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16. Abstract

Many corridors in the Texas State highway system are facing increasing congestion while having severe right-of-way limitations. The best form of congestion relief may not be additional highway lanes and/or grade separations. The best solution may be the introduction of a higher capacity transit system. Bus Rapid Transit (BRT) has been increasingly regarded as a cost-effective solution for improving mobility and alleviating congestion in urban transportation networks. Our research was aimed at providing TxDOT with comprehensive guidelines for planning and designing BRT that allows development of a BRT scenario in the traditional alternatives analysis. Specifically, this research developed a decision procedure to help TxDOT engineers/MPO planners decide the role of BRT as an integral part of existing/future transportation systems. The research team included identification and evaluation of analysis tools and methods for measuring the effectiveness/impact of BRT. Design criteria was developed for BRT concepts, including possible street re-alignment, geometric considerations, right-of-way acquisition, signal preemption, dedicated/shared busways on major state arterials, as well as integration of BRT into existing and future managed lanes (HOT/HOV). A BRT planning and design case study for El Paso, Texas and Austin, Texas was completed.

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# Guidelines for Incorporating a Bus Rapid Transit Scenario into the Analysis of Texas Highway Corridors

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# Products

This report contains Product 1, guidelines for incorporating a Bus Rapid Transit (BRT) scenario into the analysis of Texas highway corridors.

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# Chapter 1. Review of Bus Rapid Transit Concepts

Work on this project has included a review of Bus Rapid Transit (BRT) services currently operating or planned in 22 U.S. cities and a parallel review of BRT planning guidance provided in current literature. Through this effort, the research team focused on two aspects of developing comprehensive planning and design guidelines for incorporating a bus rapid transit scenario into the analysis of Texas highway corridors. These aspects are:

- What does a BRT system look like?
- What are the criteria for corridor selection for BRT implementation?

## 1.1 What Does a BRT System Look Like?

One of the most important aspects of Bus Rapid Transit implementation is the image projected by the system. BRT is a mode where "branding" and establishing an identity for the system are vital to the system's success (Federal Transit Administration 2004). Using specialized bus and station designs, for instance, emphasizes to the public the differences between BRT and other transit options. Many features differentiate BRT from standard bus service. In particular, seven major components have been identified as providing such differentiation:

1. Running ways,
2. Stations,
3. Vehicles,
4. Service patterns,
5. Route structure,
6. Automatic fare collection, and
7. Intelligent transportation system (ITS) aspects

A system referred to as BRT ideally includes all seven of these, although many communities use only a few of the components. In order to develop a typical characterization of a BRT system, the research team has examined 22 existing and planned BRT systems in various U.S. metropolitan areas where services are operating or planned as of September 2006. These BRT systems include:

1. Boston (Silver Line)
2. Chicago (Express)
3. Honolulu (City Express)
4. Las Vegas (North Las Vegas Max)
5. Los Angeles (Metro Rapid)
6. Miami (BUSWAY)
7. Oakland (Rapid Bus)

8. Orlando (LYMMO)
9. Phoenix (RAPID)
10. Pittsburgh (BUSWAY)
11. Seattle (RapidRide)
12. Eugene (EMX)
13. Alameda (San Pablo Rapid)
14. Santa Clara (VTA Rapid 522)
15. Kansas City (MAX)
16. Dulles (planning)
17. Cleveland (planning)
18. Albany (planning)
19. Minneapolis (planning)
20. Hartford (planning)
21. Charlotte (planning)
22. Montgomery (planning)

Each of these major BRT systems was investigated and component details are shown in Appendix A.

### 1.1.1 Running Ways

Exclusive bus-only freeway lanes, or busways, are the hallmark of the Bus Rapid Transit mode. Among the 22 BRT systems examined, 16 of them use exclusive freeway lanes or the combination of dedicated lanes and mixed flow lanes, while the others use mixed flow lanes. However, BRT can operate in mixed traffic on arterial streets. Decreased interaction with other types of vehicles improves the operating speed and travel time reliability of BRT systems, although such interaction cannot always be avoided. As indicated, several U.S. BRT systems make use mostly of busways, although this practice is changing somewhat as communities seek to implement minimum cost transportation alternatives (Transportation Research Board 2003).

### 1.1.2 Stations

Stations and vehicles are the most visible components of a BRT system and are therefore ideal means of conveying the “image” and identity of the system. TCRP Report 90, Volume 2, outlines the primary concerns in the design and layout of BRT stations. Among these items are:

- Provision of a full array of amenities, including shelters, passenger information, telephones, lighting, and security
- Disabled-passenger accessibility
- Although BRT stations should be readily accessible by other modes, those other modes should be separated from one another and from BRT by the station design

- Vehicle design and fare collection schemes should be tied into station design
- Coordination of station design with the surrounding community
- Provision of far-side stops or stations at sites where the route intersects other roadways at grade
- Convenient transfers and integration with other transit routes

Among the 22 BRT systems examined, most of them (19 out of 22) use enhanced shelters.

### 1.1.3 Vehicles

Perhaps the most effective method of "branding" the BRT system is through the appropriate consideration of BRT vehicles. Many communities with BRT, in an effort to visually separate standard bus service from BRT service, use specialized BRT vehicles that resemble more the modern light-rail vehicles used in light rail service. Additionally, various types of propulsion systems can provide "cleaner," environmentally-friendly means of transportation, minimizing air pollution and noise generated.

Vehicle options involve both the vehicle size and propulsion system. A recent study (Institute for Transportation & Development Policy 2006) suggests that for high-demand corridors, 160-passenger articulated vehicles have become standard. Feeder vehicles from lower-density residential areas will typically range from small mini-buses or vans to standard-sized buses, depending on the demand profile of the area. Innovative new technologies and fuels have substantially reduced BRT vehicle emissions. Such clean vehicle technologies include clean diesel, compressed natural gas, liquid petroleum gas, biofuels, hybrid-electric vehicles, and electric trolleys.

Among the 22 BRT systems examined, 2 systems (Boston and Las Vegas) use specialized BRT vehicles, 1 system (Alameda) uses van pool buses, and the others use standard, stylized standard, or articulated vehicles. Four systems (Los Angeles, Oakland, Pittsburg, and Phoenix) use clean fuel, either compressed natural gas (CNG) or liquidized natural gas (LNG). Five systems (Las Vegas, Eugene, Alameda, Cleveland, and Albany) use diesel-electric hybrid vehicles.

### 1.1.4 Service Patterns and Route Structure

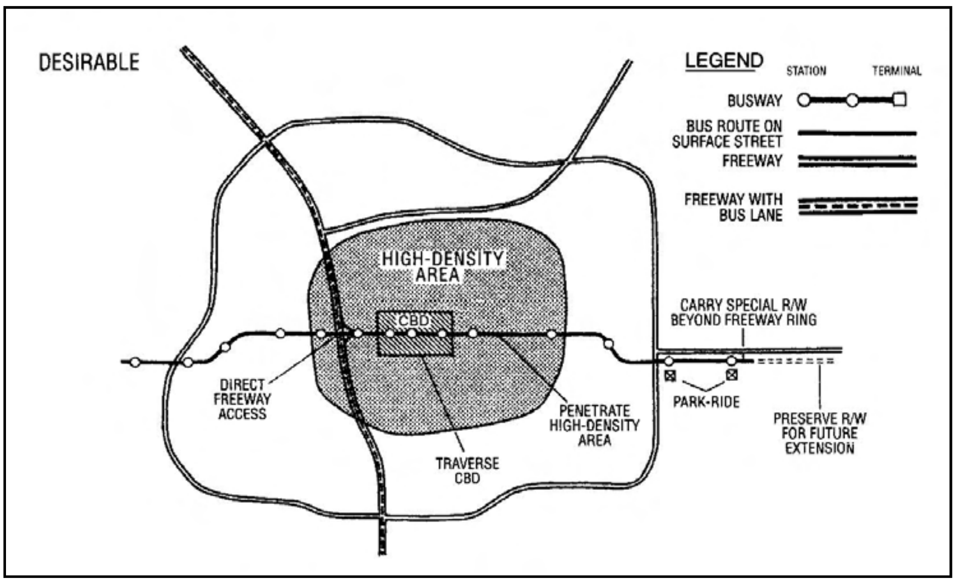
Service patterns can depend to a large extent on the design of the vehicles involved. Some vehicle innovations limit service patterns due to the BRT vehicle's inability to operate in mixed traffic on existing infrastructure. Specifically, door arrangements (some vehicles have left-side doors), platform heights, or propulsion systems may limit the coverage potential for some systems (Transportation Research Board 2003).

Locating busways should be done in such a way that travel time savings are notable over other alternative alignments (at least five minutes), congested freeway locations, and places where major road expansion is not a viable option. In maintaining the identity of the BRT system, its presence should be conspicuous within the corridor.

The literature emphasizes the need for busways to penetrate major transit markets. In the absence of such a routing structure, ridership levels will not justify the cost incurred. Ideally, a BRT system should exhibit the following 10 characteristics (Transportation Research Board 2003):

1. Radial character from the city center outward
2. Market penetration (including high-density and low-density development)
3. Through service
4. Simplified, direct route structure with minimal branching and frequent service
5. High operating speeds comparable to automobile speeds
6. Station access by foot, bicycle, automobile, or bus
7. Station spacing that varies inversely with population density
8. Convenient transit, pedestrian, and automobile interchange
9. Maximum driver productivity (maximizing the number of peak-hour passengers per bus driver)
10. Downtown distribution

Figure 1.1 shows an example of a desirable busway configuration, bisecting the hypothetical city, passing though the central business district, with direct freeway access and park-and-ride sites.




*Source: Transportation Research Board 2003*

*Figure 1.1: Desirable busway configuration route structure*

Route structure follows similar guidelines to that of service patterns. Radial routes emanating from the city center are ideal and the occurrence of branching routes should be minimized. Direct routes between major trip ends eliminate the need for transfers, which decrease substantially the attractiveness of using transit. Additionally, color-coding BRT routes provides for easy recognition of the appropriate route and minimizes passenger confusion.

### 1.1.5 Fare Collection

Fare collection in BRT systems may be accomplished on-board the bus, as in standard bus services, or before boarding the vehicle. Although fare collection prior to passenger boarding facilitates faster boarding (and thus shorter dwelling times) and allows boarding through multiple vehicle doors, these systems are not common for BRT in the U.S. and Canada and are more common overseas. Types of off-board fare payment include prepayment, auxiliary platform personnel, vending machines and proof of payment, and free-fare zones.

On-board fare collection may be accomplished through conventional on-board fare boxes, "pay enter inbound, pay leave outbound," passes, and smart card technology. Making use of smart card technology, electronic fare cards provide for swift boarding because the cards can be read from a distance. In addition, hybrid innovative fare collection systems, such as "passebus" in Joinville, Brazil, have improved BRT system functionality while reducing dwell time (Passebus-Brasil 2005). The hybrid system allows users to have a more convenient payment method, avoiding the use of coins or cash at boarding points.

Among the 22 BRT systems examined, most of them use on-board fare collection systems that permit an array of cash and card payment options; only the Cleveland system limits users to off-board payment.

### 1.1.6 ITS Implementations

Electronic fare collection through the use of smart cards is only one of many ITS technologies that may be used in facilitating BRT. Other types of ITS used in BRT include automatic vehicle location (AVL), real time information displays, traffic signal priority, automatic passenger counters, and bus guidance technologies. Through ITS implementations such as real-time information displays, BRT customers gain vital system knowledge that makes journeys more efficient and less stressful. ITS also sometimes plays an important role in system management by giving the BRT authority the power to track and control the speed and location of operators.

Among the 22 BRT systems examined, the majority (17 out of 22) have transit signal priority implementations.

## 1.2 Corridor Selection for BRT Implementation

Very limited documentation exists for BRT corridor selection. However, corridor selection might be the most important as well as the most difficult job in BRT implementation. The selection of BRT corridors will not only determine the usability of the BRT system for large segments of the population but will also have profound impacts on the future development of a city. Like many optimization problems, the typical objectives of selecting a BRT corridor should include minimizing costs and maximizing benefits. A recent study by the Institute for Transportation & Development Policy (2006) has suggested that BRT corridors and specific arterials should be prioritized by the following criteria:

- Maximize the number of beneficiaries of the new BRT system
- Minimize the negative impacts on general traffic
- Minimize operational costs
- Minimize implementation costs

- Minimize environmental impacts
- Minimize political obstacles to implementation
- Maximize social benefits, especially to lower-income groups.

### 1.2.1 Transit Demand Analysis

The most important issue in selecting a BRT corridor is determining the level of transit demand. To improve the usability/ridership of a BRT system, minimizing travel distances and travel times for the largest segment of the population is a key. Aiming at this objective, typical BRT corridors may include roads sitting near major destinations such as central business districts (CBD), major employers, hospitals, universities and schools, shopping malls, and major recreational areas. The transit demand profiles and origin-destination (O-D) results from transportation planning and demand modeling should be able to lay a foundation for decision making. In addition to reviewing the results of the transit demand analysis, other key indicators informing corridor decisions include the existing locations of:

- Standard bus services
- Central business district (CBD)
- Educational centers
- Large commercial centers
- Business parks and industrial areas
- Areas of rapid urbanization

(Institute for Transportation & Development Policy 2006)

### 1.2.2 Arterials for BRT Implementation

Primary arterials are usually major segments of many existing BRT corridors because:

- Population densities are generally highest near major arterials.
- Major arterials tend to serve medium and longer distance intra-municipal trips, which are ideal for BRT.
- In developing countries, only major arterials form clear and logical connections with other major arterials to form an integrated network.
- Major arterials tend to have concentration of existing bus or paratransit routes.
- Arterials also tend to host a concentration of major destinations such as businesses and shopping areas.

(Institute for Transportation & Development Policy 2006)

Other reasons that may make primary arterials preferable for BRT corridors include:

- There is less concern about noise, emission, and traffic impacts as primary arterials already have a significant presence of traffic.

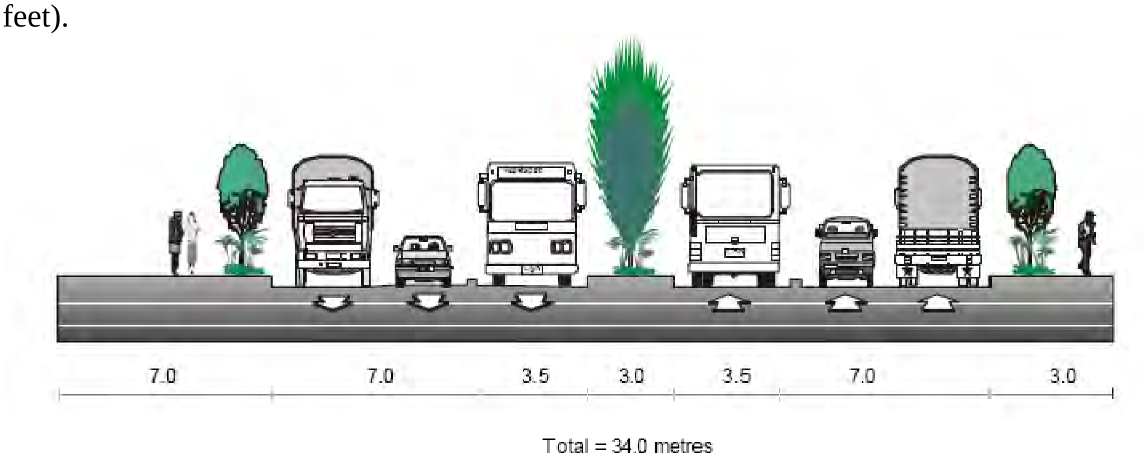
- Primary arterials better serve the goal of BRT systems to provide high speed and safe bus services instead of residential streets or dense commercial streets.
- Choosing roads with existing concentrations of transit vehicles also means that locating these vehicles in an exclusive lane will help to decongest the remaining mixed traffic lanes.

A report presented at the Second Urban Street Symposium in 2003 (Levinson 2003) outlines 14 planning, design, and operational guidelines to facilitate BRT operation on city streets. Among these guidelines are:

- BRT routes should be radial in nature with respect to the layout of the community;
- BRT should make use of relatively free-flowing streets;
- Busways, bus lanes, and queue bypasses should be provided in areas of high congestion, provided there is appropriate street geometry, community willingness, and enough buses using the route to justify these special running ways;
- The function and layout of specialized bus lanes and busways need to consider and provide for the nearby land uses in place and/or planned; and
- Reasonable percentages of street space to be dedicated to BRT and other street users.

### 1.2.3 Road Width and Available Right-of-way

A standard vehicle lane is about 12 feet in width. However, lanes can be as narrow as 10 feet in some places. A BRT vehicle and many conventional buses are about 9 feet in width while a standard passenger car is approximately 7 feet in width. The optional BRT corridor is constrained by the road width and available right-of-way. More often the road width and available right-of-way determine the service patterns and layout of a BRT system. There are no hard rules regarding the necessary road width. However, in an ideal situation, the roadway width will support a median station, one or two BRT runways, two mixed traffic lanes, and adequate space for pedestrians and cyclists. Figure 1.2 shows a typical BRT road configuration (1 meter = 3.3 feet).




*Institute for Transportation & Development Policy 2006*

*Figure 1.2: A typical road configuration for BRT*

The following sections outline the different types of “traditional” BRT running ways. TCRP Report 90, Volume 2 (2003), provides extensive guidance on cross-sectional designs for BRT running ways, as well as appropriate delineation and signage recommendations.

*1.2.3.1 Mixed Traffic Operations*

The least-expensive type of running way is that in which the BRT vehicles intermingle directly with all other vehicle types. Implementing such a running way is quickly done, although the interaction with other vehicles substantially reduces the benefits of a Rapid Transit System through lower operating speeds, reduced reliability, and a weaker identity for the system. For these reasons, operations in mixed traffic should be restricted to only those radial streets with fairly free-flow conditions, branch lines, and for residential collection (Levinson 2003). Cities where such operations occur include Los Angeles, Honolulu, and Vancouver.

Minimizing delays incurred on running ways with mixed traffic can be accomplished through a variety of means including grade separation, intersection channelization, signal coordination and priority, and longer curb radii.

*1.2.3.2 Concurrent Flow Curb Bus Lanes*

Dedicating a curb lane to BRT use is one option for providing a more separated running way than mixed traffic operations. In such a case, the 11- to 13-foot curb lane is delineated with pavement markings and appropriate signage. When right-of-way permits, these lanes may be widened to 20 feet in order to allow buses to avoid conflicts with cars stopped on the curb. These lanes are relatively inexpensive to install, although conflicts can arise from right-turning or unloading vehicles.

In cases where demand justifies doing so (more than 90 buses per hour), two bus lanes may be installed, if right-of-way and circulation patterns are sufficient, to allow buses to pass one another. In such a case, however, right turns by other vehicle types should be forbidden (Levinson 2003).

*1.2.3.3 Concurrent Flow—Interior Bus Lanes*

Similar to concurrent flow bus lanes, in this case, buses run in lanes adjacent to a lane of parked cars. Such a configuration reduces conflicts with parked cars and allows for right turns from the bus lane or by restricting parking on intersection approaches. Again, the lanes (at least 11 feet in width) are delineated with pavement markings and signage (Levinson 2003).

*1.2.3.4 Contra-flow Bus Lanes*

Contra-flow bus lanes in a grid network are typically used on one-way streets, and may be used for short distances on two-way streets to allow buses to turn around. Reasons for use of these lanes on one-way streets may include allowance for passenger boarding on both sides of the street and avoidance of peak-hour queues (Levinson 2003). On two-way arterials, contra-flow bus lanes permit buses to make use of underutilized lanes in the off-peak direction (Transportation Research Board 2003).

*1.2.3.5 Median Bus Lanes*

One-way or two-way use of median bus lanes has received mixed recommendations for use in BRT operations. Enforcement is difficult when the lanes are not physically segregated from adjacent traffic lanes with barriers, and passenger boarding, which requires crossing to the median, introduces the potential for pedestrian-vehicle conflicts. TCRP Report 90, Volume 2 (2003) provides extensive guidance for the design of median arterial bus lanes. To provide desirable operating conditions, total curb-to-curb widths on such streets should generally be no less than 75 feet, and 100-foot (or greater) widths are recommended.

## 1.3 Summary

The research team has examined what a BRT system should look like and the corridor selection issues. It was found that a BRT system differs from a conventional bus service in running ways, stations, vehicles, service patterns, route structure, fare collection, and ITS aspects. In general, a BRT system can be defined as a high quality, bus-based transit system that delivers fast, comfortable, and cost-effective urban mobility through the provision of segregated right-of-way infrastructure, rapid and frequent operations, and excellence in marketing and customer service (Institute for Transportation & Development Policy 2006).

The identification of a BRT corridor is very important for the success of a BRT system. Also, it has profound impacts on the future development of a city. There is very limited documentation on BRT corridor selection. Through literature review, it was found that the factors that should be incorporated into the BRT corridor selection process include transit travel demand/land use analysis, arterial selection, road width and available right-of-way, and layout of BRT lanes.

# Chapter 2. Investigating Incremental Effects of Typical BRT Elements and Combinations

The objective of this chapter is to analyze the marginal changes (if any) of performance measures as a consequence of various BRT element implementations. In other words, the goal is to identify the positive and negative effects of combining different BRT elements with corridor characteristics previously described in Chapter 1; for example, by how much Bus Signal Priority (BSP) improves travel time speed or how much the use of Automatic Fare Collection (AFC) reduces bus dwell time and improves schedule reliability.

To accomplish this objective, the research team has created two tables (Appendix A) including BRT system elements (such as dedicated lane, fare collection method, capacity, and comfort) in rows and the corridor characteristics (such as right-of-way, shelters, ridership, travel time) in columns to show their relationships and interactions. Both tables allow distinguishing the element-characteristic relationships as well as level of impact and potential benefit with corresponding comments in each cell. It is important to remind readers that such marginal change could be extremely local, depending on the characteristics of each corridor.

## 2.1 Identifying BRT Elements and Corridor Characteristics

Although there is not a single definition for Bus Rapid Transit (BRT) in the United States, its basic elements are similar in almost every existing operational system and planned project nationwide. Since the first BRT system was developed in Curitiba, Brazil, technical documents have shown that a BRT line or system requires coordinated improvements in transit system infrastructure, equipment, operations, and technology (Levinson et al. 2003a; Wright 2004; Currie 2006; Darido et al. 2006).

A large number of BRT systems are in operation worldwide; those currently operating in the United States were analyzed first. As a result of such analysis, a set of the most frequent elements and corridor characteristics were generalized and are listed in Table 2.1. Table 2.2 lists international BRT projects. The second table reveals different characteristics, elements, and other interrelations, especially for those BRT systems developed in Latin American, Asia, and Australia from which TxDOT can draw international experience.

The selected BRT elements included in both tables were basically those described in Chapter 1. In addition, other BRT elements and corridor characteristics were included when their benefit (or detriment) was outstanding and clearly described in technical documentation.

Tables 2.1 and 2.2 include corridor characteristics with the following features:

- Running ways and lane configuration
- Stations and shelters
- Park-and-ride facilities
- Transit oriented development
- Ridership and travel time
- Traffic congestion and intersection control
- Service patterns and type of operation

- Land use and environmental impact
- System cost and safety

Similarly, BRT elements include the following components:

- Dedicated guideway
- Contra-flow way
- Fare cost and method of collection
- Vehicle capacity and comfort
- Route coverage and service frequency
- Real-time passenger information system
- Operating speed
- Type of vehicle propulsion
- Passenger accessibility (includes wheel chairs and bicycles)
- Signal priority
- System cost

## 2.2 Table Structure

The creation of tables was made according to BRT system locations and two different groups: *U.S. systems* (Table 2.1), related to those planned or operational within the United States, and *Non-U.S. systems* (Table 2.2), those systems outside the United States, were represented. The relationship between rows (BRT elements) and columns (corridor characteristics) is shown in corresponding cells, which include the literature review resources.

## 2.3 U.S. Systems Data

The information included in Table 2.1 was gathered mainly from published documents on BRT evaluation and performance, including *"The Eugene-Springfield, Oregon Experience"* (Carey 2006), *"Honolulu BRT project Evaluation"* (Darido et al. 2006), *"Performance and Lessons from the Implementation of BRT in the United States"* (Darido et al. 2006), *"Performance and Lessons from the Implementation of BRT in the United States"* (Darido et al. 2006), *"Bus Rapid Transit in Australasia, Performance, Lessons Learned and Futures"* (Currie 2006), *"Applicability Of Bogota's TransMilenio BRT System To The United States"* (Cain et al. 2006), among others.

The list of U.S. BRT systems reviewed includes, but is not limited to:

**Table 2.1: BRT Systems within the United States**

| City | BRT Name | Main Source |
|---|---|---|
| Albuquerque, NM | Rapid Ride | Rapid Ride 2007 |
| Boston, MA | Silver Line | Darido 2006; Levinson et al. 2003a |
| Eugene, OR | EMX | Carey 2006: Levinson et al. 2003a |
| Honolulu, HI | City Express | Darido 2006; Levinson et al. 2003a |
| Las Vegas, NV | North Las Vegas Max | Darido 200 6; Kim et al. 2005 |
| Los Angeles, CA | Metro Rapid | Darido 2006; Levinson et al. 2003a |
| Miami, FL | BUSWAY | Darido 2006; Levinson et al. 2003a |
| New York, NY | Albany-Schenectady | Falbel et al. 2006; Levinson et al. 2003a |
| Orlando, FL | Lymmo BRT | Kimbler 2005 |
| Pittsburgh, PA | BUSWAY | PAOAC 2007; Levinson et al. 2003a |
| Kansas City, KS | MAX | MARC 2006; KCATA 2007 |
| Santa Clara, CA | VTA Rapid 522 | Dahlgren and Morris 2003 |
| San Francisco, CA | Bay Area BRT | Miller 2005 |
| Virginia, VA | Capital Beltway Proposal | Barker et al. 2004 |

## 2.4 Non U.S. Systems Data

Several international BRT projects were analyzed according to their local distinctiveness. The decision to create a second table was based on increasing development of the BRT transportation mode in well-known international cities including Curitiba, Beijing, Bogota, Mexico City, Sydney, and Ottawa, to name a few. The BRT systems in these and other foreign cities have been evaluated in terms of mobility impact and city benefits.

BRT has proven to be a sustainable transport system. The relatively recent implementations of BRT in Europe, Australia, Asia, and Latin America have shown a successful structure with some initial (and somehow common) anomalies. However, evaluation of those systems has helped transportation planners and authorities understand what might be the cause of the anomalies, and most importantly, how they can be prevented in future projects (BTI 2007).

Table 2.2 lists the evaluated non-U.S. BRT systems.

**Table 2.2: BRT Systems outside the United States**

| City | BRT Name | Main Source |
|---|---|---|
| Adelaide, Australia | North East Busway | Currie 2006; Wright, 2004; Levinson et al. 2003a |
| Beijing, China | BRT Line 1 | GTZ 2006; Hidalgo et al., 2007 |
| Bogota, Colombia | TransMilenio | Cain et al. 2007; GTZ 2006; Hidalgo et al. 2007; Levinson et al. 2003a |
| Brisbane, Australia | South East and Inner Northern Busway | Currie 2006; Wright 2004; Levinson et al. 2003a |
| Curitiba, Brazil | BRT Curitiba | GTZ 2006 ; Wright 2004; Levinson et al. 2003a |
| Hang Zhou, China | BRT Line B1 | GTZ 2006 |
| Jakarta, Indonesia | TransJakarta | Hidalgo et al. 2007; Wright 2004 |
| Mexico City and Leon Mexico | Metrobus and Optibus | Martínez 2007; Hidalgo et al. 2007 |
| Ottawa, Canada | Transitway | Wright 2004; Levinson et al. 2003a |
| Quito, Ecuador | Ecovía and Trole | Hidalgo et al. 2007; Wright 2004; Levinson et al. 2003a |
| Sydney, Australia | Liverpool-Parramatta Transitway | Currie 2006; Wright 2004; Levinson et al. 2003a |
| Sao Paulo, Brazil | BRT Sao Paulo | GTZ 2006; Wright 2004 |
| Santiago, Chile | Transantiago | GTZ 2006 |

## 2.5 Analysis and Results

The following sections describe the most significant marginal changes and observations of combining BRT features, and with different corridor characteristics. The discussions are drawn from lessons learned from the U.S. and non-U.S. systems.

### 2.5.1 Right-Of-Way

After evaluating several systems, it was found that one of the most common BRT attributes is dedicated or grade-separated guideways (or lanes). Dedicated guideways help improve service frequencies and headway control between vehicles due mainly to the fact that this type of guideway avoids mixed traffic and makes the system depend purely on planned vehicles (buses). Observations indicate that the concept of dedicated guideways appear more frequently in Latin America than in the United States. However, the form and practice of implementing dedicated guideways in the United States is changing considerably as different neighborhoods and districts search for the implementation of minimum-cost transportation alternatives (Levinson et al., 2003a and 2003b).

The Transit Capacity and Quality of Service Manual (TCQSM) includes the benefits of implementing exclusive right-of-way in terms of capacity and service reliability. Nevertheless, it also warns about the higher capital cost needed in comparison with other right-of-way types (Kittelson & Associates et al. 2003). For instance, results of simulations made in northern Virginia show that a combination of High Occupancy Toll (HOT) lanes and BRT tend to attract transit ridership and might present the most cost effective way to reduce congestion (Barker et al. 2004). In this case, the benefits are mainly attributable to the nature of HOT lanes, in that HOT lanes combine High Occupancy Vehicle (HOV) exclusive lanes along with price strategies that allow single occupancy vehicles to access HOV by paying a toll.

As previously stated and also mentioned in Chapter 1, dedicated lanes cannot always be implemented. Therefore, different alternatives such as busway tunnels or the combination of dedicated lanes and mixed flow could also be considered, depending on the street configuration and infrastructure availability. Although other alternatives might be inconvenient for the BRT, usually a few adjustments help to ameliorate what seems to be an adverse situation. For example, Chapter 1 stated that feasible solutions to minimize delay in mixed traffic BRT corridors include applying grade-separated right-of-way, intersection control, signal coordination, longer curb radii at main intersections, and bus priority signals.

The case of Bogota's *TransMilenio* (Colombia) is interesting in terms of express service. An innovative combination of dedicated lanes with adjacent over-passing lanes at some sections, the system allows increasing system capacity and speed, reducing travel time, and consequently attracting ridership. These benefits have a direct impact on transit operating and maintenance costs, and on the overall fare. *TransMilenio's* fare is around $0.40 USD per trip, and does not receive any type of subsidy (GTZ 2006).

### 2.5.2 Travel Time Savings and Ridership Attraction

Travel time savings and ridership attraction are perhaps the most important and reliable benefits of BRT. Such benefits are achieved through different elements, including its innovative way to transport people in a fast, safe, comfortable, and affordable manner, which distinguishes BRT from other mass transportation modes.

Research involving travel time savings and ridership attraction indicates that BRT elements with the highest influence were those that most closely describe a fundamental BRT description: dedicated guideway, high frequency service, high capacity vehicle, extensive route coverage, high operating speed, high passenger accessibility, bus signal priority, advanced fare collection methods, and real time rider information are just some of the ridership "attractors." This gives the impression that BRT is, in fact, a group of elements that have been used to improve public bus service over decades and are now combined as a single package to perform as a rapid transit service. From all of the available systems evaluations, the common factor is undoubtedly ridership attraction mainly as a result of travel time savings.

## 2.6 Shelter and Stations

Shelter location and station appearance are possibly the most visible characteristics in BRT corridors. Their architecture, accessibility, and comfort play a vital role to determine the BRT quality of service. Moreover, shelters and stations should be planned for attracting not only existing regular bus service users, but also users that for obvious and convenient reasons prefer the comfort of private passenger cars. As an example, the TCQSM (Kittelson & Associates et al. 2003) mentions that the very presence of shelters alerts non-users to the existence of transit service in the areas that they normally travel past in their automobiles, resulting in an increase in ridership. Also, TCQSM states that a dirty or vandalized shelter can raise questions in the minds of non-users about the comfort, quality of transit service, and other aspects of the service, such as maintenance. Some transit systems, such as the Bay Area Rapid Transit (BART) in the San Francisco Bay Area, have established standards for transit facility appearance and cleanliness, and have also established inspection programs. Another study developed in Santa Clara, California, demonstrated the passengers' needs and preferences, available technologies, and the combination of improvements that would be most valued by them (Dahlgren and Morris 2003). The survey found that shelters should not necessarily be equipped with the latest technology to be safe or attractive to passengers. According to this study, user perception of an ideal shelter or station is a cleaned, well-maintained, and patrolled place that also provides the most important item: accurate schedule information.

