2.6. System Management

The heart of many advanced-technology systems is the *system management component*. The system management component performs various functions, depending on the system architecture. Central to system management is usually a database consisting of users, resources (e.g., vehicles), reservations, and trip information. Various functions that act on this database include, but are not limited to: reservations management, check-out and check-in processing, trip data logging, resource management (and maintenance), and accounting (i.e., billing). Not all of these functions are required, and many of the functions may be spread out across different computer platforms. Further, all of the functions may be tightly integrated automated processes; while in other systems, some functions may be loosely coupled and/or non-automated.

3.2.7. Reservation Management

In many transportation systems, the ability to make reservations is becoming increasingly easy. In a low-technology implementation, a user can call a reservation center (system management center) and request a particular resource. An operator then checks previous reservations for the resource(s) of interest, and if a time slot is available, the reservation is recorded. Over the last several years, there has been significant development and proliferation of *automated* reservation systems throughout society in general. For example, lodging, traditional car rental, and the airline industries now employ automated reservation systems that can be accessed both from the phone (entering data via a touch-tone pad) and from the Internet. For transit-related services, it is a natural fit to have both phone- and/or Internet-based automated reservation systems. Generic automated reservation systems can easily be modified for these systems, little specialization is required for this implementation. Most on-line automated reservation systems show a calendar with dates and times for which there are available vehicles and have a simple intuitive interface.

Reservations provide users with the comfort and security of knowing that their resource is available for them at a specific time and place. Reservations are also useful for system management, allowing the system to maximize resource use throughout the day.

Although reservations can provide user security and can enhance system operations, many resource usage (e.g., vehicle trips) in our lives are not planned well in advance. Often there is a need on a walk-up, “on-demand” basis. On-demand access to shared resources provides high convenience to users; however, it places additional burden on system management to satisfy user demand. Pure on-demand systems exist today (i.e., systems operating without any reservation capability). In pure on-demand systems, a “check-out” process in which participants use a kiosk terminal located near the resource can replace the reservation process. As an example, Figure 3.6 (below) shows a touch-screen kiosk terminal located in a small building near shared-use electric vehicles. The check-out process in this case usually involves going through a few input data screens that are required for checking out a vehicle. Once the check-out request is complete, the user can go to the appropriate vehicle, obtain access, and carry out the requested trip. In some resource systems, a kiosk terminal may not be necessary; in this case, the user simply approaches an available resource and performs the check-out and resource access process in one step.

For the on-demand check-out of resources, going first to a kiosk terminal may seem like an unnecessary step in the overall process; however, there are several cases when a kiosk terminal proves valuable. For example, if there is a set of homogeneous resources located at a single location, then the kiosk computer, running system management algorithms, can play an important role in the resource selection process. If all of the resources are the same and can satisfy all needs, then other factors can be used in the resource selection process. For example, in a shared-use vehicle system, choosing the vehicle with the most appropriate fuel level or rotating vehicle use so that all vehicles are used approximately equally over time.

The process of going to a kiosk prior to accessing a resource can be circumvented through the use of wireless-enabled PDAs or Internet-capable cell phones. In this case, a user would simply access a website that performs the resource check-out process without going to a stationary kiosk terminal.

Figure 3.6. Touchscreen kiosk terminal (located inside small building) used to check-out shared-use vehicles (electric pickups and electric city cars).

3.2.8. Accounting Systems

An important part of any system management is the ability to access data logs for billing purposes. Further, it may be necessary to evaluate resource use based on a number of factors.

Various queries and filters can be designed to quickly sort such data. User billing can be handled as a standard back-office operation, which is prevalent on today's Internet.

3.3. IMPLEMENTATIONS

A thorough evaluation of ITS technology associated with shared-use vehicle systems and smart parking has been carried out to provide a detailed understanding of specific data communications and constraints that need to be considered for TODs. As described previously, there are three basic shared-use vehicle system models. They include neighborhood carsharing, station cars, and multi-nodal shared-use vehicles. Recently, the first two models have advanced beyond their original visions, largely due to advanced technologies (e.g., electronic and wireless communication systems) that facilitate system management and vehicle access. Thus, the initial carsharing and station car concepts have evolved to include common elements of each model (e.g., commuter carsharing).

3.3.1. Carsharing

Today's typical carsharing organization places a network of shared-use vehicles at strategic parking locations throughout a dense city (see Figure 3.7). Members typically reserve shared-use vehicles in advance. At the time of the rental, the user gains access to the vehicle, carries out her trip, and returns the vehicle back to the same lot she originally accessed it from (this is also known as a "two-way" rental because the user is required to rent and return a vehicle to the same lot during one continuous rental period). Participants pay a usage fee (typically based on time and mileage) each time a vehicle is used. The carsharing organization as a whole maintains the vehicle fleet (including light trucks) throughout a network of locations, so users in neighborhoods and business areas have relatively convenient vehicle access. Usually there is also a small monthly subscription fee or a one-time deposit or both.

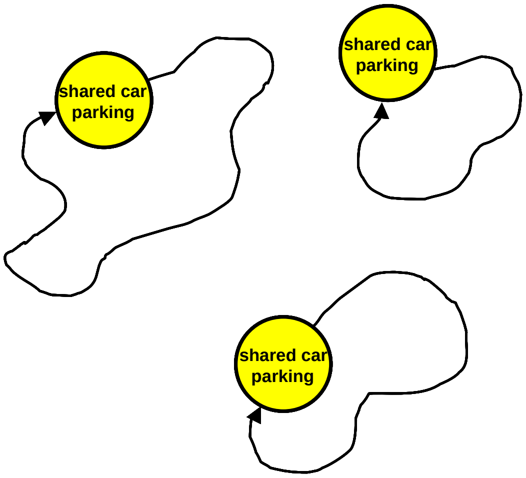

Figure 3.7. Neighborhood carsharing model.

Internationally, carsharing organizations are the most prevalent type of shared-use vehicle system. The vehicles are most often placed in residential neighborhoods; less frequently, they are located in downtown business areas and rural locations. To summarize, the premise of carsharing is simple: Short-term usage and vehicle costs are shared among a group of individuals. Lots are located so carsharing users can conveniently access vehicles for tripmaking. Often carsharing results in increased transit ridership (as well as other alternative modes, such as biking), as users become much more conscious of the individual costs of each automobile trip.

3.3.2. Station Cars

Another shared-use vehicle system model is known as “station cars”. A typical station car scenario is depicted in Figure 3.8 (below). When station cars are placed at major rail stations along a commute corridor, they can serve as a demand-responsive transit feeder service on both ends of a commute (see [Shaheen, 2001]). For example, a user can drive a station car from home to a nearby transit terminal, parking it at or near the station while at work. The user then commutes by rail or bus to their destination. After arriving at their destination station in the morning for work, a second station car could be rented to travel from the station to their office, and during the day the individual also might use that same vehicle to make business and personal trips throughout the day. In the evening, the user again drives the station car to travel from work to the station. At the end of the transit commute, this same individual takes another station car to drive home. In this scenario, “reverse” commuters often use the same dedicated station car for their station-work/station-home trips. Furthermore, other users could also make non-commute trips during the day when the vehicles would otherwise sit idle at a station [Bernard & Collins, 1998].

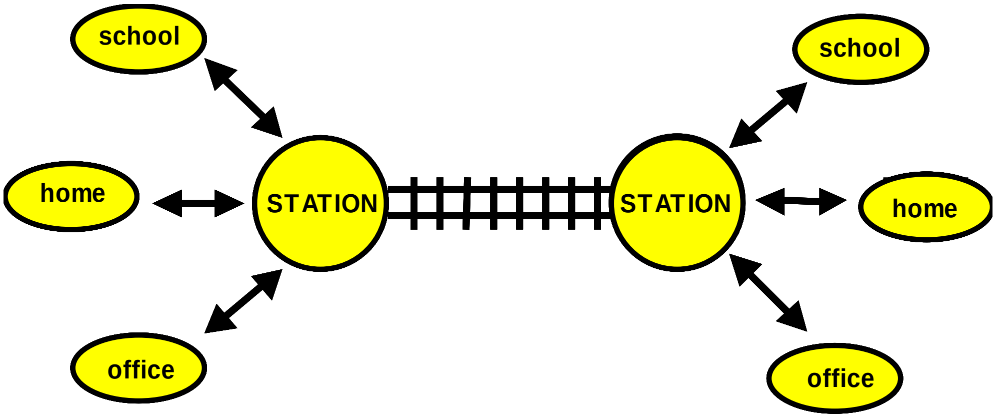

Figure 3.8. Station car model.

3.3.3. Other Shared-use Vehicle System Models

A more generalized shared-use vehicle system is one in which the vehicles are driven among *multiple* stations or nodes to travel from one activity center to another. Such systems may be located at resorts, recreational areas, national parks, corporate & university campuses, and TODs. For example, a user may arrive by rail or bus, then rent a shared-use vehicle to drive from the station to a corporate site, hotel, or residence, as depicted in Figure 3.9 (below). Later on, the same individual may travel from the hotel to a shopping mall or other attraction. In this way, the trips are more likely to be *one-way* each time in contrast to the typical roundtrips made in a traditional station car or neighborhood carsharing program. Users share vehicle costs and usage, similar to carsharing.

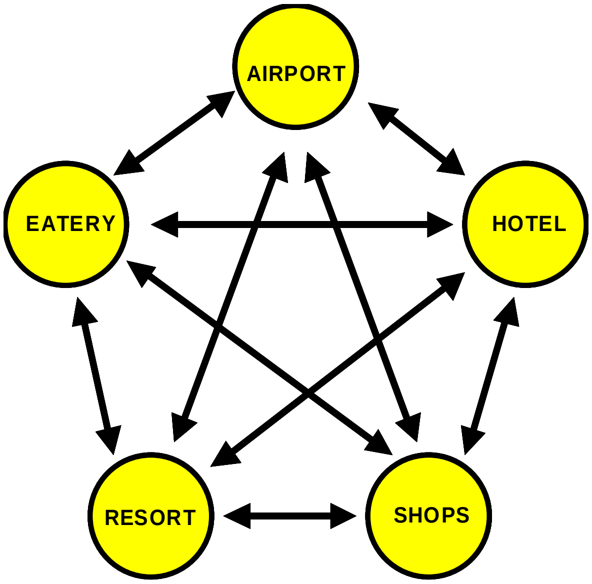

Figure 3.9. Multiple-station shared-use vehicle model.

An advantage of a multi-station system is that vehicle trips can be “one-way” versus “two-way” only. One-way rental introduces significant flexibility for users but management complexities, including vehicle relocation. Advanced technologies can make multi-nodal systems much easier to manage and cost effective as well.

The most effective configuration of a shared-use vehicle system within a TOD will be a function of many variables. The integration of other compatible transit options can influence the overall role of the shared-use vehicles significantly. The shared-use vehicles may be dedicated solely as a transit feeder service. Other alternatives may include a TOD with high internal mobility via a shared-use vehicle system, and the transit station being one of many potential destinations within the shared-use vehicle system. The various shared-use vehicle system architectures have been evaluated to explore the full range of implementation possibilities within a TOD.

4. Intelligent Bus Priority Lane Analysis

Buses operating in mixed-traffic lanes experience delays 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.

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. This analysis considers both conservative and liberal approaches. In both approaches, vehicles merge while discharging from intersection queues in anticipation of preventing the formation of a queue in the bus lane further downstream.

An Intelligent Bus Priority lane is best suited for bus routes with large headways on major urban and suburban multi-lane arterial roads that experience medium traffic congestion during peak periods. If traffic congestion is too heavy, the costs to other traffic of BLIP operation may be too great; if congestion is too light, the benefits to bus passengers are minimal. Traditional bus lanes are excellent at providing unimpeded right-of-way to bus transit vehicles, as the lane is rendered unavailable to non-bus traffic. In situations where the bus headways (times between bus arrivals) are minimal, this side effect is justified. However, in situations where the headways are larger (around 15 minutes), reserving a single lane for buses cannot be justified. However, the alternative of operating transit vehicles in mixed traffic, results in slow and unreliable service.

Reserving the lane for buses can yield benefits of two types: reduced travel time and reduced travel time variation. Travel time is reduced by the elimination of merge delays (delay experienced by buses merging back into mixed traffic lanes) and signal queue delays (delay imposed by queues at intersections). By removing factors prone to stochastic variation (e.g., merge delay and signal queue delay) from those that influence the buses' travel time, roundtrip bus travel time variability can also be reduced. 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 AVL system that transmits its trajectory information to a central control system. This control system then projects the trajectory of the bus and determines at which intersections the bus might be queued. 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 creates a signal plan to ensure that signals at those intersections instruct drivers at the appropriate time that the rightmost 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 with any changes.

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, which include accommodating right turns and dealing with pedestrians blocking right-turn movements, are not in the scope of this analysis. Other research is focusing on these issues. 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 transit signal priority (TSP). In TSP implementations, signal cycles are changed to give priority to transit vehicles. TSP reduces the delay caused to transit vehicles caused by the red signals (signal stop delay). A BLIP can be effective at reducing the delay caused by the queue at an intersection (signal queue delay). In implementations where TSP and priority lanes can be paired, the bus will only need to stop for passenger boarding and alighting. This will ultimately decrease the travel time on the route and increase the reliability of the system by ensuring schedule adherence.

4.1. BASIC ANALYSIS

4.1.1. Scenario Description

The intelligent bus priority lane analysis uses a simplified scenario for evaluating the impacts of the bus on through traffic. First, the analysis ignores turning traffic. It is noted below when non-trivial turning traffic impacts the analysis. 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.

4.1.2. Supporting Concepts

***Kinematic Wave Theory*—**this analysis 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. This analysis assumes a triangular fundamental (flow/density) relationship for all lanes combined as displayed in the diagram in Figure 4.1 (below). 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. 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.

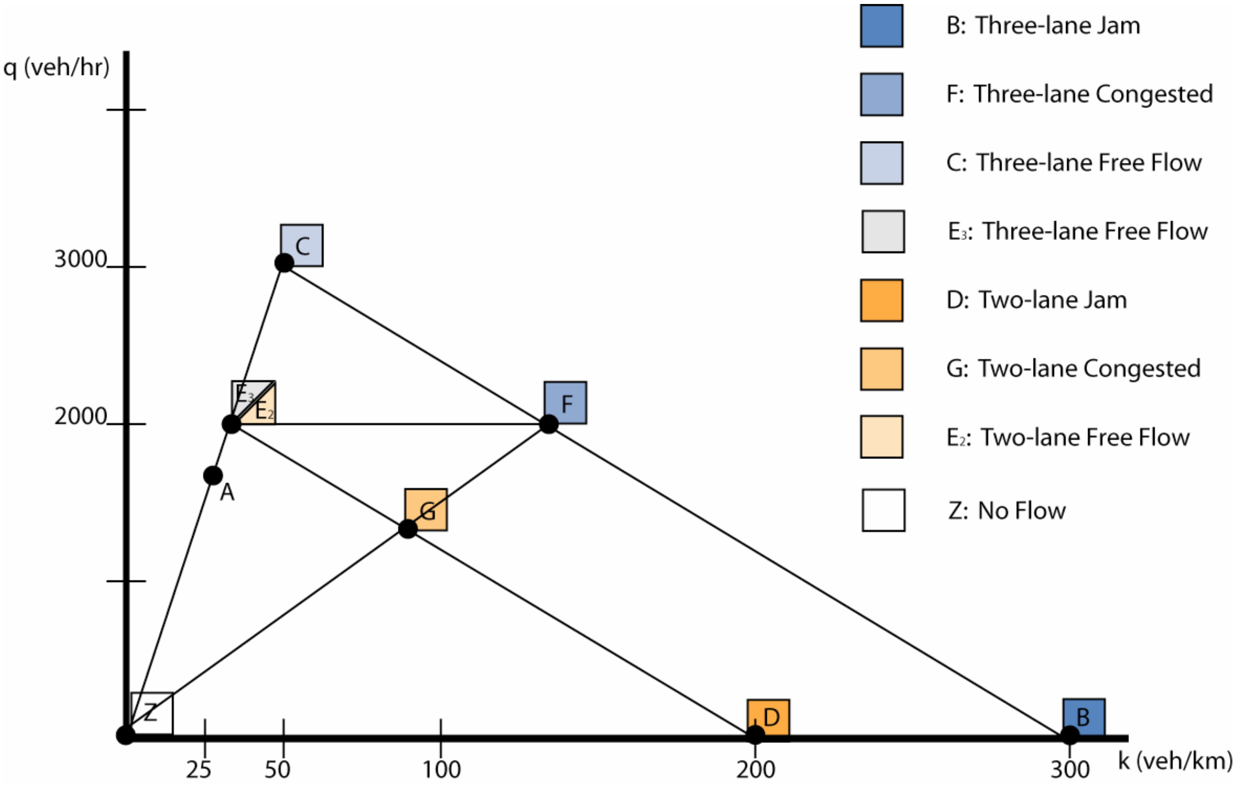

Figure 4.1. Flow/Density diagram. This specific diagram represents a three-lane roadway being reduced to a two-lane roadway.

4.1.3. Overview of Approaches

As discussed above, this analysis considers two approaches: once conservative and one liberal. Both approaches restrict private access to the right lane at the onset of a green phase of an intersection's signal. The conservative approach imposes the restriction for a full cycle length. The liberal approach imposes the restriction only long enough to ensure that private vehicles do not queue in front of the bus. The conservative and liberal approaches are displayed in Figure 4.2 and Figure 4.3, respectively (below).

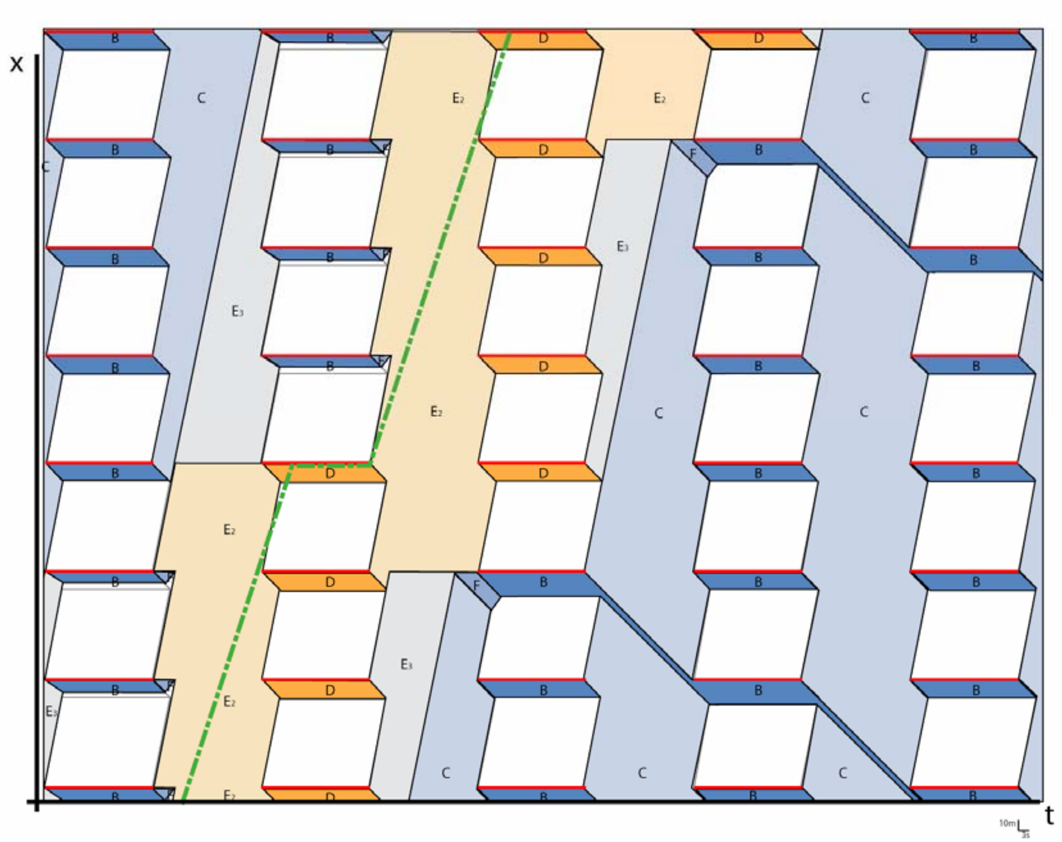

Figure 4.2. Illustration of the conservative approach.