BRT infrastructure in particular, and public transportation in general, should integrate a comprehensive design to fulfill the requirements for different types of passengers and make the service universal, i.e., provide access to all passengers regardless of their physical capabilities (Kunieda and Roberts 2006). This will benefit not only persons with a disability, children, or elderly people, but also the entire BRT system and corresponding authorities as the reduction in boarding time immediately produces benefits in operating speeds, energy consumption, and quality of service.

One of the BRT elements that helps achieve user accessibility is Precision Docking Technology (PDT). This technology has been primarily developed in the United States by California Partners for Advanced Transit and Highways (PATH), and has become an important BRT feature that reduces maneuvering while improving the overall system operating speed. PDT is one of the several applications of Intelligent Transportation Systems (ITS) to BRT systems. Chapter 3 will define in detail the most common applications of this technology. Meanwhile, in the following section, a general overview concerning the benefits of including such technology in BRT will be described as part of BRT corridor characteristics.

## 2.7 ITS Technology Applied to BRT

Precision Docking Technology (PDT), Bus Signal Priority (BSP), Real Time Passenger Information System, Automatic Fare Collection (AFC), and Lane Assistant are a few examples of ITS applications used in BRT enhancement. Two potential benefits of ITS are corridor safety and operating speed improvements.

Precision Docking basically allows the bus to be automatically steered, and to approach a curbside bus stop by itself (Chan et al. 2003). This technology diminishes vehicle operator's maneuvers as well as dwell time at designated stops.

Implementation of BSP has grown rapidly among U.S. transit systems. Bus signal priority attempts to maximize efficiency along the corridor in three different areas: social, environmental, and economic. The main benefit in BSP is travel time reduction, energy efficiency, and improved system capacity in traveler's throughput.

The main contribution of Real Time Passenger information to the BRT system is the prevention of crowded stations or shelters. The TCQSM includes an excellent explanation of the resulting benefits of using such technology: *"When passengers know that another vehicle will arrive in 1 or 2 minutes, some will choose not to board the first, typically crowded, vehicle in favor of a later, less-crowded vehicle. This helps spread out passenger loads among the vehicles and may help keep the lead vehicle from falling further behind schedule"* (Kittelson &

Associates et al. 2003). Besides these benefits, real-time information in combination with enhanced shelters might keep promoting the BRT image as a high quality transportation service.

Automatic Fare Collection (AFC) usually has a direct impact in faster passenger loading, and it generates important data for demand forecasting and operational planning (Hidalgo 2007). However, three recent examples demonstrate that AFC implementation is not as simple as originally thought. The first example is AFC equipment in the *Silver Line* (Boston, MA). This equipment was initially implemented with the purpose of saving running time. However, after AFC implementation and evaluation, contrary to the expectation, travel time has increased. Thus, such experience illustrates the importance of dwelling time control (Darido et al. 2006). The second and third examples refer to the Quito (Ecuador) and Jakarta (Indonesia) BRT systems. In those cities, the implementation time for user adaptation was very short, causing "insufficient testing and quality assurance." In addition, their fare collection systems are incompatible with other public transportation modes, or in some cases, incompatible even among different BRT corridors (Hidalgo et al. 2007).

## 2.8 Transit Oriented Development (TOD)

Transit Oriented Development (TOD) can provide large benefits for market activities and property values along a transit corridor. TOD refers to a densification of development along transit corridors (Wright 2004). Concentrating activities beside the BRT corridor (especially shelters and stations) might reduce the number of passenger transfers, depending on the characteristics of local demand. Additionally, TOD increases commercial activities and can reduce maintenance cost for the entire system. Examples of these benefits are (1) Brisbane (Australia) where the land value increased around 20% along the BRT corridor; (2) Bogota (Colombia) and Washington D.C. who reported an increase in apartment rentals along their BRT projects; and (3) San Francisco-Bay Area Metro with a $1,578 USD premium for every 0.2 mile closer a home is to a BRT station (Wright 2004).

Transfer points or facilities might also be included in generating market activities in neighborhood planning. Intermodal and transference facilities permit integration with other types of services. This expands the BRT service area, and consequently, potential ridership (Kim et al. 2005).

## 2.9 Vehicle Design, Capacity and Comfort

Vehicle performance can be considered as a distinctive element of the BRT systems. BRT vehicles offer plenty of benefits when compared to other mass transportation vehicles. High capacity, low-floor, multiple doors, wider door design, and comfort are some of the features that are often found in BRT vehicles. All the above mentioned features greatly contribute to an increase in operating speed and quality of service.

A low floor can reduce boarding time for the simple reason that fewer steps eliminate extra time. Another advantage of low-floor buses is that when they use ramps to board passengers with disabilities, they represent a faster boarding access compared to conventional lifts used by standard buses. Although low floors represent a direct benefit for saving boarding time, the feature might also represent a disadvantage in terms of seat capacity if the seat layout is not selected appropriately. For this reason, Weststart-CALSTART, a nonprofit organization, has issued a report in partnership with the Federal Transit Administration about BRT vehicles offered by a variety of bus manufacturers. The report summarizes important information for decision makers about some outstanding BRT features such as bus configuration, capacity, system performance, safety, and cost (Weststart-CALSTART 2006).

Several Latin American cities such as Curitiba, Goiania, and Sao Paulo in Brazil, Bogota in Colombia, Quito in Ecuador, and Mexico City and Leon in Mexico, have adopted the platform mode for boarding and alighting. This might solve the problem of boarding time presented in no level floor-no platform buses. However, platforms also increase the cost of the entire project. A considerable advantage in using high station platforms or precision docking at stations is the fact that they have been shown as being disability-friendly, which complies with regulations of the Americans with Disabilities Act (ADA).


*Source: Veolia Transportation North America & Urban Transport Issues Asia*

*Figure 2.1: Low Floor BRT on Las Vegas "MAX" (Left) and High Floor on BRT Mexico City "Metrobus" (Right)*

In terms of capacity, BRT can also be competitive with rail systems. One of the greatest myths about BRT systems is that they are unable to reach high capacity operation. Wright (2004) reported that Bogota's BRT (Colombia) moves around 36,000 passengers per hour, per direction, and Sao Paulo (Brazil) transports up to 30,000 passengers per hour, per direction. These capacities are apparently higher than any other rail-base systems, including Light Rail Transit (LRT) (Wright 2004). Furthermore, BRT offers significantly lower emissions than LRT systems. This issue makes BRT attractive to those cities in which air quality is a priority.

## 2.10 Environmental Benefits

In the United States the benefits of transportation systems are usually measured by a reduction in total travel time rather than environmental factors. However, a study developed by Vincent and Jerram (2006) demonstrates the benefits of using a hypothetical reduction strategy. This hypothesis assumes the case in which 20 cities would implement 40-ft Compressed Natural Gas (CNG) transit vehicles; they could achieve total emissions reductions over 20 years in excess of 13 million metric tons. Obviously, reductions could be much higher if the cities also execute additional changes in route coverage, such as addition of new corridors or through land use-transit integration.

Some developing countries are taking advantage of international financial funds through BRT technology applications when a reduction in pollutant emissions is analytically demonstrated. For example, the Mexico City BRT corridor expects to eliminate 280,000 tons per year of $CO_2$ equivalent emissions that result from a direct travel time savings of over two million hours during peak periods ($1.3 million USD). Overall, the financial and health benefits of implementing Mexico City's BRT are estimated to produce $3 million USD benefits per year (Martínez 2007).

In addition to vehicles powered by internal combustion engines, all-electric vehicles can be adapted to BRT. These vehicles generally use an external power source that makes it completely environmentally friendly in both air and noise emissions. Direct current (DC) traction motors usually employed for such vehicles can actually provide more consistent torque (more power) across the full range of bus speeds than is available from internal combustion engine powered buses (Levinson et al. 2003b).

## 2.11 Safety

In terms of safety, one of the common problems found in BRT systems is the interaction between BRT vehicles and other users in intersection crossing areas. Thus, an effective solution is planning the use of an at-grade pedestrian crossing, depending on the pedestrian volume at intersections. Operators of Sydney's Liverpool-Parramatta Transitway System in Australia proposed a 2-minute headway threshold to determine if an intersection should be grade separated to avoid possible interference of pedestrians with the BRT right-of-way. Certainly, this suggestion could be implemented in other BRT projects. Nonetheless, Adelaide's North East Busway planners (also in Australia) have designed functional at-grade crossings with headways shorter than 2 minutes (Currie 2006). This example proves that interaction of BRT elements with corridor characteristics depends largely on the local conditions.

A common risk for bus users exists during boarding and alighting vehicles. An alternative to diminish the risks during boarding is the implementation of high station platforms that may be complemented with wheelchair ramp access, as in the case of Las Vegas Metropolitan Area Express (MAX) BRT service (Kim et al. 2005). According to the report, the Las Vegas MAX system experienced reliability problems with precision docking, which was temporarily disrupted in favor of manual steering (Phillips 2006).

According to the FTA, one of the most likely ITS elements to be applicable in the near future to increase BRT safety is lane assist, which permits BRT vehicles to operate at higher operating speeds (Kulyk and Hardy 2003). This technology will be implemented in the BRT systems in Orlando and Minneapolis. Despite the possible benefits lane assist might bring to BRT, the application is not yet popular among existing BRT systems in the United States.

## 2.12 Other Elements and Characteristics

Some other BRT elements and characteristics are being originally implemented by transit authorities. The use of communication technologies such as internet or cellular telephones has transformed distance communication and the way people interact. Thus, BRT might represent an excellent alternative to take advantage of this type of technology, improving passengers' productivity while in buses (Wright 2004). The TCQSM explains one of the reasons for a transit system to be less attractive in terms of ridership: "*Transit is less attractive when passengers must stand for long periods of time, especially when transit vehicles are highly crowded. When passengers must stand, it becomes difficult for them to use their travel time productively, which* *eliminates a potential advantage of transit over the private automobile"* (Kittelson & Associates et al. 2003).

For all the above mentioned technologies, some transit authorities have implemented new features to increase user comfort along with communication technology to offer users a better way to manage their travel time with the potential to increase their productivity. Such is the case for Rapid Ride BRT in Albuquerque. Rapid Ride has introduced a wireless secured internet access in which users can take advantage of their trip to exchange data, voice, or video information. Special communication antennas are installed at selected traffic signals to form the "network" along the route (Rapid Ride 2007).

*Source: http://www.cabq.gov/wifi/rapidridewifi.html*

*Figure 2.2: "Rapid Ride WiFi," a Wireless Internet Access that Enhances User's Bus Trip*

New technology encourages transit agencies to keep searching for innovative features, providing a constant improvement process for BRT and promoting mutual benefits through enhanced user satisfaction.

## 2.13 Summary

In this chapter, BRT elements and corridor characteristics have been combined and analyzed to describe the impacts or benefits, documented through evaluations of more than 15 corridors within the United States and 15 others, worldwide.

The most common benefit observed in the BRT system (relative to the conventional bus transit mode, and in some way relative to other competing public and private transportation modes) is ridership attraction. This can be achieved by the implementation, and preferentially, the combination of BRT distinctive elements: dedicated guideway, ITS, enhanced shelters and stations, advance fare collection, bus signal priority, express services, vehicle design, safety considerations, and others.

Based on the available technical documents, BRT shelters need to be built according to the forecasted passenger demand. Moreover, intersections and access facilities might need satisfactory access control to allocate all passenger flow and avoid boarding and alighting accidents. To ensure user satisfaction and potential increases in ridership, shelters should not necessarily be equipped with the latest technology; clean and secure places with accurate schedule information and equity of access can fulfill transit user needs at minimal cost.

Most importantly, when implementing BRT elements, decision makers need to accept that some of the features do not always lead to the expected positive impacts. For this reason, meticulous analysis, simulation, and evaluation of local conditions are recommended. Pilot tests on selected lines may be needed to gather user feedback to improve the design before full scale implementation.

The use of ITS technology increases safety and operating speed. Several elements such as precision docking, bus signal priority and advanced fare collection are being used in BRT corridors mainly in the United States.

BRT vehicle selection should be supported by a feasibility study before its implementation. Vehicle design is an extremely important factor for achieving the greatest possible number of benefits described in this report (e.g., high capacity, safety, comfort, accessible), including those related to environmental protection conditions.

In terms of safety, one of the most common safety problems is the interaction between BRT vehicles and pedestrians around at-grade intersections. A practical solution is the use of an at-grade pedestrian crossing. Nevertheless, planners must be aware that corridor characteristics depend largely on local conditions. Thus, the best solution should be the one that provides the best suitable environment after a detailed analysis and evaluation.

Concentrating activities beside the BRT corridor (particularly at shelters and stations) might reduce the number of passenger transfers depending on the characteristics of local demand, promote commercial activities, and increase the land value in the corridor's vicinity.

# Chapter 3. Assessing Transit ITS and Advanced Bus Technologies for BRT Applications

This chapter focuses on assessing the transit ITS and advanced bus technologies for BRT, and briefly outlines the relevant technologies applicable for BRT.

An advanced communication system (ACS) is an important aspect of BRT implementation. A reliable communication system is essential between the BRT system and the Transportation Management Center. Traditionally, communication has relied upon radio systems, which basically include analog and digital systems like land mobile radio systems, specialized mobile systems, proprietary systems, and commercial services. As the requirements for ACS are growing with the advances in transit networks in the U.S., a need for better ACS systems has been identified. Orbital Transportation Management Systems (TMS), a leading provider for passenger information equipment for the Intelligent Transportation Systems (ITS) market, has developed some useful adaptive solutions that are not only cost-effective, but are technically flexible and customizable. They are mobile data computer (MDC), OrbCad, OrbCad Paratransit, SmartCount, SmartData, SmartMDT, SmartMDT II, SmartStop, and SmartTraveller. These technologies offer a number of transit solutions using real time data, and display the information through a variety of modes such as message signs, monitors, kiosks, and internet devices.

One other area of research in this project is the potential ITS/IVI technology. Intelligent Vehicle Initiative, commonly abbreviated as IVI, is the program initiated by the U.S. DOT by combining the vehicle-focused ITS activities. By integrating driver assistance and motorist information, like presence of obstacles, pedestrians, etc., IVI helps drivers process information and make safer and faster decisions. With cooperative efforts from the Federal Transit Administration (FTA), public transit agencies, the private sector and several universities, six IVI solutions have been identified for collision avoidance in the urban transit environment. These are Frontal Collision Warning System (FCWS), Side Collision Warning System (SCWS), Rear Impact Collision Warning System (RICWS), Driver Vehicle Interface (DVI), Integrated Collision Warning System (ICWS), and Vehicle-Lane Assist Technology.

In spite of significant research growth, the transit industry is suffering from a number of challenges basically arising from limited funding. Growth trends in population segments such as the elderly and urban migration are tending to worsen congestion problems. However, bus-based transit systems show great potential for minimizing urban traffic congestion. To realize this potential, ITS plays an integral role as it enhances BRT performance using technologies like Automated Fare Collection, Real-Time Passenger Information, Signal Priority, Advanced Parking Management, and Enhanced Passenger Security. Apart from these, other IVI technologies that can potentially boost effectiveness are categorized in Table 3.2, depending on applications.

One such advanced technology system is the Collision Warning System. It basically warns the driver of any impending collision with any surrounding object. In order to warn the driver, it is most important to accurately identify vehicle surroundings, process information, and display relevant information in a convenient manner. These functions are handled through a sensor. This chapter highlights some of the sensor technology attributes for non-imaging and imaging configurations on a comparative scale: predominantly radar, optical, infrared, laser, ultrasonic, and electro.

Partners for Advanced Transit and Highways (PATH) demonstrated the implementation of Automated Bus Technologies in 2003. Precision docking, automated lane-keeping, automated lane-changing, fully automated bus driving, and automated virtual-train were demonstrated during this time. The demonstration showed how precisely the automated technologies can be harnessed to enhance driving experience in special conditions. The special situations consisted of docking the vehicle precisely at a boarding platform with a minimum gap to help the elderly and people with special requirements; driving in a narrow lane in case of deficient right-of way; automated lane changing to reach off-line stations and avoiding traffic delays; automated driving in HOV lanes and while docking; and automated virtual-train to augment transit capacity by maintaining a constant distance between vehicles across a range of speeds. PATH also demonstrated the Frontal Collision Warning System, Intersection Decision Support, and Precision Docking.

Right-of-way is one of the issues of concern in the implementation of BRT systems. Due to limited right-of-way available in some cases, maneuvering becomes difficult for buses. Lane assist and precision docking systems have been found to be useful when right-of-way is limited. The University of Minnesota ITS Institute conducted a technology assessment in the lane assist/precision docking systems on the basis of infrastructure costs to compare technologies like curb guidance, rail guidance, grid guidance, vision guidance, magnets, magnetic tapes, and the University of Minnesota DGPS. By comparing the production status, costs per mile, weather and topographical limitations, Table 3.5 provides a brief idea of the infrastructural characteristics of the lane assist/precision guidance systems. Similarly, Table 3.6 compares vehicular characteristics on the basis of parameters like vehicle sensor cost, computational complexity, control features (like mechanical or hydraulic actuation of steering system) and bus features (such as low floors, euro design, etc.).

The last section stressed in this chapter is transit signal priority and Automatic Vehicle Location (AVL). Transit signal priority systems prioritize the movement of transit vehicles over the crossing street traffic at signals, and thus help in maintaining schedules. The AVL technologies, on the other hand, help identify the transit vehicles on the network, which forms an integral part of schedule adherence to ascertain how fast or slow vehicles are running. The four basic technologies described under AVL are Signpost and Odometer, Radio-Location systems, Dead Reckoning systems, and Global Positioning Satellite systems. Each of these systems has its own advantages and drawbacks, but the GPS is the most popular. Managed by the U.S. Military and operated on a system of 24 satellites, GPS provides an enhanced data-coverage all over America, and due to recent technological advancements it provides excellent accuracy.

## 3.1 Advanced Communication Systems

Successful BRT deployment requires essential use of ITS technologies. These ITS technologies further need strong communication systems for data transmission, which can only be achieved through the use of Advanced Communication Systems (ACS). Traditionally, the communication between the BRT vehicle and the Transportation Management Center has relied upon radio systems, which include analog and digital as follows (MitreTek Systems):

- Land mobile radio systems in the public safety spectrum
- Specialized mobile radio systems such as:
    - Analog systems at 150, 450 MHz bands
    - Digital, trunked systems in the 150, 450 MHz bands

  - Digital, trunked systems in the 800 MHz band (transit owned)
  - Digital, trunked, 800 MHz system (transit partner in state or local government group)

- Proprietary Systems such as Mobilenet's Voice-over IP
- Commercial Service such as CDPD

With the increasing requirements of advanced transit networks all over the U.S., traditional communication systems are unlikely to meet advanced needs. Thus, many transit agencies have modified their existing communication systems to handle the data needs of Automatic Vehicle Location (AVL) systems and Mobile Data Terminals. With the requirement arising for newer and advanced communication systems, some research has been done to materialize the needs. Some of the common ACS developed by Orbital Transportation Management Systems are summarized in Table 3.1.

**Table 3.1: Orbital's ACS and Description**

| Sr. no. | ACS | Description |
|---|---|---|
| 1 | Mobile information provider | MDC (Mobile Data Computer) helps the field staff identify accidents and make service calls using real-time information. |
| 2 | AVL system | OrbCAD acts as a computer-aided dispatch and a locator system for vehicles. |
| 3 | Paratransit assistance | OrbCAD Paratransit integrates the technology of OrbCAD with any suitable paratransit scheduling vendor for reliable paratransit assistance. |
| 4 | Passenger counter | Using infrared sensors, SmartCount can determine the number of passengers getting on and off the bus. |
| 5 | Data handler | By combining data warehousing and data mining technologies SmartData can handle large data easily and also customize it as required. |
| 6 | Fleet management | The SmartMDT can interface with the VHF, UHF, simulcast radio system. It can monitor the engine status, vehicle speed, and silent alarm. SmartMDT II has features similar to SmartMDT, but can handle heavy duty applications. |
| 7 | Stop announcer | SmartStop uses the internal/external signage to make unfamiliar travelers aware of the next stop on the route. |
| 8 | Traveler info | The SmartTraveler acts as an effective information disseminator as it displays travel information through smart modes such as message signs, monitors, kiosks, and internet devices. |

## 3.2 Potential ITS/IVI Technologies

The Intelligent Vehicle Initiative (IVI) program has been formed by the U.S. DOT and combines the vehicle-focused ITS activities. It acts as a multi-agency research and development program by emphasizing the role of drivers in roadway safety. By integrating driver assistance and motorist information such as the presence of obstacles, pedestrians, etc., IVI helps drivers process information and make better decisions while driving, thus enhancing the overall roadway safety.

The FTA has funded six current IVI program initiatives to heighten the development of different collision warning systems, which are potentially available to the transit industry through the Volpe National Transportation Systems Center. They are described below:

### 3.2.1 Frontal Collision Warning System (FCWS)

The FCWS basically combines the data collected from sensors such as radar systems, ultrasonic sensors, and laser range finders with algorithms to detect potential frontal hazards. The system then warns the driver through a signal that increases in intensity as the proximity to collision increases. A prototype has been developed to conduct field-testing of different elements of FCWS and for validating final requirement specifications. Analysis of Driver Vehicle Interface (DVI)—which communicates the warning to the driver—showed that FCWS could warn the driver without unduly interfering with the primary job of driving.

Partners in the FCWS project are FTA, Federal Highway Administration (FHWA), California Department of Transportation (Caltrans), San Mateo County Transit District (SamTrans), University of California at Berkeley Partners for Advanced Transit and Highways (PATH), and the Gillig Corporation.

### 3.2.2 Side Collision Warning System (SCWS)

The SCWS was developed after several iterations of testing a commercial rear-looking and side-looking Collision Warning System (CWS) on a transit bus. The sensors detect obstacles and the drivers are warned through audible and/or visible warnings. It was shown that 70% of the drivers who participated in the tests favor SCWS.

Partners in this project are FTA, Port Authority of Allegheny County (PAAC), Pennsylvania Department of Transportation (Penn DOT), Carnegie Mellon University Robotics Institute (CMRI), Transportation Resource Associates, Inc., Clever Devices, and Collision Avoidance Systems, Inc.

### 3.2.3 Rear Impact Collision Warning System (RICWS)

The RICWS warns the driver about potential collisions behind the vehicle. The Ann Arbor Transportation Authority (AATA) and Veridian Engineering Division were responsible for designing the performance for the RICWS. They found that the most commonly involved rear impact collisions in transit buses occur in friendly, not unfavorable, driving conditions. The sensor designed for forward collision warning was found unsuitable for rearward applications, and further data collection was recommended to achieve sufficient significance in the experimental design.

### 3.2.4 Driver Vehicle Interface (DVI)

The DVI development was initiated to support FCWS and SCWS while emphasizing the concepts of display. Two phases have been identified to assess the progress of DVI. Phase I developed a set of preliminary display concepts for the avoidance of bus collisions. Phase II involved the testing and evaluation of preliminary DVI designs along with the examination of human factors design considerations.

### 3.2.5 Integrated Collision Warning System (ICWS)

ICWS is regarded as an advancement in transit IVI technologies. The driver is likely to get distracted due to the presence of both FCWS and SCWS. The ICWS integrates them to become a system that can be deployed in the commercial sector. Chief goals of this program include integration of SCWS and FCWS into one transit operator interface, development of a DVI prototype, testing and evaluation of enhanced transit-use commercial systems, and development of an ICWS for a commercial setting.

### 3.2.6 Vehicle-Lane Assist Technology

This is a likely IVI application for BRT initial implementation systems. It enhances the safety of BRT vehicles in unique situations such as narrow lanes, HOV lanes, and bus shoulder lanes. This technology helps the BRT vehicles operate at high speeds while maintaining the safety of passengers and vehicles.

Metro Transit and the University of Minnesota have formed a team to enhance the safety of transit vehicles in narrow lanes. Their goals include assessing the requirements for precision docking and lane assist systems, providing recommendations on integration of technology, and studying the interaction between drivers and the vehicle-lane assist technology.

## 3.3 Transit Industry Challenges

In spite of the remarkable growth in the above discussed technologies in communication systems and ITS/IVI technologies, the transit industry has other challenges that need to be addressed for current and future needs. Some key problems faced by the transit industry are outlined below:

- Limited budgets as a result of reduced funding from government
- Considerable support to the auto industry has attracted more potential passengers than the transit industry
- Transit industry has to cut service and increase fares to manage within limited budgets
- As the transit industry has to bear the burden of expensive technologies on its own, less effective service to customers is obvious
- The attractiveness of transit service is further reduced due to the complex trip patterns of most people
- Negative perceptions among the masses about the industry and problems with worker interest hampers growth

With projected demographic trends, including population growth, population aging, and migratory trends, it is clear that the role of transit buses in mitigating traffic congestion and providing comfortable transit service will be very important.

## 3.4 Initiatives in BRT—ITS

Intelligent Transportation Systems (ITS) concepts are an integral part of BRT. Applying appropriate ITS technologies to BRT can improve its reliability, efficiency, and safety, which can help mitigate the challenges faced by the transit industry. The FTA is focusing on the following ITS areas related to BRT (FTA and VOLPE 1999):

### 3.4.1 ITS Standards and Architecture

All projects containing ITS should conform to the National ITS Architecture and Standards, and should be used to develop a BRT system that is compatible with other ITS systems in the region.

### 3.4.2 Automated Fare Collection

It helps riders to board the vehicles quickly and easily, and also helps in multi-door entry and reduction in backdoor management operations.

### 3.4.3 Real-Time Passenger Information

It includes information for passengers en-route and waiting for the bus. En-route passengers get information regarding schedule adherence, current incidents, weather conditions and special events, while waiting passengers are informed about transit routes, schedules, transfer options, fares, etc.

### 3.4.4 Signal Priority

Tools are used to extend green times, to allow buses behind schedule to get back on schedule.

### 3.4.5 Advanced Parking Management

It aids parking management using ITS technologies. Some of the technologies include driver guidance to available parking facilities, parking availability notifications, parking reservations, space assignments and automated fee collection.

### 3.4.6 Enhanced Passenger Security

Passenger security is an important factor in increasing ridership. Enhanced service is used to report emergency situations to passengers inside the vehicle (using silent alarms) and to those waiting (using emergency call box buttons at the stops).

Similar to the ITS initiatives, some transit-related IVI applications that can potentially boost efficiency and safety can be classified into the following categories (Table 3.2):

**Table 3.2: IVI Systems and Applications**

| Sr. No. | IVI systems | IVI applications |
|---|---|---|
| 1. | Warning Systems | In-vehicle collision avoidance/warning system |
| | | In-vehicle obstacle and pedestrian warning system |
| | | Intersection collision avoidance systems |
| | | Railroad crossing collision avoidance systems |
| 2. | Informative Systems | Real-time transit passenger information network |
| 3. | Data collection Systems | Safety event recorders |
| 4. | Automated Systems | Fully automated vehicle control at a given facility or in dedicated HOV lanes |
| | | Precision docking system |
| 5. | Other | In-vehicle passenger monitoring system |
| | | Cargo/passenger identification |

*Source: FTA and VOLPE (November 1999)*

## 3.5 Review of Sensor Technology

A sensor is an integral part of a collision avoidance system in that it senses the changing surroundings of the vehicle. Captured signals are processed through a logical algorithm that can be displayed to the intended transit crew. The sensor creates a complete picture of the surroundings of the vehicle using very limited information and displays it to the driver. It distinguishes between useful information and clutter before creating a final picture.

Collectively, an ideal sensor should have the following essential attributes:

- Detects objects from a distance
- Provides information about the relative position of the vehicle
- Receives focused images
- Determines how far neighboring objects are
- Is long-lasting, cheap, compact, and requires minimal repairs
- Is highly compatible with and thus works efficiently in a system
- Provides necessary information in a complicated system
- Differentiates between useful and useless information
- Consumes less power

Providing all the above characteristics in a single sensor is difficult. A single sensor technology can obviously work well in a confined environment, but to support a practical setting involving a diverse and large environment, multiple sensor technologies are a must.

Tables 3.3 and 3.4 give a brief review of the types of sensors and their comparative abilities.

**Table 3.3: Summary of Sensor Technology Attributes for Non-Imaging Configuration**

| | Radar | Optical | Infrared | Laser | Ultrasonic | Electro. |
|---|---|---|---|---|---|---|
| **Type: active or passive** | Active | both | both | active | active | active |
| **Senses at a Distance?** | Yes | yes | yes | yes | yes | yes |
| **Directional?** | Yes | yes | yes | yes | yes | no |
| **Can be Focused?** | Yes | no | no | yes | no | no |
| **Ranging Information Available?** | Yes | no | no | yes | yes | no* |
| **Compact, durable, inexpensive?** | yes | yes | yes | yes | yes | yes |
| **Use in sophisticated system?** | yes | yes | yes | no | no | no |
| **Rejects clutter well?** | yes | no | no | no | no | no |
| **Draws Little Power?** | yes | yes | yes | yes | yes | yes |

*Source: FTA and VOLPE (November 1999)*

**Table 3.4: Summary of Sensor Technology Attributes for Imaging Configuration**

| | Radar | Optical | Infrared |
|---|---|---|---|
| **Type: active or passive** | active | both | both |
| **Senses at a Distance?** | yes | yes | yes |
| **Directional?** | yes | yes | yes |
| **Can be Focused?** | yes | yes | yes |
| **Ranging Information Available?** | yes | no | no |
| **Compact, durable?** | yes | yes | no |
| **Inexpensive (comparatively)?** | no | yes | no |
| **Rejects clutter well?** | yes | no | no |
| **Draws Little Power?** | yes | yes | yes |

*Source: FTA and VOLPE (November 1999)*

## 3.6 Research Done by PATH

Partners for Advanced Transit and Highways (PATH) demonstrated the Automated Bus Rapid Transit (A-BRT) technologies in August 2003 to emphasize the practical implementation of these technologies and how transit service can be improved. PATH had three buses with sensing, automation, communication, and computation systems that operated automatically. Two of the buses were standard-size 40-foot long and operated on compressed natural gas (CNG), and the third was a 60-foot long articulated bus powered by a diesel engine. PATH focused chiefly on precision docking, automatic lane-keeping, automatic lane-changing, fully automated bus driving, and automated virtual train of buses during the demonstration (California PATH—Intellimotion 2003).

### 3.6.1 Precision Docking

Through demonstration, it was shown how precisely the bus could make a stop at different platforms, with a gap of less than an inch between the bus floor and the platform using both automated steering and stopping.

### 3.6.2 Automated Lane-Keeping

This demonstration showed how a driver could keep the vehicle on a narrow lane, typical of the case in which narrow lanes are mandated by costly or restricted right-of-way. The driver has control over the automatic system in case he/she needs to take over during emergency situations.

### 3.6.3 Automatic Lane-Changing

In order to enter and exit the A-BRT bus-ways and reach the off-line stations, avoiding any traffic delays, automatic lane-changing assisted the driver in changing lanes automatically with the least amount of effort.

### 3.6.4 Fully Automated Bus Driving

Demonstrated usefulness during low speed (docking) operations as well as during fast speeds (highway driving). Once control is transferred to the vehicle, the driver is not required to do anything except to take over vehicle control at the end of the HOV lane. It can also be further enhanced to make driving fully automated, i.e., driver-less driving.

### 3.6.5 Automated Virtual-Train

By coupling one bus behind another electronically, the buses were demonstrated to run at mutual separations of 40m and 15m between them. The separation of 15m was capable of accomodating high passenger volumes, thus behaving like a virtual train. With large separations between them, failure of the leading bus did not affect the following bus, thus maintaining undisturbed flow. With the help of the automated virtual train system, buses can carry as many as 70,000 seats/hr, on par with high capacity rail transit.

Apart from this, PATH also demonstrated the results of three current research projects at the National IVI meeting at Washington, D.C. They are explained in the following section.

*3.6.5.1 Frontal Collision Warning System*

After several years of research analyzing the causes of frontal collision involving motorists, this prototype was developed for frontal collision warning using radar, lidar, a computer to watch the operating environment, and a driver vehicle interface. The frontal collision warning system works as a warning indicator for potential frontal collisions. Whenever the vehicle equipped with this system approaches a leading vehicle very closely, the driver is signaled with two orange LED lightbars on each side of the windshield that glow sequentially and intensify depending upon the proximity of the vehicle to the collision. This means that the lights will begin glowing much faster if the vehicle is closer to the leading vehicle. PATH researchers also worked closely with SamTrans drivers to improve on the system by considering their expectations and their operational environment. Through their input, PATH created the essential Driver Vehicle Interface (DVI), which forms an integral part of advanced bus technologies.

*3.6.5.2 Intersection Decision Support*

PATH demonstrated how a vehicle could be warned about the presence of an incoming vehicle at an intersection and prevented from making an unsafe left turn. When the left turns are unsafe the system displays a "No Left Turn" road sign that grows 50% in size and thickness and continuously flashes attracting the driver's attention before the turn. Using the radar, lidar, GPS, and the inductive loop detector technologies, this system can safeguard intersection left turns effectively.

*3.6.5.3 Precision Docking*

The demonstration by PATH showed how the bus approached the platform with absolute computer control, and docked near the platform with an accuracy of 1 cm. Following a series of magnetically delineated paths, the bus could conveniently reach the platform without driver assistance. With a boarding level close to the raised platform, precision docking discards the need to raise/lower the boarding level for elderly or physically disabled passengers, thus increasing reliability. Despite being an automatically controlled bus, it also had LED lights onboard at the disposal of the driver to keep him informed of the status and the readiness of the vehicle. The driver can even switch between full and partial automation to ensure smooth transitions and reduce the likelihood of pedestrian injuries at the platforms while boarding, and alighting.

## 3.7 Technology Assessment

The University of Minnesota ITS Institute conducted an assessment/comparison of the technologies in the lane assist/precision docking systems (Tables 3.5 and 3.6). This technology assessment was done on the basis of infrastructure cost categorized into high, medium, and low cost technologies.

Curb-guided buses, rail-guided systems, and grid-based systems are the systems with high infrastructure costs. The systems associated with vision and magnetic plug/tape are classified as medium infrastructure costs. The DGPS-based systems have been identified as low infrastructure costs.

**Table 3.5: Summary of Infrastructure Characteristics for Various Lane Assist and Precision Guidance Systems**

| Technology | Production Status | Road Infra-structure Cost/Mile | Supporting Infrastructure Costs | Dedi-cated lane | Weather Limitations | Topographical Limitations |
|---|---|---|---|---|---|---|
| **Curb Guidance** | Presently out of production | $2.65M/mile | 0 | Yes | Heavy snow & ice problematic | None |
| **Rail Guidance** | Prototype (2 systems) | $15.5M/mile | 0 | No | Ice may jam up guide rail | None |
| **Grid Guidance** | Prototype (one bus system) | $7.5M/mile (including pavement) | 0 | No | Likely just plowing of deep snow | None |
| **Vision Guidance** | In Production | None | Cost of surveying painting and repainting reference stripes | No | Yes—fog heavy rain snow in air UV & heat on paint stripes | Some—roads must be kept clear so stripes are visible. |
| **PATH Magnets** | Prototype | None | $20,000 mi (survey & installation of magnets) | No | No | None |
| **3M Magnetic Tape** | No Longer Supported | None | $3–$5 per lineal foot of magnetic tape installed | No | No | None |
| **University of Minnesota DGPS** | Prototype (one system on one bus) | None | $250/lane-mile to map roadway GPS base stations at $25k each + base station software ~$100,000 | No | No | Yes—need clear view to sky for satellite signals |

*Source: Donath et al. 2003.*

**Table 3.6: Summary of Vehicle Characteristics for Various Lane Assist and Precision Guidance Systems**

| Technology | Vehicle sensor cost | Computational Complexity | Lane Assist/ Precision Docking | Control Features | Bus Features |
|---|---|---|---|---|---|
| **Curb Guidance** | $15,000–$30,000 | None | Yes/Yes | Mechanical actuation of steering system | Conventional bus equipped with mechanism |
| **Rail Guidance** | Not Known | Low | Yes/Yes | Mechanical or hydraulic connection to guide rail | Low floors, Euro design, 3 articulated sections |
| **Grid Guidance** | Vehicle cost not clear | Medium | Yes/Yes | Electrically actuated steering, | Low floors, Euro design, 3 articulated sections |
| **Vision Guidance (CIVIS)** | Vehicle cost is ~$1M per vehicle, estimate 10% is technology cost | High | Yes/Yes | Electric actuation of steering | CIVIS—Low floors, Euro styling |
| **PATH Magnets** | $5000-$10000 for sensors, | Medium | Yes/Yes | Electric actuation of steering, retrofit | Retrofit onto existing bus |
| **3M Magnetic Tape** | $5000-$10000 for sensors, | Medium | Yes/Yes (modifications needed for low speeds) | Electric Steering, retrofit | Retrofit onto existing bus |
| **University of Minnesota DGPS** | $25,000–$30,000 for sensors (in volume) | Medium | Yes/Yes | Electric Steering, retrofit | Retrofit onto existing bus |

*Source: Donath et al. 2003.*

## 3.8 Transit Signal Priority Systems

One of the crucial items in the BRT deployment is schedule adherence. BRT must strictly follow a regular schedule to attract more passengers. The Transit Signal Priority system plays a vital role in achieving strict compliance. These systems identify the bus when it reaches the signal and prioritizes bus movement by extending the green time so that the delay that is induced due to waiting at the traffic signal can be minimized. Some of the preliminary technologies that go into creating this crucial tool are vehicle detection, vehicle identification, and location systems to identify a bus and communicate a location to the roadside signal controller cabinet, Global Positioning Systems (GPS), Differential GPS, and dead-reckoning (explained later) for vehicle positioning and wireless communication.

Transit signal priority can, thus, reduce passenger transit time and increase effectiveness in terms of passengers per revenue hour or mile. On the other hand, it tends to increase the overall cost due to the requirement of roadside equipment and other wireless communication systems, as well as increase delay to crossing street traffic at the intersection.

## 3.9 Automatic Vehicle Location (AVL)

AVL helps track the location of vehicles in the network with the help of fleet management technologies. Transit agencies have clear information regarding the vehicle by simply knowing its exact location. The AVL system can automate vehicle information to be available for current operations and planning purposes.

An AVL system has the potential of providing the following benefits:

- Improvement in vehicle dispatching
- More conformance to time
- Better co-ordination for transfer
- Rapid disruption response
- Information that can be applied in passenger information systems
- Enhanced safety for drivers and passengers
- Superior response to mechanical failures
- Reduction in number of road supervisors
- Traffic signal input for signal preemption
- Better automatic data collection in terms of quantity and quality at a lower cost

The four basic technologies employed for AVL systems are as described below (Gillen and Johnson 2002).

### 3.9.1 Signpost and Odometer

In this system, the bus usually carries a receiver, and transmitter for the receiver is mounted on signposts and utility poles along the route. As the bus passes by the poles the signals are transmitted to the bus receivers. The distance of the bus from the last pole can be used to locate the exact location of the bus along the route. Though the system can run in reverse (i.e., multiple receivers on the route and the transmitter on the bus), it proves ineffective in case the bus needs to change its route. As one can rightly guess, this system requires extensive maintenance because large numbers of transmitters and receivers are involved.

### 3.9.2 Radio-Location Systems

These systems use a low frequency radio signal to locate buses. Though based on the most common type of land-based radio station, called LORAN-C (Long Range Aid to Navigation), it has some major drawbacks, including interference from the overhead power lines or adjacent power sub-stations, and also weak signals in canyons.

### 3.9.3 Dead Reckoning Systems

Being one of the oldest navigation tools, it can measure the distance and direction from a fixed point even with an odometer and compass. This is a relatively inexpensive system that acts as a supporting tool for another AVL system. Being a very basic and old system of measurement, it has a few drawbacks. Some of the shortcomings include the facts that hilly terrain compromises the information; recalibration is required in case of tire wear; and location information may not be available if the vehicle leaves its fixed route.

### 3.9.4 Global Positioning Satellite Systems

With the drawbacks associated with the other AVL systems, GPS has evolved to be the most popular location technology. Administered by the U.S. military, this system operates on signals received through 24 satellites that cover most of North America. Because the system is based on signals received from satellites it eliminates the need of transmitters along the route. The accuracy of GPS has been increased from 10–20 m several years ago to 1 m at present. The accurate and pervasive availability of this technology has led to its popularity. Notwithstanding, this advanced system still has some drawbacks of poor signal availability in tunnels and blockage of signals because of tall buildings. Typically dead reckoning works well in conjunction with GPS to fill in such gaps. Many of the transit agencies in California are eager to use AVL systems; however, preference for GPS-based systems remains high.

## 3.10 Summary

This chapter has presented a brief description of transit ITS and advanced bus technologies, and has briefly outlined the relevant technologies that are or may become applicable for BRT systems.

# Chapter 4. Estimating Costs for Major BRT System Elements

This chapter presents an analysis of the costs of seven major components of an enhanced BRT system. These include the following:

1. Running ways
2. Vehicles
3. Stations
4. Automatic fare collection
5. Intelligent transportation system (ITS) aspects
6. Service patterns
7. Route structure

Each of these seven components has intricate variety and diversified functional settings to choose from. In such cases, selecting a suitable system component to suit a constrained budget is a daunting task, and hence, a detailed cost analysis is very important. The current report has been prepared by elucidating the various cost aspects of a BRT system focusing primarily on the components listed above.

## 4.1 Running Ways

Running ways form an integral part of a BRT system. Based on the particular conditions of a highway system, they are chiefly classified into three categories: busways, freeway lanes, and arterial streets. A running way should be designed very comprehensively, considering the image of the BRT system and maximum utilization of the right-of-way along with essential future LRT adaptabilities. According to TCRP Report 90, Volume 2, the typical speeds for a freeway–busway range from 25–50 mph depending upon whether the service is all-stop or non-stop; while speed for an arterial street is between 8–19 mph. The reported construction costs for them are $6–20 millions per mile and $1–10 millions per mile respectively (1). This is a simple confirmation that, as the benefits from a running way increase, its cost escalates simultaneously.

A BRT system is normally characterized by degree of segregation, running way marking, and lateral guidance. The degree of segregation is critical to a BRT system because the level of service depends largely on the extent to which buses are segregated from other traffic. The cost of BRT increases significantly with the enhanced degree of segregation because giving preferential right-of-way to buses may involve tremendous improvement to existing infrastructure and additional costs for maintenance. Table 4.1 gives the cost ranges of various types of BRT running ways based on the different degrees of segregation.

**Table 4.1: Costs of Various Running Ways Based on the Degree of Segregation**

| Component | Cost (Millions) per lane-mile | |
|---|---|---|
| | Low | High |
| *Grade-separated busway* | | |
| Below grade (tunnel) | $60 | $105 |
| Flyover | $12 | $30 |
| *At-grade busway* | | |
| Standard and bi-directional lanes | $6.5 | $10.2 |
| *Mixed flow lanes* | | |
| Queue jump | $0.1 | $0.29 |
| *Designated arterial lanes(excluding ROW costs)* | | |
| --- | $2.5 | $2.9 |

The running way markers are used to delineate the pavement from the other lanes on the route to restrict the non-BRT vehicles from using the BRT-dedicated lanes, thereby reducing unwarranted conflicts. The reported running way markings used in Canada, Mexico and Japan include signage and striping, raised lane delineators, and alternate pavement color/texture (Diaz et al. 2004). The cost for running way markers is insignificant compared to other costs and normally not included in the analysis.

Lateral guidance is a driver-assisting system that works on set of readers/sensors on the BRT vehicle coupled with necessary installations either underneath or on the surface of the pavement. The on-board receiver receives the signal from the sensors along the traveled way to direct the vehicle along its precise path. In some cases, a mechanical guidance is also used, which works on a physical connection between the running way and the steering mechanism of the vehicle. With the advancement in intelligent transportation systems (ITS), the cost for the sensors has dropped significantly in recent years. Table 4.2 summarizes the cost for the lateral guidance systems in use (Diaz et al. 2004).

**Table 4.2: Costs of Various Types of Lateral Guidance Systems**

| Guidance Type | Cost | Example Locations |
|---|---|---|
| Optical Guidance | $11,500 - $134,000 per vehicle | Rouen, France; Las Vegas $95,000 per vehicle |
| Electromagnetic Guidance | | |
| • Magnetic sensors | $20,000 per mile | -NA- |
| • Hardware and integration | $50,000 - $95,000 per vehicle | -NA- |
| Mechanical Guidance | -NA- | O-Bahn, Adelaide Australia |

## 4.2 Cost Analysis of Existing BRT Systems

This section provides information about the costs of existing BRT systems in the United States. Hess et al. (2004) compared most of the existing BRT systems on the basis of different types of running ways as well as their effectiveness in terms of providing buses preferential services. Table 4.3 shows the BRT cost estimates on the basis of the three types of running ways mentioned above.

**Table 4.3: Comparison of the Costs of Different Running Ways (in thousands, 2002 $)**

| Running way | Bus stop/station (per stop) | AVL/signal priority (per mile) | Bus arrival information (per stop) |
|---|---|---|---|
| Arterial | $38 (LA Wilshire I) to $57 (LA Ventura) | $83 (Oakland) to $100 (LA Wilshire I) | $6 (Oakland) to $10 (LA Wilshire I) |
| HOV | $135 (Vancouver) to $450 (Nashville) | $34 (Santa Clara) to $1,800 (Nashville) | $53 Santa Clara |
| Busway | $240 (Eugene) to $240,000 (Hartford) | $16 (Eugene) to $468 (Honolulu) | NA |

The following sections highlight the different running way components including busways, bus lanes, transit signal priority (TSP) system, queue jumps/bypass lanes, and curb extensions. Each of these components can be used in particular situations and their applicability depends largely upon the specific site conditions and the desired level of service.

## 4.3 Busways

The busways are the exclusive bus lanes provided either within the entire right-of-way or with a separate right-of-way. They are normally used to connect the city center with the outskirts. They can be designed in various forms varying from radial busways, parallel busways, tunnels, at-grade busways, partially or fully grade-separated busways.

Development costs for different types of busways are shown in Table 4.4. The development costs include the costs of land acquisition, construction, and engineering and vary significantly from one location to another.

**Table 4.4: Reported Costs of Busway Development (in U.S. Dollars)**

| Busway Type | System | Cost (millions) |
|---|---|---|
| Bus Tunnels | Boston - Silver Line | $1,350 |
| | Seattle | $450 |
| Grade-Separated Busways | Adelaide (guided bus) | $67.9 |
| | Brisbane | $330.1 |
| | Ottawa | $297.1 |
| | Pittsburgh - South Busway | $27 |
| | Pittsburgh - East Busway | $130 |
| | Pittsburgh - East Busway Extension | $68.8 |
| | Pittsburgh - West Busway | $249.9 |
| At-Grade Busways (Off-Street) | Hartford - New Britain (proposed) | $145.0 |
| | South Miami-Dade | $59 |
| | South Miami-Dade Extension | $13.5 |
| At-Grade Busways (On-Street) | Bogotá – TransMilenio | $184 |
| | Cleveland - Euclid Avenue | $168.4 |
| | Quito - Trole Bus | $57.6 |

The above table was organized by referring to Exhibit 4-14 from the BRT Practitioner's Guide (2007) by modifying its structure and contents making it more suitable for this report.

Apart from development costs, the construction costs of busways also vary depending upon the type of busway employed. Typically the below-grade busway type is the most costly option, ranging from $60 million to $105 million per lane mile. The approximate costs of other types are:

- At grade: $6.5-10.2 million/lane mile
- Aerial: $12-30 million/lane mile
- Additional lanes:
- $2.5-3.0 million/lane mile (in current roadway profile)
- $6.5-10.2 million/lane mile (outside current roadway profile)

## 4.4 Bus Lanes

Bus lanes are designated lanes set aside for BRT vehicles on the arterials that fall in the BRT path. Vehicles other than BRT are prohibited from using these lanes through effective means such as physical barriers or requisite police control. They are flexible, to be operated on either short streets or some specific segments of a BRT route. In some cases, the BRT lanes may have special colored pavements to mark their unique identity. The cost for adding new bus lanes is slightly higher than the cost of adding a normal additional traffic lane; the approximate estimates are:

- $2-$3 million/lane mile for curb or offset lanes
- $5-$10 million/lane mile for median transit way

## 4.5 Transit Signal Priority (TSP)

TSP is altering the signal timing at a signalized intersection to give priority to the transit vehicles. During a TSP phase the BRT vehicle is identified by the signal controller equipment at the intersection. Based on this identification priority is generated for the transit vehicle using necessary TSP equipments installed at the intersection and on the vehicle. As per *Characteristics of Bus Rapid Transit for Decision Making* (*CBRT for Decision Making*), August 2004, the cost for TSP elements is approximately:

- Signal priority software : $300–$600
- Signal controller hardware : $4,000–$10,000
- Vehicle hardware : $500–$2,000

Table 4.5 provides sorted information about TSP detection systems.

**Table 4.5: Costs of TSP Detection Systems**

| Type of Cost | High | Low | Moderate |
|---|---|---|---|
| Cost/Intersection | $20,000 for roadside reader | $2,500 per amplifier for Smart Loops | $15,000 for Optical |
| Cost/Bus | -- | $250 for roadside reader; $500 for Smart Loops | $2000 for Optical |

Source: Final Draft - Bus Rapid Transit Practitioner's Guide (modified from Exhibit 4-38)

## 4.6 Queue Jumps/Bypass Lanes

Queue jump or bypass lanes allow the BRT vehicles to bypass the queues in front at signalized intersections so as to decrease travel time. Some lanes are added specifically for the BRT vehicles; some of them are upgraded from existing right turn and left turn lanes. The main purpose for queue jump or bypass lanes is to help BRT vehicles avoid delays caused by traffic signals.

The cost of a queue jump/bypass lanes depends upon various factors including the availability of existing lanes at the intersection, the costs of roadway signing and striping, and provision of separate signal for queue jump. In situations where the lanes required for queue jumps are already available, the costs are limited to signing and striping ranging from $500–$2,000 per intersection. The queue jump signal can be an addition to either loop- or video-based traffic signal systems and range from $5,000–$15,000 per installation. In the cases where a new lane construction is required, the costs will depend largely upon the extent of construction needed at the site, right-of-way acquisition costs, and the extent of utility modifications.

## 4.7 Curb Extensions

Curb extensions are the extended sidewalks into the pavement area. Such extensions are very advantageous because they facilitate stopping of the buses in their travel lane and save the time lost in the pulling in and out of the travel lanes. They also provide more parking space, which is an additional benefit.

The costs for curb extensions basically arise from the shifting of the drains, manholes, street lights, poles, street furniture, fire hydrants, and other features required for adequate drainage provision. In San Francisco, curb extension costs have ranged from $40,000–$80,000 each.

## 4.8 Vehicles

An important BRT attribute is the BRT vehicle itself. The vehicle used for public transit should be judiciously selected as the passengers spend most of their time inside the vehicle and are thus involved with it more closely. The vehicles form a brand of the BRT. They should have some essential requirements such as low-level platforms, multiple doors for quick and easy boarding and alighting; branded exteriors consistent with the station design; spacious interiors to handle peak hour transit comfortably, and also quiet and low-emissive engines.

WestStart-CALSTART, in partnership with the Federal Transit Administration (FTA), is focusing on the development of vehicles with emphasis on cleaner, quieter vehicles that are fuel-efficient and are also working towards new vehicle concepts. Besides, various manufacturers in and outside of the United States provide vehicles that have these attributes for BRT use. A summary of such advanced vehicles as well as their costs for is shown in Table 4.6.

**Table 4.6: Cost Ranges of the Common BRT Vehicles**

| Type of vehicles | Name | Price |
|---|---|---|
| Conventional standard vehicles | 40 Foot Standard NABI 40 | LFW $300,000 to $340,000 |
| | 41 Foot Standard Orion VII | $525,000 to $550,000 Hybrid |
| | | $325,000 to $350,000 CNG |
| Stylized Standard Vehicles | 40 Foot Stylized New Flyer - Model Invero D40i | -unavailable- |
| | 40 Foot Stylized New Flyer - Model D40LF | -unavailable- |
| | 41 Foot Stylized Standard Van Hool - Model A330 | -unavailable- |
| | 40 Foot Stylized NOVA LFS | -unavailable- |
| | 45 Foot Stylized NABI CompoBus® 45C – LFW | $360,000 to $395,000 |
| Conventional Articulated Vehicles | 60 Foot Conventional Articulated NABI 60 – LFW | $475,000 to $525,000 |
| | 60 Foot Conventional Articulated NEOPLAN AN 460 LF | -unavailable- |
| | 60 Foot Articulated New Flyer - Model DE60LF | -unavailable- |
| Stylized Articulated Vehicles | 60 Foot Stylized Articulated NABI 60 – BRT | $610,000 to $675,000 |
| | 60 Foot Stylized Articulated New Flyer - Model DE60-BRT | -unavailable- |
| | 61 Foot Stylized Articulated Van Hool - Model A300 | -unavailable- |
| BRT Specialized Vehicles | 60 Foot Specialized BRT APTS – Phileas 60 | -unavailable- |
| | 60 Foot Specialized BRT Irisbus CIVIS | $980,000 |
| | 60 Foot Specialized BRT New Flyer - Model DE60i-BRT | -unavailable- |
| | 80 Foot Specialized BRT APTS – Phileas 80 | 1.1 to 1.3 M Euros |

A detailed description of each of the above vehicles with the contact information of the respective manufacturers is provided in the catalog as a ready reference for public information (WestStart-CALSTART 2005).

It has been estimated that the cost of implementing a BRT system is $102.5 million (2002 dollars) of which majority of expenditures (42.0 million) are attributed to vehicles. The vehicles thus contribute to about 40 percent of the implementation costs of BRT. The BRT vehicles also come in a variety of options to choose from. They range from a conventional 12 m (40 ft) bus carrying 60 to 80 passengers to the articulated buses that can commute 270 passengers. They can be operated on diesel, electric, or CNG power sources and also have a good service life of approximately 15, 20, and even more than 30 years. The designer has to make a comprehensive analysis of the available vehicles in the market and arrive at a justifiable choice that best fits the demand.

Table 4.7 shows a similar comparison of the various transit vehicle technologies, focusing on their relative strengths in terms of operating environment, power source, passenger capacity, service life, and the respective costs (Calgary Transit 2002).

**Table 4.7: Transit Vehicle Technology**

| Operating Environment | Type of Vehicle | Passenger Capacity | Service Life (years) | Unit Cost (2000 $Cdn) |
|---|---|---|---|---|
| Urban roadway | Standard Bus (Diesel) | 60 to 80 | >15 | $0.4 million |
| | Articulated Bus (Diesel) | 110 to 120 | >15 | $0.7 million |
| Urban roadway with catenary | Trolley Bus (Electric) | 60 to 80 | >20 | $0.85 million |
| | Articulated Trolley Bus (Electric) | 110 to 120 | >20 | $1.8 million |
| | Electric Street Car (Electric) | 100 to 150 | >25 | $1.8 million |
| Separate R.O.W with track & catenary | Light Rail Vehicle (Electric) | 180 to 220 | >30 | $4.0 million |
| Urban roadway with vertical clearance of 14.3’ | Double Decker Bus (Diesel) | 110 to 120 | >15 | $0.6 million |
| Urban roadway with overhead or in-ground power | Tram (Electric) | 150 to 200 | >30 | $3.0 million |

## 4.9 Automatic Vehicle Location (AVL) System

One of the important applications of information and communication technology to BRT systems is the advanced vehicle location system (AVL). An AVL system is used to track the location of BRT vehicles on its route network with the help of certain diagnostic systems and security features. It provides real-time monitoring of the vehicles and serves as a quick responder for vehicle breakdowns and other emergencies. The four most commonly used technologies for vehicle location systems are Global Positioning System (GPS), Differential GPS (DGPS), Signpost system, and odometer and compass system. The reported capital costs of different AVL systems are shown in Table 4.8.

**Table 4.8: Reported Capital Costs for AVL Systems**

| Type of AVL | Agency | Number of Vehicles with AVL | Total Capital Cost of AVL System |
|---|---|---|---|
| GPS | RTD | 1,111 | $15,000,000 |
| | City Bus | 25 | $150,000 |
| | DTC | 189 | $12,000,000 |
| | Fairfax CUE | 12 | $60,000 |
| | Glendale Beeline | 20 | $171,000 (includes the capital cost of 2 signs) |
| | San Francisco Muni | 827 | $9,600,000 |
| | TriMet | 689 | $7,000,000 |
| | ATC Bologna | 450 | $4,891,400 |
| | Taipei | 135 | $270,000 |
| | Centro | 6 | $705,300 |
| | Dublin Bus (Ireland) | 156 | $660,300 |
| Signpost | London Buses (U.K.) | 5,700 | $23,251,500-$27,901,800 |
| | King County Metro | 1,300 | $15,000,000 |
| DGPS | Kent County Council | 141 | $2,000,000 |
| DGPS and signpost | YTV | 340 | $1,400,000 |
| Loop inductors | LADOT/LACMT A - Metro Rapid | 150 | $2,100,000 (includes cost of TSP system - signal equipment, roadway sensors, etc.) |

The above table has been prepared from Exhibit 4-106 of the TRB BRT Practitioner's Guide (2007), in a way that more readily and appropriately suits the purpose of the current research project.

## 4.10 Driver Assist and Automation Systems

A driver assist and automation system assists the driver in controlling the vehicle in conjunction with the BRT technologies such as the collision avoidance system, precision docking system, and other vehicle guidance systems. The guidance systems need not be necessarily used throughout the entire BRT route. Instead they can be used at locations where desired. The guidance systems are basically classified into physical, optical, and electronic systems with increasing level of sophistication and service respectively. Table 4.9 highlights the costs of some driver assist and automation systems as compiled by the BRT Practitioner's Guide (2007).

**Table 4.9: Costs for Driver Assist and Automation Systems**

| Assist and Automation System | Cost |
|---|---|
| Loop detectors | $13,500/intersection |
| Curb-guided, rail-guided, grid-based | $3 to $15.5 million /lane-mile |
| Magnetic tape (3M) | $5,000-$1,000/vehicle |
| DGPS | $250 /lane-mile (building cost of digital map) |
| Vision and magnetic plug/tape-based | $20,000 /lane-mile |

*Source: TRB BRT Bus Rapid Transit Practitioner's Guide 2007.*

## 4.11 Stations

Stations are one of the most important components of a BRT system. They act as a key link between the transit system and its patrons. They help in providing a unique identity to the BRT system, and also boost their neighborhoods economically. There are a variety of BRT station designs around the globe. They range from small, well lit open shelters to closed stations with plentiful passenger amenities while the patrons wait for the next bus. These BRT stations carry greater significance as compared to the classical bus-stops due to their unique identity and functionality. They serve higher demand than the conventional bus stops for the city buses. As a result they are widely spaced, have fewer stops, and should be designed for large number of people. The many features added to BRT stations distinguish them from conventional bus stops, which normally are placed at short distances and can accommodate a limited number of people. Designing such a unique and important part of a BRT identity involves an elaborate study of the available options with detailed cost analysis. A brief study of such a cost analysis is presented this section.

The cost of a BRT station is associated with its features. The type of running way (e.g., busway, freeway shoulder lanes, etc.), type of stops (e.g., simple stop, enhanced stop etc.), roadway features (e.g., bus pullouts and passing lanes at stations), and station components (e.g., benches, shelters, bus information, telephones, etc.) all influence the BRT station cost. Table 4.10 provides the reported range of BRT station costs depending upon the type of running way.

**Table 4.10: BRT Station Costs Based on Type of Running Ways**

| Type of running way | Cost /station (millions) |
|---|---|
| Busway | $0.15 (Miami) - $3.30 (Ottawa) |
| Freeway shoulder lanes | $4.40 (Ottawa) |
| Median arterial bus lanes | $0.30 (Cleveland) |
| Mixed traffic or bus lanes | $0.06 (Los Angeles) - $0.25 (Las Vegas) |

*Source: TRB BRT Bus Rapid Transit Practitioner's Guide 2007.*

*CBRT for Decision Making* classifies the station options on the basis of degree of enrichments attributed to a station (Diaz et al. 2004). The four basic BRT station types identified by the report are simple, enhanced, designated station, and intermodal terminals or transit. These options are summarized in Table 4.11 with a brief description of comparative cost ranges and the locations.

**Table 4.11: Reported Costs According to Type of Stations**

| Type of stop | Features | Cost range | Example locations |
|---|---|---|---|
| Simple stop | Basic stop with a simple shelter | \$15,000 - \$20,000 | San Pablo Rapid Bus Shelter |
| Enhanced stop | Enhanced shelters which differentiate it from other stations; limited passenger amenities | \$25,000 to \$35,000 per shelter | Los Angeles Metro Rapid Shelter |
| Designated station | Level boarding, alighting and a full range of passenger amenities | \$150,000 to \$2.5 million per station | Brisbane South East Busway Station |
| Intermodal Terminal or Transit Center | Most complex and costly; accommodates transfer from BRT service to other transit modes | \$5 million to \$20 million per facility or higher | Ottawa Transitway Intermodal Station |

## 4.12 Roadway Features

A BRT station should be equipped with a passing capability that allows other vehicles including BRT to pass a stopped BRT vehicle to avoid delays. The two known options are bus pull-outs and passing lanes (Diaz et al. 2004).

- Bus pull-out—they pull the vehicles out of the running way. Cost ranges from \$0.05 million to \$0.06 million per pull-out (per station platform).
- Passing lanes—they allow express vehicles to pass in full speeds. Cost ranges from \$2.5–\$2.9 million per lane mile (excluding R/W costs)

As previously mentioned, an important factor adding to the station costs is the extent of passenger amenities provided at the stations. The costs for individual items also vary from one location to another. Following are some of the reported cost variations at few BRT stations (TRB BRT Practitioner's Guide 2007).

- Benches: \$2000 (*Cleveland*), \$60 (*Miami*)
- Ticket machines: \$10,000 (*Cleveland*), \$27,700 (*Miami*)
- Artwork/ landscaping: \$1 million (*Cleveland*); special painting/logo- \$350 (*Miami*)
- Trash receptacle: \$1000 (*Cleveland*), \$6 (*Miami*)
- Telephone: \$500 (*Cleveland*), \$850 (*Miami*)
- Bus shelter: \$44,600 (*Vancouver*), \$4,500-\$15,000 depending on size (*Ottawa*)

## 4.13 Fare Collection

Fare collection adds to the station costs more than even the passenger amenities. It has a great influence on the performance of the BRT system. A variety of fare collection systems as well as their performance have been documented and are basically classified into two types: on-board and off-board collection systems. An on-board collection system includes payments with exact change, tickets as a proof of purchase, and pass scanners. Similarly, an off-board collection system includes payment booths at the stations, ticket vending machines, and prepayment boarding areas. Apart from this, the fare payment is further divided into three essential attributes for its design viz. collection of fares (on-off board), its media (cash, card etc.), and the fare structure applicable to the entire system (such as using a single payment for the entire trip, provision of free transfers, etc.) Table 4.12 gives the cost ranges of installation, operation and maintenance of various bus fare collection (TRB BRT Practitioner's Guide 2007).

**Table 4.12: Fare Collection Cost Ranges**

| Type of Cost | Elements | Value ranges |
|---|---|---|
| Capital Cost | Mechanical farebox | $2,000 -$3,000 |
| | Electronic registering farebox | $4,000 -$5,000 |
| | Electronic registering farebox (with smart card reader) | $5,000 -$8,000 |
| | Validating farebox (with magnetic card processing unit) | $10,000 -$12,000 |
| | Validating farebox (with smart card reader) | $12,000 -$14,000 |
| | Validating farebox (with magnetic & smart card reader) | $13,000 -$17,500 |
| | Stand-alone smart card processing unit | $1,000 -$7,000 |
| | Magnetic fare card processing unit (upgrade) | $4,000 -$6,000 |
| | Onboard probe equipment** | $500 -$1,500 |
| | Garage probe equipment** | $2,500 -$3,500 |
| | Application software (smart card units) | $0 -$100,000 |
| | Garage hardware/software | $10,000 -$20,000 |
| | Central hardware/software | $25,000 -$75,000 |
| Payment Media | Magnetic or capacitive cards | $0.01 -$0.3 |
| | Contact-less cards (plastic) | $2 -$5 |
| | Contact-less cards (paper) | $0.3 -$1 |
| | Contact cards | $1.5 -$4 |
| Operation and Maintenance | Spare parts (% of equipment cost) | 10% -15% |
| | Support services include training, documentation, revenue testing, and warranties (% of equipment cost) | 10% -15% |
| | Installation (% of equipment cost) | 3% -10% |
| | Nonrecurring engineering & software costs (% of equipment cost) | 0% -30% |
| | Contingency (% of equipment/operating cost) | 10% -15% |
| | Equipment maintenance costs (% of equipment cost) | 5% 7% |
| | Software licenses/system support (% of systems/software cost) | 15% 20% |
| | Revenue handling costs (% of annual cash revenue) | 5% 10% |
| | Clearinghouse (e.g., card distribution, revenue allocation) *** (% of annual Automatic Fare Collection revenue) | 3% 6% |

* Actual cost depends on functionality/specifications, quantity purchased, and specific manufacturer.
** In an integrated regional system, there is no additional cost for probe equipment.
*** This depends on the nature of the regional fare program, if any.