As illustrated in Figure 4.2, the conservative approach creates a "rectangular" region of two-lane traffic. Vehicles entering from the "bottom" and the "left side" of the rectangle are instructed to merge when entering the restricted region. The restricted region is large enough to ensure that no vehicle in the region will interact with the bus at some other point in time. As the figure illustrates, notification of the road status (restricted or unrestricted) can be communicated to the drivers by the signals at the intersections, and each signal will display the restriction status for an entire green phase.

This approach is likely to be less confusing to drivers, as signals will not change mid-phase, and the restricted regions do not physically (in space) abut unrestricted regions. The restricted and unrestricted regions do abut temporally (in time), and these transitions are modeled as part of the analysis. The negative aspects of this approach are that it causes a much larger disturbance to traffic and requires the merging of many vehicles that would not be interacting with the bus.

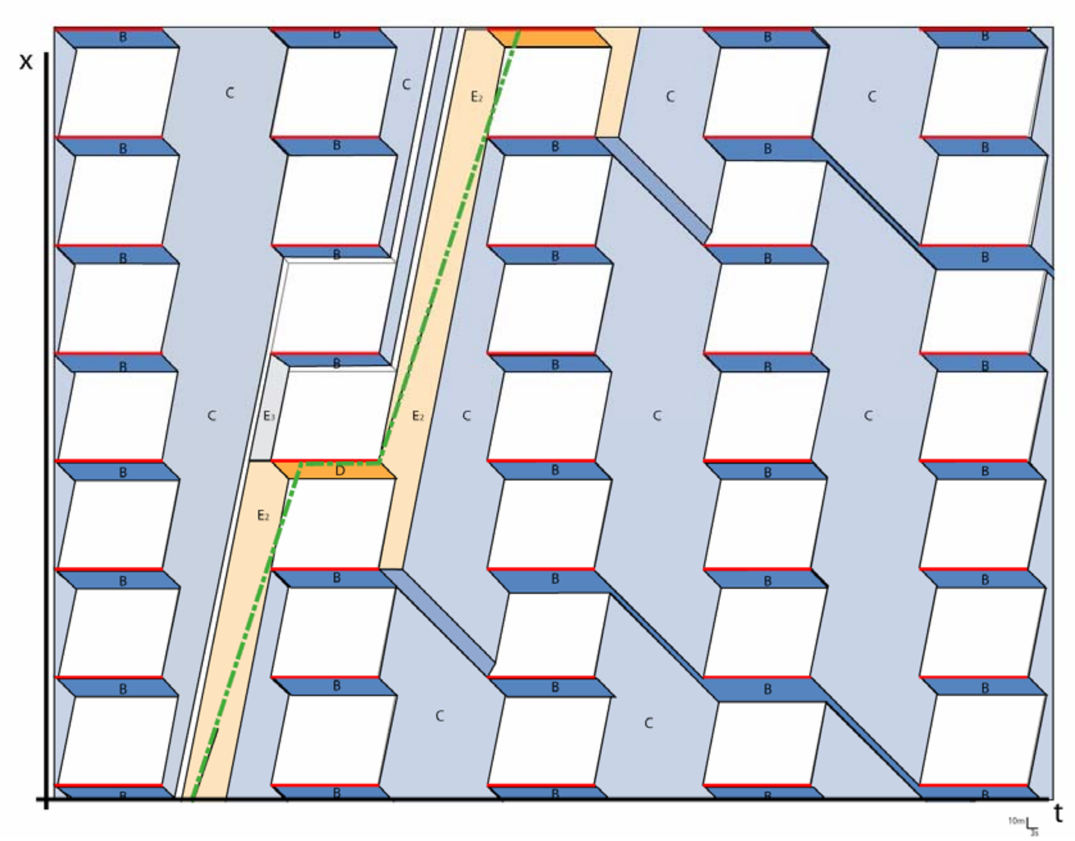

Figure 4.3. Illustration of the liberal approach.

Figure 4.3 illustrates the liberal approach. This approach does not create a rectangular restricted region, but instead it 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”. As with the conservative approach, notification of roadway status can be communicated to drivers at the intersection signals. However, this would require not only fractional restriction notification, but switching a lane's status from “unrestricted” to “restricted” and back again during a single green phase.

This approach only affects vehicles that would potentially queue in front of the bus, and therefore minimizes the disturbance to traffic. However, there may be implementation difficulties and driver confusion due to the restriction signalization lasting for less than a full green phase. Additionally, the restricted region abuts in space the adjoining unrestricted regions on both sides. This could cause additional driver confusion, as drivers could be tempted to “follow the lead” of the unrestricted vehicles ahead of them.

4.1.4. General Findings

In this section, the authors define two types of effects found by this “first blush” analysis. First, the startup effect is the capacity reduction due to the beginning of the bus along its route. Second, the intersection effect is the capacity reduction that results from the subsequent merging movements along the route. The reason for the two effects is that the startup disturbance creates platoons of lower flow in the traffic stream that travel upstream at about the same speed as the bus. These low-flow platoons reduce the impact of subsequent merging movements. This is illustrated in Figure 4.2, where vehicles leaving the "top" of the restricted regions (labeled E_2) continue upstream unrestricted. However, due to the conservative nature of this approach, these vehicles are requested to merge again after queuing at subsequent signals. This merging causes no capacity reduction, as the vehicles in question are at a less-than-capacity traffic state (state E_3), which can easily fit into two lanes without queuing.

The first finding of this analysis is that the conservative approach has a significant startup effect, and a moderate intersection effect. The startup effect is illustrated in Figure 4.4 (below), where the traffic disturbances caused by the bus beginning its route are readily apparent. Secondly, as illustrated in Figure 4.3, the liberal approach has *no startup effect* and the same intersection effect as the conservative approach.

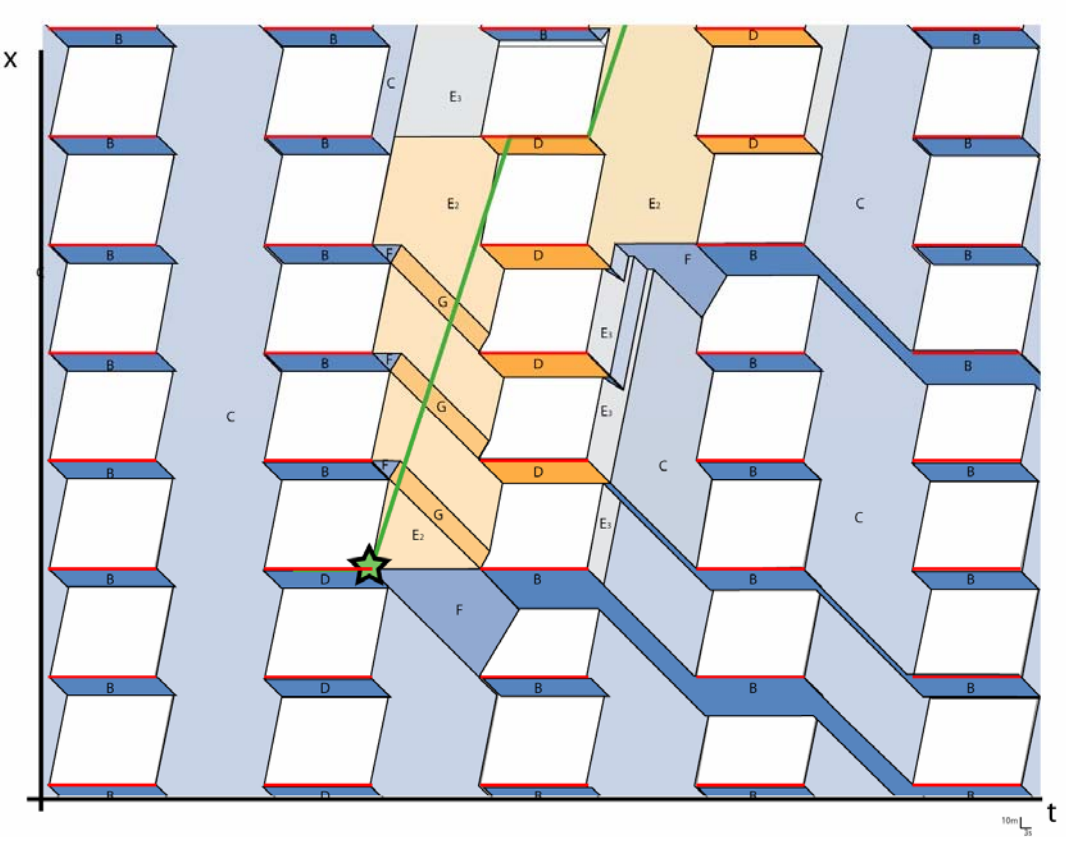

Figure 4.4. The "startup effect" of the conservative approach. The star indicates where the bus enters the roadway.

The intersection effect displayed by both approaches can be seen on both figures as a thin "ribbon" of queue that travels backwards along the roadway. The potential impact of this backward-moving congestion is discussed in the next section.

4.1.5. Macroscopic Analysis

As the above analysis has indicated, the BLIP implementation will create queues that travel upstream when traffic demand is at capacity. Considering that subsequent buses can be delayed by these queues, further analysis is necessary.

If we zoom out to a much larger scale of analysis, some insight can be shed on the problem. At a macroscopic scale, the impacts caused by the signals can be averaged into a new fundamental diagram: The free flow speed (v_f) would be the average speed of traffic (ignoring the bus); the maximum flow (q_C) would be the original road capacity multiplied by the fraction of green (g/c); and the jam density would stay the same (k_j). (This has the effect of reducing the backward wave speed (w), which should be expected since—Figure 4.3—disturbances are also slowed at the signals when the signals are red.) This modified macroscopic fundamental diagram is displayed in Figure 4.5 (below).

The bus can now be modeled as an ordinary moving bottleneck. Moving bottlenecks create different traffic conditions upstream and downstream of the bottleneck: the upstream traffic in a congested state and downstream traffic freely flowing at a reduced volume. The interface between these traffic states is the bus, which travels at an average speed of v_B. On the fundamental diagram, this speed is shown as a line from the origin with the slope v_B, as well as a parallel line connecting the upstream and downstream states. The downstream traffic state *D* will be assumed to be the capacity of the road minus one lane, $q_C(n-1)/n$, which is a conservative estimate of the flow that will discharge from the bottleneck. The upstream state *U* is determined by following the line of slope v_B from state *D* to the congested branch of the diagram.

If the road was infinitely long and there was an infinite demand waiting to enter, the introduction of a single BLIP bus would result in the beginning of the roadway being predominately in state *U*. This is illustrated in Figure 4.5b. Therefore, we can consider the flow at this state (q_U) to be the capacity of the single-bus BLIP system on a very long street. It should be noted that the state *D* would be the traffic state resulting from a dedicated bus lane implementation, and its flow q_D is significantly less than q_B. Also, it should be reiterated that the traffic state *U* is a function of the bus speed; therefore, increasing the average speed of the bus (v_B), increases the capacity of this simplified single-bus system. Finally, it should be obvious that the ideal application of a BLIP implementation is in a situation where the traffic demand is somewhere between q_D and q_U.

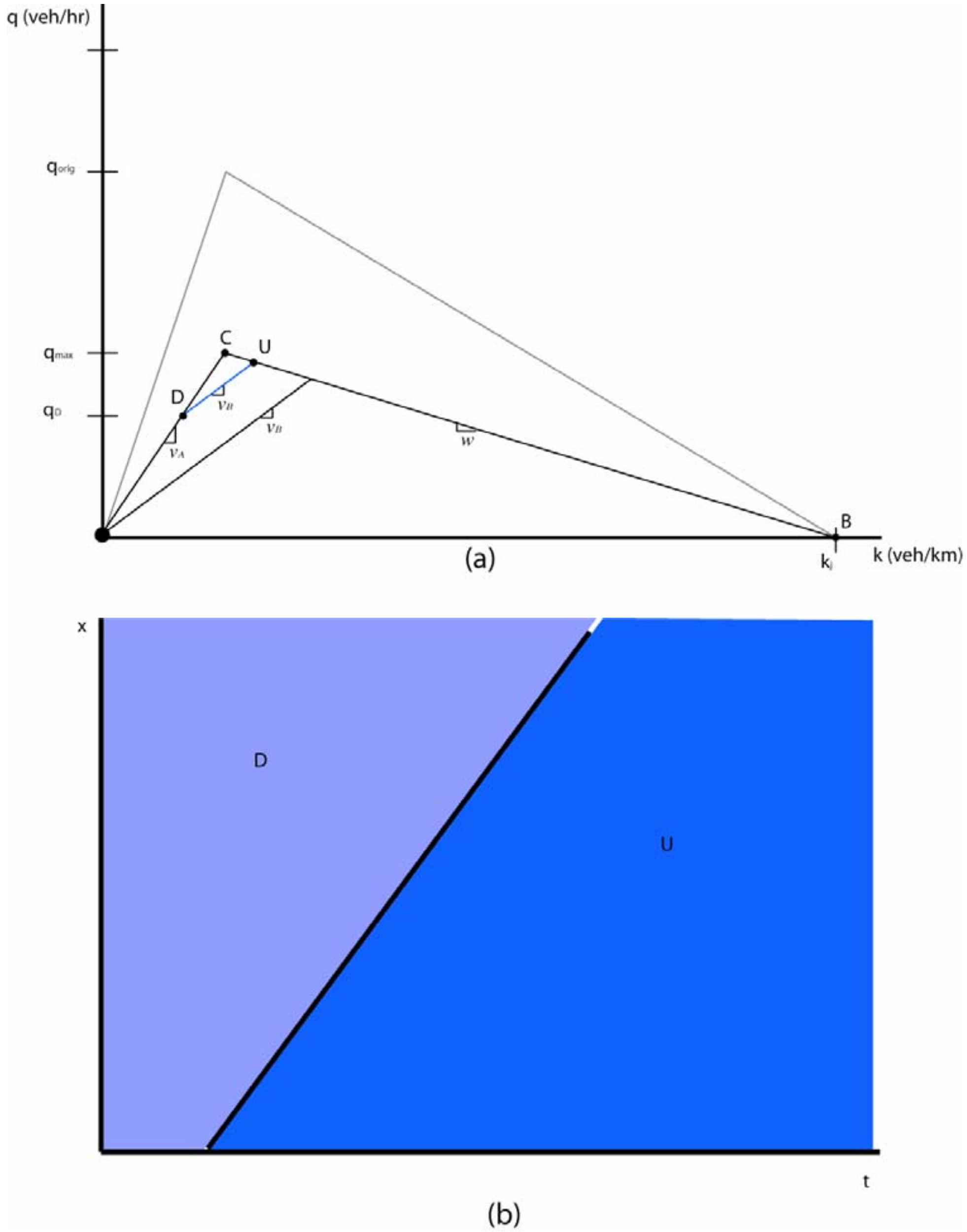

Figure 4.5. Fundamental diagram and time-space plot for the macroscopic view: infinite roadway and a single bus.

Extending the analysis to more than one bus presents complications, as subsequent buses could be affected by queues created by previous buses. Luckily, roads and bus routes are not infinitely long, and the complications are inconsequential. Figure 4.6 (below) illustrates the situation where the BLIP lane makes up a portion of length L of the roadway in question. The fundamental diagram for this situation, Figure 4.6a, indicates the traffic demand state *A*. The time/space diagram in Figure 4.6b shows that the downstream reduced capacity state *D* meets with and cancels out the congested upstream traffic state *U* from the previous bus. We see that the flow of state *A* (q_A) can be sustained for as many headways as necessary, as long as $q_A < q_U$. And this is true independently of L and H. Thus, we can think of q_U as the car-carrying capacity of the system.

We assumed in the construction of Figure 4.6 that the headways are so short that the clearing wave between states U and D does not reach the upstream end of the BLIP section—even if the upstream demand is q_U. Note from the figure that the lower bound of the time interval following a bus arrival at the upstream end of the BLIP until the passage of its clearing wave is:

$$T = L\left(\frac{1}{v_B} + \frac{1}{w}\right).$$

Thus, the wave cannot reach the upstream boundary if $H \leq T$. This is the condition for capacity q_U to be achieved. For typical systems, the factor in parentheses above relating T to L should be on the order of 10 min/mile. Hence, the maximum headway for a (short) two-mile BLIP is (long) about 20 min. We expect most BLIP applications to satisfy this condition: $H \leq T$. Fortunately, if the condition is not satisfied, the car-carrying capacity is *greater*. In this case, as illustrated in Figure 4.7 (below), the maximum entry flow in each headway cycle alternates between q_U (for T time units) and q_A (for H-T units). Thus, the complete capacity formula is:

BLIP car-carrying capacity approximation:

maximum flow of cars $\cong q_U(T/H) + q_A(1-T/H)$, if T < H. (4.1a)

$\cong q_U$, otherwise. (4.1b)

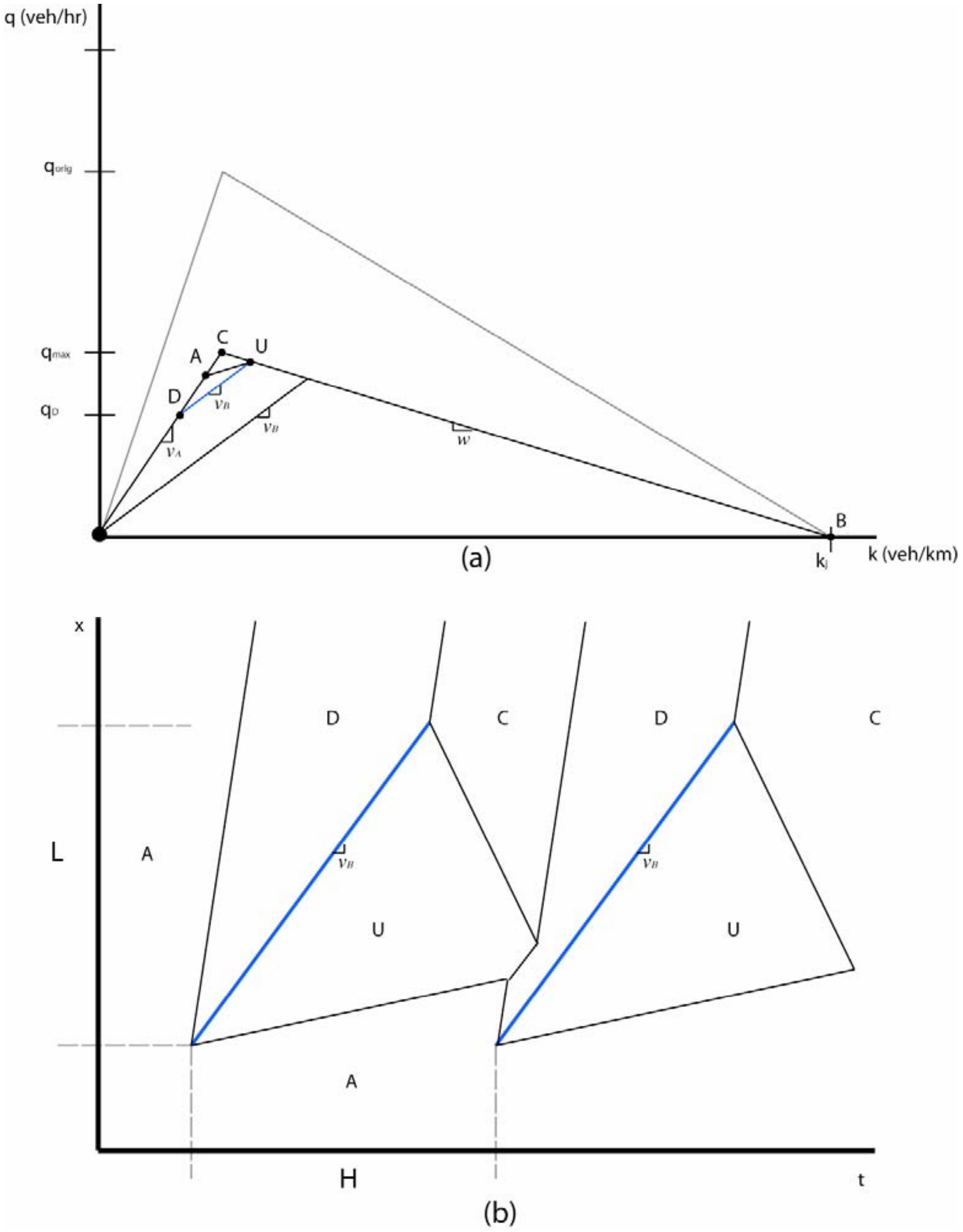

Figure 4.6. Fundamental diagram and time-space plot for macroscopic analysis, showing two buses. Note the downstream traffic state (D) from the second bus cancels out the congested traffic state (U) from the first.