## 4.14 Intelligent Transport Systems Aspects

Intelligent Transport System (ITS) is becoming a fundamental component for a BRT. It provides a multitude of applications that make the transit operation stress-free, comfortable, and speedy using the up-to-date vehicle information and communication technologies. With the help of these new technologies, real time information can be conveyed to the passengers; signal priority can be achieved for BRT vehicles on a real-time basis; vehicles can be located automatically on the network; and buses can be guided through its path for enhanced safety. Some of the ITS aspects that have extensive application in BRT systems are outlined in this section.

## 4.15 Real Time Passenger Information Systems

Many transit systems currently in use have at least one of the following features: a telephone information station, information announcements on board, or real time information at stations. Some of the systems such as Silver Line at Boston and Metro Rapid at Los Angeles have all three. Several cities in the United States like Los Angeles, Las Vegas, Phoenix, Pittsburg, and Boston have either implemented or begun implementing real time passenger information systems. Typical examples where such systems are in use outside the United States include Brisbane, Curitiba, Ottawa, and Vancouver. The reported costs of such passenger information components are shown in Table 4.13.

**Table 4.13: Reported Costs of Passenger Information Systems**

| Components | Costs | Examples |
|---|---|---|
| Status signs (at the stations) | $4,000-$8,000 | Los Angeles Metro Rapid ($5,000); TriMet ($4,000) |
| On-board passenger information | $2,000-$7,000 per bus | Los Angeles Metro Rapid ($4,000) |
| Voice and video monitoring | $4,000-$5,000 capital costs | ---- |
| Electronic information kiosk | $1.3 million | New York City (20 kiosks) |

Source: Exhibit 4-137, BRT Practitioner's Guide (2).

## 4.16 Route Structure and Service Patterns

BRT service plans can be measured in terms of route structure, service span, service frequency, and station spacing. Because a BRT system has to provide faster and reliable service, BRT service may consist of single or multiple routes including high level services on major routes and degraded service on feeder routes. Guidelines for developing BRT service plans are provided in the TRB BRT Practitioner's Guide (2007).

BRT service plan costs include the capital and operating costs. Capital costs depend upon the number of BRT vehicles in service, whereas operating and maintenance costs depend upon the type and extent of BRT service provided. Estimates should be made considering the unique BRT service aspects, such as lower peak-to-base ratio than local bus service, faster service, operating costs sensitive to BRT drivers' wages, etc. With characteristics unique to local conditions and tailored facilities that more appropriately suit the particular needs, it is not easy to present the costs for BRT route structure and service patterns in a representative manner. Nevertheless, studies of some prominent BRT applications that closely match the project under construction would be particularly helpful.

## 4.17 Cost Consideration of BRT Element Combination

The BRT elements discussed above can be further divided into several subcategories. For example, running ways can be categorized into mixed traffic lane, queue jumper, bus only lane, median busway, and HOV lane on freeway. Similarly there are established subdivisions for the other BRT elements. With the existing variety of options available to choose for BRT planning and implementation, it is essential to arrive at a beneficial combination of BRT components for optimum community benefit and to avoid undesirable project overruns. A judicious BRT element combination concerning its costs is thus a key factor in BRT planning.

The following outlines in brief some of the useful guidelines provided by Miller et al. (2006) in terms of the cost estimates regarding BRT combinations:

- The costs of BRT elements change with the type of technology being used. For example, the cost of transit signal priority depends upon the instrumentation of intersections and transit buses. Prior deployments have ranged from $8,000 to $35,000 per intersection.
- BRT elements can be integrated to save on the costs. In the past, the ITS and bus technologies have been mostly used in less than a fully integrated manner. By careful design, integrated deployment of BRT elements can be carried out, which can reduce the capital costs.
- Suitable consideration must be given towards operation and maintenance costs. Some BRT elements require huge capital investments making the transit agencies reluctant to consider the operation and maintenance costs. These costs should not be neglected.

Table 4.14 gives a further summary of the representative costs for the development of BRT components.

## 4.18 Summary

A typical BRT system usually consists of seven components viz. running way, vehicles, stations, service patterns, route structure, automatic fare collection, and Intelligent Transportation Systems. This memo was prepared to provide informative knowledge about each component of the BRT system with focus on the cost analysis. Because each BRT system component has elaborate sub-components involved within them, an analysis covering each one of them is utterly essential to help the transit planning researchers and practitioners in their planning process.

**Table 4.14: Representative Costs of a BRT System**

| BRT Component | BRT Subcomponents | Unit | Cost (in 2004 USD)/Unit |
|---|---|---|---|
| Running Way | Off-street busway | | |
| | *At grade* | Per route-mile | $5 million |
| | *Grade-separated* | Per route-mile | $13 million |
| | *Grade-separated Elevated* | Per route-mile | $50 million |
| | *Grade-separated Tunnel* | Per route-mile | $200 million |
| | On-street | | |
| | *Median arterial busway* | Per route-mile | $4 million |
| | *Bus lane - new construction* | Per route-mile | $25 million |
| | *Bus lane - striping lane* | Per route-mile | $100,000 |
| Preferential Treatments for Transit | Queue bypass | | |
| | *Parking removal* | Per approach | Negligible |
| | *Use of right turn lane* | Per approach | Negligible |
| | *Added lane* | Per approach | $300,000 |
| | Curb extension | Per extension | $60,000 |
| | TSP | Per intersection | $30,000 |
| | Special transit phase | Per intersection | $10,000 |
| Stations | Basic | Per station | $21,000/direction |
| | Enhanced | Per station | $30,000/direction |
| | At grade | Per station | $150,000 |
| | Grade-separated | Per station | $2.5 million |
| | Intermodal center | Per station | $12.5 million |
| | Passing lane | Per lane-mile | $2.7 million |
| Vehicles | Conventional standard | Per vehicle | $325,000 |
| | Stylized standard | Per vehicle | $330,000 |
| | Conventional articulated | Per vehicle | $570,000 |
| | Stylized articulated | Per vehicle | $730,000 |
| | Specialized BRT | Per vehicle | $1.3 million |
| Fare Collection | On-board Magnetic card media | Per vehicle | $15,000 |
| | On-board Smart media | Per vehicle | $20,000 |
| | Off-board Magnetic card media | Per machine | $60,000 |
| | Off-board Smart media | Per machine | $65,000 |
| Passenger Information | Information At-station | Per sign | $6,000 |
| | Information On-vehicle | Per vehicle | $4,000 |
| Branding | Branding | Per system | Negligible |
| ITS Applications | On-board security | Per vehicle | $10,000 |
| | Optical/magnetic sensors for vehicle guidance (on-board) | Per mile | $20,000 |
| | Hardware integration for vehicle guidance (on-board) | Per vehicle | $50,000 |
| | Optical/magnetic sensors for precision docking (on-board) | Per station | $4,000 |
| | Hardware integration for precision docking (on-board) | Per vehicle | $50,000 |
| | On-board performance monitoring | Per vehicle | $2,000 |
| | AVL | Per vehicle | $8,000 |

This table has been derived from Exhibit 5-4 of the TRB BRT Practitioner's Guide (2007) by modifying its contents. It gives the BRT costs of different elements by identifying the various subcomponents within each BRT major component.

# Chapter 5. Representative BRT System Deployment Phases

## 5.1 Background

Bus Rapid Transit (BRT) can be defined as a combination of elements and corridor characteristics with high performance and rail-like operations. A complete list of those elements and characteristics has been previously described in Chapters 1 and 2 of this document. Unlike rail systems, BRT projects rarely include the whole set of possible attributes in the first stage. Rather, they are gradually developed. During the planning process of a BRT system, one of the most important stages is the deployment of a planning strategy that determines that BRT elements will be included in the BRT system as well as when they will be deployed (deployment sequence) (Miller and Golub 2007).

The nature of BRT allows an incremental deployment process that is highly complex because of the numerous elements that can be incorporated in any number of distinct phases. The complexity of the problem dramatically increases when a fundamental factor is added to the deployment process: the unique and local conditions.

During the planning process of a BRT system many operations and design approaches are involved. In some cases, companies that are responsible for planning and implementation of these types of systems do not fully consider integrating an optimal set of elements at different phases (Zimmerman et al. 2006). Consequently, those systems may not be the most cost effective for maximizing the benefits to both the transit line and the transit ridership. Moreover, some agencies do not have enough knowledge about BRT systems, and they propose implementing models that are more likely to be used in traditional transit or rail systems. Therefore, it is extremely important that the definitions of each alternative, deployment strategies, system-design options, and project elements are chosen following the standard guidelines and practices that characterize a BRT system (Diaz et al. 2004).

As described in this chapter, the research team has developed a methodology that involves three different deployment phases. Each of them features different levels of BRT configurations. The first, referred to in this section as “limited,” includes basic elements that were identified as part of the primary phase of construction in a BRT project. The second, cited in this document as “moderate,” consists of a more complete group of characteristics that have specifically demonstrated an improvement in the system level of service (capacity and travel speed). The third phase, termed “aggressive,” groups those key characteristics that provide high quality service or excellent performance in terms of operation and comfort of the entire system. Additionally, the method includes estimated capital and operating costs using data from Chapter 4. The intention of cost integration is to provide TxDOT with solid justification for not pursuing other types of road improvements on a given corridor. The results of this chapter are aimed to help TxDOT and transit agencies when they are conducting BRT feasibility studies. The cost associated with each characteristic and its potential improvement in the level of service will help in the evaluation of the BRT alternative against other alternatives. These results are of immediate interest to transit agencies for deployment of cost-effective BRT systems.

## 5.2 Phases Description

The three aforementioned phases include groups of different alternatives or elements. The following section describes the characterization of each phase as well as the various levels of improvements within each phase (if any).

### 5.2.1 Limited Phase: Basic BRT Elements

Very often, the very first stage or deployment phase of a BRT corridor is just an enhancement of the existing bus route. The subsequent phases usually include some type of lane segregation, Intelligent Transportation Systems technology application (ITS), an improved fare collection system, signal priority systems, and other enhancements (Miller et al. 2006). Based on the existing literature review, the research team determined that the basic elements or characteristics in a "limited" phase could include some form of bus priority but not full segregated busway, segregated busway/single corridor services, improved travel time, on-board fare collection, higher quality shelters, clean vehicle technology, and marketing identity (Wright 2004). Financially and technically speaking, this deployment phase represents a low-cost set of attributes that are relatively easy to put into operation. Additionally, the limited phase mostly offers a short-term advantage in its implementation.

Examples of basic busways are Los Angeles (San Bernardino Freeway, Harbor Freeway), New York City (Lincoln Tunnel), Philadelphia (Ardmore busway), Alameda and Contra Counties (AC Transit Rapid Bus), Albuquerque (Rapid Ride), Boston (Silver Line Washington Street), Chicago (NEBR), Denver (16th Street Mall), Honolulu (City/County Express), Kansas City (MAX), Los Angeles (Metro Rapid Wilshire Boulevard), Phoenix (RAPID), and Santa Clara (VTA).

### 5.2.2 Moderate Phase: BRT

This phase includes more advanced characteristics such as segregated busways, typically pre-board fare collection/verification, higher quality shelters, clean vehicle technology, and marketing identity.

Some infrastructure elements of the moderate phase (Wright 2004) are:

- Segregated busways or bus-only roadways over the majority of the length of the system's trunk/city center corridors. And, at least two of the following features:
- Existence of an integrated network of routes and corridors;
- Enhanced stations that are convenient, comfortable, secure, and weather-protected;
- Stations provide level access between the platform and vehicle floor;
- Location of the busways in the median of the roadway rather than in the curb lane;
- Pre-board fare collection and fare verification;
- Special stations and terminals to facilitate physical integration between trunk routes, feeder services, and other mass transit systems (if applicable);
- Fare-integration between routes, corridors, and feeder services;
- Entry to system restricted to prescribed operators under a reformed business and administrative structure (closed system);

- Distinctive marketing identity for system.

Examples of BRT (moderate phase) include Boston (Silverline), Eugene (EmX), Los Angeles (Orange Line), Miami (Miami-Dade), Orlando (Lymmo), Pittsburg (Busway), Las Vegas (MAX), Quito (Ecuador), Brisbane (Australia), Ottawa (Canada), Guayaquil (Ecuador), Leon (Mexico), Mexico City (Mexico), Pereira (Colombia), and Jakarta (Indonesia).

### 5.2.3 Aggressive Phase: Full BRT

The main characteristics that distinguish this phase are metro/subway-quality service, integrated network of routes and corridor, close/high quality stations, pre-board fare collection/verification, high frequency and rapid service, modern and clean vehicles, marketing identity, and superior customer service.

Some infrastructure elements of the aggressive phase (Wright 2004) are:

- Segregated busways or bus-only roadways over the majority of the length of the system’s trunk/city center corridors;
- Location of the busways in the guideway median rather than in the curb lane;
- Existence of an integrated network of routes and corridors;
- Enhanced stations that are convenient, comfortable, secure, and weather-protected;
- Stations provide level access between the platform and vehicle floor;
- Special stations and terminals to facilitate physical integration between trunk routes, feeder services, and other mass transit systems (if applicable);
- Pre-board fare collection and fare verification;
- Fare- and physical-integration between routes, corridors, and feeder services;
- Entry to system restricted to prescribed operators under a reformed business and administrative structure (closed system);
- Distinctive marketing identity for system.

Based upon this definition, Wright stated that there exist only two truly full BRT systems in the world: Bogota, Colombia and Curitiba, Brazil (Wright 2004).

### 5.2.4 Elements and Sub-Elements of BRT Deployment Phases

In chapters one and two of this report, several BRT elements were analyzed. As a consequence of such analysis the research team concludes that existing BRT systems around the world are not alike and vary depending on the local characteristics. However, according to the TCRP report 118 (Kittelson & Associates 2007), all BRT systems will have at least running ways, stations, and vehicles. Other authors considered a larger amount of basic features or fundamental elements for a BRT to exist. For instance, Miller et al. include the following items as basic elements of a BRT system: (1) running ways; (2) stations; (3) vehicles; (4) intelligent transportation systems; (5) fare collection; and (6) service and operations plan. Each of these six primary elements may be further disaggregated into separate sub-elements (Miller et al. 2006). As the main goal of this chapter is to design representative elements of each phase, some BRT elements are included in more than one category (phase) because they are not mutually exclusive in the different phases.

A BRT system can be gradually enhanced. Each phase or group of elements will depend on both the demand characteristics and the resources invested. The three phases above described could include (1) addition of elements or features to the existing conditions; (2) upgrade of some or all of the vital elements (vehicles, stations, or right-of-way); (3) relocation of the running ways, or (4) a simple extension of the system (Kittelson & Associates 2007).

Table 5.1 provides a complete list of elements and sub-elements that might be included on a BRT system. Additionally each element includes the possible deployment phase in which that element is more suitable or recommended.

## Table 5.1: Capital Costs by BRT Component in Three Different Deployment Phases

BRT COMPONENTS

| Running way and lane configuration | | PHASE 1 LIMITED | PHASE 2 MODERATE | PHASE 3 AGGRESSIVE |
|---|---|---|---|---|
| **Mixed Flow** | | $0.5-2.0 Million/mile | | |
| **Dedicated guideway (2006)** | | | $20+ Million/mile | $20+ Million/mile |
| **Contra-flow way (2006)** | | $2.0-15.0 Million/mile | $2.0-15.0 Million/mile | $2.0-15.0 Million/mile |
| **Grade separated exclusive guideway (2003)** | **Below grade** | | | $60-105 Million/lane/mile |
| | **At grade** | | | $6.5-10.2 Million/lane/mile |
| | **Aerial** | | | $12-30 Million/lane/mile |
| **Queue Jumpers (2003)** | | $0.1-0.29 Million/lane/mile | $0.1-0.29 Million/lane/mile | |
| **Overpass lane (Express Service)** | | | | $2.5-2.9 Million/lane/mile |
| **Median lane runway** | | | $5-10 Million/lane/mile | $5-10 Million/lane/mile |
| **Curb lane** | | $3-15.5 Million/lane/mile | | |
| **Curb extension** | | $40,000-80,000 each | | |
| Stations | | | | |
| **Enhanced Shelters** | | $25,000-35,000 unit | $25,000-35,000 unit | |
| **Level Platforms** | | | N/A | N/A |
| **Provision of a full array of amenities, (shelters, passenger information, telephones, lighting, and security)** | | | N/A | N/A |
| **Automatic passenger counter (mats, infrared beams)** | | | N/A | N/A |
| **Intermodal and transfer facilities** | | $5-20 or more Million/facility | $5-20 or more Million/facility | $5-20 or more Million/facility |
| Vehicles | | | | |
| **40'-60' Diesel articulated** | | $300,000-980,000 each | $300,000-980,000 each | |
| **80' double articulated (2007)** | | | | €1.1-1.3 Million<br>$1.6-1.9 Approx. |
| **Standard Diesel Buses** | | $300,000-400,000 each | $300,000-400,000 each | $300,000-340,000 each |
| **CNG fuel vehicle** | | $325,000-350,000 each | $325,000-350,000 each | $325,000-350,000 each |
| **Electric (trolley-like)** | | $0.85-1.8 Million each | $0.85-1.8 Million each | $0.85-1.8 Million each |
| **Hybrid/ dual mode** | | | $525,000-550,000 each | $525,000-550,000 each |
| **On-board fare collection** | | N/A | N/A | |
| **ATMS- GIS** | | | | N/A |
| **Wi-Fi service** | | | | N/A |
| **40' Low-floor vehicles** | | | $300,000-340,000 each | $300,000-340,000 each |
| **Multiple doors** | | | | N/A |
| **Design identity according to the community** | | N/A | N/A | N/A |

*Table 5.1: Capital Costs by BRT Component in Three Different Deployment Phases (continued)*

| Intelligent Transportation System | | PHASE 1 LIMITED | PHASE 2 MODERATE | PHASE 3 AGGRESSIVE |
|---|---|---|---|---|
| Automatic vehicle location –AVL (2002) | | | $16-468 Thousand/mile | $34-1,800 Thousand/mile |
| Close circuit cameras | | | | N/A |
| Passenger information system | | | $2,000-7,000 per sign | $2,000-7,000 per sign |
| On-board real-time passenger information system | | | | $2,000-7,000 per vehicle |
| Transit signal priority (2007) | | $2,500 -8,000 per intersection | $15,000 per intersection | $20,000-35,000 per intersection |
| Collision warning | | | | N/A |
| Precision docking | | | | N/A |
| Lane assist system (LAN) | | | | $11,500-134,000 per vehicle |
| Automatic steering-guidance system | | | | $70,000 per mile |
| Automatic speed and spacing control system | | | | N/A |
| Voice and video monitoring | | | | $4,000-5,000 per system |
| Signal coordination | | N/A | N/A | N/A |
| Fare collection | | | | |
| Proof-of-payment or pre-board fare | | N/A | N/A | N/A |
| Cash payment | | N/A | | |
| Smart cards | | | N/A | N/A |
| Magnetic strip cards | | | $15,000 per vehicle<br>$0.01-0.30 per card | |
| Service and operation | | | | |
| Large route coverage | | | | N/A |
| High service frequency | | | N/A | N/A |
| Feeders system | | | | N/A |
| Reduced number of stations | | N/A | N/A | N/A |
| On-time performance monitoring | | | | N/A |
| Multiple routes | | | N/A | N/A |
| Route length extension | | | N/A | N/A |
| Marketing identity | | N/A | N/A | N/A |

It can be observed from Table 5.1 that each element belongs to one or more deployment phases. The selection was made based on the evaluation of existing BRT systems in the U.S. For instance, the first group of elements (running ways) was divided into four different stages. Mixed flow and contra flow lanes correspond to the limited phase (initial), while a more advanced phase includes the use of dedicated (moderate) or, as in the case of aggressive phase, the most advance feature: grade separated/exclusive way.

Similarly, the BRT stations are generally more advanced that those normally used in regular bus transit routes. They can combine state of the art passenger information technology, with the comfort and convenience of rail stations, along with improved safety and fare collection systems (Wright 2004). Their design, type, platform usage, and capability could represent an improvement in the overall system performance. In this case, the research team considered enhancement of stations and intermodal transfer facilities as elements that are applicable to any of first two phases. Because the aggressive phase theoretically implies the BRT best practices, the use of a complete set of amenities is recommended in this deployment phase. The use of level platforms and automatic passenger counters were considered part of the advance phase given the fact that they represent a more contemporary and attractive image to the users similar to a rail station (Kittelson & Associates 2007).

Regarding the vehicle selection, the standard diesel bus of both 40- and 60-feet has been commonly implemented for BRT operations. However, there is a trend toward innovation and originality in vehicle design in recent years. For instance, full BRT systems at the aggressive phase seek the acceptance of BRT users and non-users using clean propulsion systems, diesel/CNG/gasoline, electric hybrids; compressed natural gas [CNG] fueled spark ignition engines, dual-modes (diesel-electric) convenient for tunnels and open spaces, wider doors, precision docking, unique and distinctive vehicles, and any other feature that fulfill the passenger's comfort and make the trip an extraordinary experience.

Intelligent Transportation Systems (ITS) technology in BRT begin with those that are operations-oriented such as fleet management, including automatic vehicle location (AVL) systems, automatic passenger counters, and surveillance systems through the use of remote sensing and close circuit TV.

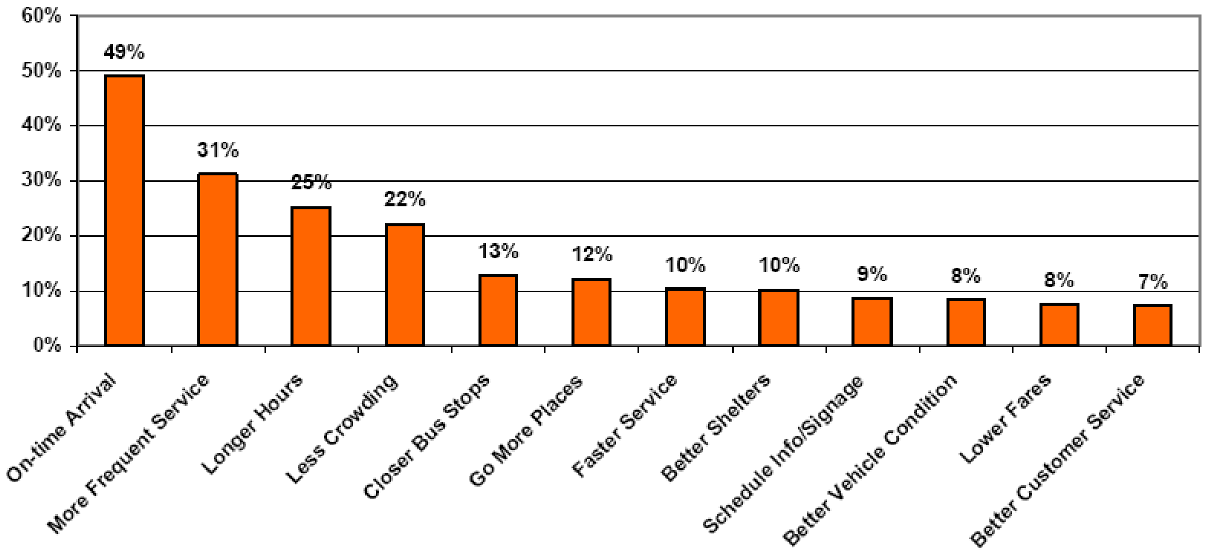
Another type of ITS technology is applicable in vehicle performance such as transit signal priority systems, collision warning systems precision docking, automatic steering control systems, and automatic speed and spacing control systems. The third group of this technology is more passenger-oriented; this includes electronic fare collection, real-time passenger information systems, and safety and security technologies (silent alarms and voice and video monitoring) (Wright 2004). ITS is by nature an advance element in vehicles, stops, and stations; therefore, its application is integrated within the moderate and aggressive phase (see ITS section in Table 5.1).

Fare collection methods vary by type of location. The preferred system will be the one that better adapts to the customer habits and customs. Methods vary from the basic off-board proof-of-payment at the limited phase to on-board transactions such as cash payment, smart cards, or magnetic stripe cards at the aggressive phase (Wright 2004).

The last group of BRT elements in the table corresponds to the service and operations plan. Marketing identity and a reduced number of stops are an excellent strategy for the limited deployment phase. These options can attract ridership and reduce delay respectively. On the other hand, due to the necessary investment in technology and operating costs, a large route coverage, high frequency, on-time monitoring system, and feeder fleets are elements that are more likely to be implemented in an aggressive phase.

An important process in the selection of elements to be considered for deployment phase is the set of improvements based on surveys. Users and non-users can express their preferences on different BRT characteristic and indirectly state the group of elements that might increase their attraction toward BRT usage. As an example, interviews among Washington D.C. citizens (bus riders and non-riders) show that the most important feature of a bus system should be reliably and high frequency (Kittelson & Associates 2007).

Figure 5.1 shows the preferred attributes of bus service in D.C. This type of survey can guide planners to a better understanding of ridership expectations facilitating the decision of priority bus elements.

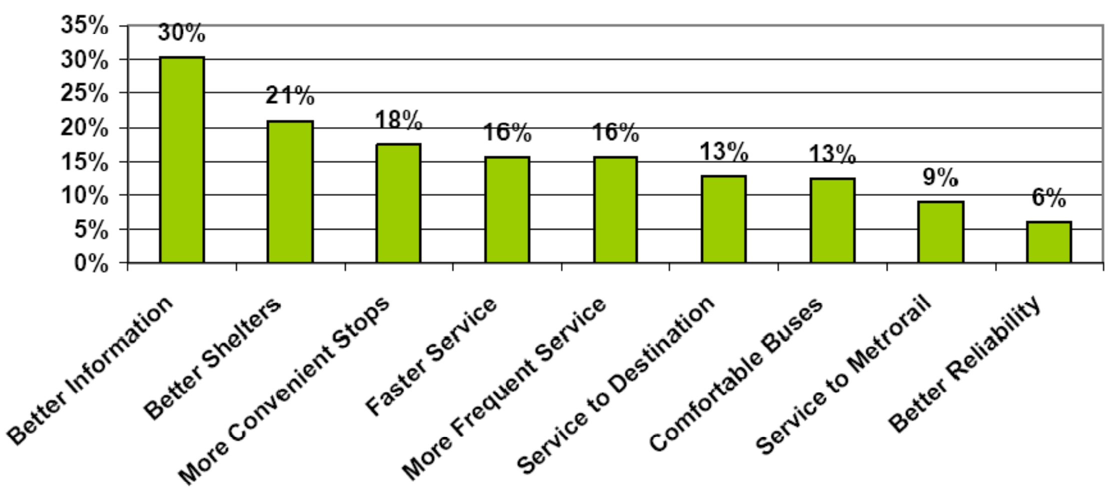



*Source: TCRP Report 118 (Kittelson & Associates 2007)*

*Figure 5.1: Results from the WMATA regional bus study (riders)*

The Washington D.C. Metropolitan Area Transit Administration (WMATA) also focused on a vital sector of the population: bus non-riders. It is significantly important to consider the desired service improvements that potential customers (non-riders) are expecting from bus/BRT systems. These improvements play a critical role in the user's mode selection or what is known in terms of transportation planning as the modal choice.

Figure 5.2 shows the preferred attributes obtained from the WMATA survey among the non-rider population sector.




*Source: TCRP Report 118 (Kittelson & Associates 2007)*

*Figure 5.2: Results from the WMATA regional bus study (non-riders)*

Moreover, some studies have demonstrated that the level of attraction of BRT systems is strongly correlated to the level of improvement on the systems. As an example, Ben-Akiva and Morikawa (2002) found that when quantifiable, BRT characteristics remain equal, riders show no interest in the systems, while Currie (2004) agreed that a BRT system is able to generate ridership equal to rail if the trip attributes of BRT and rail are the same. These examples imply that amenities advantages in BRT systems attract ridership (users or non-users of BRT). This information is very useful at initial stages (limited and moderate phases) to determine the set of improvements to be developed from existing conditions.

## 5.3 Capital Costs by BRT Component

The overall available resources for capital, operating, and maintenance requirements are essential (Kittelson & Associates 2007). Available funding for BRT can largely influence the set of BRT features in any of the deployment phases. For instance, in places where funding is limited, BRT may have to operate on city streets rather than on off-street busways (Kittelson & Associates 2007). Thus, in limited-phase systems, existing vehicles may possibly need to be used at the initial stage with some additional enhancements such as some distinctive colors.

Table 5.2 shows the allocation of capital costs according to information of existing and under-construction BRT systems. The first row shows the range of capital costs taking the maximum and minimum value observed from the different systems.

## Table 5.2: Allocation of Capital Costs by BRT Component (Wright 2004)

| **BRT System** ***Deployment Phase*** | **Total Development Costs (millions)** | **Land Acquisition** | **Running way** | **Stations** | **Buses** | **ITS/TSP** | **Design/ Adminis tration/ Super-Vision** | **Other** |
|---|---|---|---|---|---|---|---|---|
| **Range of Capital Cost** | **$3.20 - $$299.10** | **0% - 14.50%** | **0%- 73.9%** | **0.9% - 48.8%** | **0% - 63.0%** | **AVL: 1.5% - 6.3% TSP: 1.3% - 55.0%** | **6.5% - 26.10%** | **—** |
| Boston *Limited/Moderated* | 37.8 | — | 60.80% | 9.60% | 27.60% | 2.0% CAD/AVL | [2] | — |
| Cleveland *Limited* | 168.4 | 8.10% | 26.30% | 10.80% | 12.80% | 5.1% TSP | 26.10% | 10.8% [3] |
| Hartford *Limited* | 145.0 | 8.30% | 37.10% | 19.70% | 7.70% | 0.7% ITS | 22.60% | 3.9% [6] |
| Las Vegas *Moderate* | 19.2 | 0% | — | 23.40% | 63.00% | 1.5% AVL; 1.3% TSP | [2] | 10.5% [5] |
| Los Angeles : Wilshire-Whittier *Limited* | 5.0 | 0% | 0% | 48.70% | 0% | 51.3% TSP | [2] | — |
| Los Angeles: Ventura *Limited* | 3.2 | 0% | 0% | 48.80% | 0% | 51.2% TSP | [2] | — |
| Los Angeles: Phase 2 *Moderate* | 101.9 | 0% | 0% | 42.90% | 0.30% | 55.0% TSP | [2] | 1.8% operations -support |
| Ottawa *Moderate* | 324.0 | — | 69.00% | 27.60% | — | — | [2] | 3.4% park-and-ride |
| Pittsburgh: East Busway Extension *Limited* | 68.8 | 14.50% | $44.20 | 2.90% | 0% | — | 24.40% | 13.4% [6] |
| Pittsburgh: West Busway (PAT) *Moderate* | 299.1 | 8.80% | 73.90% | 0.90% | 0% | — | [2] | 16.4% [7] |
| Vancouver, BC: 98B (from IBI Group) *Limited/Moderate* | 41.3 | 8.90% | 22.8% [1] | 6.30% | 33.40% | 1.0% ITS; 3.9% TSP; 6.3% AVL | 6.50% | 10.9% garage |

[1] Includes 3.9% for landscaping
[2] Design/administration/supervision costs no itemized in source data
[3] 1.0% for a maintenance facility, 0.6% for art, and 9.2% for contingencies
[4] 0.6% for traffic signals, 1.0% for railroad crossings, and 2.3% for a multi-use trail
[5] 0.6% for dynamic message signs and 9.9% for ticket vending machines
[6] 7.3% for a linear park and 6.1% for a park-and-ride lot
[7] Wabash HOV facility
NOTE: CAD = computer-assisted dispatch

## 5.4 Summary

This chapter summarizes the importance of implementing different deployment phases in the BRT planning process. The research team proposes three different deployment phases. Each phase has a different level of BRT configurations (set of attributes) that corresponds to the degree of advancement in the BRT life-time.

The first proposed phase, called “limited,” includes basic elements that were identifying as part of the primary phase of construction in a BRT project. The second, cited in this document as “moderate,” consists of a more complete group of characteristics that have specifically demonstrated an improvement in the system level of service. Finally the third phase, called “aggressive,” groups those key characteristics that provide high quality service or excellent performance in terms of operation and comfort of the entire system. Additionally, this chapter analyzed other factors that might influence the BRT planning and decision making process. Factors such as the level of funding, capital and operating costs, and public preferences (riders and non riders) should be taken into account while selecting BRT attributes.

# Chapter 6. Framework for Determining Optimal BRT Deployment Phases

Based upon the proposed implementation phases described in Chapter 5, the objective of this chapter is to develop a deployment framework consisting of both quantitative and qualitative analysis. To achieve this objective, a simplified mathematical method using the System Dynamics (SD) approach will be used. The SD theory is useful for this framework because there are several variables interacting with each other and the nature of any public transportation model is dynamically changing over time (Wang et al. 2008) (Sterman 2000). Once again the BRT elements play a substantial role in each stage as the BRT system can be fully or partially implemented over time.

## 6.1 Background

During the BRT system planning process, many operations and infrastructure design approaches are involved. In some cases, companies that are responsible for planning and implementation of these types of systems do not fully consider integrating an optimal set of elements at each phase (Kittelson & Associates 2007). Consequently, those systems may not be the most cost effective for maximizing the benefits to both the transit line and the transit ridership. Moreover, some agencies do not have enough knowledge about BRT systems and they propose implementing elements that are more likely to be used in traditional transit or rail systems. Therefore, it is extremely important that the definitions of each design alternative, deployment strategies, system-design options, and project elements are chosen following the standard guidelines and practices that characterize a BRT system (Wright et al. 2007).

## 6.2 Systems Dynamics Theory

The System Dynamics Society describes system dynamics as a "*methodology for studying and managing complex feedback systems, such as one finds in business and other social systems.*" This methodology has been used to address practically every sort of feedback system (System Dynamics Society 2008). A feedback is a situation in which one variable affects the other and vice versa. If a system is described by two variables "X" and "Y", feedback then refers to the situation of variable "X" affecting variable "Y" and "Y" sequentially affecting "X" through a chain of causes and effects. Therefore, neither X nor Y should be independently considered, but rather the link between Y and X should be analyzed as a whole system (a feedback system) in order to achieve correct results (System Dynamics Society 2008).

Usually the analysis of SD problems requires the interaction of several variables forming loops under different parameters. For this reason, the usage of computer software becomes necessary when the objective is to save time in the calculation and analysis process.

Currently, there are four software programs that can facilitate the building and use of System Dynamics modeling: Dynamo, iThink/Stella, PowerSim, and Vensim. Additionally, there are several other modeling and simulation environments that can be also helpful for building system dynamics models such as AnyLogic, Berkely Madonna, Exposé, MyStrategy, and Simile. Although it is not practical, it is important to notice that a good system dynamics model can also be achieved by using different tools, including spreadsheets and programming languages (VENSIM 2008).

### 6.2.1 Structure, Variables and Equations in SD

A system dynamic model has two main characteristics: it can be dynamically simulated and it contains feedback structures (Richardson and Pugh 1981). Feedback structures may be defined as the transmission and return of information with special emphasis on the "returned information" because it will change the system behavior (Haghani et al. 2002). As a result, a feedback loop will be a feedback structure involving two or more variables. These feedback loops can be either "positive" (self-reinforcing) or "negative" (equilibrating or self-correcting) (Sterman 2000).

Any SD approach should deal with dynamic behavior (variable values that change over time), time horizon (length of the simulated time, and reference mode (general patterns of the system states over time). Additionally, SD modeling variables are commonly of three different types: Level, Rate, or Auxiliary. A "level" variable accumulates or integrates a certain flow over consecutive time periods. The "rate" variables represent such flow during a given time period and finally the "auxiliary" variables are used to identify or clarify rate variables (Haghani et al. 2002). When modeling or sketching dynamic systems, variables are commonly linked using arrows. These arrows represent the correlation between variables and the arrow's head symbolizes the influence that one variable has upon the other. If the arrow includes the symbol "=" in the middle, then the influence will not be felt immediately (i.e., a time period will delay the "cause and effect" relationship) (Ventana Systems Inc. 2008).

All variables included in an SD model will be expressed by equations. These equations can be simple arithmetic differences as in "level" variables, algebraic ones as in "rate" and "auxiliary" variables, or even more complex structures as in conditional relationships and/or special scripts. A feedback structure is defined as the transmission and return of information, but the emphasis is on the return (Haghani et al. 2002).

### 6.2.2 Overview of System Dynamics in Transportation Systems

Some efforts to model transportation systems using SD have been made. A study by Emmi and Forster (Emmi and Foster 2003) focused on the growth dynamics of North American metropolitan regions based on roadway expansion. This study used STELLA software to develop the model structure. Other studies include the analysis of urban transportation systems by Wang, Lu, and Pei (Wang et al. 2008). This paper presents a system dynamics model of an urban transportation system and its application. Using the Vensim PLE software, the authors developed and applied an SD model simulating different policy scenarios.

An SD approach to land use/transportation system performance is the topic of two papers by Haghani, Lee, and Byun (Haghani et al. 2002). The paper describes an SD approach to model simultaneous land use/transportation interactions based on casualty functions and feedback loops between a large number of physical, socioeconomic and policy variables. The study is divided in two sections: section I describes the methodology used to develop the model and sub-models, and section II deals with the application of such models, comprehensive analysis, and final results.

The research work entitled "Land Use Changes in Ciudad Juarez, Chihuahua: A System Dynamic Model" was also reviewed (Pena and Fuentes 2007). The study presents a simulation using an SD model dealing with demographic and urban growth that involves variables from both sides of the U.S.-Mexico border. The model structure was implemented using the STELLA software.

Finally, a very helpful source for building SD models and understanding SD theory is the book entitled "Business Dynamics: System Thinking and Modeling for a Complex World" written by John D. Sterman (Sterman 2000). This book introduces readers to SD modeling for analysis of policy and strategy, presenting a perspective and set of conceptual tools to understand the structure and dynamics of complex systems.

#### 6.2.3 The SD Model Description for BRT

As stated in Chapter 5, the BRT deployment phases involve a set of elements that will gradually influence and change the BRT system. In addition, BRT systems change over time making their variable interconnection "dynamic" with respect to time. This chapter covers the analysis of the BRT system and subsystems, taking into account changes that might occur when a variable is affected by exogenous or endogenous factors.

The model involves the BRT elements previously described in Chapter 1 as well as the relationship between those elements and the expected benefit or detriment.

The general model has the purpose of presenting an overall view of the system without a detailed explanation. Sub-models on the other hand are built with a higher level of detail and both exogenous and endogenous variables.

Figure 6.1 presents a general BRT system model approach including its main elements as sub-models (in boxes) and some other important variables (i.e., ridership and operating speed). This general BRT model structure is based on a key component in any mass transit system: ridership. For total ridership estimation purposes three different sub-models are interconnected: the "Additional Ridership," the "Forecasted Ridership," and "Total Ridership." Basically, the "Total Ridership" sub-model feeds the rest of the sub-models and, simultaneously, all sub-models feed total ridership back through the "Additional Ridership" variable. At this level a detailed model configuration cannot be observed. However, the next section expands the sub-models to their completed form.

Users and decision makers should be aware that other variables may also be integrated to this general model. Nevertheless, all models are limited by the availability of data and quality of information. "*The number of variables that might affect a system vastly overwhelms the data available to rule out alternative theories and competing interpretations*" (Sterman 2000).

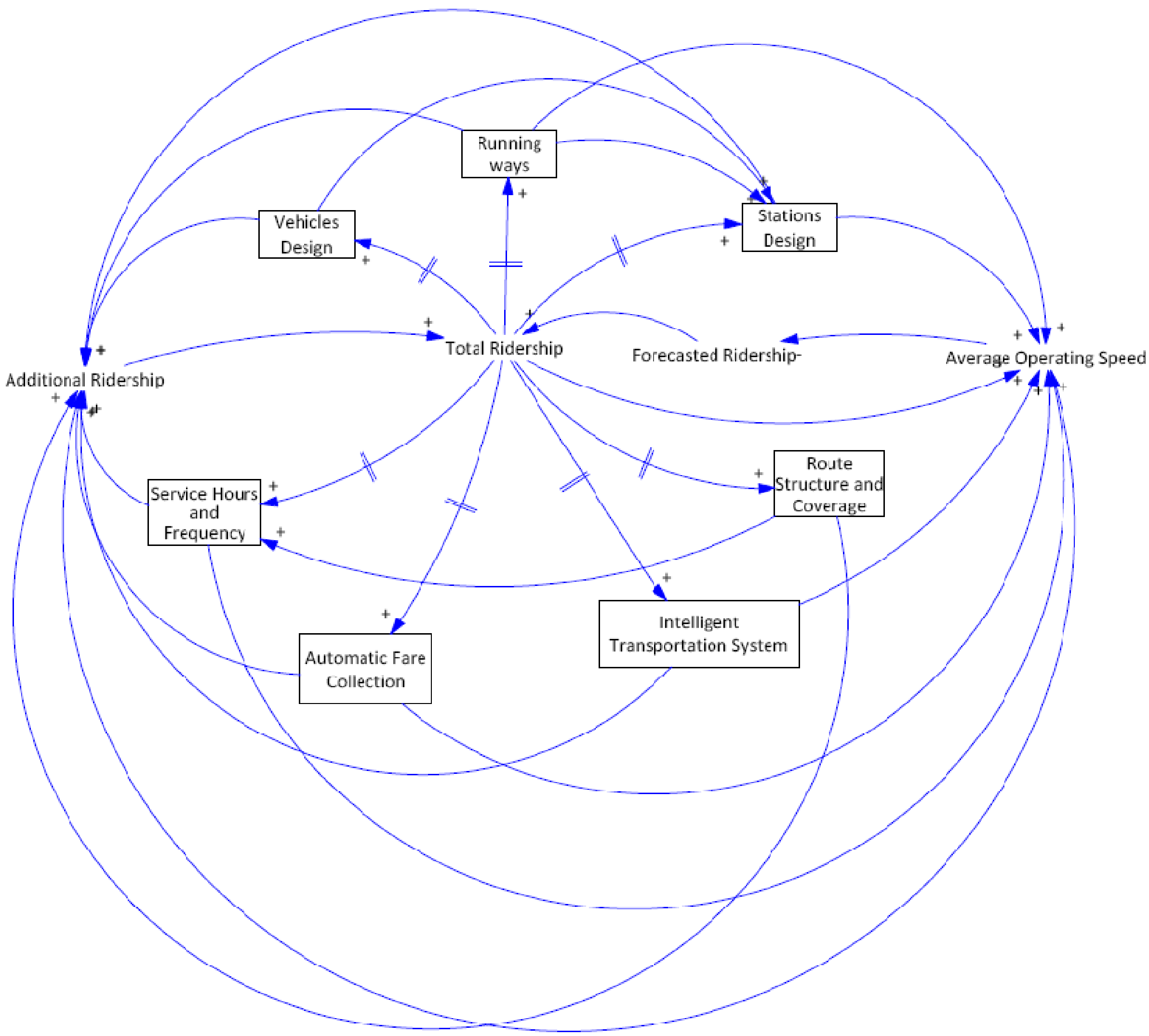



*Figure 6.1: General BRT Model*

### 6.2.4 Population Sub-Model

Construction of sub-models is a convenient technique for analysis, given that the sub-models are more detailed. This technique allows a better understanding of the system and links the key variables on every subsystem (Grant et al. 1997).

After a detailed analysis, the research team identified population growth as the most important variable to be considered in the BRT model. Public transportation ridership is directly attached to corridor demographic variables and therefore will be the first model to be built in the system.

In order to construct the population model, a logic structure from previous researchers was used (Sterman 2000) (Pena and Fuentes 2007) (Ventana Systems Inc. 2008) (Wang et al. 2008). The difference between this and previous models is that while the entire local population growth rates remain, the total population of interest is limited to the one along the corridor.

This sub-model represents the total population along the corridor and is affected by the number of new inhabitants (net migration and new births) as well as the number of deaths. The model functions as a stock-flow relationship. The total population along the corridor may increase or decrease depending on the inflow and outflow. Simultaneously, the three above mentioned variables are affected by rate-variables that regulate the growth and final output. The signs represent the relationship between the variables; for instance, the positive sign linking “Birth Rate” and “Births” indicates that as the birth rate increases the number of new births will also increase as indicated in Figure 6.2.

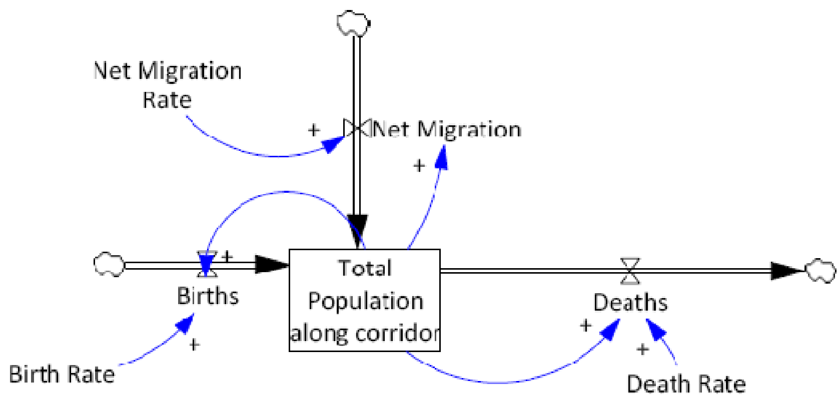



*Figure 6.2: Population Model*

After modeling the population along the corridor, the next step is to add a different sub-model for the behavior of the potential ridership and the total ridership along that corridor. This was done with a simple mathematical formulation involving the “BRT Share” variable (percentage of trips that use transit as a transportation mode) and the “Potential Ridership” that was derived from the total population level.

Figure 6.3 shows the relationship of these additional variables. As one can observe, the “Potential Ridership” variable will increase if the variable “Total Population along Corridor” increases.

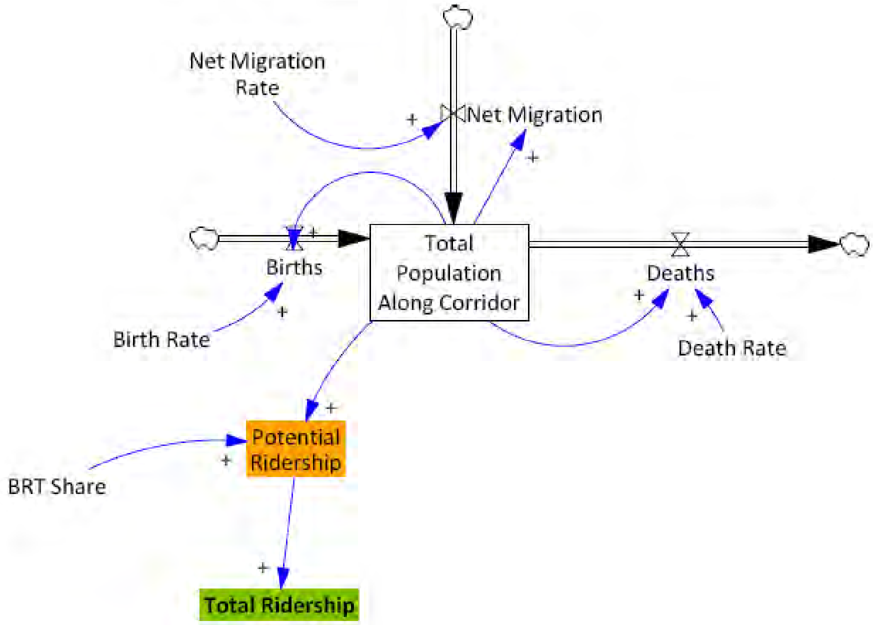



*Figure 6.3: Total Ridership Estimation*

As stated in Chapter 2, one of the outcomes after BRT implementation is ridership attraction. The level of attraction will depend on the combination of BRT elements as well as the corridor characteristics. According to Report 118 (Kittelson & Associates 2007), the following BRT components were identified as the main ridership attractors. Notice that the sum of all components (100% in Table 6.1) produces a maximum 25% ridership incremental increase (i.e., a sum of 100% will represent a 25% real increment).

**Table 6.1: Additional Ridership Impacts**

| | COMPONENT | PERCENTAGE |
|---|---|---|
| 1. | Running Ways (not additive) | 20 |
| | Grade-separated busways (special right-of-way) | (20) |
| | At-grade busways (special) | (15) |
| | Median arterial busways | (10) |
| | All-day bus lanes (specially delineated) | (5) |
| | Peak-hour bus lanes | -- |
| | Mixed traffic | -- |
| 2. | Stations (additive) | 15 |
| | Conventional shelter | -- |
| | Unique/attractively designed shelter | 2 |
| | Illumination | 2 |
| | Telephones/security phones | 3 |
| | Climate-controlled waiting area | 3 |
| | Passenger amenities | 3 |
| | Passenger services | 2 |
| 3. | Vehicles (additive) | 15 |
| | Conventional vehicles | -- |
| | Uniquely designed vehicles (external) | 5 |
| | Air conditioning | -- |
| | Wide multi-door configuration | 5 |
| | Level boarding (low-floor or high platform) | 5 |
| 4. | Service Patterns (additive) | 15 |
| | All-day service span | 4 |
| | High-frequency service (10 min or less) | 4 |
| | Clear, simple, service pattern | 4 |
| | Off-vehicle fare collection | 3 |
| 5. | ITS Applications (selective additive) | 10 |
| | Passenger information at stops | 7 |
| | Passenger information on vehicles | 3 |
| 6. | BRT Branding (additive) | 10 |
| | Vehicles & stations | 7 |
| | Brochures/schedules | 3 |
| | Subtotal (Maximum of 85) | 85 |
| 7. | Synergy (applies only to at least 60 points) | 15 |
| | ***Total*** | ***100*** |

NOTE 1: Applies to a maximum of 10-min. travel time bias constant (e.g., percentage of 10 min.)
NOTE 2: Applies to a 25% gain in ridership beyond that obtained by travel time and service frequency elasticities

*Source: Estimated by research team of Report 118*

Additional ridership is added to the model using seven auxiliary variables that directly represent the BRT level of implementation. "Branding" accounts for the uniqueness of the stations and vehicles; "Shelter and Stations" accounts for the physical design of boarding and alighting places; "Running ways" considers the bus guideway; "ITS applications" deals with any type of transit technology; “Service Patterns” takes into account the line coverage, frequency and hours of service. Two additional auxiliary variables are the “Fare Collection Method” and “Vehicle Design.” These BRT elements are affected by a variable called “Initial Phase.” This variable controls the deployment phase to be analyzed once the simulation starts. Figure 6.4 shows the interconnectivity of all the above mentioned variables with the population and ridership sub-models.

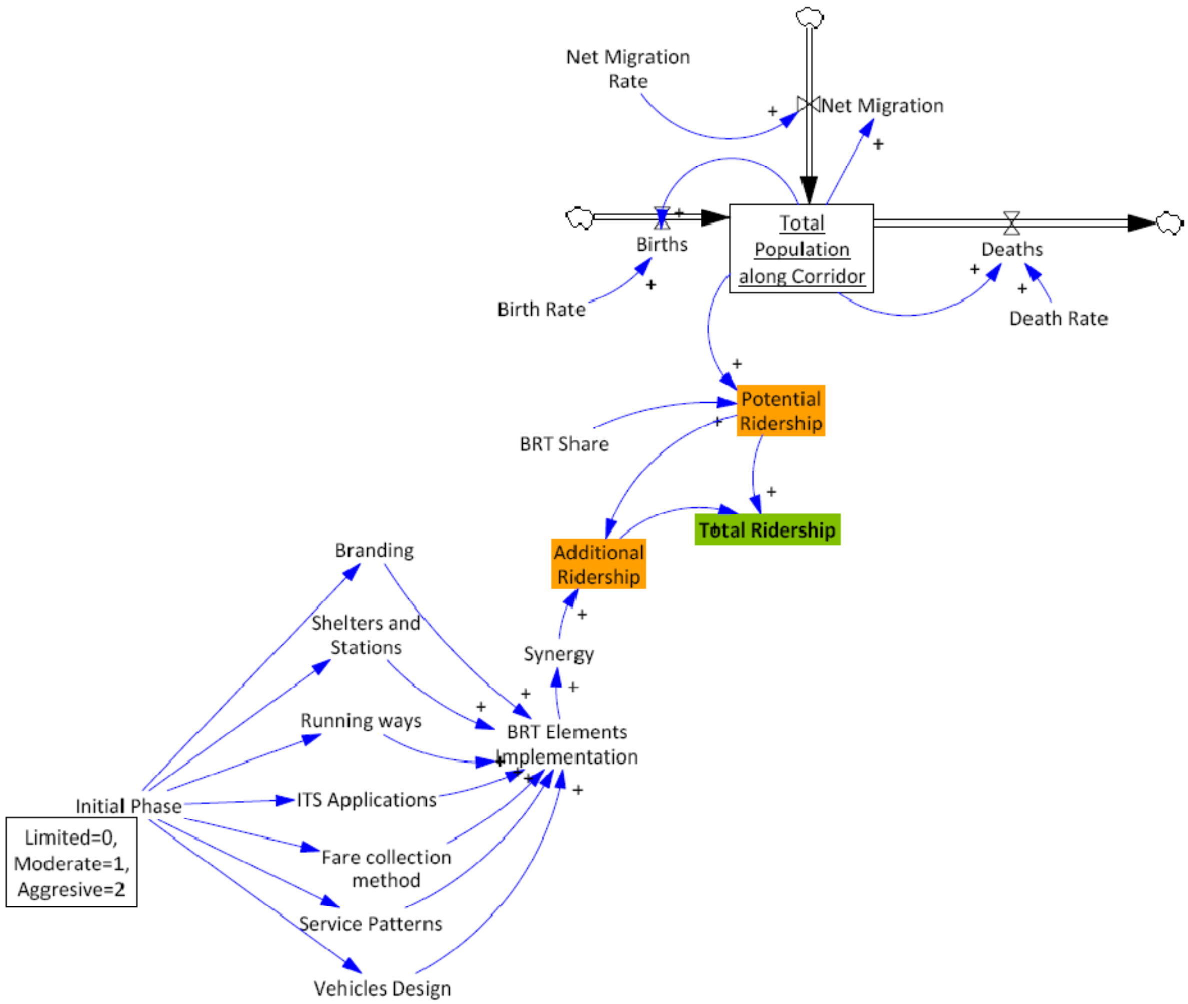



*Figure 6.4: Additional Ridership Estimation*

Finally, a capacity sub-model is added to the structure. Its outcome represents the forecasted number of vehicles or transit units the line may need through the years (“Fleet Size”), as well as the recommended headway for an optimal line operation. For modeling purposes, the “Total Ridership” was converted to “Design Hour Volume” and the “Vehicle Capacity” variable was calculated upon the initial phase the user may select. The forecasted outcome variables “Headway” and “Fleet Size” were a product of the estimated transit units frequency along the corridor (Frequency) and the roundtrip bus travel time (T) obtained by surveys. All relationships were calculated following the recommendations given by the Transit Capacity and Quality of Service Manual (TCQSM) (Kittelson & Associates et al. 2003) and the first chapter of the book

"Urban Transit: Operation, Planning, and Economics" (Vuchic 2005). The complete model structure is shown in Figure 6.5.

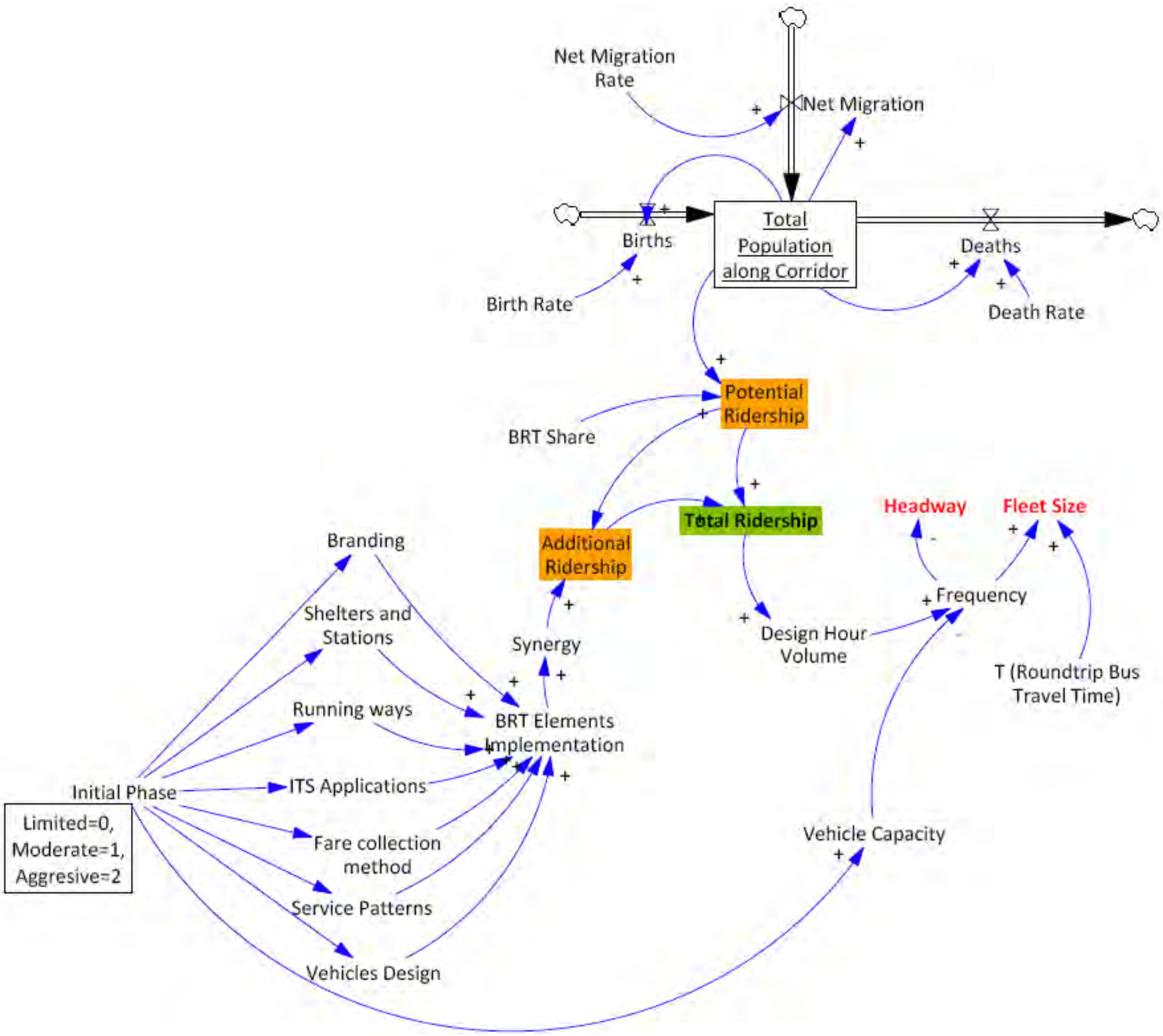



*Figure 6.5: Complete Model Structure*

## 6.3 Mesa Corridor Case Study

In order to test the efficiency of the SD model, an example was selected to demonstrate the application and validation. The city of El Paso, Texas—specifically, the N Mesa Street Corridor—served as the sample for the model evaluation.

Demographic data was obtained by examining the local time series from the Border Region Modeling Project (Fullerton 2008). This data set provided by the University of Texas at El Paso is perhaps the most important and reliable data source for demographic and socioeconomic analysis in the El Paso del Norte Region. Alternatively, the potential ridership data were estimated using Geographic Information Systems (GIS) techniques and following a service coverage method included in the TCQSM as well as various geographic data sets from the El Paso Metropolitan Planning Organization (El Paso MPO 2008). Ridership and transit share values along the corridor were estimated using 2007 transit counts provided by the El Paso transit agency "Sun Metro."

Once all the information was loaded into the Vensim SD simulation program, a unit checking procedure was performed to avoid inconsistent or unrealistic results. As a final step, three lookup simulations were made for the three deployment phases (limited, moderate, and aggressive) proposed by the research team in Chapter 5 of this report.

## 6.4 Analysis of Results

One of the most important variables and perhaps the main feeder for these model simulations is the total number of riders using the BRT system. The simulation results in Figure 6.6 show that the behavior of the three simulated phases is similar. The major differences among them are due to the additional ridership. For instance, if the BRT system begins operations with very basic components (limited phase), the total ridership the system is able to attract is estimated in 42,196 passengers per month for the base-year (2007) and 69,959 passengers per month by 2035.

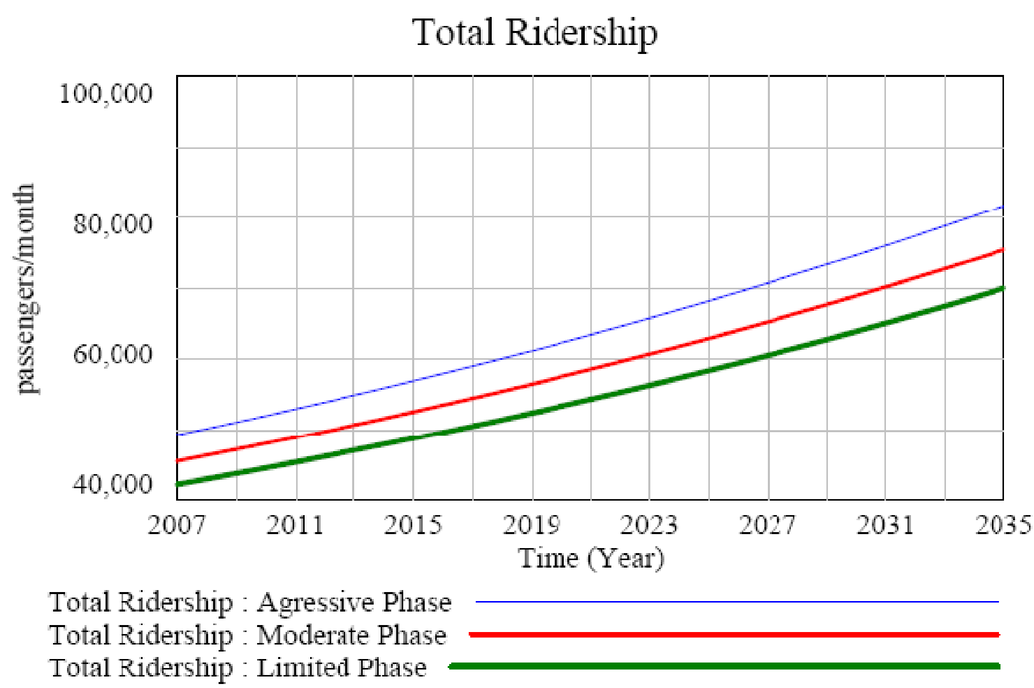



*Figure 6.6: Total BRT Ridership Estimations 2007-2035*

For the service headway, the simulation results show a logical reduction at every time step (year), with the same vehicle type and vehicle capacity. Because the Aggressive phase includes vehicles with higher passenger capacity, the headway at the base-year was estimated to be near 20 minutes. The moderate and limited phases have estimated headway values of 16 and 14 minutes respectively. By the year 2035, the simulations indicate that the recommended headway would be 12 minutes for the aggressive phase, 10 minutes for the moderate, and 8 minutes for the limited phase. Apparently, headways tend to converge at some point in the future as the difference among phases is higher for the base-year than for the horizon year 2035. Figure 6.7 illustrates this difference for the three deployment phases.