This formula is an approximation based on our "zoom concept". It assumes that the section of interest has many blocks and that a bus-headway includes many cycles. If these conditions are violated, then the approximation is invalid. But then, one would not be considering BLIP lanes.

It should be obvious from Figure 4.6 that if the flow of state A (q_A) increases and exceeds q_U, the cancellation effect is removed, and headways greater than T would be necessary to accommodate such flow. Figure 4.7 (below) illustrates the situation. In this case, the congestion caused by the first bus will slow the second bus unless, as pictured, the headway (H) of the buses is greater than the time needed to allow the congestion to dissipate before the following bus begins its route, indicated as time (T) on Figure 4.7. The reader can verify that the critical headway (for which the sliver of state "A" in Figure 4.7 disappears) is the value of H for which (1a) yields $q_{A.}$ (This is an alternate way in which (1a) could have bee derived.)

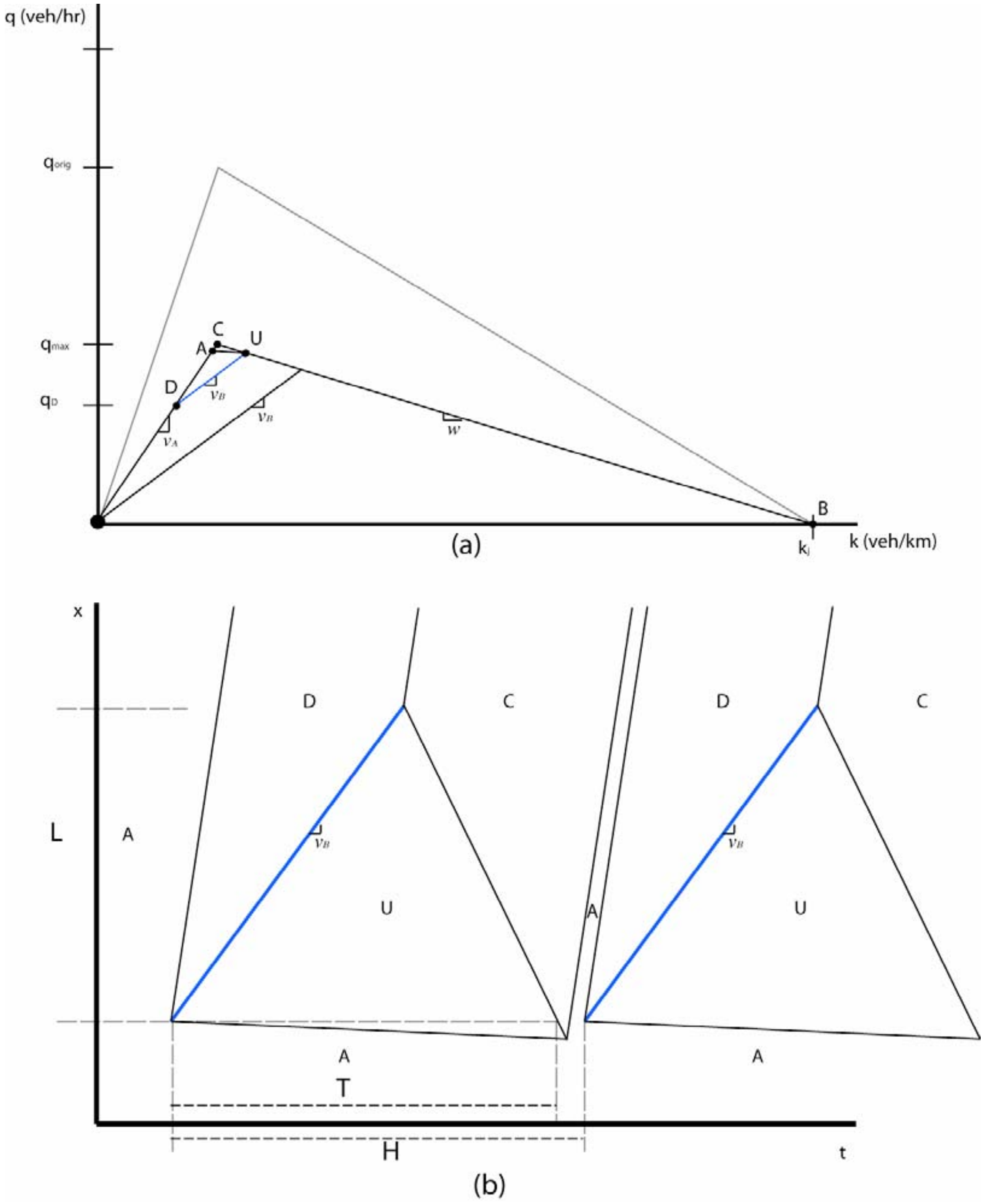

Figure 4.7. Fundamental diagram and time-space plot showing macroscopic analysis where demand flow q_A is greater than congested flow q_U.

To summarize the conclusions from this macroscopic analysis, we see that a BLIP implementation can accommodate any car flow q_A less than q_U – independently of the BLIP's length or the bus headway. But, higher car-flows are possible if the bus headways are greater than "T"; this critical time is *roughly* estimated at about 10 minutes per mile of BLIP.

4.2. DETAILED ANALYSIS

4.2.1. Analysis Overview

The following detailed analysis explores boundary conditions for feasibility of the liberal approach. Since it was determined above that the intersection effect is the same for both approaches, the resulting formulae will also apply to determining the feasibility of the conservative approach. The liberal approach follows a rule that traffic merges upstream of a potential bus interaction while discharging from a queue. Once the queue has cleared, traffic is no longer instructed to merge. This analysis determines the queue clearance time of a signal, which is a function of the offset between the signal and the next upstream signal. As such, the authors first explore calculating the effective offset of a signal, and then determine the queue clearance time. Finally, the impacts in space and time are evaluated.

Figure 4.8 (below) 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 they 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 at the downstream intersection after the bus has passed or they will be stopped at an intermediate intersection.

4.2.2. Supporting Concepts

***System Inputs*—**the following variables will be used throughout the detailed analysis.

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.

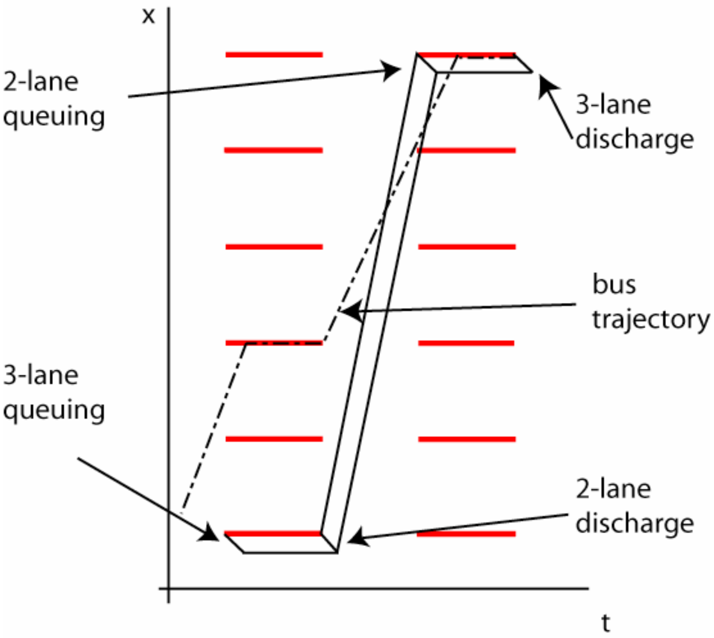

Figure 4.8. Example of BLIP activation. Traffic merges from 3 lanes to 2 lanes while discharging from an upstream signal in anticipation of queuing in 2 lanes downstream. The broken line represents the trajectory of the bus, and the solid lines represent the first and last vehicle that will queue at the intersection where a bus is expected.

***Offsets*—**an offset is the 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 4.9 (below). The basic equation for the effective offset is simply the absolute value difference of the relative offset:

$$O_{E\,basic} = |O_R|.$$

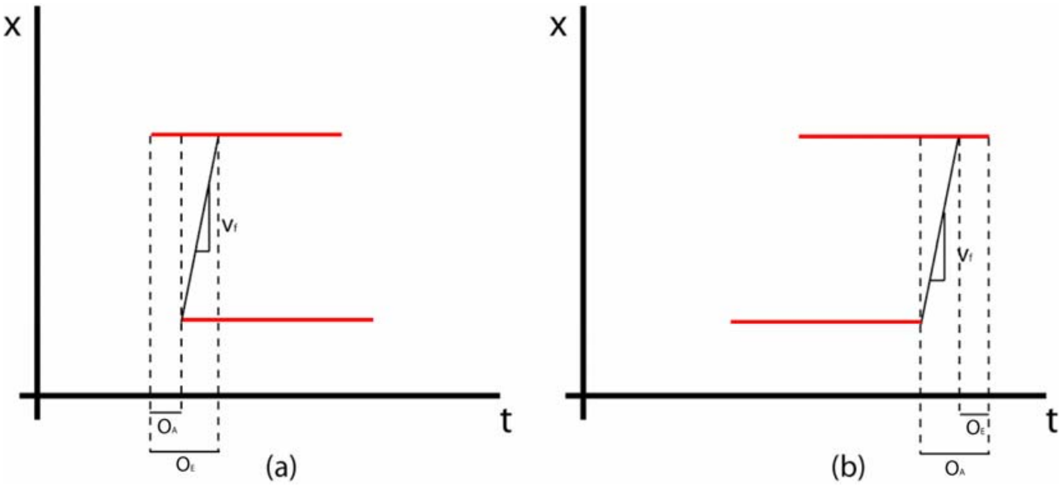

Figure 4.9. Comparison between actual and effective offset. The actual offset is represented by t_a and the effective offset is represented by t_O. Part (a) shows a negative actual offset; part (b) shows a positive actual offset.

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.

Due to the cyclical nature of traffic signals, this basic formulation must be further refined to accommodate for 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 activation of a BLIP 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 4.10, 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.

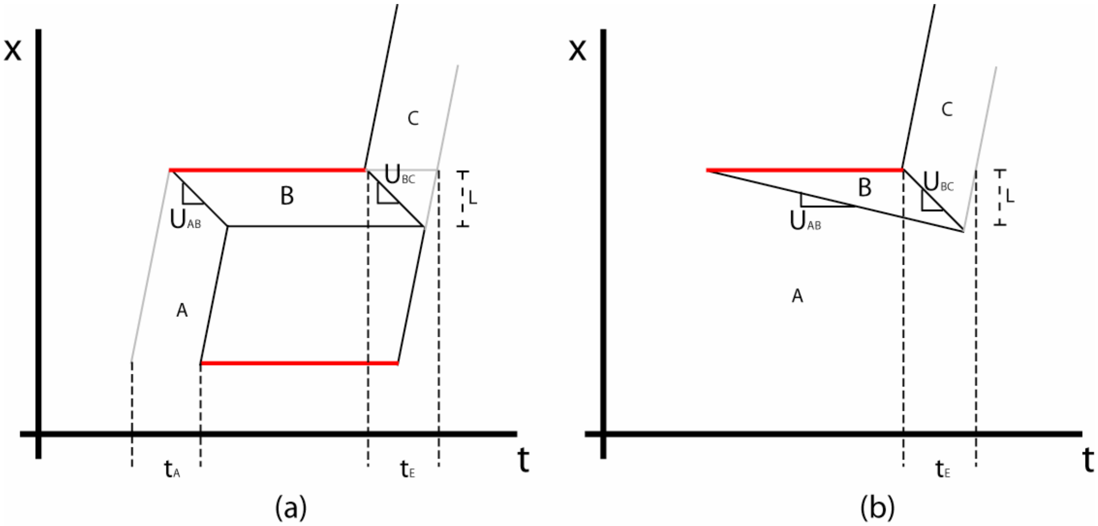

Figure 4.10. Queue clearance time for non-isolated (a) and isolated (b) intersections.

For an intersection in a series, as illustrated in Figure 4.10a, 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 4.10b, 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.

4.2.3. Other Factors

In addition to the system inputs described above, there are other factors that should be given consideration. These factors are primarily concerned with the design and location of bus stops. Bus stop locations are named according to their relation with the intersection: far-side, near-side, or mid-block. An arterial using near-side bus stops has the most to gain from a BLIP implementation, as the passenger movements can be made while the bus is stopped at a signal. Far-side and mid-block bus stops may not gain as much overlap benefit.

Bus stops can be configured as bus bays (or turn-outs), bus bulbs, or curb-side stops. Bus routes along arterials with bus bays will gain more benefit (merge delay reduction) than in-lane bus stops (bus bulbs and curb-side stops). This is because bus routes with in-lane bus stops do not experience merge delays.

These factors should be considered when determining the feasibility and benefits of a BLIP implementation. Bus routes that use only bus bays and near-side bus stops have the most to gain from a BLIP implementation. Bus routes with far-side bus bulbs, for example, have the least. They might only benefit from a reduced signal queue delay. Each intersection and bus stop should be considered independently with its unique characteristics.

4.2.4. Feasibility Analysis

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.

4.2.4.1. Impacts 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 analysis 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.

Figure 4.11 (below) 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).

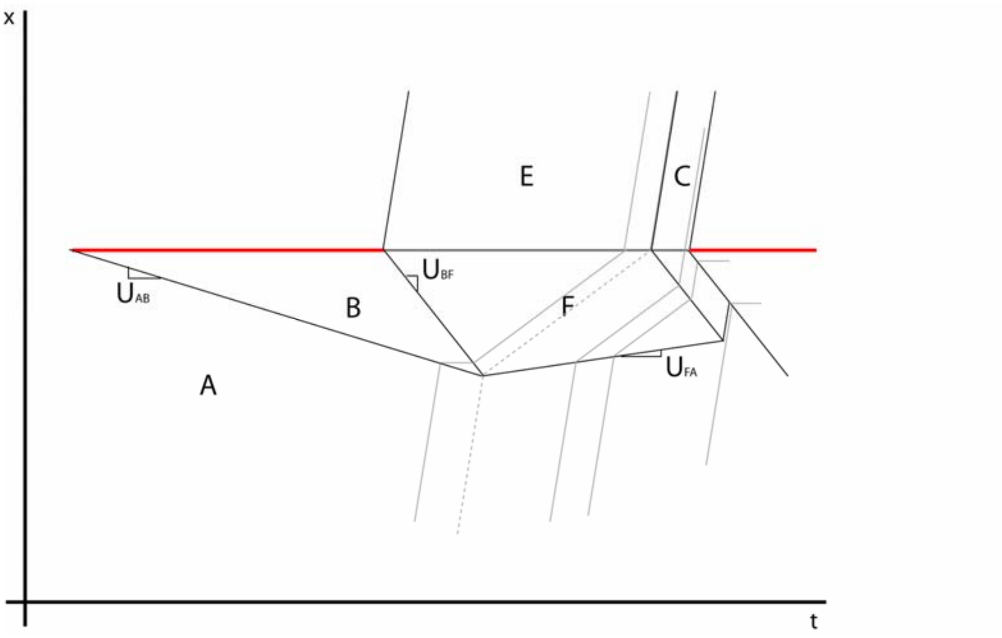

Figure 4.11. Time-space diagram illustrating merge during the activation of the priority lane. For example, vehicles traveling in state A queue in three lanes (state B), but they merge to two lanes as they cross the stop line (state E). A three-lane congested state (F) results directly upstream of the intersection. The grey lines represent vehicle trajectories, and the dashed line represents the last vehicle in the queued state B. Once this vehicle reaches the stop line, subsequent vehicles proceed through the intersection in the original traffic state (C).

The duration of the disturbance caused by the activation of a BLIP is called the relaxation time. The starting point for determining the relaxation time of the disturbance is a queuing diagram, such as the one displayed in Figure 4.12 (below). This relaxation time *n*, expressed in either cycles, can be determined analytically through the following supply and demand metaphor. 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.

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

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:

$$gq_C - cq_A > 0 \text{ => } q_A < \frac{g}{c} q_C.$$

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.

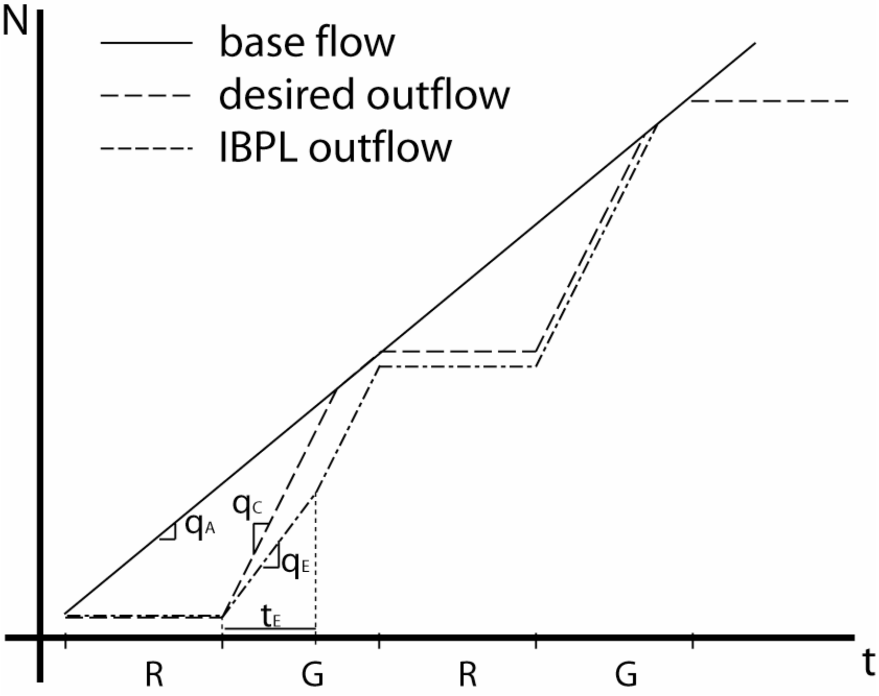

Figure 4.12. Queuing diagram showing the dissipation of the disturbance caused by the BLIP activation. The demand for the intersection is a constant, q_A, represented by the solid line. Normally the intersection has a saturation flow rate of q_C. It is obvious that the intersection can support the base demand. Under BLIP activation, the outflow of the intersection is reduced to q_E, represented by the lower dashed line. This low outflow lasts until the last queued vehicle leaves the intersection (after t_E seconds) when normal saturation flow q_C resumes. During the following cycle, the "disturbed flow" catches up to the expected, undisturbed intersection outflow.