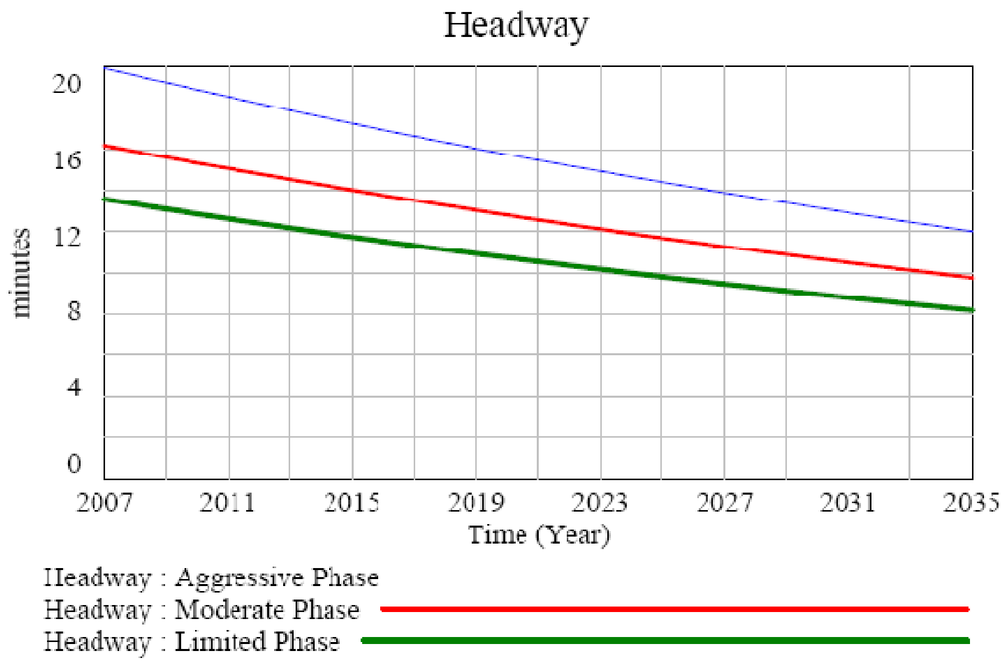



*Figure 6.7: Forecasted Headway 2007-2035*

To conclude with the analysis of results, the number of vehicles or transit units (TU) that might be needed for the BRT line was forecasted. According to the model simulation, the estimated numbers of vehicles needed for an optimal line service in the base-year are four, five, and six for the Limited, Moderate and Aggressive phases respectively. By 2035 these numbers may increase to five, six, and seven units in that same order (Figure 6.8).

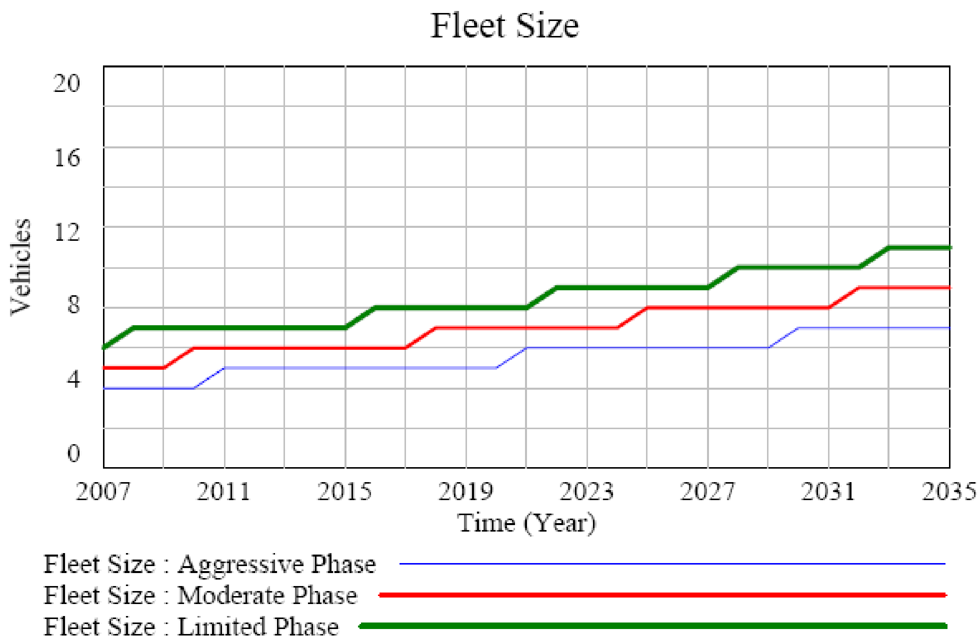



*Figure 6.8: Forecasted Fleet Size*

Again, the average number of passengers a vehicle can transport (bus capacity) plays a key role in the fleet size variations. As an example, the fleet size in the aggressive deployment phase remains constant for longer periods (from years 2011 to 2020 and 2021 to 2029), while the limited phase (lower vehicle capacity) shows increases in shorter periods of time (e.g., 2022 to 2027 and 2028 to 2032). This behavior clearly indicates the advantage of having a higher capacity vehicle running along the corridor. Note that the number of auxiliary vehicles (extra vehicles available at transit depot) was not included in this analysis.

## 6.5 Summary

A system dynamics (SD) modeling approach has been described and demonstrated as a means of providing a framework for BRT phased implementation. The SD model has been applied to an El Paso-based Mesa Corridor example.

# Chapter 7. Developing BRT Architecture

## 7.1 Physical Layout of BRT

The physical layout is the initial stage in BRT development, which basically involves design and planning of the running ways. The running ways, which range from exclusive busways and bus terminals to regular street lanes, are crucial to the quality of service of a BRT system. The type of running ways, together with BRT vehicles and BRT stations, also form the image and identity of a BRT system.

A wide variety of bus running ways is currently in operation in the United States, normally classified into three categories based on the type of the facility (Levinson et al. 2003).

- Busways
  - Bus tunnel
  - Grade-separated busway
  - At-grade busway
- Freeways
  - Concurrent flow lanes
  - Contra flow lanes
  - Bus only or priority ramps
- Arterial Streets
  - Median arterial busway
  - Curb bus lanes
  - Dual curb lanes
  - Interior bus lanes
  - Median bus lanes
  - Contra flow bus lanes
  - Bus only street
  - Mixed traffic flow
  - Queue bypass

The exclusive BRT running ways are designed to offer preferential services to buses by providing segregated bus lanes on freeways and arterial streets. The mixed running ways, on the other hand, either designate one or more lanes to buses during a specific time period (e.g., during peak hours) or let buses travel on the general purpose lanes and gives them prioritized treatments at intersections. While the exclusive bus running ways may attain highest level of service for buses, the cost for construction and maintenance is also a lot higher than mixed running ways.

The selection of a proper type of bus running way is dependent on a variety of issues including the desired quality of service of the BRT system, the cost for construction and maintenance, the ease of upgrading existing roadways to BRT-friendly running ways, and the potential impacts to general traffic and pedestrians. In the following section, a brief review of existing busways and the associated construction costs is provided, followed by an analysis from the prospective of the ease of upgrading and/or constructability of these busways.

### 7.1.1 Bus Tunnels

Bus tunnels are the exclusive busways used by rapid buses only and are recommended if the busway has to be routed in hilly and mountainous terrains, as in Seattle, WA (Figure 7.1). There is another proposed tunnel construction in Boston, which is scheduled to be completed by 2011.

*Figure 7.1: The Bus Tunnel in Seattle (1)*

As per the TCRP report on BRT Practitioner's Guide (Kittelson & Associates 2007), the cost for a bus tunnel ranges from $60–105 million per lane mile.

### 7.1.2 Grade-Separated Runways

Grade-separated runways are the busways that are separated from the roadways for regular traffic to attain the maximum possible speed for BRT vehicles (Figure 7.2). Being completely segregated from the traffic at intersections and highway interchanges, these running ways offer fast and safe service with enhanced reliability.

*Figure 7.2: Grade-separated Busway, Pittsburgh (2)*

According to *CBRT for Decision Making* (Diaz et al. 2004), the cost of grade-separated transit-ways ranges from $12–105 million per lane mile.

### 7.1.3 At-Grade Busways

Unlike the grade-separated runways, the at-grade busways run at the same grade but are physically separated from the general traffic by barriers or pavement markings (Figure 7.3). BRT vehicles on at-grade busways interact with the cross-street traffic only at intersections.

*Figure 7.3: At-grade Busway, Pittsburgh (Diaz et al. 2004)*

As per *CBRT for Decision Making*, the cost of at-grade busways ranges from $6.5–10.2 million per lane mile (Diaz et al. 2004).

### 7.1.4 Concurrent Flow Lanes

Concurrent flow lanes are the BRT lanes that flow concurrent to the traffic, i.e., in the same traffic direction (Figures 7.4 and 7.5). Such lanes are either constructed on the curb as concurrent flow curb bus lanes or in the interior as concurrent flow interior bus lanes.

*Figure 7.4: Concurrent Flow Curb Bus Lane—Silver Line, Boston (Levinson et al. 2003)*

*Figure 7.5: Concurrent Flow Interior Bus Lane—Silver Line, Boston (Levinson et al. 2003)*

The concurrent flow curb and interior bus lanes have their own pros and cons and the selection of either depends upon the onsite preferences at a given location. For instance, the curb bus lane provides the advantage for passengers to load from the curb while the interior bus lane retains the curb parking.

### 7.1.5 Contra Flow Curb Bus Lanes

Contra flow curb bus lanes operate in the directions opposite to the traffic flow and are usually constructed on one-way streets (Figure 7.6). They may even be provided in the inner lanes when the curb lanes are to be used for other purposes.

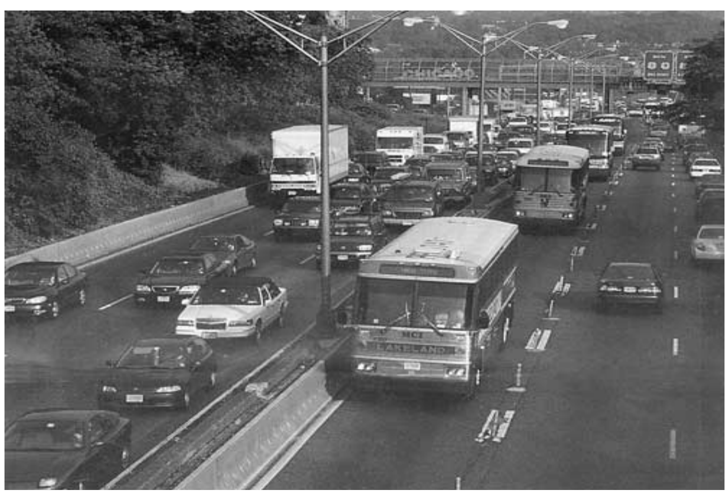


*Figure 7.6: Contra Flow Lane—Lincoln Tunnel, New Jersey (Levinson et al. 2003)*

### 7.1.6 Median Busways

BRT can also operate on median lanes along a roadway. This type of layout is physically separated from the adjacent traffic through separators such as barriers, but it can also be used by LRT (Light Rail Transit) and other buses (Figure 7.7). Additional lanes need to be provided at the bus stops on the medians so that the non-stopping buses are not blocked.

*Figure 7.7: Median Busway (Midgley 2004)*

### 7.1.7 Bus Streets

Bus streets are considered a cost-effective downtown distribution. They are recommended for narrow streets with high bus volumes and are used by buses only (BRT and other buses). A single lane in each direction can be used where the volume is lower than 60 peak hour buses each way. Passing lanes and dual lanes should be used in cases of higher bus volumes.

Table 7.1 categorizes the various BRT running ways in terms of the ease of constructability.

**Table 7.1: Classification of BRT Running Ways Based on Constructability**

| Degree of ease | Definition | Types of layout |
|---|---|---|
| Maximum ease of construction | This category identifies the BRT layout with maximum ease of construction i.e. requiring least BRT-specific construction while still maintaining its identity | a. Concurrent flow curb lanes<br>b. Mixed flow lanes with minor improvements such as bus bulbs and queue bypasses |
| Moderate ease of construction | This category identifies the layouts with moderate ease of construction and requiring slight BRT-specific constructions or modifications | a. Concurrent flow interior lanes<br>b. Dual curb lanes<br>c. Contra flow bus lanes |
| Least ease of construction | This category identifies the layouts with least construction ease, in other words, requiring BRT-specific construction for maximum speed and reliability | a. Grade separated running ways<br>b. Bus tunnels<br>c. Median busways<br>d. Bus only streets and bus malls |

## 7.2 Design of BRT-Friendly Streets

Converting a general purpose arterial street into a BRT-friendly facility will involve identifying a number of feasible options that are either used in some existing BRT systems or can be suitably employed with requisite changes in the running way layout considering its overall pros and cons.

### 7.2.1 Median BRT Lanes

*7.2.1.1 Two Way Left Turn Lane (TWLTL) as a Reversible BRT Lane*

One of the feasible options to make a street corridor BRT-friendly is to convert the Two Way Left Turn Lane (used for left turns in the center of the roadway envelope, as shown in Figure 7.8) into a BRT lane. Depending on the roadway conditions, this may involve widening the TWLTL lane to two BRT lanes or making the TWLTL lane a single BRT lane that is reversible for morning and afternoon peaks.

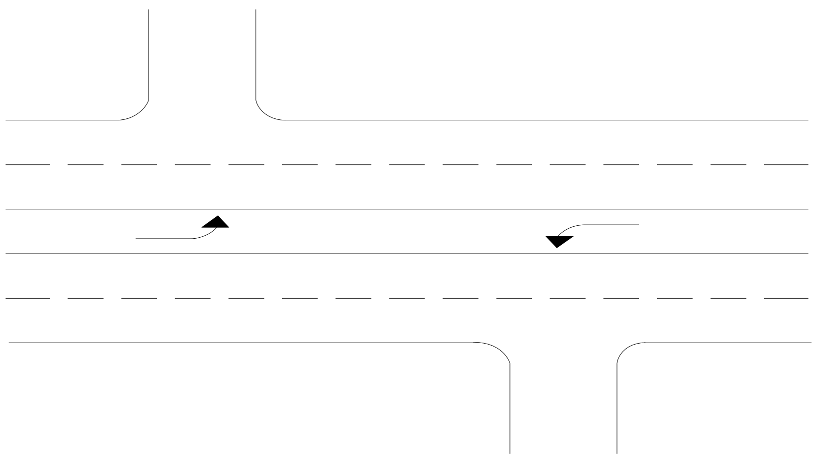
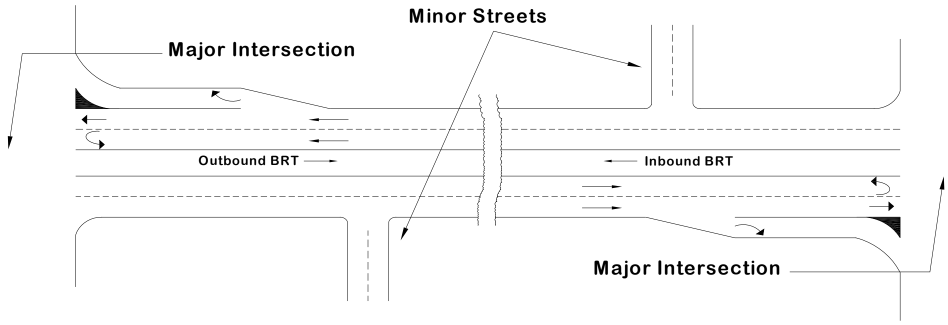
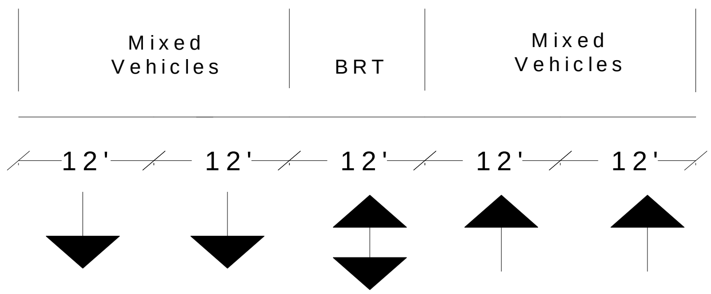


*Figure 7.8: A Typical Two Way Left Turn Lane*

Single lane BRT operation is very economical and space conservative. In the case of the single BRT lane, BRT buses are allowed to use the TWLTL lane during the morning and afternoon peak periods (e.g., 7:00–9:00 a.m. and 4:00–6:00 p.m.) for different directions. During this period the central left turn lane will only be used by buses and left turns will be prohibited on both major and minor streets. This can be enforced by various ways, such as placing warning signboards with timings along the route. The major intersections upstream and downstream of the reversible lane segment will need to be modified to adapt to this daily change in traffic management. The peak periods will have the TWLTL occupied by the buses, making a U-turn mandatory at the major intersections. Also, in the case of a 4-lane segment, the addition of an exclusive right-turn lane may be necessary. This is depicted in Figure 7.9.




**(a) Layout**




**(b) Lane Use Details**

*Figure 7.9: TWLTL Converted to Reversible BRT Lane*

Though reversible design is not popular with BRT systems, its application seems reasonable when conditions warrant its use and other options are not easy to implement. It should be noted that reversible lanes should be used with comprehensive network design to maintain the desired headway in both the inbound and outbound trips with requisite enforcement strategies for essential traffic safety. The roadway will need re-striping and additional control devices. For instance, the reversible lanes may need an additional signal for BRT at the intersection that would provide the right-of-way to buses during its peak periods and to other traffic for the rest of the day.

A single BRT lane can also be provided in a way that both the inbound and outbound buses are accommodated at the same time. In such a case, refuge areas need to be provided along the BRT route as illustrated in Figure 7.10. Managing such a facility will require a signaling system that can detect the presence of vehicles when the lane is occupied. Right-of-way can be provided through the signal to the directions with peak demands. Such a system is currently in operation in Eugene, Oregon, where the block signal system is used to manage the BRT traffic in both directions.

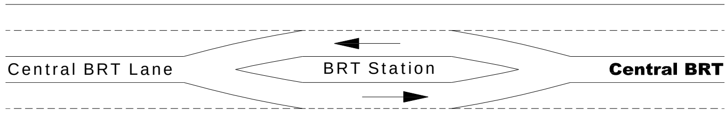



*Figure 7.10: Two-way accommodation for single lane BRT*

*7.2.1.2 TWLTL Widened for Two BRT Lanes*

The single TWLTL lane can also be converted into two BRT lanes by reducing the width of the adjacent travel lanes and sidewalks. According to the TxDOT Manual for Roadway Design (Texas Department of Transportation 2007), the widths of TWLTL lanes, general purpose lanes, and sidewalks are listed in Table 7.2.

**Table 7.2: Lane Widths**

| | |
|---|---|
| TWLTL | 12 ft–14 ft (12 ft min) |
| General purpose lanes | 11 ft for low speed urban streets<br>12ft for high speed freeways, rural arterials |
| Sidewalk widths | 5 ft min<br>6 ft if immediate to curb |

The minimum width required for a high speed BRT operation is 11 ft according to a TCRP report (Kittelson & Associates 2007). If the adjacent lanes are assumed to contain mostly of passenger cars (vehicle width 7 ft) and single unit trucks (vehicle width 8 ft), the lane width can be suitably kept at 10 ft in a street network. Thus, each lane can sufficiently contribute 2 ft (=12 ft - 10 ft) for BRT use. A four lane urban street with a 14 ft TWLTL would provide a total of 14 ft + 2*4 ft = 22 ft for a two-way BRT operation that requires a minimum of 2*11 ft = 22 ft right-of-way. Similarly, 6-lane streets with a TWLTL of 12 ft min in the center will provide a total of 12 ft + 2*6 ft =24 ft additional width. Figure 7.11 shows the modification of a four-lane street.

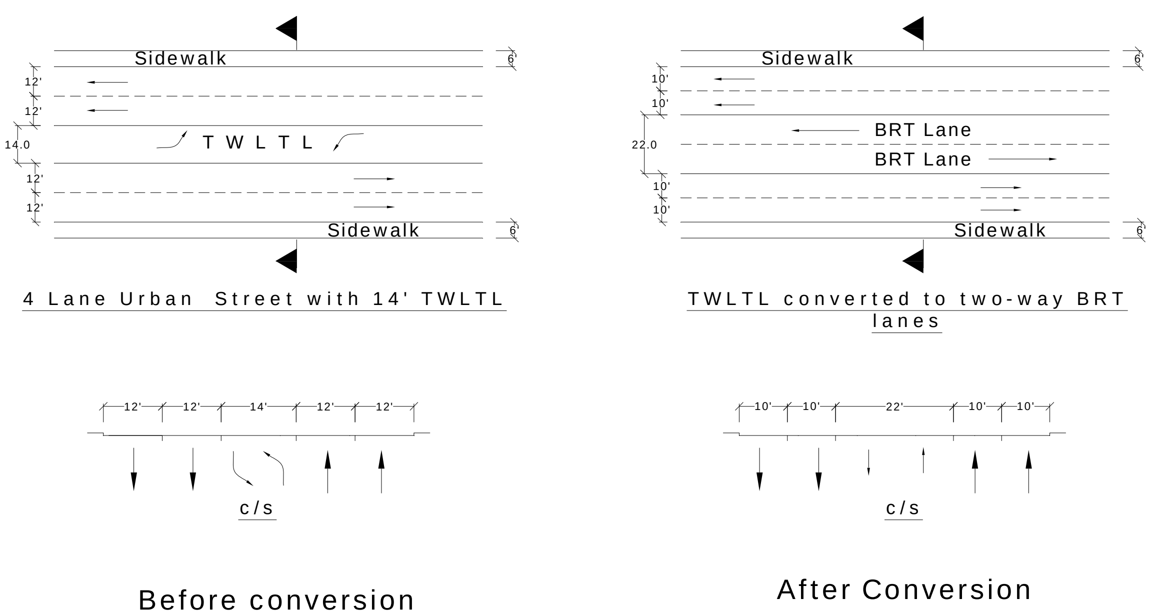



*Figure 7.11: TWLTL converted to two BRT lanes*

It is clear that this conversion will eliminate the TWLTL lane and the resultant prohibition of left turns along the BRT lanes. The left turn lane traffic can be adequately accommodated by U-turns at the major intersections. The minimum turning radii for commonly used vehicles as provided by AASHTO (2004) are listed in Table 7.3.

**Table 7.3: Minimum Turning Radii**

| | |
|---|---|
| Passenger Car | 24 ft |
| Conventional School Bus | 38.9 ft |
| Single unit truck | 42 ft |
| Intercity Bus | 45 ft |

Therefore, intersection widening may be necessary at some locations to accommodate the U-turn movements of large size vehicles at the major intersections.

*7.2.1.3 Central Lanes for BRT*

Many BRT applications worldwide use the central lanes as BRT lanes. Curitiba (Brazil), Liege (Belgium), Rouen (France), and many others have the median BRT lanes in use. The advantage of using the median lanes for BRT is that the other vehicles can use the curb lanes to make right turns at locations having considerable business developments. The central lane for BRT also eliminates the need for the BRT to change the lane near the intersection for moving ahead of the queue. One of the drawbacks of this layout, as in the case of the TWLTL BRT lanes, is that it impedes the left turn movement of mixed traffic at the signalized intersections. This can be tackled by applying a special signal phase for the left turn vehicles at the intersections. The signal phasing should be designed using a detection system that can detect the approaching BRT vehicle and truncate the green phase early or extend the red phase for the mixed traffic until the BRT clears the intersection. Once the bus passes, right-of-way can be granted to the left-turning vehicles (see Figure 7.12).

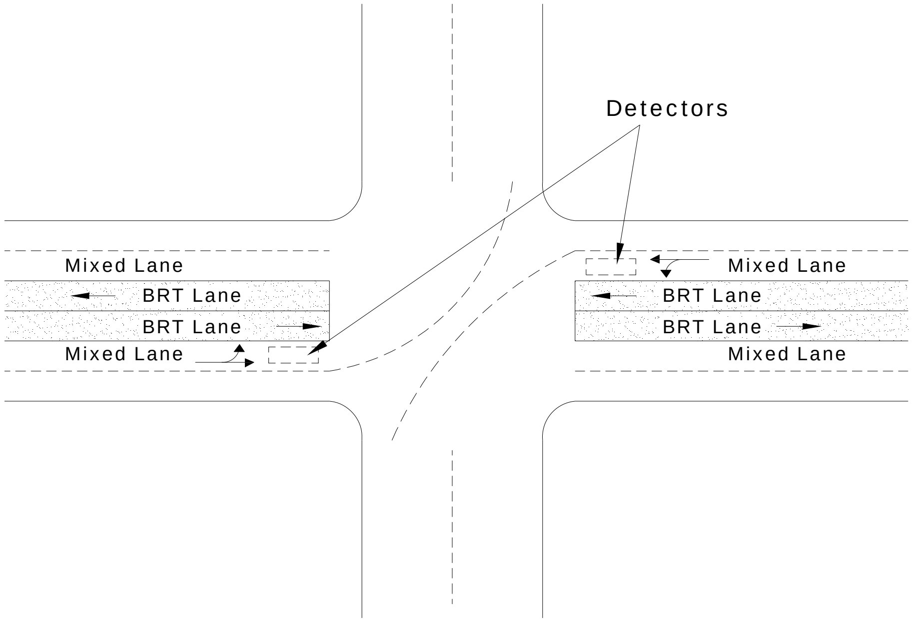



*Figure 7.12: Detectors to provide preference to BRT*

Bus stations can be accommodated on medians having a width of 10-12 ft and should be able to hold at least two buses to ensure acceptable peak service. Depending upon the type of bus service used, the length of the loading area may range from 100 to 150 ft with higher values for the longer BRT vehicles.

*7.2.1.4 Converting a Collector Median into BRT Lanes*

The congested localities often have dense degree of habitation adjacent to the roads and hence it is difficult to widen the existing roadway limits for accommodating new facilities like BRT. However, those roads with a wide median in the center can be upgraded to BRT lanes in situations where no right-of-way is available outside the road limit (see Figure 7.13). The design of converting wide medians into BRT lanes will have its pros and cons. The beneficial factor is having a BRT presence that essentially saves the transit time and reduces the delay caused by heavy traffic. On the other hand, the median openings needed for the commercial setup are omitted.

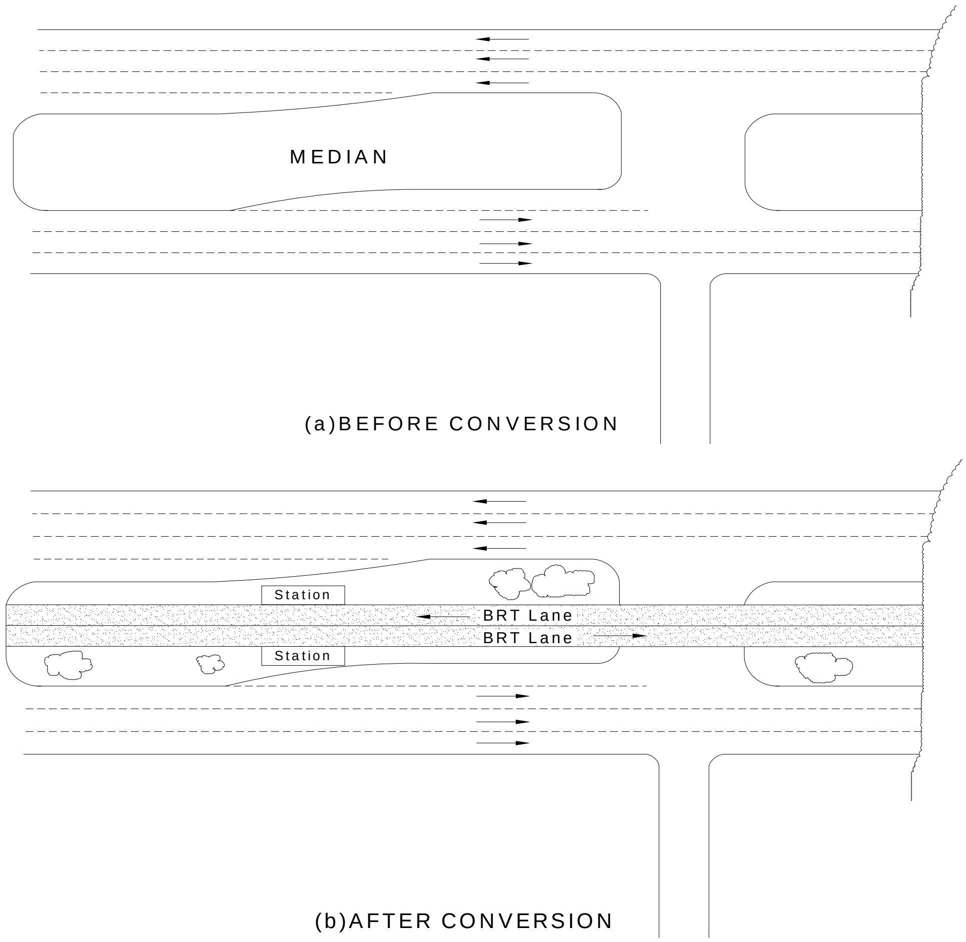



*Figure 7.13: Wide median converted to BRT lanes*

*7.2.1.5 Accommodation of Left-turn Vehicles in Median BRT Lanes*

One of the problems associated with the median BRT lanes is the accommodation of left-turn vehicles along the BRT route. In some situations, such as suburban localities, the BRT roadway envelope may have numerous intersections that give rise to frequent left turning demands along a given roadway stretch. A high volume of left-turning vehicles would increase the number of conflicts with the BRT vehicles and would cause a safety risk. Closing the left turns for these vehicles at these locations would eliminate the conflicts and ease BRT operations. To achieve this, the left turn movements are accommodated by providing far side U-turns coupled with right turns. As illustrated in Figure 7.14, a left turn is prohibited at the minor intersections thus avoiding the conflicts and boosting a faster and safer BRT operation.

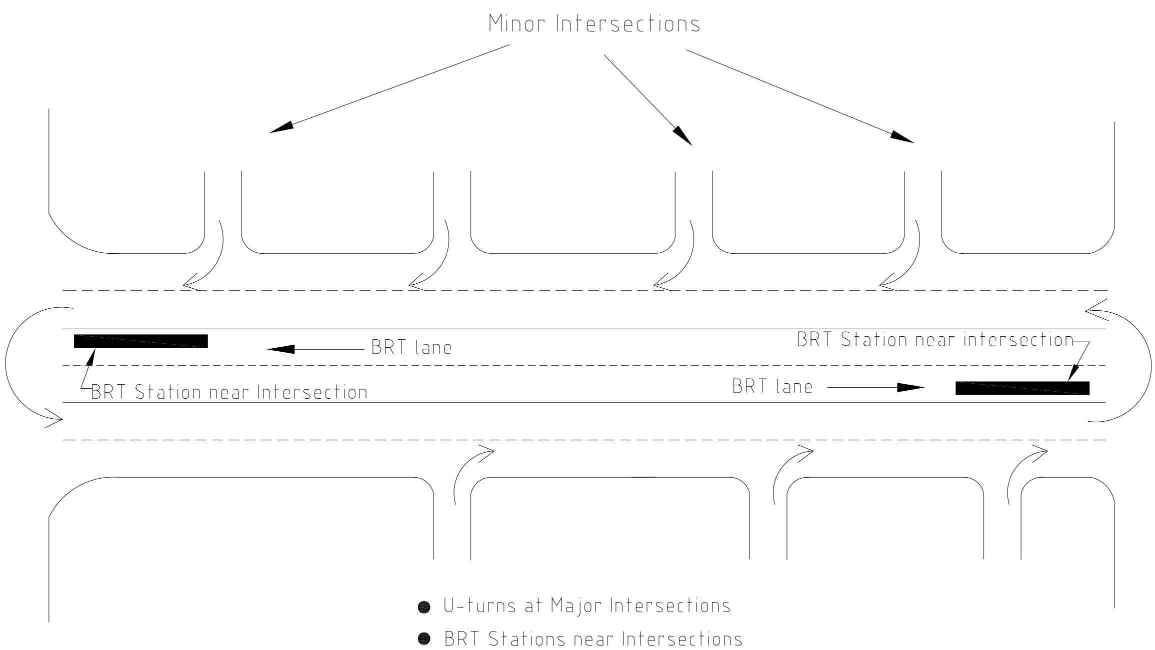



*Figure 7.14: Conversion of multiple left-turns into a U-turn*

## 7.3 Curb BRT Lanes

### 7.3.1 Curb lanes

A BRT can also be operated along the curb lanes of a roadway envelope. A BRT lane can be created by using the outside lane of the street arterial without significant geometric modification. Depending on the demand of transit vehicles, the curb lane can be made available only to BRT vehicles either for a specific time of a day (e.g., morning and afternoon peak hours) or the whole day. This conversion will require painting the lane to designate this change using the standard practices. It will also need special signs along the BRT route to show the details such as time period for BRT operation, as well as other context-sensitive policies as may be applicable. Figure 7.15 illustrates an example layout of the markings and signs for peak hour BRT operation. With such minor installations and changes necessary on the existing corridor for its implementation, this option can be economical and still effective.

In the cases in which the traffic demands are not trivial, fully dedicating the outside lane to BRT may not be feasible because it may result in severe traffic congestion. In such a case, the curb BRT lane can be created by converting the TWLTL lane into a reversible general purpose lane to serve the peak hour traffic alternately during the morning and afternoon peaks. This design will make the outside lane available to BRT during the designated time period while keeping the total number of lanes for general traffic intact.

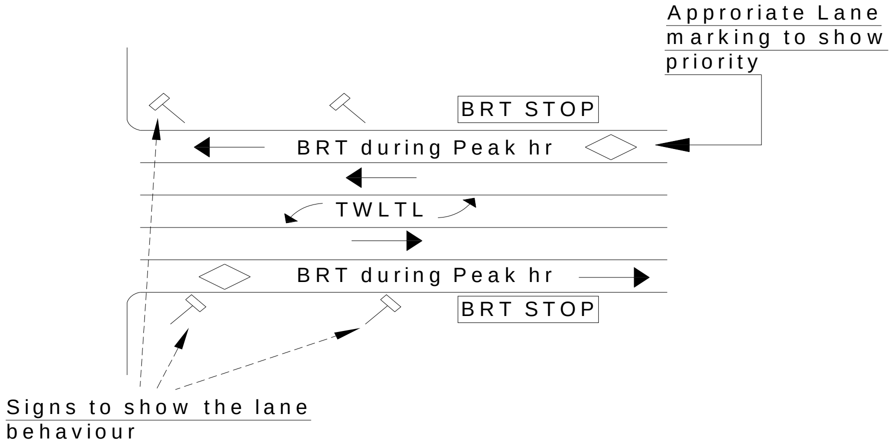
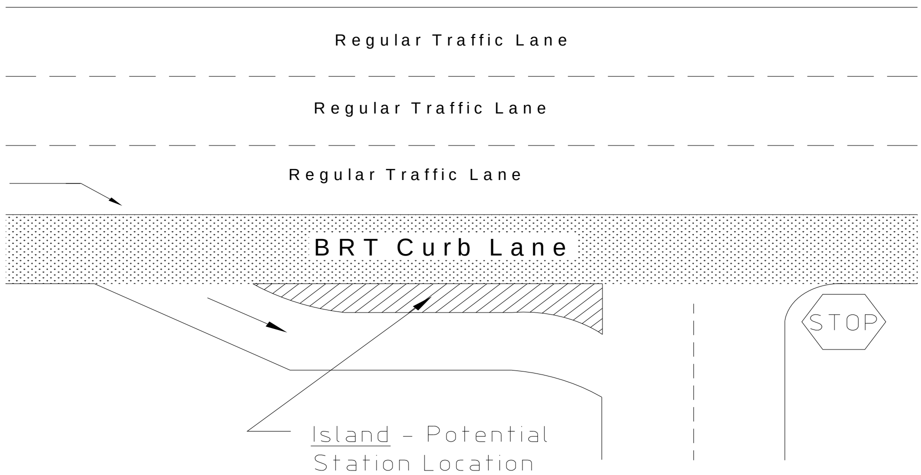
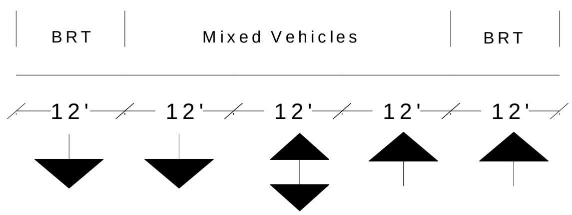



*Figure 7.15: Peak hour BRT operation*

Curb BRT lanes create conflicts with the right-turning vehicles at the intersections. To work around this situation, an island guiding the right turn movement can be provided at the intersection. As illustrated in Figure 7.16, such islands can also be utilized as BRT stations if they are created with sufficient length and width. Provision of such an island at the intersection would enable and guide the right-turn maneuver and reduce the impact of the BRT lane on the right-turning vehicles. For an intended right turn, the vehicle will remain on its designated lane and yield for the approaching vehicles on the BRT lane.




**(a) Layout**




**(b) Lane use details**

*Figure 7.16: A curb BRT lane*

## 7.4 Summary

This chapter has presented alternatives for developing BRT lanes at a variety of existing facility cross sections. Facilities provided for BRT running are extremely important to the potential speed and reliability of the system and thereby extremely important to the image that users and potential users develop regarding the system.

# Chapter 8. Developing Integrated BRT System Concepts

## 8.1 Running Ways and Stations

BRT running ways may have a variety of different configurations, as discussed previously. Each of the running ways has its own design purpose and the BRT stations should be suitably integrated with the running ways. Station spacing, capacity, and facilities provided depend to a large extent on the type of running ways. BRT systems with exclusive running ways should have larger station spacing with adequate station facilities to suit the long distance between the BRT stations. Similarly, the BRT systems with less exclusivity for the bus running ways can be managed with fewer facilities at the stations as the stations are usually more closely spaced.

Standards for the design of common bus stops would suffice for curb BRT stations, unless specific upgrades are needed to highlight the identity of the BRT service. If the running way is along the roadway median, comprising one lane for each direction, the station should be suitably integrated in such a way that it can serve both lanes by constructing it in the middle of two lanes. It is desirable that the stations be designed in a way that would require minimum roadway widening and still be sufficient to serve the peak hour passenger demands.

BRT stations located in the center of the roadway carrying two adjacent BRT lanes will leave very little space for bike parking or storage. Therefore, supplementary parking facilities should be provided in the proximity of the BRT stations to accommodate passengers who need parking for their bicycles. Shifting the associated facilities (e.g., the parking place for bicycles) away from the boarding stations would eliminate the need to create wide platforms and save the construction cost for roadway widening. Figure 8.1 illustrates how a BRT station located in the center of two BRT lanes might fit the running way design. In such a case, either an overpass or a pedestrian signal might be added to the facility to provide safe passage for passengers.

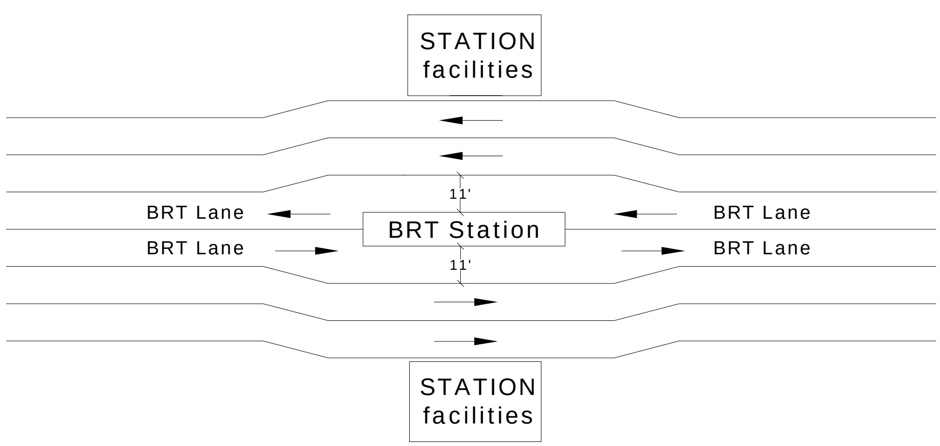



*Figure 8.1: A conceptual BRT station for the median lanes*

## 8.2 Running Ways and Vehicles

The running ways need to be suitably integrated with the BRT vehicles through mutually complementary designs. The width of bus lanes with machine-based visual or mechanical guidance can be narrower than those without it. The geometry of the roadway including curvature of the horizontal alignment on the BRT route may affect the selection of BRT vehicles. When operating on tangent sections, virtually all BRT vehicle sizes can suitably accommodate 11’ lane widths; however, smaller size buses may become necessary if BRT routes involve short radius horizontal curves or intersections with minimal curb return radii.

For a conservative BRT system where buses either do not have exclusive running ways or have limited exclusivity, operation of smaller size buses coupled with relatively higher service frequency is desirable. To accommodate the frequency of BRT vehicles and minimize the impacts on general traffic, provision of additional lane/lanes at BRT stations may become necessary for better quality of service.

The BRT operation can also be designed in a way wherein two different lanes would be used during different times of day. For example, a TWLTL in the center can be used by BRT during peak periods while the curb lane can be used by BRT during other times for mixed flow BRT operations. For such a system two different types of BRT vehicles could be used. A specialized vehicle might use the dedicated BRT lane, giving it priority over other traffic during peak hours; and mixed use lanes can be used by regular buses during the off-peak hours. Such a system would eliminate the necessity of creating a specialized BRT lane along a corridor and can suitably integrate the existing running ways with regular buses, requiring specialized BRT vehicles only during peak demand times.

## 8.3 Running Ways and ITS

The quality of service of a BRT system can be greatly elevated by the ITS technologies currently available in the market. Such technologies as collision avoidance, collision warning, and precision docking can be integrated with the running ways for safer and enhanced BRT service.

A BRT system with two median BRT lanes serving opposite directions without physical separation between the bus lanes can pose a side collision threat. Using collision warning devices, the bus driver can be alerted in a timely manner when such a risk emerges in the field. Similarly, a pedestrian warning system can detect pedestrians conflicting with the BRT vehicle and alert the bus driver in advance.

An effective way to incorporate ITS technologies into the BRT operations without dedicated bus lanes is development of the transit signal priority system (TSP). In such a system, the location of a BRT vehicle is continuously monitored by an on-board AVL device. The speed and location of the bus is used to estimate its arrival time to the next intersection, where the signal timing plan is adjusted to favor its passage through the intersection.

Advanced driving assistance systems such as automated platoon and hands-free driving show considerable promise in assisting BRT vehicles on various types of running ways. In an automated platoon system, BRT vehicles can be operated at very close spacing through vehicle-to-vehicle communication links and magnetic sensors buried in the pavement. While traveling on the properly instrumented busways and within a platoon, buses are under fully automated control and coordinated with each other. Advanced fully automated steering and speed control systems can allow BRT vehicles to run under machine control along an HOV lane and return to driver control at its end. Such applications could enhance BRT performance in the future by improving the lane capacity of the bus running ways as well as the quality of service of a BRT system.

## 8.4 Stations and Vehicles

BRT stations can be designed from an array of options including regular stations, BRT stations with special identity, intermodal terminals, and transit centers with variable types of platforms. A wide variety is also observed in BRT vehicle styles in terms of size, lift style, and number of doors. By adjusting the height of the station platforms to vehicle floor heights, these two elements can be integrated for better service.

To reduce the boarding and alighting time, a BRT station with heavy passenger demands can be designed in a way to optimally route passengers into and out of the vehicle. As conceptualized in Figure 8.2, this can be designed by providing railings with openings at specific locations for boarding and alighting. The bus must stop at a precise location such that the door openings match the openings at the station. This can be achieved either by driver control aided by markings on the curb/pavement or through an automated bus docking system. Such integrated BRT systems with specially designed stations coupled with buses capable of precision docking are in use in Curitiba, Brazil.

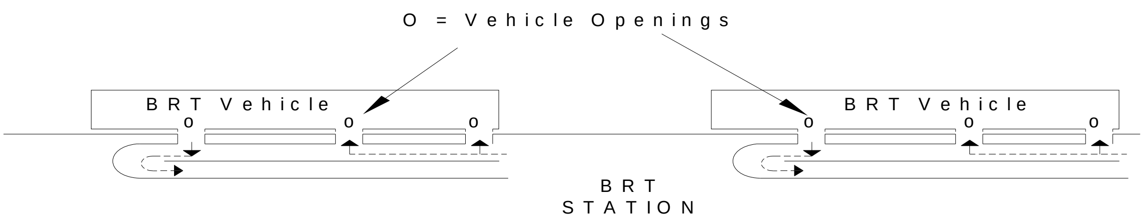



*Figure 8.2: Guided boarding and alighting at a BRT station*

## 8.5 Stations and ITS

ITS technologies can be collaboratively applied to BRT stations in various situations through the effective use of transit and traffic data. A passenger information system can provide real-time bus arrival information to the passengers waiting at stations, while operations management technology can be used to do real time matching of numbers of in-service vehicles to passenger demand.

The supporting technology for a bus arrival information system includes the Advanced Vehicle Location system that uses GPS technology to trace the movement of BRT vehicles, and the associated wireless communication technique that transmits the predicted bus arrival time information to the stations. For a transit management system, a key supporting technology is the passenger counting device installed on the bus and/or at the stations for capturing accurate passenger demands.

With the support of the bus arrival information system and passenger counting devices at bus stations, the level of service of a BRT system can be greatly enhanced. Dispatching of BRT buses can be based upon real-time onboard passenger data and passengers waiting at stations. Bus drivers can be assisted by real-time data from stations as they decide to skip stations without alighting and boarding demands.

It is likely that during the peak hours some BRT stations along the route may periodically not have enough space for arriving vehicles. Congestion at BRT stations could be a combined effect of the station size, its capacity, the size of the BRT vehicles, and the bus schedules. Possible mechanical breakdowns would also result in such undesirable situations. ITS technology implemented at the bus stations can greatly reduce the level of disruption and improve the quality of service of the BRT system.

A highway network having multiple BRT routes can be designed to serve buses from different routes on the overlapped portion of the route. BRT stations handling multiple routes and heavy bus demands should have the arrival times scheduled in such a way that the stations are not crowded during the peak hour flow. Real-time information can be used to expedite or delay vehicle arrivals, facilitating uncongested arrival at busy stations. Bus schedules need to be developed in a coordinated manner so that the time for waiting and transfer is minimized. In the case of headway-based BRT systems that do not follow fixed schedules, advanced technologies such as automated bus platoon management systems should be advanced further to maintain the desired headway.

## 8.6 Stations and Fare Collection

The fare collection process is of great importance to the performance of a BRT system. With the vast range of options available among current fare collection systems, one that is suitable for the specific type of BRT system can be designed.

Electronic fare collection devices can be provided at bus stations to speed up the fare collection process. Barrier-enforced fare payment systems can be employed in the proximity of the loading area. These involve turnstiles, fare gates, ticket agents, or a combination of the three for quick off-board payment. In addition to saving time, barrier-enforced off-board payment systems can decrease the amount of lost bus fare revenue.

Ticket-vending machines can be provided, coupled with Proof-of-Payment services at the station, to confirm the proof of payment when the passengers are about to leave the station. For unpaid customers a counter can be maintained that would accept the payment and deliver adequate proof of payment. Sufficient integration can be achieved between fare collection and stations by instituting a system of passes (e.g., once a week or once a month payment) that would enable patrons to avoid the hassle of paying the same fare everyday and provide a small incentive.

Advanced technologies like smart cards can be used for contactless transactions that are fast and flexible. The single-payment feature of smart cards especially benefits passengers who need to transfer and/or use parking facilities at BRT stations. Smart cards also offer the capability of differentiated fare structures (e.g., time-based and distance-based fares) and fare integration across several modes and/or operators. Therefore, provision of single payment most desirably through smart cards would greatly enhance the user friendliness of a BRT system.

BRT stations should be designed in accordance with the vehicle type and the fare collection system. For a BRT system with short distances among stations, the stations would probably be small without shelters and other facilities. Providing ticket vending machines at every station would also be expensive. Instead, for system designs featuring frequent stations, fare collection might be provided inside BRT vehicles and adequate measures can be taken to avoid fare evasion. Measures such as locating the fare collection system near the driver's seat with a mandatory front door passenger entry can help the driver ensure fare collection from every boarder.

## 8.7 Vehicles and Fare Collection

Integration of the fare collection system with the BRT vehicles can be achieved through various design techniques that identify typical needs of passengers and their common travel patterns. Depending upon the space available inside BRT vehicles, fare payment can be installed in different places on-board.

A fare collecting machine can be installed inside the vehicle that would collect the fare through multiple modes. The ability to collect the fare through cash, coins, flash passes, and smart cards will broaden the media of payment among the patrons and suit the individual choices. Increasing the number of fare collection machines within the BRT vehicle will also be especially beneficial to accelerate the payment process during the peak hour demand. Such collection pattern would be helpful in articulated buses that are 60 or 80 feet long and serve a higher transit demand. Passenger entry and exit passengers to and from vehicles should be planned in a way that would discourage fare evasion.

Similar to the off-board fare collection vending machines, the on-board fare collection machine should also be able to issue various types tickets to suit transferring passengers. A rider should be able to pay the complete fare for the entire trip on the first BRT vehicle boarded. Such a service would be beneficial to long distance riders who board from stations without automatic ticket vending machines.

## 8.8 Internet-based Fare Collection

ITS technologies can be applied to improve the effectiveness of the fare collection systems through the use of the internet. Internet-based fare payment will be of great convenience to both the transit companies and the passengers. Proof of payment can be either stored in portable electronic devices like cell phones, or printed out as tickets. Such a system is being developed in Hong Kong and mainland China and is expected to be implemented into practice in the near future.

## 8.9 Vehicles and ITS

BRT system performance can be enhanced by integrating ITS features with the vehicles. Through the use of advanced vehicle detection and monitoring technologies as well as enabling wireless communication systems, a BRT system can be made safer, faster, and more capable.

Technologies like driver assistance and automation systems can be applied to BRT vehicles to aid in precision docking and collision avoidance. By employing ITS technologies like automated bus docking, the BRT vehicle can dock precisely and automatically at the stations. Transit Signal Priority (TSP) at the signalized intersection route crossings can facilitate faster BRT operations. Technologies like passenger counting and on-board passenger information systems can be integrated with BRT vehicles to enhance efficiency and passenger friendliness. Other technologies like automated dispatching systems use real time vehicle location data and schedule adherence to insure reliable service. Vehicle mechanical monitoring and maintenance systems can be used to automatically monitor the conditions of in-service transit vehicles and provide timely potential mechanical failure warnings. Passenger counting systems can provide passenger load information as an important tool for deciding when and where to dispatch additional vehicles.

Silent alarm technologies can be suitably integrated with BRT vehicles to alert passengers to important information by displaying the message on exterior sign boards. Voice and video monitoring systems can be harnessed to monitor activities inside the vehicle for security purposes and transfer the data to the transit control center for timely action.

### 8.9.1 Integration of Running Ways, BRT Vehicles and Stations

A BRT system using median lane operation can be designed with a single station located in the center serving the running ways on both sides, instead of two stations to serve the vehicles with right-side doors. The vehicles for such a station would have left-side doors to allow entry and exit to the central station located on its left side. At localities with limited right-of-way, this integration can help solve station space problems. Figure 8.3, separated by the line in the center, illustrates schematically the possibilities for station adaption with left side doors.

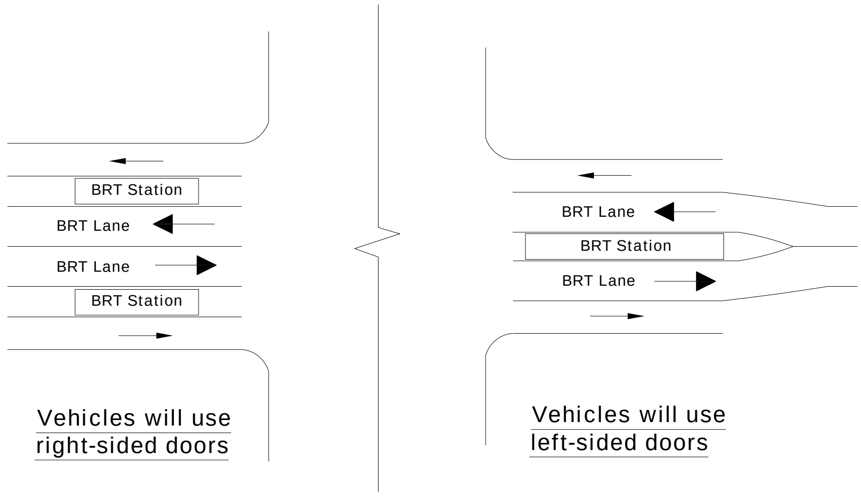



*Figure 8.3: Two Stations Condensed to One through Integration*

As illustrated, BRT vehicles would use the right-side doors at the regular station setup (shown on the left side of the figure). This setup would be modified in case of right-of-way restrictions and can be well accommodated in the center as shown on the right side of the figure.

## 8.10 Summary

This chapter has presented a brief summary of some of the potential ITS-BRT integration opportunities. These integration efforts can significantly enhance passenger perceptions of BRT services and provide service providers many tools for monitoring and improving service reliability and efficiency.

# Chapter 9. Case Studies: North Mesa Street Corridor in El Paso, Texas and Lamar Boulevard Corridor, Austin, Texas

Two case studies were chosen to illustrate the application of BRT in corridors needing additional capacity. Typical urban area issues make addition of highway lanes difficult. Therefore, both the Mesa Street and Lamar Boulevard corridors are under active consideration for BRT implementation by the local authorities in El Paso and Austin. The analyses presented here are not intended to critique or conflict with the local plans for either corridor, but simply to illustrate how the BRT concept may have merit as a potential corridor improvement. A detailed analysis of the Mesa Street corridor is presented here because that project is, at the time of this report, in the planning stages while analysis of the Lamar corridor is more conceptual because Capital Metro announced an almost complete plan for BRT implementation in that corridor before this study was completed.

## 9.1 Case Study 1: North Mesa Corridor, El Paso, Texas

### 9.1.1 Background

The El Paso Metropolitan Planning Organization (MPO) has proposed a Bus Rapid Transit (BRT) route for the city of El Paso (El Paso MPO 2004). The route is intended to run along the North Mesa Street corridor, which is one of the major arterials on the west side of the city. As shown in Figure 9.1, a similar route configuration was published by the City of El Paso's GIS Department with larger area coverage and an expansion to the neighboring city of Sunland Park, New Mexico (City of El Paso 2007).

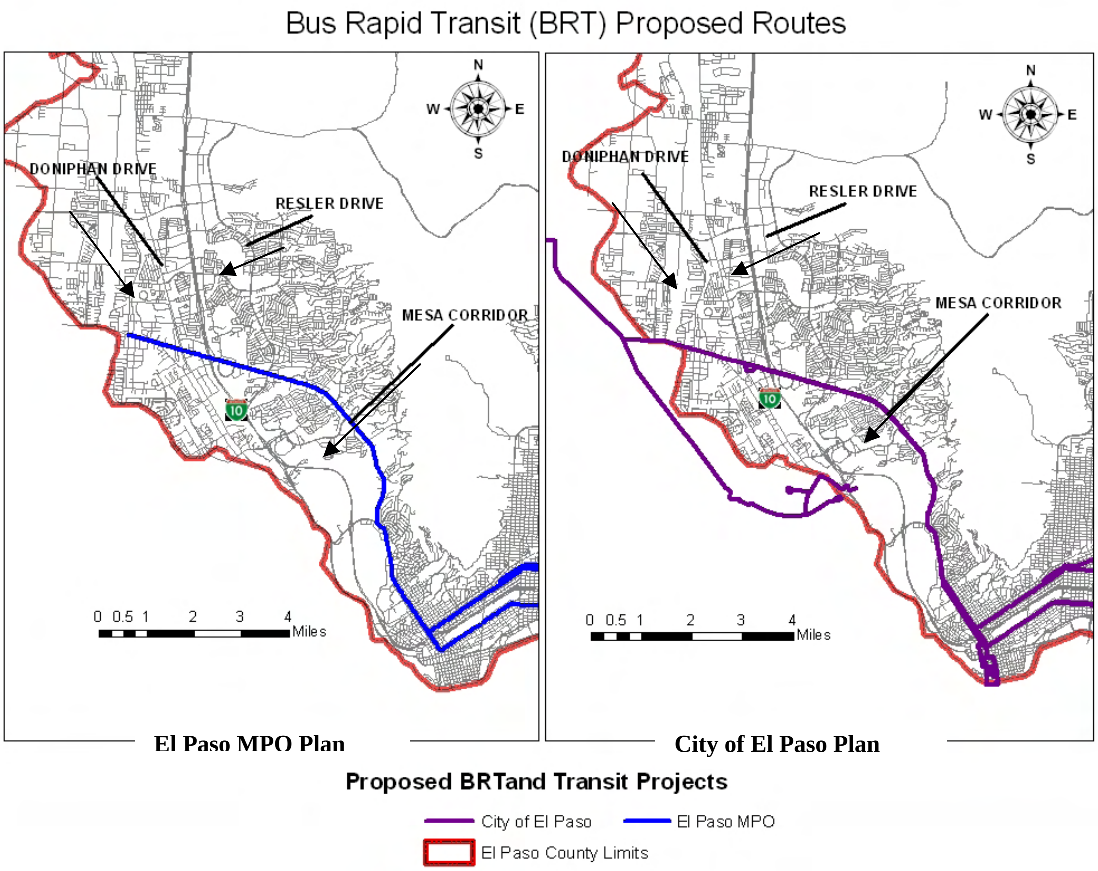



*Figure 9.1: BRT Route alternatives for El Paso*

### 9.1.2 BRT Corridor Selection in El Paso

As a first approach, the methodology of identifying the Transit Supportive Areas (TSA) can be used to select the corridor. For this purpose, each Traffic Analysis Zone (TAZ) was evaluated to determine whether it meets the criteria for being "transit-supportive" (household density of three households per acre or a job density of four jobs or more per acre) (Kittelson & Associates, 2003). The results of this spatial analysis are shown in Figure 9.2.

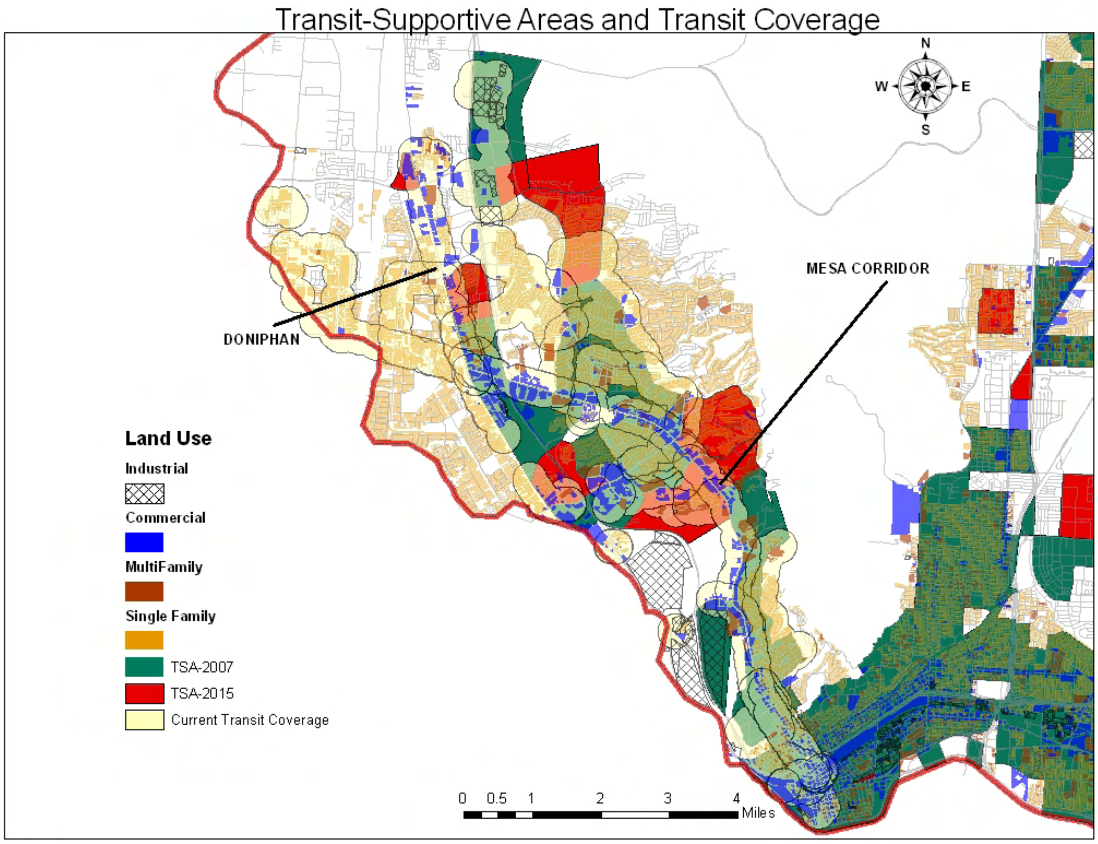



*Figure 9.2: TSA and coverage analysis*

Although the analysis of TSAs indicates that the east side could potentially be a better option for the implementation of a BRT system, in recent years metropolitan transit city planners have focused on the mass transit development along the Mesa Street corridor, which is one of the major arterials in the west part of the City. This decision was probably took into account factors such as the level of congestion, Right-Of–Way (R/W) policies, operational and maintenance costs, cost benefit analysis, or the guidelines of the current Transportation Mobility Plan (TMP), Transportation Improvement Plan (TIP), or the Metropolitan Transportation Plan 2030 for the El Paso del Norte Region. Therefore, from this section on, the analysis will be based on the west part of the city, specifically the surrounding areas of Mesa Street. Another important reason that may influence operation of a BRT line along the Mesa Street corridor is the number of local bus lines that currently operate along this corridor. Figure 9.3 shows two lanes in each direction along one segment of the corridor. A new BRT line could avoid schedule conflicts, increase the road capacity by saving space, and reduce operating costs and vehicle emissions.


*Figure 9.3: Mesa Street Corridor—Segment with two lanes in each direction*

### 9.1.3 Characteristics of the Mesa Street Corridor

The Mesa Street corridor begins at the Border Highway, which is located along the border line with Mexico. The street at this segment is identified as S Mesa Street and extends north to downtown. After crossing E San Antonio Avenue at downtown (Figure 9.4), the street is designated as N Mesa Street (State 20) and extends northwest until crossing Doniphan Drive. The corridor's approximate length is 10 miles and it crosses 73 traffic intersections. The intersection design along the corridor consists of 41 coordinated traffic signals and 32 intersections. Mesa Street lane configurations vary depending on the zone location. Segments with one (downtown area), two (transition zone), and three circulation lanes per direction can be found. The speed limit also varies along the corridor. The permitted posted speed limits range between 30 and 50 miles per hour.

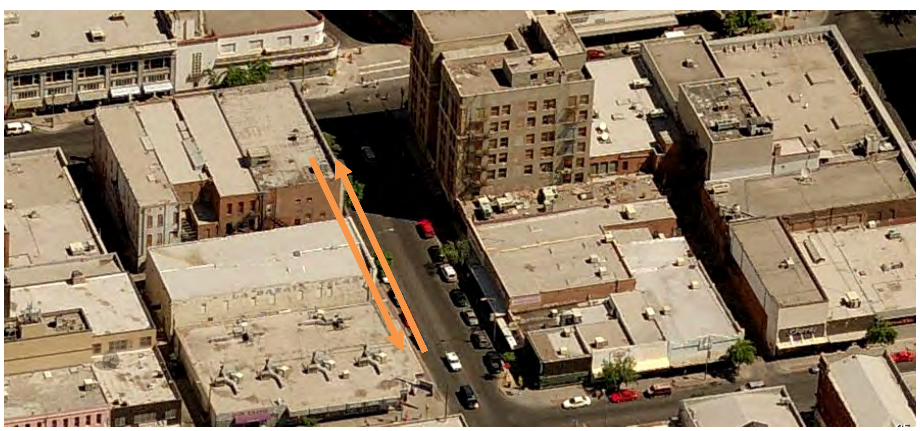


*Figure 9.4: S Mesa St. before crossing E San Antonio Ave. at downtown El Paso*

The segment along S Mesa Street consists of only one lane per direction, and the outer lanes in each direction are used as parking spaces. The configuration of the downtown area is mostly historic neighborhoods as well as small retail stores, restaurants, and office spaces. The connection between South and North Mesa Street is not a typical intersection. Drivers traveling north at South Mesa Street are required to turn right at E San Antonio Ave, and then turn left onto N Mesa Street. The same requirements exist when traveling south, but with a turning left movement. Although the difference in divergence is only 40 feet, buses may have difficulties maneuvering at this intersection.

North Mesa Street from E San Antonio Avenue to East Main Drive consists of one lane in a northwest direction and two lanes in a southeast direction. This segment of the corridor crosses two light intersections and there is parking available only on the side of the northbound traffic. San Jacinto plaza, which is the center plaza in the downtown area, and also a main connection to the Sun Metro buses, is located at this segment. The Mesa Street corridor passing E Main Drive converts into two lanes without parking spaces in the outer lanes, and no turning left lane in the center.

Passing E Franklin Avenue up to Glory Road, the corridor has a left turn lane in the center, and there are no designated parking spaces in the outer lanes. This parking restriction continues through the entire Mesa Street corridor starting from this point. This segment crosses 10 simple intersections and 12 traffic light intersections.