The delay to other vehicles can be easily evaluated using the input-output diagram displayed in Figure 4.12. 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 the above queuing diagram, one can easily calculate 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. These costs will be discussed later in the report.

It should be noted that this delay might not be newly created delay: the interaction between buses and private vehicles often causes delay. The delay calculated here could simply be a representation of normal interaction delay. The determination of 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 interactions.

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

4.2.4.2. Impacts in Space

Any disturbance in traffic flow not only persists in time, but it 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. The length of a queue created by a BLIP's activation can be analyzed using time-space diagrams.

The length of a queue is a function of the red time and the arrival flow rate. For isolated intersections, this calculation 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 4.13 (below) illustrates queues growing and dissipating at isolated and networked intersections. For isolated intersections, as shown in Figure 4.13a, vehicles arrive in stationary traffic state A, and the speed at which the back of the queue grows is U_{AB}. 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_1U_{AB}. The location of the front of the queue after discharging for a time t_2 can be represented by t_2U_{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:

$$L = t_1U_{AB} = t_2U_{BE}$$

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 a criteria for possible implementation if a BLIP 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 value of q_A:

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

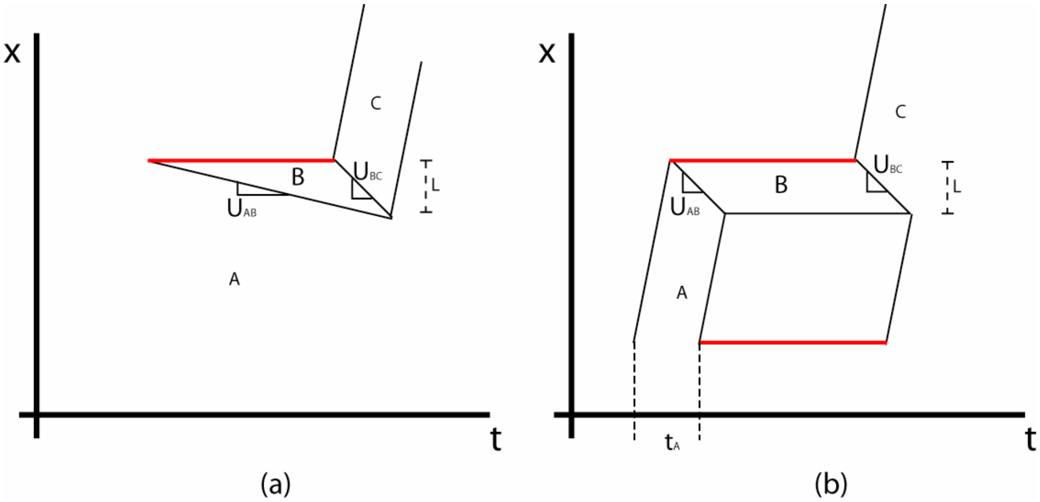

Figure 4.13. Graphic illustration of impacts in space for isolated and non-isolated intersections. a) The queue length (L) at an isolated intersection is a function of the arrival and discharge traffic states (A and C respectively). b) The queue length (L) at a non-isolated intersection is a function of the traffic state (A) and the offset from the previous signal.

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 4.13b. 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:

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

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.

4.2.5. Benefit Analysis

The benefits of a BLIP implementation fall into two categories: reduced mean travel time and reduced travel time variation. These are explored below.

4.2.5.1. 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 time required to stop 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.

4.2.5.2. Reduced Signal Delay

Signal delay for a transit vehicle is defined as the delay experienced at signalized intersections. This delay can be broken 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. Transit Signal Priority (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. This BLIP proposal attempts to eliminate the signal queue delay portion of signal delay.

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 the delay depends on the traffic volume as well as the bus arrival time at the intersection in relation to the cycle. Figure 4.14 (below) shows examples of time savings as a function of arrival time. If the bus arrives just as the signal turns red, as in Figure 4.14a, 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. 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 4.14c, will gain much benefit from jumping the queue.

The fundamental diagram in Figure 4.1 applies to this analysis, and the 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

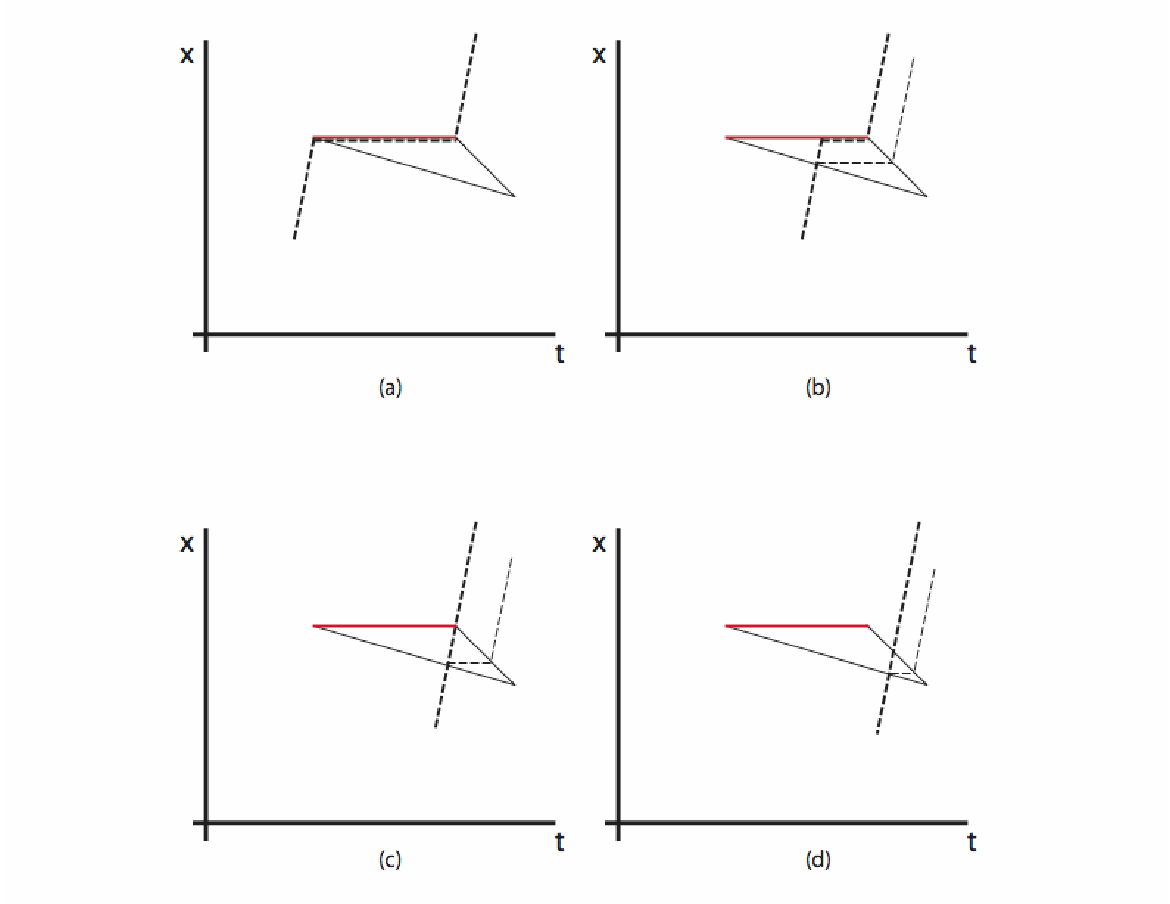

Figure 4.14. Delay reduction benefits as a function of bus arrival time. The thick dashed line represents a bus trajectory that uses a BLIP, and thin dashed line represents trajectory of bus without priority treatment. a) Bus arrives at onset of red signal and receives no benefit. b) Bus arrives near 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.

Figure 4.15 (below) 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.[1] The delay that would have been experienced by the bus is represented by the horizontal line at x_q, and it 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 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	$x - x_B = v_f(t - t_0)$	n/a

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 equation now represents the location where the bus would have reached the back of the queue (x_q). 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:

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

If we define ω_R as signal queue delay experienced by vehicles who also experience signal stop delay (if unqueued, 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:

---

[1] Actually, 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.

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

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

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:

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

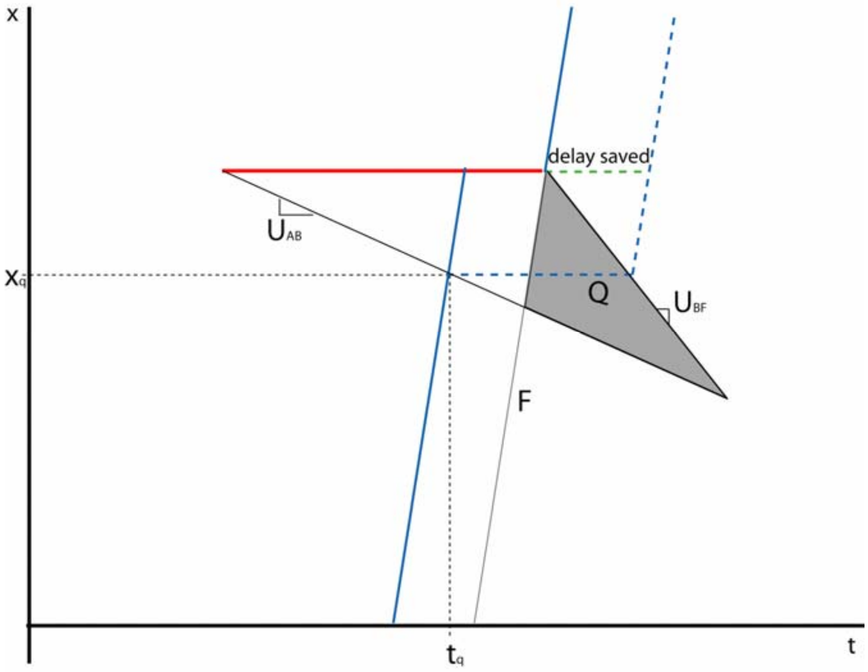

Figure 4.15. Time-space diagram illustrating signal stop delay and signal queue delay. Trajectories crossing through the shaded triangle Q experience delay due to other vehicles at the signal. The delay of any vehicle trajectory stopped at the signal can be decomposed into signal stop delay and signal queue delay; however, vehicles arriving at the back of the queue after the signal has changed experience only queue delay. The bold (blue) line illustrates the trajectory of a bus receiving priority treatment at the intersection. The dashed line illustrates its trajectory without priority treatment. The horizontal component of the dashed line through the shaded triangle Q represents the delay saved by the priority treatment.

Figure 4.16 (below) graphically displays the relationship between arrival time of a bus at a signal and the delay saved (signal queue delay) by the BLIP. Figure 4.16 illustrates that the bus with a trajectory will reap the maximum benefit, 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):

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

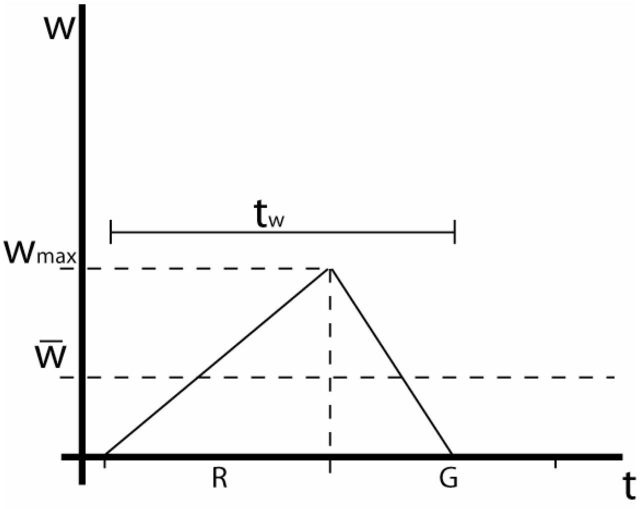

Figure 4.16. Diagrammatic illustration of signal stop delay as a function of arrival time at an intersection.

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 an arriving vehicle 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 4.17 (below) shows the graphical result of a numerical analysis implementing the equations defined above. It illustrates the same shape as the diagram in Figure 4.16 and validates the above formulations.

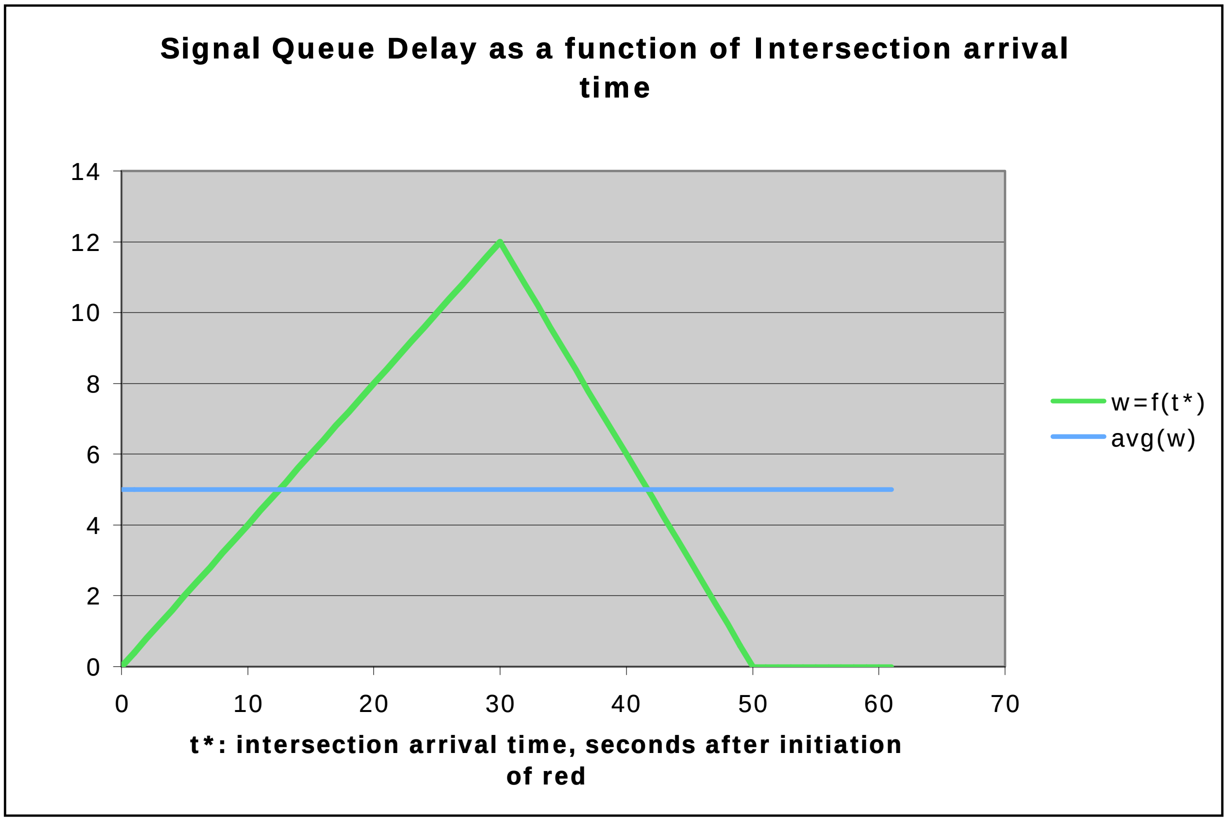

Figure 4.17. Signal queue delay as a function of intersection arrival time, calculated under the following conditions: C=60s, G=30s, q_A=1200 vph, q_C=3000 vph, v_f=60 kmph, U_{AB}=-12 kmph.

For non-isolated intersections that are somewhat coordinated, the calculation of delay saved is not as straightforward. 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 queue at a given signal. Figure 4.18 (below) 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 et al., 2005].

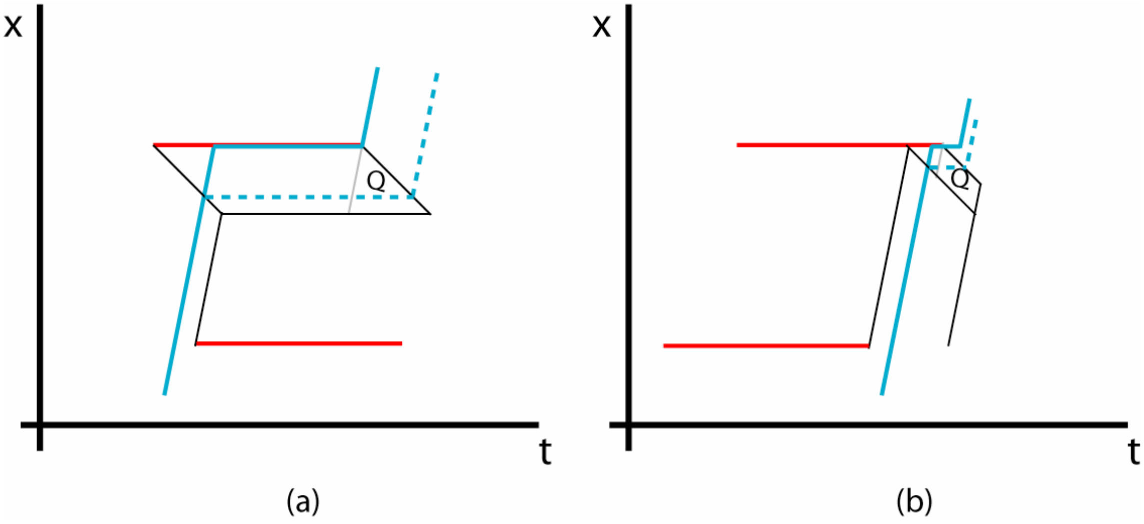

Figure 4.18. Time-savings benefits for non-isolated intersections; a) illustrates a negative actual offset and b) illustrates a positive actual offset.

The above analysis calculates the time savings per intersection at which the bus would normally have queued. However, this does not 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-savings bonus can be reaped when nearside 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 percent overlap of signal stop and bus stop time, resulting in even further time savings.

4.2.5.3. 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. Traditionally, this merge delay is not separated from acceleration time. 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, reducing merge delay, where as far-side and mid-block intersections do not have this benefit.

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. 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 (HCM) [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.

4.2.6. 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 and acceleration and deceleration rates 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 4.19 (below) 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 $\bar{v}$, which is 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 (i.e., traffic accident, pedestrians blocking right turns), the boarding of a wheelchair-bound passenger, etc. The grey dashed lines represent the trajectories of the slower buses, if intelligent priority lane treatment had not been activated.

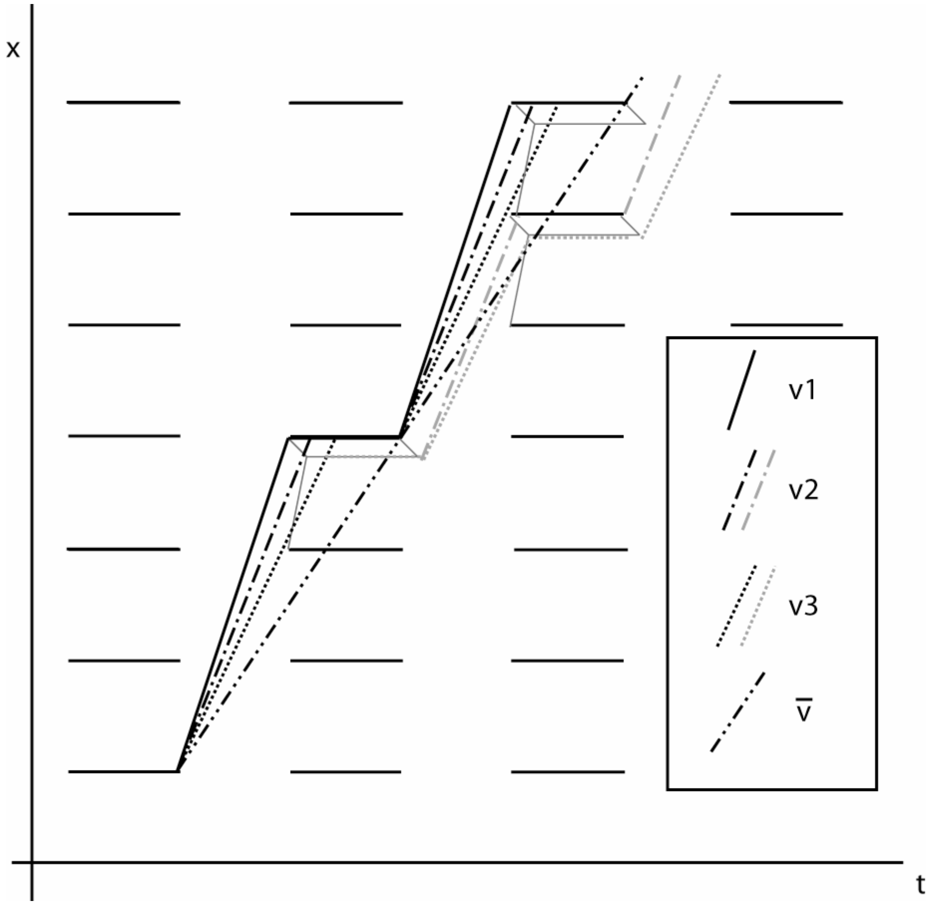

Figure 4.19. Illustration of various bus trajectories with speeds v_1, v_2, v_3, all of which under BLIP have the same average speed $\bar{\mathbf{v}}$. The gray lines represent the v_2 and v_3 trajectories without BLIP treatment.

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 will 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.

4.2.7. 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.

4.3. COST ANALYSIS

4.3.1. Increased travel time for traffic

As discussed above in the feasibility discussion, the delay imposed on private vehicle traffic can be estimated using the queuing concepts used to determine the impacts of a BLIP activation in time. The area between the desired arrival curve and the actual arrival curve, as shown in Figure 4.12, represents the additional delay imposed on traffic. 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 the provision of bus priority at intersections and stops.

Also, as noted above, this delay may not be additional delay to traffic but instead documentation of existing delay caused by the bus-traffic interaction.

4.3.2. Installation and operating costs

All of the technologies required for a BLIP implementation are currently available. In pavement lights are currently being used at crosswalks across the U.S. and have been implemented in dynamic lane assignment applications internationally. Changeable message signs are commonly used for dynamic speed limit assignment and roadside warning messages. However, for roadside signs, a simple “Lane Reserved For Bus When Flashing” sign could prove effective.

It may be possible to implement a BLIP with pre-approved signals available in the Manual on Uniform Traffic Control Devices. However, it may be necessary to propose new signs and signals.

Transit agencies should be able to work with vendors of traffic signs, signals, and signal controllers to determine the implementation costs of a BLIP.

4.4. BENEFIT/COST COMPARISON

The benefits and costs of a BLIP implementation can be compared using basic cost/benefit analysis. One possible formulation of such a ratio would be the following.

$$C/B = \frac{\gamma_0 + \gamma_1 \Sigma \tau_{i1}}{\beta_1 (\sum_i n_i \tau_{2i} + \sum_j m_j \tau_{3j}) + \beta_2 \tau_4}.$$

γ_0	installation and operating costs, averaged over bus round trips.
γ_1	dollar value assigned to an additional minute of delay caused to other traffic.
τ_{1i}	delay caused to other traffic, per intersection *i*.
β_1	dollar value assigned to reduced bus travel time, per passenger per minute.
n_i	number of passengers on bus at intersection *i*.
τ_{2i}	time-savings at intersection *i* in minutes.

m_j	number of passengers on bus leaving bus stop *j*.
τ_{3j}	time-savings per bus stop *j* in minutes.
β_2	dollar value assigned to reduced time variation per minute.
τ_4	time variation savings per trip in minutes.

5. TOD System Architecture Analysis

Prior to providing details on the specific TOD architecture analysis, it is necessary to establish a framework within the National ITS Architecture. The National ITS Architecture was created as a national planning guide for the implementation of ITS strategies in urban, suburban, and rural regions. As described in Section 2, the architecture is often organized by user services as perceived from the viewpoint of a transportation user. The architecture is further segregated into a logical architecture (how data flows) and physical architecture (interrelation of components). The transportation components within the physical architecture are referred to as subsystems. Figure 5.1 (below) shows the National ITS Architecture of Subsystems and Communications as shown in the National ITS Reference Guide (Iteris, 2005). The subsystems are the white boxes, while the four general communication methodologies are shown in the pink ovals.

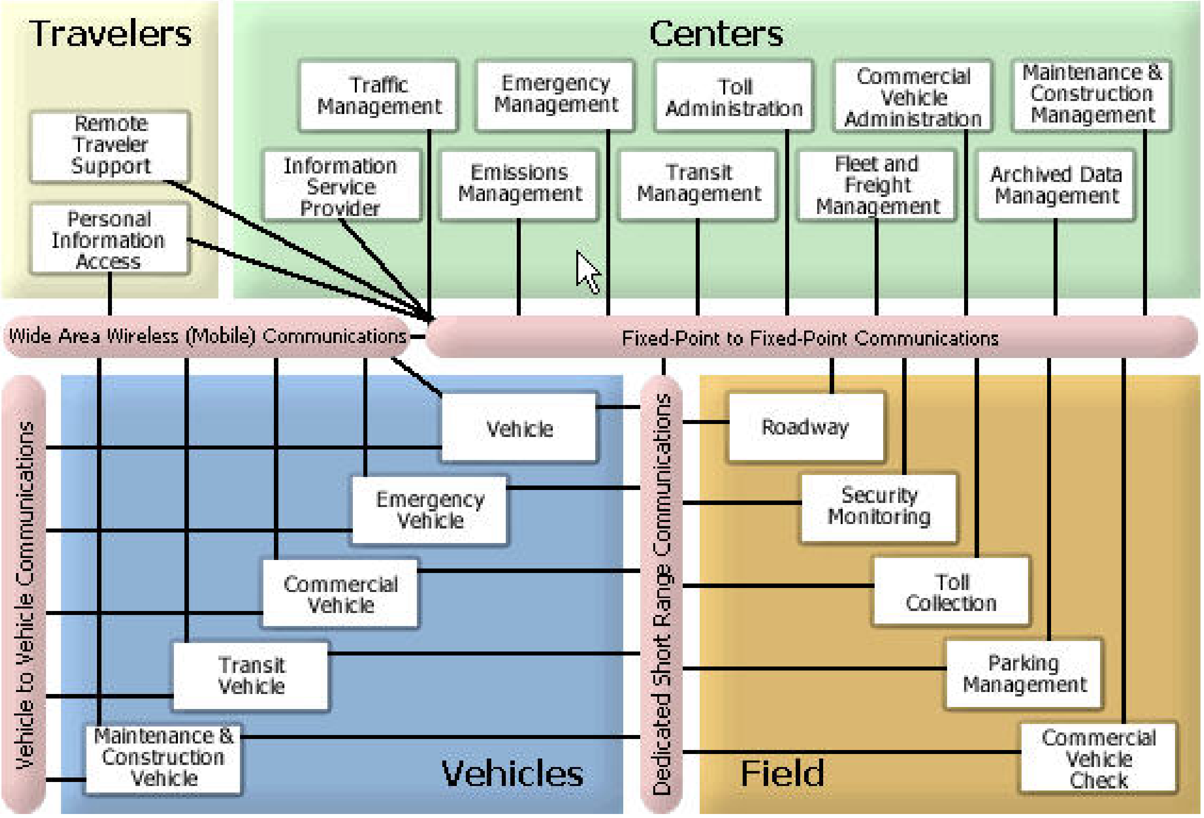

Figure 5.1. National ITS Architecture of subsystems and communications.

This research investigation focused on numerous subsystems shown in Figure 5.1. These subsystems include:

- Transit vehicles;
- Vehicles;
- Remote traveler support;

- Personal information access;
- Transit management;
- Fleet management;
- Information service provider;
- Roadway; and,
- Parking management.

Additionally, all of the four communication methods could potentially be used for implementing the full array of subsystems listed above.

The National ITS Architecture creates a framework for implementing the various user bundles, subsystems, and ITS components. When considering the daunting task of implementing all these components in an integrated manner, a TOD implementation-specific architecture is required.

5.1. MODULAR ITS IMPLEMENTATION FOR TOD

Complex systems that perform multiple functions incorporating electronics, data transfer, software, and hardware are often designed in a modular fashion. The benefits of a modular design for a sophisticated ITS application include:

- Interchangeable components,
- Self-contained assemblies,
- Upgradeability,
- Functionality isolation, and
- Scalability.

These characteristics prove valuable from initiating design, through systems implementation, and during long-term operation. The modular design allows for the exclusion of original components and the inclusion of future unforeseen components. The modular design also allows for a system to be launched with basic services adding more complex services as time and budgets allow. Based on all these characteristics, a modular design architecture is preferential for enhancing a TOD with ITS.

5.2. REVIEW OF SYSTEM ARCHITECTURE SCENARIOS

Systems must contain a common interface if they are to be designed in a modular fashion. ITS subsystems that use shared data must have both the physical and functional capability to transmit/receive relevant data. The majority of ITS strategies discussed within, operate on transportation system-related data in an autonomous fashion to increase the efficiency of the overall system. Therefore, the best ITS architecture that can enhance the TOD design will have interrelated components to possess the ability (at least partially) to communicate on the same data network.

The National ITS Architecture presents four general communication methods:

- Dedicated short range communications (DSRC),
- Vehicle-to-vehicle communications,
- Fixed point to fixed point communications, and
- Wide area wireless communications (cellular).

Careful evaluation of the ITS Architecture will provide some insight into preferred communication methods for the proposed application. The vehicle-to-vehicle communications (as seen in Figure 5.1) is intended to provide only vehicle-based communications and is likely less than ideal. Additionally, dedicated short-range communications are not sufficient to communicate between centers and travelers. Wide-area wireless and point-to-point communications will receive further evaluation for the applicability as a modular data bus with a TOD.

5.2.1. Physical Network Characteristics

Wide-area wireless communications is defined as "a communications link that provides communications via a wireless device between a user and an infrastructure-based system". The wireless Wide Area Network (WAN) can be created site-specific on a licensed or unlicensed RF. Alternatively, wireless WAN services can be purchased from a cellular provider. Due to the cost of a typical installation, a private wireless WAN is typically isolated to a few communication nodes (< 4) with high data transfer and/or security requirements (wirelesswans.com, 2005). Applications that require many wireless communication nodes separated by a significant distance are typically configured on a pre-existing wireless WAN or cellular service. Each communication device then incurs a fee for data transfer.

The National ITS Architecture defines fixed point-to-point communications (FP2FP) as "a communication link serving stationary entities". The FP2FP communications methodology has been in existence since the early telegraph and has evolved to include numerous methods of data transfer, including:

- Twisted pair,
- Coaxial cable,
- Fiber optics,
- Data modems, and
- Microwave relay.

The telecommunications industry has an extensive network of communications infrastructure installed nationally. This network consists primarily of twisted pair and fiber optics. Several FP2FP communication methods use wireless data transfer independent of cellular networks. These include data modems, microwave relay, and satellite communication. The FP2FP communication methods that employ wireless RF signal conversion (data modems, microwave relay) are prohibitively expensive for systems with many data end points.

Many TOD ITS implementations exist that do not require Internet-based communications. These implementations are frequently associated with the management and allocation of a transportation resource (e.g., vehicle, bike locker, Segway HT, or parking space). These are often standalone systems that do not transmit data to a remote site or database. Through the systematic design and incorporation of these standalone systems, an all-encompassing modular structure can be adopted to improve user mobility from one mode to another.

Based on the information provided, each subsystem within the TOD micro-architecture should possess the ability to communicate on a shared data network. Based on installation requirements and cost considerations, the preferred shared networks include:

1) Pre-existing cellular networks, and

2) Pre-existing telecommunications network (twisted-pair and fiber-optic).

5.2.2. Communication Protocol

The physical components that carry the data are only one consideration of the TOD micro-architecture. Similar consideration must be given to data communication protocols. All components connected to the central data network must be able to send and/or or interpret data sent on the data network. The more common protocols that exist for the FP2FP are:

- Transmission Control Protocol/Internet Protocol (TCP/IP),
- Virtual Private Networks (VPN),
- User Datagram Protocol (UDP), and
- Point-to-Point Protocol (PPP).

These protocols are primarily used for computer network communications. Since the majority of data being transmitted on the micro-architecture may need to be processed by a computer, these are potential protocol options. The UDP protocol sends data without confirmation and therefore lacks transmission confidence. TCP/IP is one of the most common transport protocols used by virtually all Internet users since 1983. Applications requiring optimum security setup VPNs, using the Internet with data encoding and decoding (encryption). While many protocols are functionally viable, TCP/IP is globally adopted for public Internet communications.

The more common cellular protocols currently in use or in deployment are:

- Code Division Multiple Access (CDMA 2000),

- Universal Mobile Telecommunications System (UMTS), and
- General Packet Radio Service (GPRS).

UMTS is being developed as the primary protocol for G3 devices (next generation wireless devices), while GPRS and CDMA are currently deployed for G2.5 devices. All three of these protocols have the ability to deliver data wirelessly to an Internet address (IP address) through a service provider.

Evaluation of these protocols defines the advantages of using the Internet as the modular data network for the micro-architecture associated with a TOD. For reasons discussed previously, specific subsystems may not be well suited for the TCP/IP protocol. The interfacing of ancillary communication methods will be addressed.

5.2.3. Ancillary Communications

Applications (subsystems) that lack the processing power or configuration to communicate via the selected protocol will require an interfacing method to function as a module on the shared data network. This interfacing method will communicate with the components of the subsystem (directly or indirectly) and transmit pertinent information to the shared data network via the selected protocol.

Communication bridges can be integrated into the TOD micro-architecture for each of the communications listed in the National ITS Architecture. The following interface methods could be used for interfacing some common data transfer modes:

- DSRC → TCP/IP via personal computer equipped with software and hardware;
- Vehicle to Vehicle → TCP/IP via on-board processor linked with cellular data modem;
- Smart Card → TCP/IP via personal computer equipped with card-reader hardware and software; and
- WirelessWAN/Cellular → TCP/IP via GPRS cellular provider or equivalent.

5.2.4. General ITS Micro-architecture for TOD Enhancement

The review of ITS Architecture communication methods and applications has provided some general guidelines and specifications for desired TOD micro-architecture requirements. ITS user bundles and system components possess additional specifications relative to communications and configuration. A general ITS micro-architecture for TOD implementation is provided in Figure 5.2 (below).

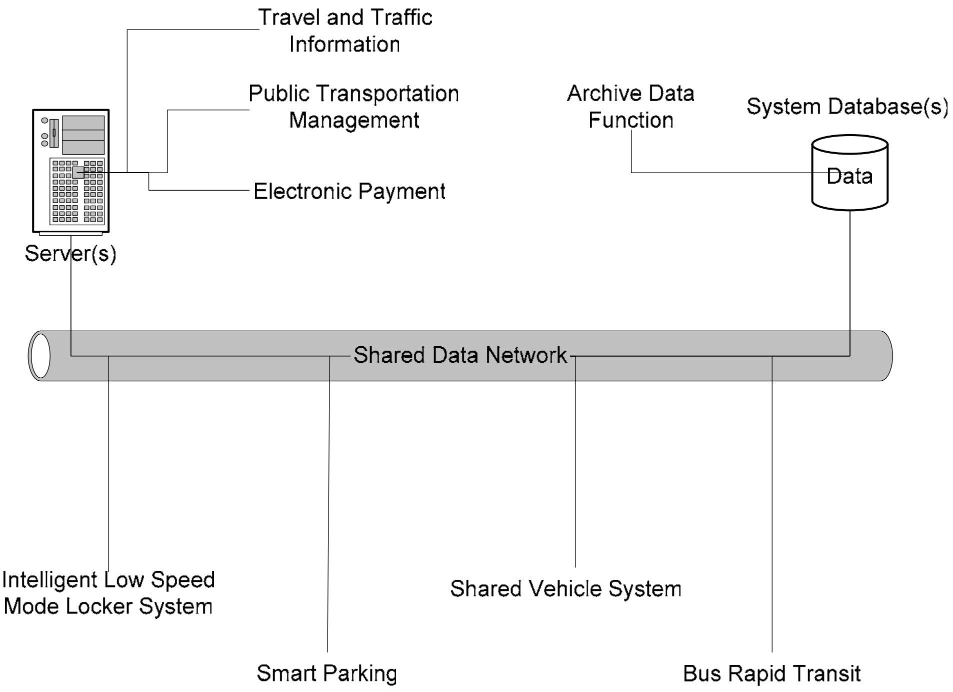

Figure 5.2. TOD general ITS micro-architecture diagram.

The TOD general ITS micro-architecture employs a shared data network for all incorporated subsystems. The configuration and transmission protocol used on the shared data network has been discussed in previous sections. An Internet-based protocol has been discussed as an example for modularity, accessibility, and implementation considerations. Additionally, Internet-specific protocols have been proposed for similar reasons. TCP/IP based protocols are suitable for much of the data communications, while additional encryption and VPNs will be needed for high security data transfer (e.g., electronic payment).

The transfer of data to and from transportation-based applications has frequently and effectively used TCP/IP and UDP Internet transport protocols whenever the sending and receiving agents are capable of processing the required formats.

Occasionally, an ITS application exists upon which the required processing and power requirements for Internet-based messages (TCP/IP) exceeds the design parameters. For example, a Neighborhood Electric Vehicle (NEV) is an ideal low speed shared-use vehicle that can be utilized within a TOD as a potential feeder service to transit users. To fully integrate the NEV with ITS electronics, vehicle *telematics* would need to be installed on the vehicle. Telematics generally refers to the integration of (wireless) telecommunications and information technology with vehicles to enhance safety, user convenience, and vehicle operation. To employ Internet-based electronics, the vehicle would have to be equipped with an on-board processor configuration suitable for wireless communications. This is technologically feasible, but the cost of configuring the components that could withstand the environment of vehicle use, have low power for running on a vehicle battery, and be sufficiently compact would be prohibitively expensive (relative to the vehicle cost). Therefore, due to specific design considerations, it is realized that secure data transfer methods need to be explored for applications upon which wireless Internet-based communications are not suitable.

Figure 5.2 also displays the interaction of National ITS Architecture (NITSA) user bundles and TOD-related ITS applications. Many of the user bundles are communications-based Electronic Payment Systems (EPS), Transportation Management, Travel and Traffic Information), therefore requiring the use of a web-based server or similar configuration. These types of services frequently use a web-based server for managing the: transmission of data, graphical presentation of data and/or user requests (e.g., reservations). The TOD micro-architecture shows these applications operating from a single server, whereas multiple servers could be employed to distribute the functions. It should be noted that the TOD micro-architecture related server(s) does not have to be dedicated to the TOD. The server(s) could be managed by independent organizations that may benefit by hosting the server application(s).

The system databasing function is shown as an independent property with the TOD micro-architecture. While the databasing function could be coupled with many of the server functions, it presents a specific functionality. The database management system serves as the "clearinghouse" and it also performs record keeping for all the shared data within the inter-connected systems. Each subsystem can query the database for specific needed information. The system databases will also provide historical records and system(s) usage for the data archiving user bundle within NITSA. The system databases will hold the following types of data:

- Vehicle trip information,
- Transit trip information,
- Reservations,
- Parking status,
- Vehicle status, and
- User information.

The database would allow the other subsystems within the TOD micro-architecture to access the relevant data for their needs. For example, the BRT subsystem would report bus location telemetry to the system database. The data on the system database would then be available for other applications to acquire, such as, traveler information and fleet management. When desired, these databases can be maintained on specific subsystem computers. When databases are maintained by subsystems the processes acquiring specific data would consist of a query or access to the data originator. In the example of the BRT system, the traveler information and fleet management servers would each make independent inquiries to the BRT subsystem computer. Each type of database configuration will allow for modularity within the TOD micro-architecture if an open message format is employed.

It is important to consider the data security issues associated with the proposed micro-architecture configuration. The subsystems using server computers must incorporate the appropriate firewalls and data security methods to insure against system intrusion. Additionally, the system database computer(s) and subsystem computer(s) must install specific protocols to insure data security (e.g., encryption, VPN, file access control, etc.). The level of security required is partially dependent upon the susceptibility of the data. Subsystems using personal information data (e.g., electronic payment) requires significant security measures.

A generalized ITS micro-architecture for TOD has been presented. This architecture can be further evaluated for implementation within specific TODs. The next section describes a site-specific micro-architecture implementation.

5.3. PROPOSED DESIGN FOR PLEASANT HILL TOD

The Pleasant Hill Bay Area Rapid Transit (BART) District station in Northern California has been selected as a TOD priority according to transportation officials. Several commercial, retail, and residential complexes are part of the TOD plan. The location is currently undergoing evaluation for improving the operational characteristics and efficiency of the travel modes available within the station (see Figure 5.3, below). An ITS micro-architecture is proposed for potential ITS technologies that have implementation potential within the TOD.

Figure 5.3. The Pleasant Hill BART District station and surroundings.

The current ITS technologies being evaluated for the Pleasant Hill TOD include:

- *EasyConnect* – low-speed mode vehicle rental (Segway HTs, Bike, and E-bike);
- *Elocker* – electronic low speed mode lockers with smart card;

- *Fleet management* – resource management for operations, maintenance, billing;
- *511.org integration* – Traveler information service;
- Internet-based reservations;
- *Parking Carma* - Smart parking; and
- *Carsharing*.

Frequently, suburban transit stations require pedestrians to cross a mix of parking and/or broad high-speed suburban arterials to access the transit platform. Similarly, to encourage transit ridership with a limited supply of available station parking, it is vital that Pleasant Hill TOD planners prioritize the creation of multi-modal connections that include walking, bicycling, carsharing, and other supportive transit, i.e., feeder buses and shuttles. The micro-architecture proposed here for Pleasant Hill BART station/TOD emphasizes these supportive transit connections that help passengers commute the first or last mile to or from the transit station. Similar to providing multi-modal station access is the need to address station-parking demands. A one-to-one replacement parking policy has limited the potential development of several TODs. The details associated with the proposed micro-architectures are discussed further below.

5.3.1. Intermediate-Level Design

Figure 5.4 (below) shows an intermediate level of ITS integration with lower integration-intensive systems being introduced first. The two main subsystems being proposed for this intermediate implementation are Elocker (intelligent low-speed mode lockers) and *EasyConnect* (low-speed mode vehicle rentals). The Elocker system will provide access controlled bike, E-bike, and Segway HT lockers. These lockers will be accessible through a users identity token (security card or electronic key) and provide secure storage for personal low-speed vehicles. The Elocker system will also be available through a system linked reservation system. The Elocker system will function collaboratively with the *EasyConnect* low-speed vehicle rental system. The *EasyConnect* system will provide rental vehicles for improving mobility within the TOD. *EasyConnect* vehicle access will be at least partially controlled by the Elocker system. Therefore, the two systems must exchange required information. Figure 5.4 shows this data exchange occurring through the *system databases*. Each subsystem will deposit and extract pertinent data to the *system databases*. As discussed previously the *system databases* can be maintained on a separate computer on the *shared communication network* (Internet) or they can be shared by the subsystem computers directly.

The subsystem ITS technologies consist of hardware components that must be integrated into the system architecture. Examples of the hardware components include: vehicles, sensors, computers, message signs, electronics, communications, wiring, low-speed vehicles, and intelligent lockers. The low-speed mode possesses several layers of potential hardware integration (simplest to more complex):

1) Manual entry of use information into database,
2) Single vehicle request unit with system interface,

3) Per vehicle/Elocker interface with system connection, and
4) User maintained wireless access point.

The implementation of the micro-architecture can be a gradual process consisting of the steps listed above. Initially, a low-speed vehicle dispatch attendant can enter user and vehicle information into the *system database*. The *system database* information is then available for system management and billing purposes. The management and billing can then evolve from more manual-based systems to more automated.

Implementation of low-speed mode access control can initiate with a single electronic access point and expand with demand and system requirements. The single access point could process one user request at a time and control numerous Elockers or low-speed vehicle checkouts. The access point would process a user request and make a vehicle or Elocker available. With increased system usage, the number of access terminals can increase to meet user demand. Each Elocker and/or low-speed vehicle can be equipped with access control electronics, if needed. The single stationary vehicle access unit interfaced with a *shared communication network* (e.g., TCP/IP) connection would allow for multiplexed-access management of the low-speed mode vehicles (one interface controlling multiple vehicles). This single unit would employ input from the user (e.g., smartcard, ibutton, Bluetooth, etc.) and interface via TCP/IP or similar protocol to the shared data network. The single interfacing unit could enable or disable the low-speed mode vehicles via electronics or electronic lockers. The connection from the access point to the shared network could occur via a processor (computer/microprocessor) with a hard line connection or using cellular data transmission (e.g., GPRS).

A fourth and more novel approach would use a cellular-based communications device possessed by the user. Current cellular devices are integrating Bluetooth technology capable of automatically setting up a Personal Area Network (PAN) when located in close proximity to other Bluetooth configured devices. The Bluetooth hardware electronics are more easily integrated than TCP/IP electronics, are relatively inexpensive, and have low power requirements. Therefore, conceptually this novel approach could provide a TCP/IP connection through a user's personal wireless device via Bluetooth and GPRS wireless data communications. The GPRS would forward the data to the micro-architecture *shared data network*.

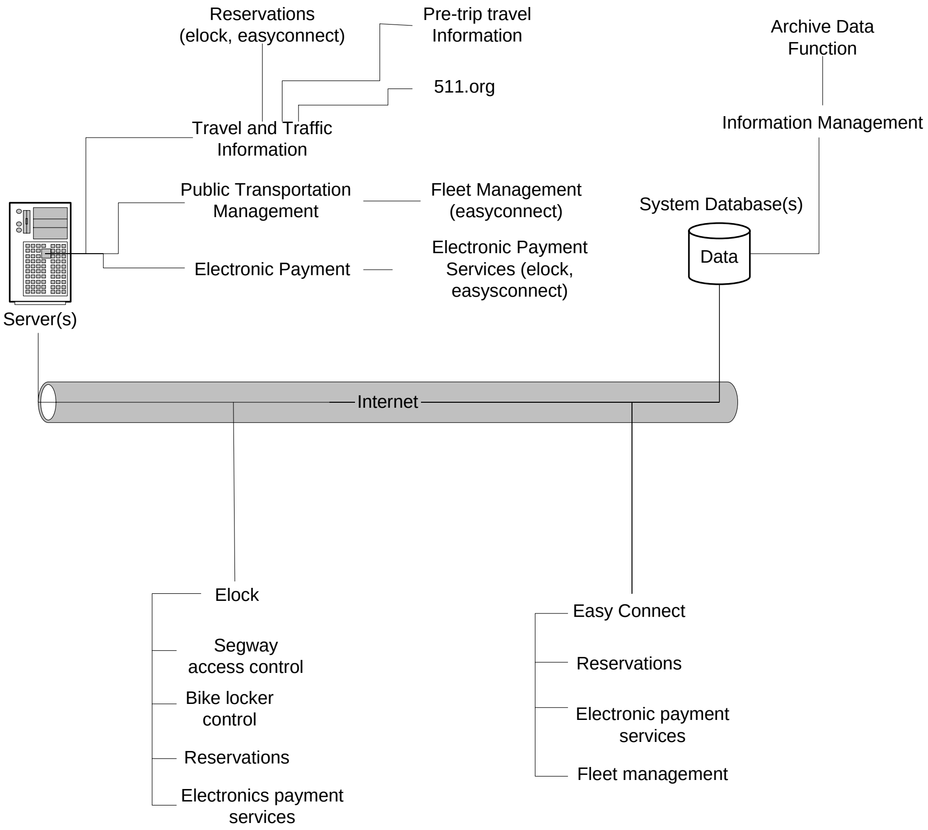

Figure 5.4. Pleasant Hill TOD moderate ITS micro-architecture diagram.

In addition to the Elocker and *EasyConnect* subsystems, several information-based systems are proposed for the intermediate level implementation. The information-based technologies include: fleet management, traveler information services, and reservations. These ITS technologies typically utilize the Internet for transmitting data and information to the users. The data associated with each of these services needs to be maintained on a database. A web server typically manages the information presented to a user. This data maintenance and web server management may already exist for a complementary system, hence allowing the new data and site to be easily integrated with existing systems. An example of a complementary system is 511.org. This web-based application provides traffic information and traveler information services and would allow for complementary implementation of a portion of the proposed systems.

5.3.2. Advanced Design

A more advanced TOD micro-architecture is shown in Figure 5.5 (below). This architecture is an expansion of the intermediate level with the introduction of smart parking (Parking Carma) and carsharing. These additional systems are modular in fashion and do not require modifications to the intermediate level of implementation. This more advanced level of implementation would allow for bundling of many services. Reservations for all modes could be provided through a single management point (server). Therefore, individuals would interact with a single source for parking, *EasyConnect* (bikes, e-bike, and Segway HT), Elockers, or carsharing. Additionally, system status for any of the subsystems could be available through a single interface. Finally, the database management could be maintained on a single device and greatly simplify the integration of future modules.

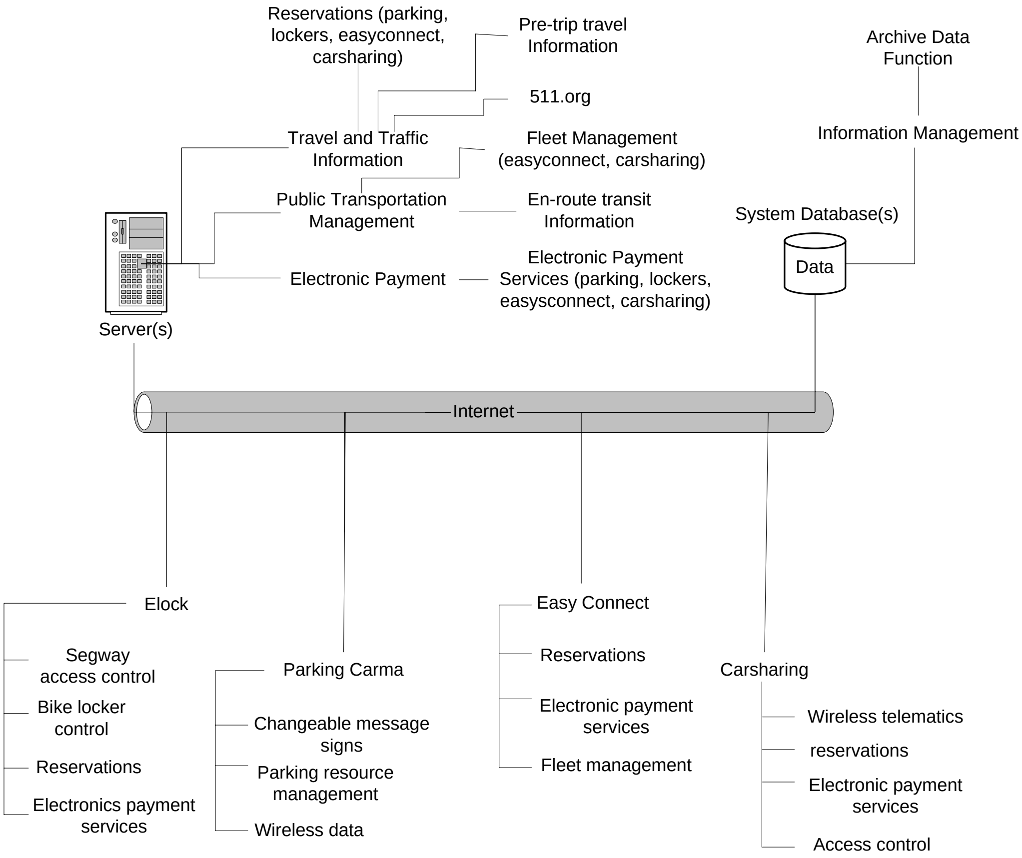

Figure 5.3. Pleasant Hill TOD advanced ITS micro-architecture diagram.

The proposed architecture for the Pleasant Hill TOD consists of: a primary shared data network (TCP/IP or VPN), wireless to TCP/IP conversion nodes (low-speed modes and smart parking), and web server/client programs (reservations, traveler information, and fleet management). It is also highly recommended to explore the potential for Bluetooth integration when a wireless-to-network link is required.

5.3.3. Distributed Database with Distributed Server Configuration

The micro-architectures listed above allow for distributed database management as well as distributed server functionality. Each subsystem can maintain their own database that is accessible through open standard protocols, such as, XML4 (Extendable Markup Language-4), RSS5 (Rich Site Summary-5), SOAP6 (Simple Object Access Protocol-6), and XML-RPC7 (Extendable Markup Language-Remote Procedure Call-7). The use of open protocols would allow for web server-based transportation service providers to use the data and offer services (e.g., 511.com). Figure 5.4 (below) shows the distributed configuration for the proposed micro-architecture.

Each potential subsystem (carsharing, Elocker, smart parking, *EasyConnect*, etc.) would provide a shared network linked open standard data exchange. This database would reside on a processor maintained by the subsystem vendor. Web server-based subsystems using the same open protocols could access each independent subsystem database and obtain required information to provide their specialized services. Several web applications could potentially be providing similar user services (reservations, travel information, and electronic payment). Carsharing reservations could potentially occur through two or three different service providers operating independently of the web server applications. The fully distributed approach promotes multi-modal, multi-vendor data in a commercially feasible manner. The overall objective is a system that:

- Provides a seamless experience for transportation users who wish to view their modal options or reserve a particular transportation resource;
- Promotes modal choice providers, who may join the information web;
- Reduced administration by the transportation operating agencies; and
- Offers rich opportunities to syndicate data to interested parties.

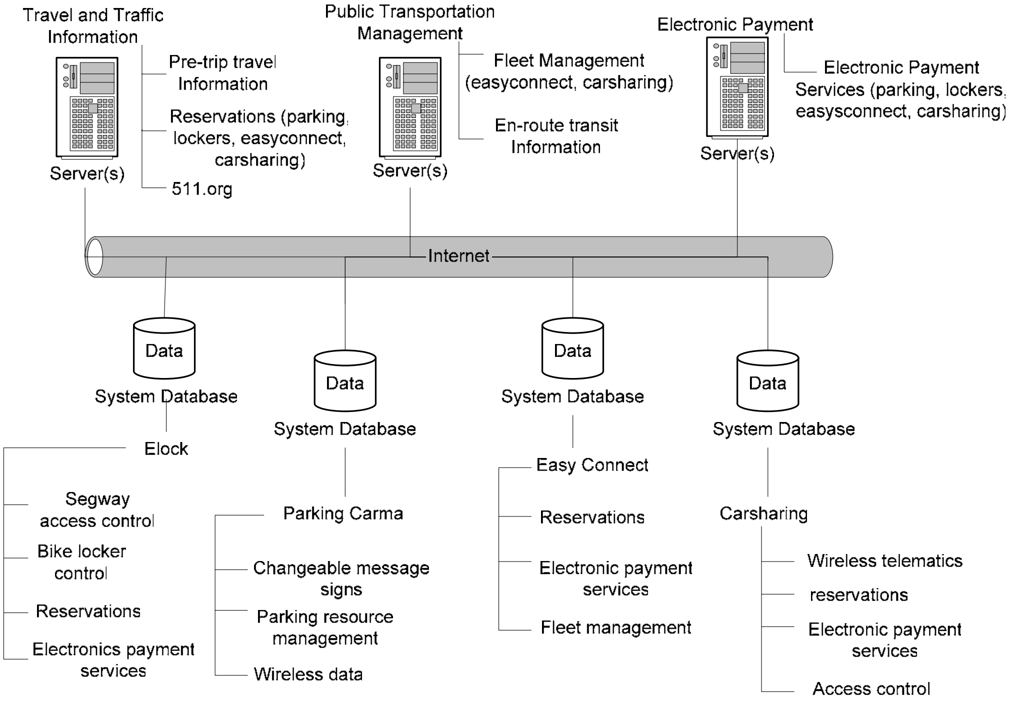

Figure 5.4. Pleasant Hill TOD distributed micro-architecture diagram.

The consistent similarity among all the proposed micro-architectures is the *shared data network* with an open protocol communication scheme among subsystems. This network backbone allows for the seamless integration of new services and the removal of unneeded services. The micro-architecture allows for a single server providing all web-based services or numerous web server applications providing competing services. Database management can reside on a single processor or be distributed among each subsystem vendor. The successful implementation of the micro-architecture is dependent upon a secure, reliable, open protocol communication network. Once a suitable network has been established, independent subsystems can be introduced in a seamless manner.

5.4. COST-EFFECTIVENESS ANALYSIS FOR VARIOUS ARCHITECTURES

The costs associated with the development and implementation of ITS technologies can vary significantly depending upon unpredictable market factors (construction parameters, development issues, technology changes, etc.). When evaluating the implementation and development costs of similar technologies, the cost confounding variables are likely to have proportional economic effects on similar technology options. An example being, increased energy prices will cause price increases on materials and implementation in relatively equal proportions. Therefore, the cost effectiveness of the most suitable architecture implementations will be compared on a relative basis to alternative implementations.

5.4.1. Development Costs

Development costs are considered to include all hardware and software design. Products that currently exist "off-the-shelf" and can be directly implemented within the Pleasant Hill TOD are considered to have zero development cost. While some technologies are close to zero development cost (i.e., Parking Carma, 511.org), they will likely require some development to integrate within the modular structure. A component that is fully developed as a standalone system will require modifications for complete integration within the proposed TOD micro-architecture. The systems with low development costs are considered to currently have a fully functional standalone system and only require software improvements for final TOD integration (see Table 5.1 below). The systems with medium development costs are considered to have software and some hardware modifications to allow final TOD integration. Accordingly, the systems with high development costs are considered to have specialized hardware and software modifications for finalized TOD integration.

Table 5.1. Relative Development Cost Comparison for Proposed TOD Strategies

EasyConnect	**Elocker**	**Fleet Management**	**511.org**	**Internet reservations**	**Smart parking**	**Carsharing**
Low	Low-Medium	Low	Low	Low-Medium	Medium	High

5.4.2. Implementation Costs

Implementation costs take into consideration the system purchase costs and the installation costs. Systems with a low installation cost are believed not to require infrastructure improvement. These components are considered to be "plug-and-play," Systems with medium installation costs require traditional power and communications. Systems with a high installation cost require significant power, communications, and/or construction. The implementation costs also consider the relative system purchase price. Systems that are primarily software have a relatively low purchase price. Systems consisting of many automobiles and infrastructure have a relatively high purchase price. The system purchase price and installation price are considered collectively in determining the implementation costs.

Table 5.2. Relative Implementation Cost Comparison for Proposed TOD Strategies

EasyConnect	**Elocker**	**Fleet Management**	**511.org**	**Internet reservations**	**Smart parking**	**Carsharing**
Medium	Medium	Low	Low	Low	Medium/High	High

5.4.3. Operational Effectiveness

The system operational effectiveness is evaluated relative to the perceived enhancement to transit use within the TOD. The objective of incorporating these strategies within a TOD is for increased transit ridership. Therefore, a general comparison will be provided. The systems associated with traveler services (availability, account information, billing, etc.) are considered to help retain users versus Adopting new users. The systems associated with resource allocation (smart parking, low-speed mode vehicle sharing, and carsharing) have shown in the past to be more influential in inducing transit use.

Table 5.3. Relative Operational Effectiveness Comparison for Proposed TOD Strategies

EasyConnect	**Elocker**	**Fleet Management**	**511.org**	**Internet reservations**	**Smart parking**	**Carsharing**
High	High	Low	Medium	Medium	High	High

Evaluation of Table 5.3 (above) displays the comparative relative operational effectiveness of proposed APVS strategies. The options that provide a complementary mode to transit are considered as having “High” operational effectiveness. The *EasyConnect* system provides low-speed mode vehicle options, while carsharing provides traditional vehicles. Similarly the Elocker and smart parking systems are considered to increase the availability and/or frequency of complementary modes. Increased parking efficiency within stations will increase the quantity of individuals parking a vehicle to use transit, therefore increasing transit usage. The same benefits are perceived for the Elocker systems, which will likely increase the use of low-speed modes leading to an increase in transit use.

Internet reservations, transportation-based web sites, and information displays are viewed as having a medium level of operational effectiveness when compared with the other proposed strategies. These systems will improve the transportation efficiency from the user perspective and lead to a more positive transit experience. Systems such as Internet reservations and 511.org assist the transit user in making informed transportation decisions and being able to manage their options. These systems are viewed as a valuable addition to TOD strategies.

Systems that are targeted toward operations and system management have received a low operational effectiveness rating. This is primarily in response to the lack of a direct transit rider impact. The ITS operational management services are targeted at improving system efficiency by increasing available information or reducing costs. Increased system operational efficiency often has an indirect benefit for the transit rider. These positive effects include: on-time arrivals/departures, well-maintained systems, smoothly operating systems, increased vehicle availability, etc. These potential improvements are certainly valuable, but this is more from the transit operator's perspective versus an operational cost reduction standpoint. Most of the enhancements achieved through operational and system management based systems can be achieved through diligent system management. While fleet management and operational-related systems have received a low relative rank for operational effectiveness, they are still considered a valuable addition for TOD enhanced strategy development.

6. Proposed Next Steps

6.1. INTELLIGENT BUS PRIORITY LANE

It would be ideal to formulate a generalized model for the feasibility and benefits of a BLIP implementation. The material described in Section 4, above, are the building blocks of such a model. This generalized model would allow transit agencies to input their roadway, traffic, ridership, and bus characteristics and quickly determine the feasibility of a BLIP implementation, as well as proposed benefits and costs.

A generalized model might take the approach of attempting to deterministically route the bus given expected traffic and passenger volumes, roadway characteristics, and other parameters. Alternatively, a stochastic model could be developed that uses expected values of passengers and traffic volumes as well as probabilities that buses will be stopped at each intersection. This formulation could result in an expected travel time and expected variance and should be able to compare these values with expected values from the same characteristics without a BLIP implementation.

Further, a generalized model will take into consideration the potential feedback effect of a BLIP implementation: if the implementation reduces transit travel time and increases travel time for private vehicles, some substitution may occur. This model should consider the demand elasticities for transit and private vehicle use to determine the changes in demand between modes, and then iteratively incorporate those changes back into the model until a steady state is reached.

Further research should include the consideration of turning traffic on this analysis. Turning traffic will have the following impacts:

- Traffic turning into the arterial during BLIP activation will need to be guided into the appropriate lane through roadside signs and in-pavement lights. This traffic will need to be considered when evaluating an individual intersection’s ability to serve general traffic after the loss of a lane to the bus.

- Traffic turning off of the arterial could provide additional delay. As discussed earlier, heavy pedestrian volumes can delay right turns. In turn, those right turns can block the bus despite the activation of the BLIP.

- If a section of roadway and the corresponding downstream intersection are approaching saturation, turning traffic can result in over-saturation. In a BLIP implementation, it may be desirable to prevent traffic from turning onto the near-saturated arterial during the activation of the BLIP. The feasibility of this depends on the available storage on the cross streets, cycle lengths, and the amount of advantage the city and transit agency wish to give the bus over the private vehicle traffic in such situations.

6.2. ITS IMPLEMENTATION FOR TOD

The implementation recommendations are based on a function of: cost (development and implementation), technology availability, and operational effectiveness. The systems and/or components that provide the greatest value (potential for induced transit trips) for the lowest relative cost will be discussed first. These systems have a high “operational effectiveness” rating from the previous section coupled with low to medium cost ratings. The two systems meeting these characteristics include *EasyConnect* and Elocker. The next level of consideration contains systems that have a medium level of operational effectiveness with lower costs. These types of systems include 511.org and Internet-reservations. The last type of system being considered for recommendation are those with high costs coupled with high value (e.g., carsharing, smart parking) or low costs associated with low value (e.g., fleet management).

The *EasyConnect* and Elocker systems can be implemented in their simplest form with low development costs. This simplest design would create a standalone system that is not Internet ready. Planned accordingly, Internet capability could be adapted at a later time without disrupting service. This Internet capability would allow future modular integration with other proposed TOD ITS enhancing systems (i.e., Internet reservations, fleet management, traveler services, including 511.org). It is proposed that the Internet-based system be introduced in a package once the *EasyConnect*/Elocker combination is in place. These Internet-based systems can be add-on web pages to other transportation services. This would limit the need to create a web server specifically for the Pleasant Hill TOD.

Finally, it is proposed to integrate the more technology dependent systems, such as smart parking and carsharing. Once the system communication modularity is demonstrated within the TOD with the other systems the integration of smart parking and carsharing will be simplified. Additionally, the previously functioning systems will provide insights that will help guide the design of these more development-intensive systems. These systems also have a longer timeline associated with implementation. Therefore, pre-planning is significantly more important with these systems than with the previously discussed systems.

7. Conclusions and Future Work

The success potentially obtainable through enhanced transit strategies is observable throughout a few of the world’s communities in which transit ridership dominates, pedestrian-friendly communities thrive, and individuals prefer not to use their privately owned vehicle. The socioeconomic factors have occasionally evolved in such manner to create these idealized transportation communities where an individual’s mobility is not linked to personal vehicle ownership. TOD and BRT strategies aim to achieve transit-based successes through strategic planning and integration.

This paper has focused on the evaluation of two key areas for enhancing ITS based transit strategies:

1) Intelligent bus priority lanes, and
2) ITS technology architectures for TODs.

In days of increasing traffic congestion and decreasing bus transit ridership, transit agencies need an efficient and effective way to reduce variable 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.

One of the key advantages associated with the Pleasant Hill TOD is the integration of ITS within the planning and construction process. Current ITS technology allows for innovative means of integrating transportation systems, improving system efficiency, enhancing operations, and promoting use. Through strategic TOD planning, mobility levels can be achieved today that have not yet been observed elsewhere. While traditional urban transit modes consist of bus and rail. New transit modes have a greater array of options to complement TODs. The options include:

- Bus Rapid Transit;
- Shared-use vehicle systems, such as carsharing;
- Smart parking;
- Vehicle monitoring;
- Electronic driver and traveler services; and
- Electronic payment services.

While many of these ITS strategies are added on to traditional and currently operating transit networks and systems, there are significant advantages to planning TOD ITS integration prior to construction. Ultimately, user convenience and system effectiveness is optimized while overall cost is reduced.

The evaluation of ITS strategies and architectures has demonstrated the requirement for data management, data communication, and real-time data access. The proliferation of Internet-based systems has demonstrated the flexibility and portability of Internet-based data transfer. Whenever possible, the Internet consistently provides the most economical and efficient means of transporting data between two ITS components. Therefore, the Internet is the data transfer medium of choice for transmitting between any ITS components that possess the ability to process Internet protocol messages, such as, TCP/IP.

In addition, the proliferation of mobile web technology and applications is continually expanding the options for ITS interfaces. Mobile web applications being developed for vehicles displays, personal digital assistants, and cellular devices will quickly broaden the availability of TOD services. Traffic information integrated with vehicle navigation is currently being deployed and will become available in most metropolitan areas in the near future. While the Internet and mobile web applications are extremely adaptable, they have limitations for some ITS applications relative to TODs and smart parking.

When Internet-based wireline communications are not suitable, the optimum solution can be achieved through a combination of DSRC, Bluetooth, and/or cellular communications. The monitoring of individual parking spaces within a smart parking system is best suited to DSRC. Maintaining a real-time telematics link with a mobile vehicle is best achieved with cellular based data transfer, such as GPRS. Access to vehicles that do not contain telematics may benefit from Bluetooth communications if other system parameters are coordinated effectively.

The above discussion of Bus Lanes with Intermittent Priority (BLIP) has illustrated a cost-effective method of increasing bus transit system speed and reliability without creating excessive delays to private vehicle traffic. The basic analysis showed that both conservative and liberal approaches have similar impacts to traffic and identical benefits. The macroscopic analysis illustrated that traffic disturbances caused by BLIP activation will not slow down subsequent buses, and that roads with medium traffic demand can easily support a BLIP implementation. The microscopic analysis provided some quantitative equations that can help decision makers determine whether a given intersection can be outfitted with a BLIP implementation within predefined parameters. Finally, a framework for cost-benefit analysis was provided.

This study has presented new and exciting ITS technology solutions for enhancing transit deployments. The ITS strategies have demonstrated the potential to provide transit users with increased mobility while limiting the dependence on the private vehicle. It has been shown that transportation efficiency and effectiveness within a TOD can certainly be enhanced with ITS. Additionally, implementation of ITS BLIPs for BRT can greatly increase system efficiencies. The goal of this report has been to identify technology bundles and architectures that have the greatest potential for increasing mobility. This study has demonstrated that ITS technologies implemented in a well-integrated fashion have the potential to promote transit use beyond levels currently observed.

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Appendix A: Literature Review of Bus Lane Intermittent Priority

Little work has been done directly addressing the idea of an intermittent bus lane. However, many of the supporting concepts and technologies have been researched quite thoroughly. These topics include the following: transit concepts, bus stop design and location, transit signal priority, in-pavement lights, and changeable message signs. Following this literature review is a summary of all articles reviewed.

INTERMITTENT LANES

A single article was found in the literature that directly discusses the concept of an intermittent lane. A paper by Jose Viegas and Baichuan Liu [2001] introduces the concept of an Intermittent Bus Lane (IBL). This paper proposes using in-pavement lights to prevent vehicles from changing into the rightmost lane as the bus approaches, but this approach relies on transit signal priority to trigger the green signal at an intersection to clear out an existing traffic queues. In effect, these lanes "flush the queue" before the bus arrives, ensuring that the transit vehicle experiences no delay from the signal.

TRANSIT CONCEPTS

The 2000 Edition of the Highway Capacity Manual (HCM) [TRB, 2000] discusses several transit concepts relevant to this analysis. First, the manual discusses the relationship between right-turn volume, pedestrian volume, and bus throughput for exclusive bus lanes that permit right turns. Because a BLIP acts as a temporary bus lane, any delays caused by right turns and pedestrians to buses in exclusive lanes will impact BLIP implementations as well.

The HMC also discusses merge delay, referring to it as "reentry delay." Many different research projects are mentioned and a table is presented providing expected reentry delay values based on adjacent lane traffic volumes. The HCM states that there are many factors that influence the reentry delay, the largest of which is the traffic state in the adjacent lane: if the adjacent-lane traffic is a discharging queue versus a platoon of vehicles from an upstream signal versus randomly arriving vehicles. As such, the reentry delay can be highly variable.

Finally, the HCM describes effects of buses on adjacent traffic lanes. One possible impact is the need of buses to cut into traffic lanes to navigate around stopped or right-turning traffic.

A TCRP report by Kevin St. Jacques [1997] analyzed bus lanes on arterials. The most relevant conclusion from this paper is that introducing an exclusive bus lane on an existing roadway reduces the capacity of the road by less than one full lane if the exclusive lane allows right turns.

BUS STOP DESIGN AND LOCATION

A few studies describe how bus stop design and location influence bus travel times. First, Emelinda et al. [1990] examines merge delay for transit vehicles. This study proposed a standard value for merge delay, around six seconds. This study did not relate merge delay to the adjacent lane traffic volume, and presented only the expected delay value (and not the variance) for merge delay. Tod et al. [1991] evaluated the impact of different bus bay designs on traffic delay and bus travel time. Again, this study made no attempt to correlate merge delay as a function of traffic volumes. Fitzpatrick et al. [1999] thoroughly document the impacts of transit stop design and location on the transit vehicle and through traffic.

QUEUE JUMP LANES

The BLIP concept is most similar to the recently established queue jump lane concept. A queue jump lane is an added curb lane that permits the bus to bypass the queue at a traffic signal. Queue jump lanes often allow right-turn traffic to use them. However, very little has been written in the literature discussing the benefits of queue jump lanes.

Tod et al. [1991] briefly discuss queue jump lanes, and the authors provide a transit vehicle time savings of between six and 29 seconds, with added delay to traffic of 0.3 to 2.9 seconds per vehicle. Mirabdal et al. [2002] documented the results of an actual queue jump implementation in San Francisco with a 38 percent mean travel time reduction, and a travel time standard deviation reduction from 103 to 44 seconds.

The HCM [TRB 2000] briefly discusses queue jump lanes. The HCM mentions that queue jump lanes are inefficient, as the lane must be extended back as far as the longest expected queue. Queue jump lanes are not discussed further in the HCM, and no documentation or analysis of potential benefits is presented.

TRANSIT SIGNAL PRIORITY

Much research has been performed on transit signal priority. Fully discussing the volumes of research is outside the scope of this literature review. For more information on transit signal priority, see the following sources: Balke 2000, Banerjee 2001, Cima 2000, Duerr 2000, Furth 2000, Garrow 1998, Hunter-Zaworski 1995, Janos 2002, Kloos 1995, Lin 2002, Nash 2001, Skabardonis 2000.

COMMUNICATION TECHNOLOGIES

The BLIP concept relies on dynamic signalization technologies to notify drivers to the status of the right-most lane: available or reserved. These technologies have been studied for their effectiveness. In one article, Panter [2003] describes the implementation of reversible lanes on the of Coronation Drive Tidal Flow system in Brisbane, Australia. This implementation includes overhead signs and in-pavement lights. The implementation was in progress at the time of the article's writing, and studies of effectiveness were not available. A study by Van Derlofske [2003] evaluated the visibility of in-pavement lights, and concluded that in-pavement lights did increase the visibility of crosswalks. Other articles were reviewed [Berman, 2001; Stainforth, 2002; Hoose, 2001], which had limited applicability to the BLIP concept.

ARTICLE SUMMARY

Viegas et al., 2001	IBL	• Introduces and discusses the concept of Intermittent Bus Lanes (IBL), where a lane is devoted to a bus only when the bus is coming. This article matches the working concept for our project. However, this article challenges the assumption that traffic will be requested to leave a lane before the traffic signal. In the given scenario, current traffic in a bus lane will be permitted to stay in that lane and flow out through the traffic signal, with the signal changed to green with enough time to permit that flow. • Discusses the integration of IBL with UTC systems. • Provides detailed mathematical analysis of the movement of vehicles and buses in the IBL. • Provides mathematical analysis of integration of IBL with UTC.
Berman, 2001	Lane Control	• Discusses using fiber optics for traffic control systems. • More discussion on the technology of the signaling systems than on traffic implications. • States that the technology explored exceeded Caltrans Traffic Signal Control Equipment Specifications for environmental hardening.
Hoose, 2002	Lane Control	• Discusses how LED signals can be used for sophisticated and radical new signaling systems, possibly moving away from the traditional red/yellow/green signals.
Panter, 2003	Lane Control	• Discusses engineering methods for dynamic lane control systems. • Uses case study of Coronation Drive Tidal Flow system in Brisbane, Australia. • Implemented for curb-side bus lane during peak periods. • Extended to perform dynamic lane allocation for auto traffic. • Road medians are indicated using high intensity pavement lighting. • http://www.saab-its.com.au/Coro_Drive.html. • http://www.saab-its.com.au/Documents/Coronation_Drive.pdf .
Stainforth, 2002	Lane Control	• Discusses more traditional CMS technologies and their current progress: higher resolution and increased legibility, advancements in production techniques.
Van Derlofske et al., 2003	Lane Control	• Discusses use of in-pavement flashing warning lights for pedestrian crosswalk safety. • Study used a flashing warning light system purchased from Traffic Safety Corporation (Sacramento, CA) that was originally designed for use on airport runways. • Study determined that there is increased noticability of the high-visibility-marked crosswalk in question once the in-pavement lighting systems were installed. • References include Traffic Safety Corporation (http://www.xwalk.com) and Light Guard Systems Inc. (http://lightguardsystems.com).
Mirabdal et al., 2002	Queue Jump	• Discusses using a bus-actuated queue jump lane for peak-hour buses making a right turn. The intersection was reworked so that the buses turned right from the left-most lane, reserved for buses. • Average travel time of the intersection dropped 38 percent, from an average of 247 seconds to 153 seconds. The standard deviation also dropped,from 103 seconds to 44 seconds.
Parentela et al., 1990	Stop Location and Design	• Paper attempts to determine the delay caused to transit vehicles due merging back into the traffic stream at a bus turnout (bus bay). • Determines that "bus stop exit delay" for stops in the traffic stream averages to about 5.7 seconds. • Determines that "bus stop exit delay" for stops that include turn-outs (bus bays)

		averages to be 10.8 and 13.4 (depending on whether a vehicle was passing the stopped bus). • Therefore, the delay incurred at the bus bay averaged to about five to sixseconds. • Faults of this study: i. traffic conditions (flow and density) for non-transit traffic were not described. ii. variance of the statistics in question was not calculated. • Range for bus turnout exit with passing was 4 to 43 seconds. Isn't it possible/likely that the exit time is a function of flow and density?
Rosenbum et al., 1991	Stop Location and Design	• Compares three case studies of different bus bay-enabled intersections with an eye to through-traffic and bus delay. • Compares standard curb-stop, far-side bus bay (Phoenix) and far-side bus bay with "queue jump lane" (Tucson). • Delay to through traffic for a standard bus stop: Averaged 1.5 seconds, from observation. i. Article hints at relationship between through traffic delay and the following criteria: bus stopped time and traffic flow rate, but it does not attempt to establish that relationship. ii. This relationship can be easily modeled analytically as a temporary bottleneck. • Delay to bus; Phoenix: eight seconds, Tucson: three seconds, calculated by comparing the amount of time required for the bus to travel 660 feet from the bus stop. i. Researcher can imagine that this type of calculation could be criticized: drivers delayed could be more aggressive upon leaving the bus bay. Then again, if aggressive drivers are able to make up this time lost, maybe it doesn't matter all that much. The cost of making up the time could be higher accident/injury rates, additional fuel consumption, etc. ii. Does not correlate delay to bus with traffic conditions. • Time saved by queue jump loop: determined a time savings of six to 29 seconds by the implementation of a queue jump loop. i. This was calculated using "results from HCM delay analysis." ii. "Estimated to be the difference between the delay to through traffic and the delay for girth-turning traffic. " iii. "The added delay for right-turning traffic… was estimated by multiplying the number of buses per cycle by the difference between the average delay for through and right-turning traffic. Based on this estimate, the additional delay would range from 0.3 to 2.9 seconds." Article recommends an acceleration lane with a taper for bus bays to reduce delay.
Balke et al., 2000	TSP	• Used TransLink® Roadside Equipment Laboratory TexSIM traffic simulation model to evaluate the priority scheme and determine delays at all approaches. a. Evaluated at vehicle to capacity ratios of 0.5, 0.8, and 0.95. b. Researchers concluded that there was a substantial negative impact on average cross-street stop delay at volume-to-capacity level of 0.95. c. The results of the simulation studies performed suggested the intelligent bus priority approach could be used at moderate traffic levels (up to v/c ratio of 0.9) without significantly affecting cross-street delays. • Describes how normal priority implementations result in increased delays, and that "many transportation agencies contend that the effects of disrupting progression and the increase in non-priority delays offset the benefits of providing priority to transit vehicles and are hesitant to implement bus priority in their jurisdictions." The reasons for this delay is usually the lack of intelligence built into the priority implementation. • Proposes "intelligent" bus priority concept, designed with the following objectives: a. Provide priority without disrupting progression on primary arterial street. b. Provide priority without significantly altering the normal sequencing and duration of the non-coordinated phases. c. Provide priority only to those buses that were truly in need of priority on the

		basis of measurable, user-defined criteria. • Resulting system keeps a fixed cycle time and provides priority to the buses by green extension, red truncation, or by inserting phases into the existing cycle to allow the bus through. a. System modeled used a 4-phase signalized intersection. b. Does not seem to account for possible queues at the intersection. c. Does account for minimum green time for each approach.
Banerjee et al., 2001	TSP	• Provides a study of a transit priority implementation in LA. • Determined that signal delay was consistently 20 percent of the base running time. "Approximately 20% of the total bus running time was spent waiting at traffic signals…" o Does not differentiate between signal delay and queue delay. • Determined that signal priority shaved seven percent off of the base running time for both bus lines. • Performed a cost analysis, determining that the annual benefit of the system is $3.3 million dollars and compared that with the $3 million TSP installation cost, resulting in a benefit-cost ratio of more than eleven-to-one.
Cima, 2000	TSP	• Describes three different TSP implementations. • Different AVL technologies used: 1) In-pavement antennas in Toronto. 2) Road-side antennas using dedicated short-range communication (DSRC) technology. • Seems the Toronto case uses near-side stops with no accommodation for delay when bus is loading/unloading. Signal remains green during this process, which caused delay at major intersections. • Makes vague differentiation between transit priority and transit preemption. Researcher believes in the context of other articles read, transit preemption is known as full priority and "transit priority" is conditional priority." • Covers technical as well as institutional arrangements required for TSP implementation. • The Vancouver, BC, study was unable to conclude whether there were any improvements in schedule adherence due to the TPS system. • From the Vancouver study: 'The continuous involvement, of the agencies responsible for the traffic signal controllers, throughout the course of the project, was a key element of attaining "buy-in", cooperation, and necessary approvals for implementing the TSP system. It is important to ensure that cost sharing arrangements with such agencies (i.e., for municipal staff time overseeing controller interfacing) are in place early on in a project in order to ensure that the contractor is not delayed.'
Duerr, 2000	TSP	• Describes using an integrated systems approach to signal priority for transit vehicles. • Discussed how transit priority can often contradict the network control scheme and can preclude a priority scheme and/or significantly disrupt traffic flow. • Introduces traffic simulation. • Describes how transit vehicles typically fall "behind the green wave" due to making passenger stops. • This article does not seem to come up with any real conclusions and since it is a simulation, its applicability to real-world scenarios is dubious.
Furth et al., 2000	TSP	• Conditional priority: defined as giving the bus priority when it is behind schedule, and denying priority when the bus is ahead of schedule. Article is a good source for definitions of conditional vs. unconditional, partial, full and relative, and active vs. passive priority. • Recommends a reference (Muller) for more detail on constructing timetables that support operational control and on the organizational process of implementing conditional priority: Muller, Th. H. J. Process Management and Operational Control in Public Transit.

		• System analyzed used Vecom loops to perform AVL for the buses, one upstream to detect the bus and begin signal changes, and one at the stop line as an exit detector. • System described operates in mixed traffic, therefore giving a bus priority like a bulldozer pushing ahead any cars that are queued up in front of the bus. As such, controller must estimate arrival time of bus and add to it the estimated amount of time to clear the queue ahead of it, and to ensure that the signal is green when the bus arrives. • Described that the conditional priority system was so popular with the bus operators that the union decided that no operator could have the route for more than a half day, page 25. • Shows via experiment that conditional priority does not increase traffic delay, page 27.
Garrow et al., 1998	TSP	• Defines conditional priority as when priority can be denied due to consideration of the well-being of the cross streets.
Janos, 2002	TSP	• Describes simulation of bus priority system in Puerto Rico. • System is a result of development "of a completely new strategy from the ground up whose objective is first to provide high-quality bus service. From the start, any attempt to maintain a common cycle and progression of offsets is abandoned." • Traffic signal control can contribute to schedule adherence: a. Reducing intersection delays reduces variance in intersection delays. b. Traffic signal control can condition transit priority on schedule deviation. (Holding up early buses and expediting late ones.) • If schedule is written that expects no signal delay, priority cannot be used to push ahead a vehicle that has fallen behind schedule. • "One way to prevent capacity loss due to buses blocking the roadway at a bus stop is to turn the signal red for the street with the bus during the blockage. If the stop is near side and the cycle can be short enough so that green returns to the bus street by the time the bus is ready to advance, this strategy will be doubly beneficial."
Lin, 2002	TSP	• Explores delay reduction using only green extension and red truncation. • Only uses fixed loop detectors in analysis, disregarding AVL techniques that could be employed. • Primary purpose of paper is to indicate how delay reductions due to transit signal priority can be calculated. • Arrives at formulas for the expected value and variance of delay reduction. a. $E(DR) = \frac{\delta}{C} R + \frac{(R^2 - R^2{}_{\min})}{2C}$ b. $\mathrm{var}(DR) = \frac{\delta}{C} R^2 (1 - \frac{\delta}{C}) + \frac{(R - R_{\min})^2 (2R_{\min} + R)}{3C} - \frac{(R - R_{\min})^2 (R_{\min} + R)^2}{4C^2}$ c. δ = time buffer in the red phase during which the bus would clear the intersection because of green extension. A reasonable value is between five and 10 seconds. • Uses "cell transmission model" to calculate numerical solutions for the delay and compares them with the analytical solution, with a very close match.
Nash et al., 2001	TSP	• Voters rejected a ballot initiative to construct a new underground transit system. Instead, they opted to implement transit priority measures to streamline the existing surface transit system. • Categorizes transit priority into four groups, one of which is Traffic Signal Priority: traffic signals that reduce delays to transit vehicles by providing them with green lights when they approach. • Transit priority implementation difficulties include: • Low technical competence and lack of expertise on transit priority techniques and implementation.

		• Lack of support or direct opposition by different agencies. • Difficulties of coordination between agencies and departments. • Pressures of automobile users. • Poor public understanding of the benefits of transit priority. • Opposition to changes by business and residents. • Stresses the importance of the support of elected officials. Zürich's elected officials became supportive after passage of a transit priority citizen's initiative in 1973. • A 1993 survey showed in that elected officials highly underestimated citizen's support for transit priority. A Santa Clara County (CA) survey illustrates the possibility of a similar underestimation. • "The fact that public officials seem to underestimate public support for transit improvements is troubling for the transit industry. Strong public official support is needed to implement complicated transit improvement projects." • Zürich designed and built a citywide traffic signal prioritization system that provides transit priority without affecting other traffic. • Implementation lessons from Zurich: • Obtain and maintain strong public support. • Enlist elected official support. • Use smart implementation techniques. • Organize government to effectively deliver program. • Careful traffic engineering and technology is critical. • Implement complementary programs to improve the transit system. • Use capital investments to leverage institutional change. • Think carefully at the systems level.
Skabardonis, 2000	TSP	• Article states that there have been relatively few successful implementations of transit priority on urban networks with signalized intersections in coordinated signal systems. • States two applicable criteria: a. Spare green time: Only grant priority if there is spare green time within the signal cycle. b. Schedule adherence: Only provide transit priority if the bus is significantly behind schedule, also considering that the benefit would be minimal if the bus is empty and/or near the end of its route with an out-of-service period to follow. • Discusses two other procedures found in literature. a. Inhibition (limit the frequency of preemption by transit vehicles), which may not be required because priority would be given only to selected, behind-schedule buses. b. Compensation (provide more green time to the non-priority traffic movements in the signal cycles after the preemption), which does not not work well in coordinated signal systems when the transit phase also serves the arterial through traffic. The additional green time given to the non-priority phase(s) would create large queues and delays to the through traffic. • Simulation modeling transit priority on an actual arterial, San Pablo Avenue through Oakland, Berkeley, Albany and El Cerrito, showed modest improvements for the transit vehicles. Passive priority strategies improved bus delay by 14 percent, and active priority reduced the delay by up to six seconds/intersection without adverse effects on the automobile traffic.
Hunter-Zaworski et al., 1995	TSP/Queue Jump	• Reports on a TSP pilot project that implemented signal priority and a single queue jump lane along a two-mile test stretch of Powell Boulevard in Portland. • Though the results were overall inconclusive, they concluded that bus travel times and bus passenger delays were both reduced with the bus signal priority. • Does not comment specifically on the time-savings of the queue jump lane.
Kloos et al.,	TSP/Queu	• Describes a pilot project in Portland, OR, testing bus priority methodologies and technologies.

1995	e Jump	• Green Extention/Early Green Return i. For far-side stops, extends the green up to 10 seconds in off-peak and 20 seconds in peak periods. • Queue Jump i. For near-side stops with right-turn-only/bus-lanes. ii. Provides green signal for the bus but not the other traffic so that it can pull ahead of the queue. • Tested TOTE and LoopComm bus detection technologies. • No clear pattern of delay developed from the studies at the four intersections. Overall, there was no substantial change to total vehicle delay. • Both bus travel time and passenger delay were reduced with bus signal priority.

Appendix B: Literature Review of ITS Technology for TODs

TRANSIT ORIENTED DEVELOPMENTS

A literature review of TODs revealed a significant amount of information regarding the characteristics, qualities, and implementation of TODs within North America [Cervero, 2003; Arrington, 2003; Cervero, 2004]. Numerous case studies were presented and details associated with each implementation were characterized [Arrington, 2003; Cervero, 2004]. The collaboration among planners, governmental agencies, and transportation agencies was highlighted. The literature with the most relevance for detailing current TOD developments was chosen for this literature review. This provided a thorough reference for current implementations, developments, and technology requirements.

INTELLIGENT TRANSPROTATION SYSTEM

ITS technology encompasses numerous industries and an enormous amount of information. Several publications were referenced in regards to TOD compatible ITS technology [FHWA, 2005; iteris.com, 2005; USDOT 2005]. These included federal publications for ITS deployment. Additional publications were referenced for vehicle telematics and traveler information services [Karbassi, 2002; Scintiei, 2004]. These presented methods for presenting information to users as well as gathering accurate information from vehicle-based systems.

ELECTRONIC PAYMENT SERVICES (EPS)

Publications associated with EPS were reviewed to obtain details associated with current technology and implementation requirements [Crocetti, 2004; ITSA 2001]. Numerous types of systems exist providing users and developers with multiple options.

INTERNET / COMMUNICATION

References were evaluated relative to communications and Internet protocols [Cisco, 2005]. Some publications directly address communications associated with transportation systems [Zimmerman, 2001]. Other references were utilized for network characteristics and associated protocols [protocols.com; wirelesswan.com].

INTELLIGENT TRANSPORTATION SYSTEM / CARSHARING

Numerous publications were evaluated relative to shared-use vehicle systems, such as carsharing. These publications provided detailed information relative to the functionality, operation, and electronic systems associated with shared vehicle systems [Barth 1999; Shaheen 2000; Barth 2001]. The electronics utilized within some shared vehicle systems are representative of systems employable for a TOD environment [Barth, 2002; Shaheen, 2002]. The data handling methods are presented for shared vehicle systems [Barth et al., 2000]. User and vehicle management methods are presented and evaluated.

SMART PARKING

Several smart parking publications and equipment provider websites (roboticparking.com) were reviewed to evaluate current technologies being implemented. Smart parking technologies range from fully autonomous parking, to real-time parking information displays, to electronic payment. A recent study focuses on the San Francisco’s Area Smart Parking options relative to the Rockridge BART station [Rodier et al., 2005]. An additional publication evaluates results from a parking information system implemented in England [Khattak, 1993].

ARTICLE SUMMARY

FHWA, 2005	ITS	• Discusses the general ITS technologies associated with User Services. • Defines User Bundles and the associated User Services. • Serves as a guide for the beginning planning stages of ITS implementations for national cohesion among ITS systems.
Scinteie et al., 2004	ITS	• Discusses technologies associated with Traveler Information services. • Provides implementation considerations of Traveler Information technologies.
ITSA, 2001	EPS	• Details the role of Electronic Payment Services with the ITS Architecture. • Provided 7 case studies of EPS deployments. • Evaluates future EPS technologies for the transportation sector.
Crocetti et al., 2004	EPS	• Discusses virtual private network for ATM. • Discusses the encryption and security methods associated with VPN/ATM network.
Cisco, 2005	I/C	• Discusses the Background and history of Internet Protocol. • Presents the format and structure for IP messaging. • Presents standard accepted methods of IP messaging.
Cervero et al., 2002	TOD	• Comprehensive overview of TOD implementations and planning. • Discuses TOD and TJD differences and implantation scenarios and examples. • Details policies, planning issues, and partnerships associated with TOD/TJD.
Zimmerman et al., 2001	I/C	• Discusses the specific roles of information and communications in the transportation sector. • Sevencase studies of specific information and communication ITS

		implementations. • Primary focuses on ITS related I/C implementations.
USDOT 2005	ITS	• Interactive web site for exploring the National ITS Architecture. • Defines the ITS Architecture components and layers. • Provides general architecture for ITS implementations. • Intended to serve as a planning and implementation guide for domestic transportation agencies.
protocols.com	I/C	• Details pertinent past, present, and near-term future wireline and wireless communication protocols. • Provide application specifics and general protocol format.
wirelesswans.com	I/C	• Describes wireless wan technology components from a technology provider perspective. • Provides general pricing for wireless wan systems.
Arrington et al., 2003	TOD	• Review of TOD and TAD US implementations. • Tensteps to successfully implementing a TOD. • Characteristics of Light Rail and TOD integration.
Shaheen et al., 1998	ITS/CS	• Describes the development of carsharing in Europe and N. America. • Presents and discusses the socio-economic factors associated with carsharing. • Discusses carsharing usage patterns. • Evaluates the direction of carsharing evolutionary development.
Britton et al., 2000	ITS/CS	• Primarily European evaluation of past and current status of carsharing. • Case studies of Praxitele and CarLink. • Broad overview of nearly all European carsharing systems. • Provides information on levels of implementation.
Barth et al., 2002	ITS/CS	• Evaluation of multiple shared use vehicle system configurations. • Focus on traditional carsharing, station car, and hybrid. • Systems with one way trips are presented.

		• Operational issues associated with each system type are presented.
Bernard et al., 1998	ITS/CS	• Describes pilot study of station car program in Bay area of California. • Relationship to BART transit is presented and discussed. • System operational characteristics are presented. • Early US station car system with low technology implementation.
Barth et al., 2001	ITS/CS	• Presents shared use vehicle system architecture with one demand one-way trips. • System operational parameters associated with system vehicle imbalances is presented. • EV-based system.
Barth et al., 1999	ITS/CS	• Presentation of on demand multiple station system architecture. • Discussion of simulation analysis techniques to evaluate system performance. • Vehicle imbalance issues associated with one way station trips is presented. • Key system operational characteristics are discussed.
Barth et al., 2000	ITS/CS	• Presentation and evaluation of ITS technologies associated with shared use vehicle systems. • Key ITS component functionality is described and presented. • Communication methods are discussed in detail.
Barth, 2000	ITS/CS	• Presentation and evaluation of ITS technologies associated with shared use vehicle systems relative to multi-station architecture. • Key ITS component functionality is described and presented. • Communication methods are discussed in detail. • Operational procedures are discussed in detail.
Barth et al., 2002	ITS/CS	• Communication requirements for shared vehicle system are presented. • Cellular and DSRC communications are discussed in detail. • The hybrid communication architecture for shared use vehicle system is discussed at length. • Advantages of hybrid system are presented.
Karbassi et al, 2002	ITS/AVL	• Vehicle AVL telematic methods are presented.

		• Route prediction is main focus. • Route mapping is discussed. • AVL vehicle technology and communication methods are discussed.
Shaheen et al., 2000	ITS/CS	• Operational characteristics of the CarLink system are presented. • User patterns are detailed. • Links to transit are presented and discussed at length. • Technology issues are addressed.
Shaheen et al., 2002	ITS/CS	• Evaluation of primarily North American carsharing systems. • Evaluation of system type, number of vehicles, technology implementations. • Analysis of carsharing growth.
Cervero et al., 2004	TOD	• Comprehensive review of the literature, surveys, interviews associated with TOD configurations and practices. • Evaluation and presentation of 10 TOD case studies within North America. • Current state of TOD practice and evaluation of the need for transit and TOD connectivity.
Rodier et al., 2005		• Evaluation of smart parking at the Rockridge BART station. • Evaluated potential effects of limited parking and reserved parking on transit use. • Surveys completed relative to smart parking and transit use.
Khattak et al., 1993		• Evaluation of information based smart parking implementation in England. • Radio broadcast of parking information and notification of historical parking use. • Parking users patterns showed significant influence from historical and real-time parking information.