The corridor from Glory Road to Doniphan Drive consists of three lanes per direction (Figure 9.5) with a median that allows space for traffic turning left at intersections. The median has a width of approximately 25 ft. At the intersection of N Mesa Street and Remcon Drive, there are two left turn lanes in each direction, but all other intersections consist of single left turn lanes.

*Figure 9.5: N Mesa corridor with three lanes per direction*

### 9.1.4 Corridor Ridership

The potential ridership was identified using the current routes traveling along Mesa or the ones that could supply passengers to the BRT route (Figure 9.6). The routes fulfilling these requirements are routes 10, 11, 12, 13 14, 15, 16, 17, and 18. Table 9.1 lists these routes named by the local transit operator, Sun Metro.

**Table 9.1: Transit Routes using N Mesa Street**

| Route | Name |
|---|---|
| **10** | UTEP/Sunset Heights |
| **11** | Mesita via Kern Place |
| **12** | Country Club via Sunland |
| **13** | Coronado hills via Fiesta |
| **14** | Westwind |
| **15** | Mesa |
| **16** | Sunland Park/ Buena |
| **17** | Three Hills New EPCC |
| **18** | Westside/Downtown |

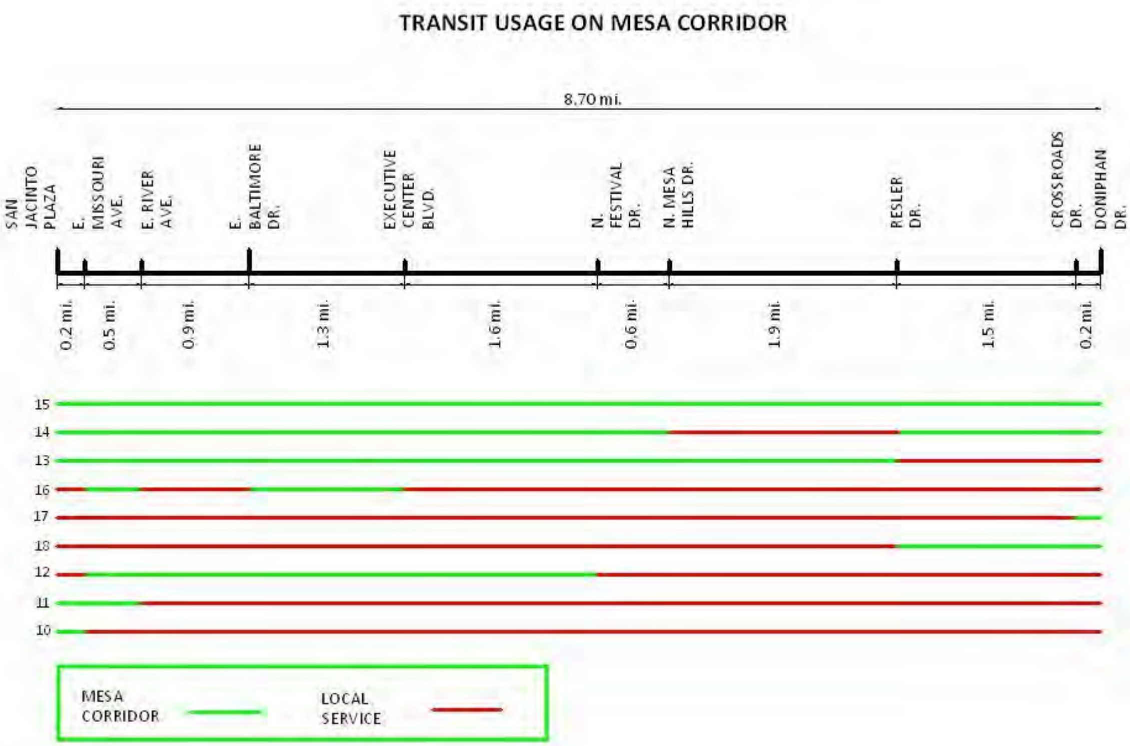



*Figure 9.6: Transit usage along N Mesa St*

Using GIS software, the research team estimated the potential ridership along the corridor for both the base year 2007 and the projected year 2035. The potential ridership was estimated using the population along Mesa Street with a buffer of 0.25 miles. From a total of 72,550 potential passengers estimated for 2007, Sun Metro reported an average of 40,000 passengers per month. This represents a transit share of approximately 55% of all potential users. If this tendency remains, the projected monthly ridership by 2035 will be near 50,000 passengers, plus all additional ridership attracted by BRT elements and corridor improvements (Kittelson & Associates, 2007).

### 9.1.5 Ridership Patterns

Perhaps the most important element for designing a BRT system is a reliable ridership forecast. The Federal Transit Administration (FTA) requests ridership forecasts for the base year, opening year, "maturity" year, and horizon year (usually 20 years after the base year) for all New Start transit projects. Moreover, it is necessary to provide peak and off-peak behavior by line segment and boarding/alighting patterns by station/stop (Kittelson & Associates, 2007). For the Mesa Street case study, a typical week-day boarding and alighting behavior was analyzed using data given by Sun Metro (see Figures 9.7 and 9.8). With this information, two key elements were identified: the passenger flow during the day, and the maximum passenger volumes (morning and afternoon peak-hours).

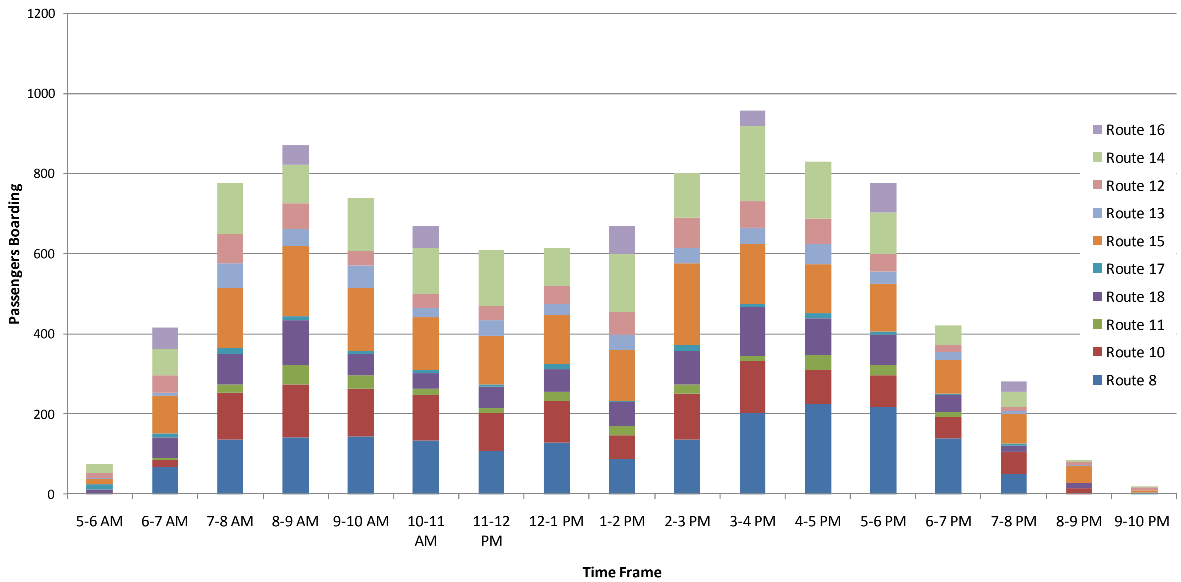



*Figure 9.7: Passenger boarding during weekdays*

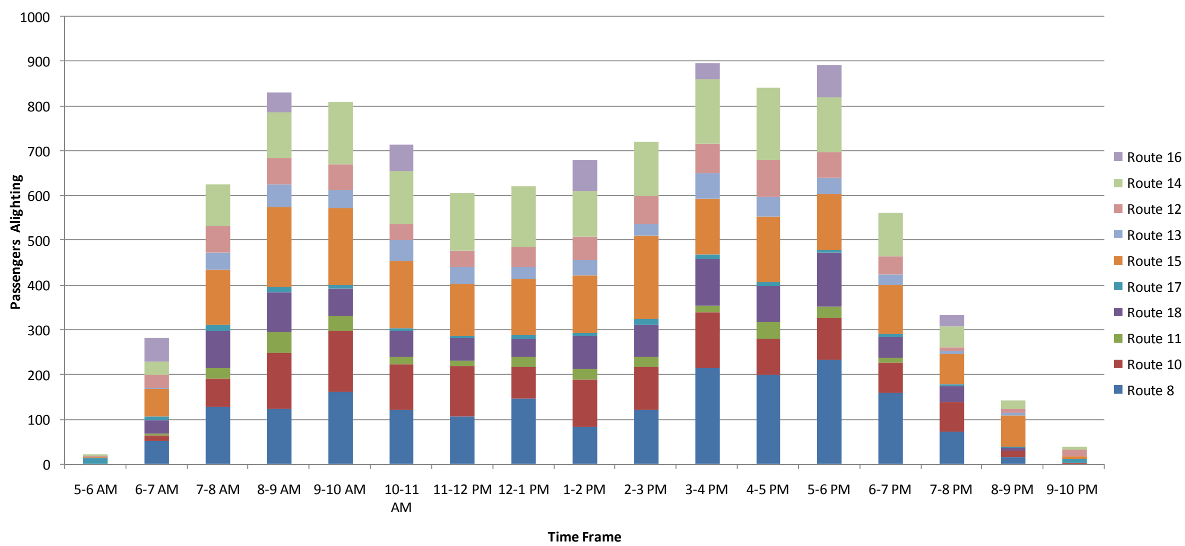



*Figure 9.8: Passenger alighting during weekdays*

### 9.1.6 Service Structure

The TCRP Report 118 gives emphasis to existing local service, indicating that these routes *should feed rather than duplicate the BRT service*. For this element, a possible development is getting a trunk-feeder system for the first two phases, and implementing a collector BRT for the third stage (see Figure 9.9). Given the current conditions in the corridor, the trunk-feeder BRT structure will allow higher frequencies along the corridor with the use of a new fleet, and also increases the coverage by using the existing fleet as feeders.

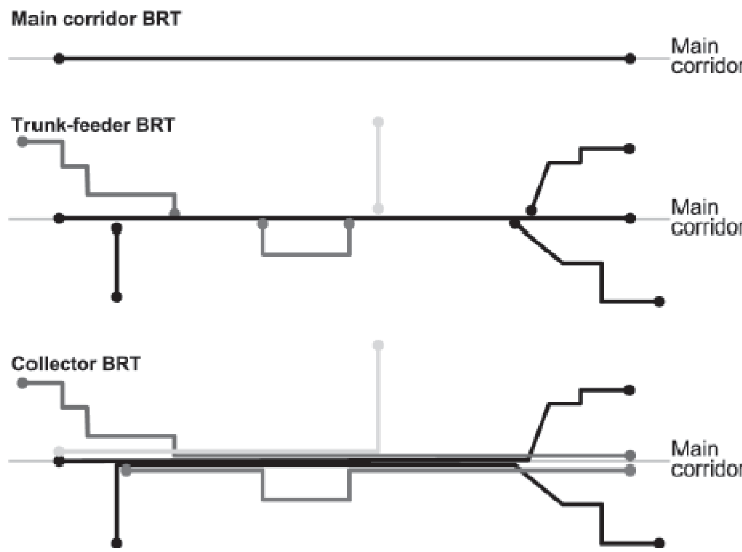



*Figure 9.9: BRT service alternatives*

### 9.1.7 Stop/Station Location and Design

After analyzing the boarding and alighting patterns along the corridor, the first approach of location selection was performed. Figure 9.10 identifies the location of higher volumes of passengers during the morning and afternoon peak hours. Additionally, the comparison of stop spacing was based on information from other BRT systems around the nation as well as recommendations made by Sun Metro representatives.

From the 92 existing stops along the corridor, a total of 12 were selected. Stop spacing is relatively closer in the downtown area due to the density that zone experiences. The farther the stops are from downtown, the greater the space between stops. Figures 9.10 and 9.11 show boarding and alighting distributions spatially for morning and afternoon peak hours along the corridor. Boarding volume in the downtown area is dominant, while alighting of passengers occurs in the first section of the trip and at the main intersections.

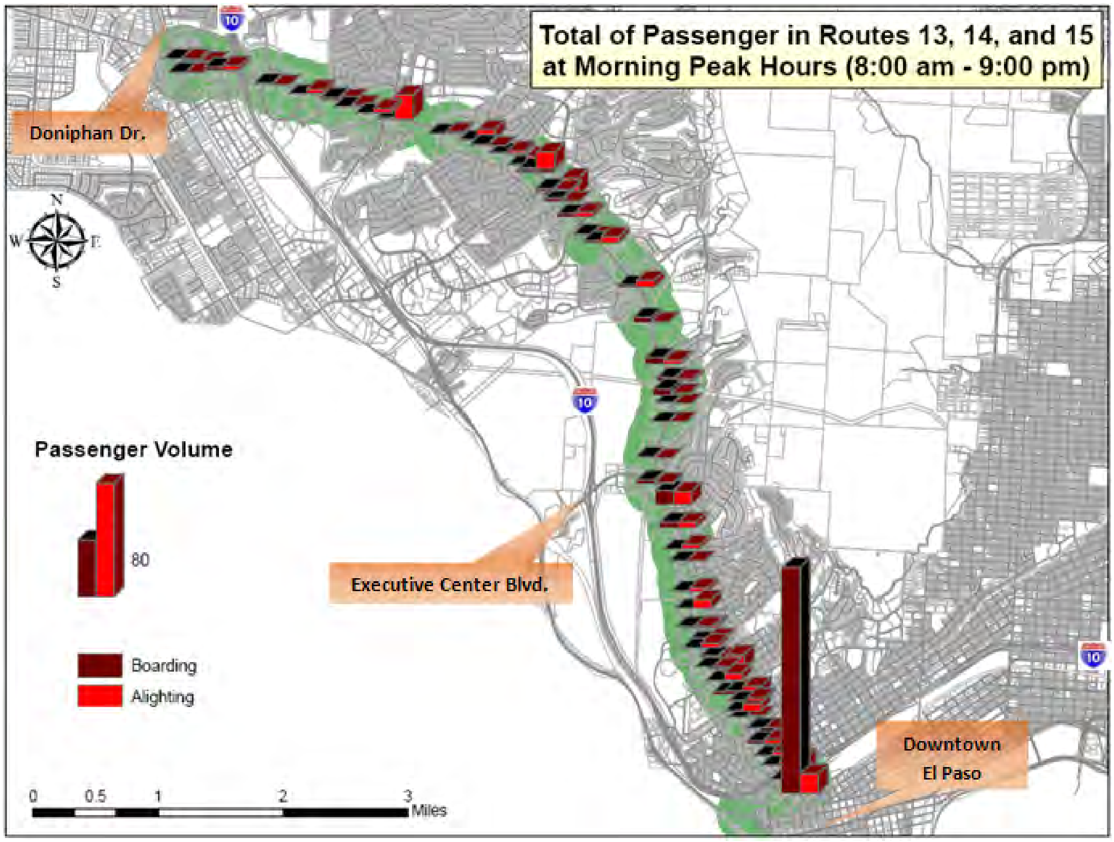



*Figure 9.10: Boarding and alighting patterns during morning peak hour*

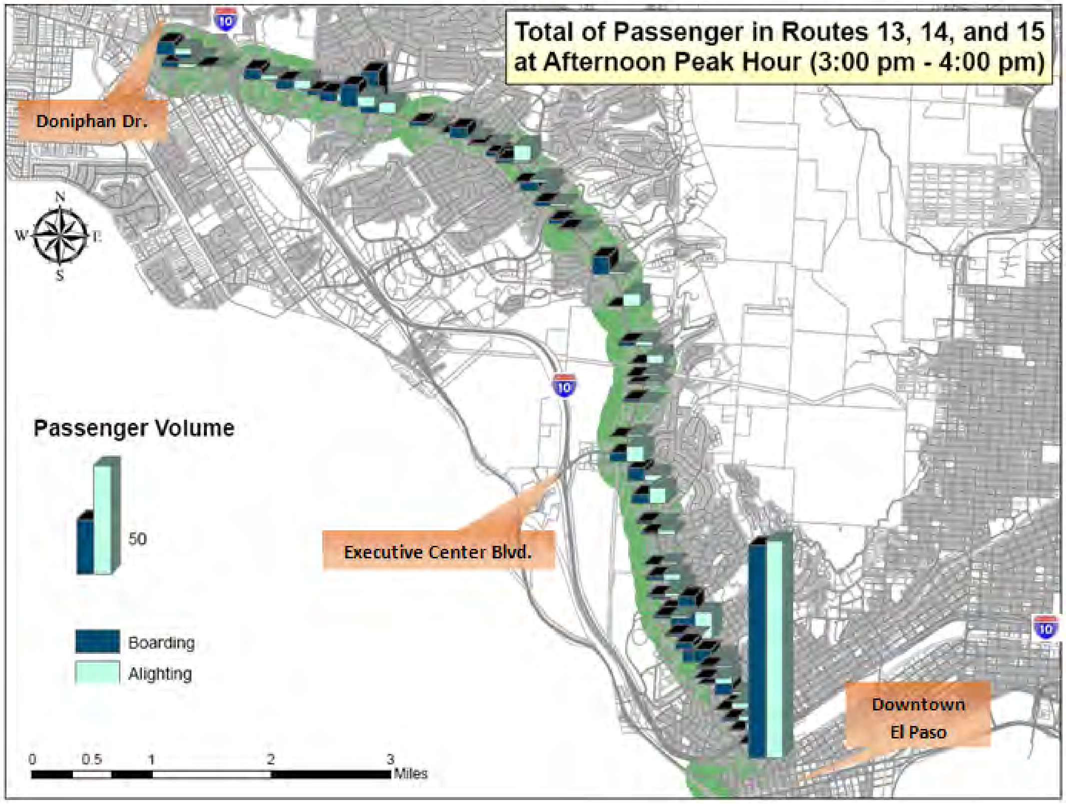



*Figure 9.11: Boarding and alighting patterns during afternoon peak hour*

Although some selected stops do not show a high volume concentration, the research team selected them because of importance during special events (e.g., Don Haskins Center) and to avoid large gaps between stops (Falbel et al. 2006). Experience in the U.S. has shown that a reduction in the number of stops improves BRT operating speed (Kittelson & Associates et al. 2003). For instance, a reduction from 6 to 2 stops per mile can save from 2.2 to 2.4 minutes per mile (excluding traffic delays). The Mesa Street corridor currently has 90 stops and 2 terminals; the proposal includes 20 and 2 terminals. This could represent a time savings of up to 2.85 minutes per mile. If it is considered that the average round trip travel time is currently 93 minutes during morning peak hours, then the savings would reach approximately 27 minutes. This amount can place BRT in a very competitive position with round trip auto travel time (47 minutes) along Mesa Street. Figure 9.12 shows the 20 stops (one per direction) and 2 terminals selected by the research team. Table 9.2 lists the proposed stop distances.

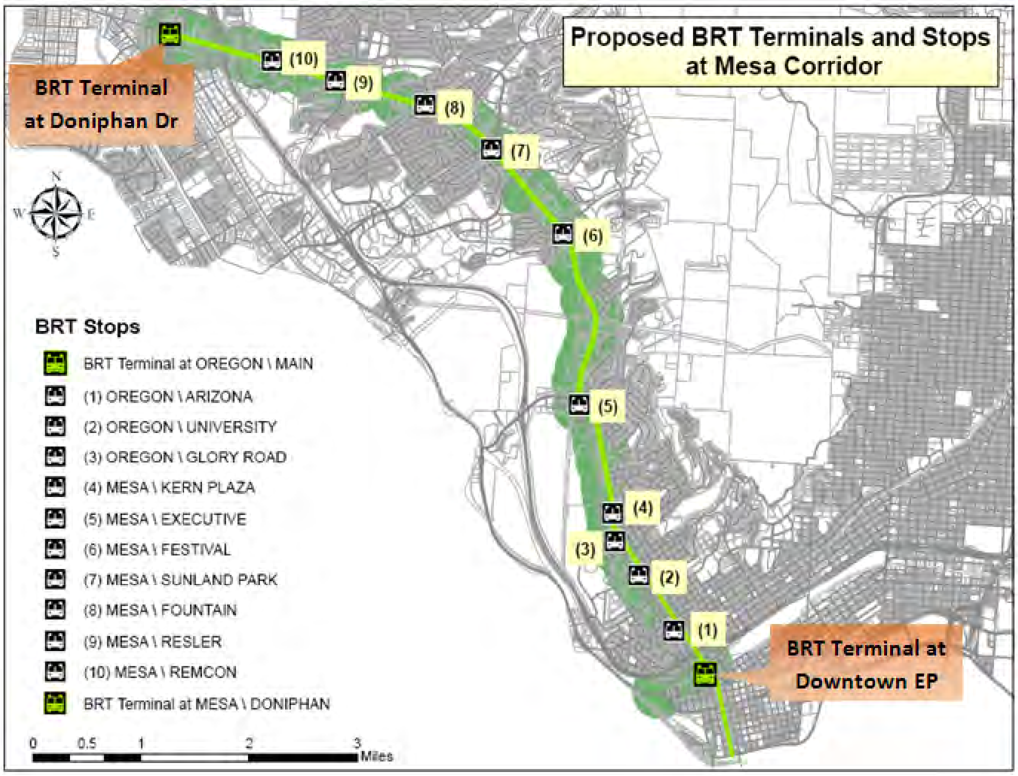



*Figure 9.12: Proposed BRT stops for Mesa Street*

**Table 9.2: Distance between stops**

| Proposed BRT Stops | Distance from previous stop (ft) | (miles) |
|---|---|---|
| BRT Terminal at Main and Oregon | - | - |
| Oregon / Arizona | 2,893 | 0.547 |
| Oregon/ University | 3,634 | 0.688 |
| Oregon / Baltimore | 2,131 | 0.403 |
| Mesa / Kern Plaza | 949 | 0.179 |
| Mesa / Executive | 5,684 | 1.076 |
| Mesa / Festival | 8,847 | 1.675 |
| Mesa / Sunland Park | 5,528 | 1.047 |
| Mesa / Fountain | 3,977 | 0.753 |
| Mesa / Resler | 4,615 | 0.874 |
| Mesa / Remcon | 3,340 | 0.632 |
| BRT Terminal at Main/Doniphan Dr | 7,462 | 1.413 |
| **Commutative distance** | **49,060** | **9.29** |
| **Average distance between stations** | **4,460** | **0.844** |

The BRT stations and stops need a distinctive design to attract new ridership through the corridor. Basic amenities are necessary (Wright et al. 2007). However, they should have the necessary space to accommodate the maximum passenger load during a week day. A proposed shelter for the first limited phase is shown later in the BRT station section.

### 9.1.8 Guideway Design

Several options for lane configuration could be applied to the corridor. However, the limited space that it currently has is not suitable for advanced features such as exclusive lane or segregated busway. The Mesa Street corridor has several segments that can be utilized as exclusive lanes. The total mileage with a fourth-lane section is summarized in Table 9.3.

**Table 9.3: Available Distance for a BRT Lane along N Mesa Street**

| | Executive Blvd-Argonaut | Festival - Doniphan | TOTAL |
|---|---|---|---|
| **Northbound** | 0.61 miles | 0.54 miles | **1.15 miles** |
| **Southbound** | 0.38 miles | 1.41 miles | **1.79 miles** |
| | TOTAL ALONG CORRIDOR | | **2.94 miles** |

Other types of possible configurations include the addition of a single lane by removing side parking from the downtown area to Glory Road, as shown Figures 9.13 and 9.14.


*Figure 9.13: Example of the fourth lane utilization for BRT vehicles*

*Figure 9.14: Queue jumper at the intersection of Mesa and Executive (left) and Mesa and Resler (right)*

The limited phase includes the mixed traffic option. This option can be improved by taking advantage of the fourth-lane sections along the corridor. As mentioned before, a total of 2.56 miles can be converted. Another alternative for this phase is the elimination of street parking along N Oregon Street (Figure 9.15). However, a parking garage needs to be constructed to accommodate private vehicles.

The moderate phase should include at least three queue jumpers at main intersections (Mesa & Executive, Mesa & Shadow Mountain, and Mesa & Resler), as shown in Figure 9.16. For better results in travel time savings, queue jumpers could be built in combination with signal prioritization along the entire corridor (Falbel et al. 2006).


*Figure 9.15: Proposal of banning side parking along Oregon Street*

*Figure 9.16: Queue jumper at Mesa and Sunland Park*

The R/W and lane configuration for the aggressive phase is taking the median as a segregated lane for BRT. Stations will be at the mid section of the road with a proper pedestrian access, making it necessary to take the complete median section, plus realignment of the existing lanes. Figure 9.17 shows an example of the possible lane configuration for an advanced deployment phase (aggressive).


*Figure 9.17: Median usage for BRT along N Mesa Street*

### 9.1.9 Intersection and Signal Control

Each BRT shelter requires special design to integrate with the lane configuration and to allow a faster flow along the BRT corridor. The following figures show a proposed shelter at three major intersections (Executive Boulevard, Sunland Park Drive, and Resler Drive).

The proposed BRT stop for the intersection of Mesa Street and Executive Avenue are located near corridor side lanes, as shown in Figure 9.18. This segment of the corridor consists of four lanes per direction, and the exclusive fourth lane for BRT is available.

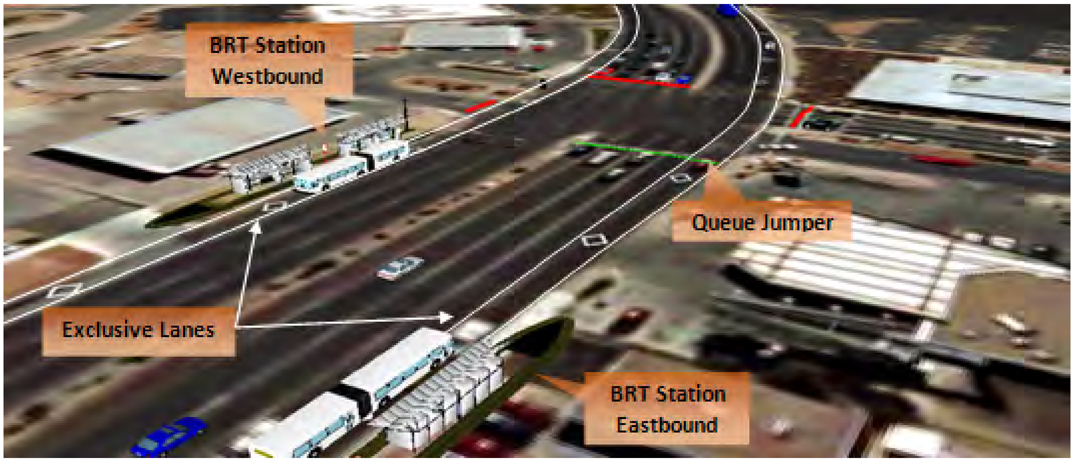



*Figure 9.18: Intersection design at Mesa and Executive*

The eastbound stop is located 40 ft downstream from the intersection with Executive Boulevard, with a length of 120 ft. The stop is proposed to be able to provide service to double articulated buses as well as 40/40 buses. Driveways at this segment need to be relocated to accommodate the stop. The westbound stop is proposed to be located 170 ft upstream of Executive Boulevard. The station is proposed to have a width of 10 ft to accommodate BRT users, and an additional space is needed for sidewalks. Land might need to be acquired for this stop. The exclusive BRT busway needs to be properly identified with a white diamond mark on the pavement with the letters “BRT only.”

The BRT stops at the intersection of Sunland Park require an exclusive access stop lane, as shown in Figure 9.19. The access lane for westbound will be located 500 ft upstream of Sunland Park, and eastbound stop at 180 ft upstream of Sunland Park This additional lane segment will allow the bus to stop without interfering with traffic at Mesa Street. Again, proper pavement marking will be required.

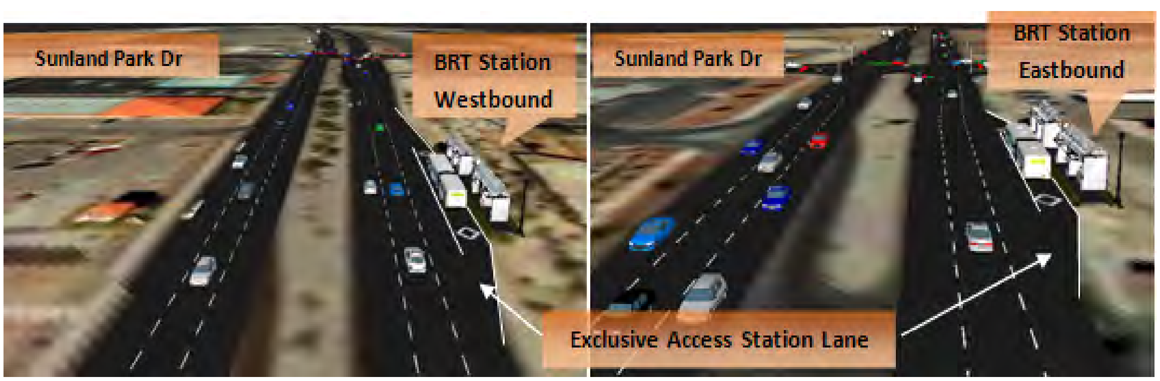



*Figure 9.19: Intersection design at Mesa and Sunland Park*

The stops for Mesa and Resler are proposed to have a similar design as the ones in Executive, as shown in Figure 9.20. The stop will be located at the near side lane, using the fourth lane as an exclusive busway. The stops are proposed to be located 300 ft upstream of Resler for westbound and 450 ft upstream of Resler for eastbound. Major driveways should be relocated upstream of stop to allow drivers to enter parking without interfering with bus route.


*Figure 9.20: Intersection design at Mesa and Resler*

### 9.1.10 Fare Collection

The implementation of an effective fare collection system is important in order to provide a good service and improve the overall travel time. In the El Paso region, the limited phase of the bus rapid transit should consist of an Off-Board method. Giving users the time to become familiar with this method is very important. Authorities should ensure that implementing an efficient information plan will avoid confusion among BRT passengers and facilitate the access of vehicles. Additionally, the limited phase will include ticket machines located at strategic stops and the two terminal stations (Figure 9.21).

*Source: GTZ 2007*

*Figure 9.21: Smart Cards and Automatic Vending Machines.*

In the moderate phase of the BRT system, another method for fare collection should be considered depending upon the ridership demand. One option is to implement ticket vending machines at certain stations to give riders the option to buy tickets beforehand, and thus, save time when boarding the bus. This Proof of Payment (POP) method can result in considerable time savings, and gives more flexibility to the customer when paying for the BRT tickets.

However, the ticket vending machines might not be located at every station because of cost, safety, and maintenance issues. An analysis will be needed in order to determine where the ticket vending machines would be better placed along the BRT route. Moreover, the cost and maintenance for such machines is considerably higher than the POP method.

In time, the BRT system might attract more riders, and thus, cause longer boarding times. With higher passenger volumes, smart cards might be justified, and could be applied to the whole BRT system structure. The electronic validation machines located at BRT stops could decrease the overall travel time of the bus and provide a better service for the El Paso community. Also, with an electronic fare collection system, local agencies could collect station demand data that might be helpful in planning future improvements (Kittelson & Associates 2007).

The different fare collection methods can also be combined in order to give more options for the passengers. For example, the proof of payment system could still be used along a new system like the smart cards. This way, customers could either show their tickets or swap their smart card when riding the bus, therefore, providing more flexibility.

### 9.1.11 BRT Vehicle

The vehicle selection for each phase will depend on the ridership demand. As ridership gradually increases, the system will need a different type of vehicle with better elements to make it suitable for transit demand. Design of BRT buses can vary depending on the city identity and marketing strategies (as shown in Figure 9.22). The following sections discuss three different options for BRT in the Mesa Street corridor.


*Figure 9.22: BRT Vehicles for Limited and Moderate phases*

### 9.1.12 BRT Station-First Phase (Limited)

The station for the first phase would consist of what it is depicted in Figure 9.23. As seen on the figure, a map would be provided to inform the passengers of the route structure, schedules, and any other information that would offer a better service. Additionally, the name of the station would be shown at the top for easy identification as well.


*Figure 9.23: BRT vehicle for the aggressive phase*

### 9.1.13 BRT Station-Second Phase (Moderate)

Figure 9.24 shows the proposed station for the second phase of the BRT implementation. This station would be equipped with an intelligent transportation system (ITS) to provide real-time information to the passengers. In addition, solar panels would be placed on the top to provide the necessary energy for the ITS and lighting. Figure 9.25 shows the proposed station, moderate phase.

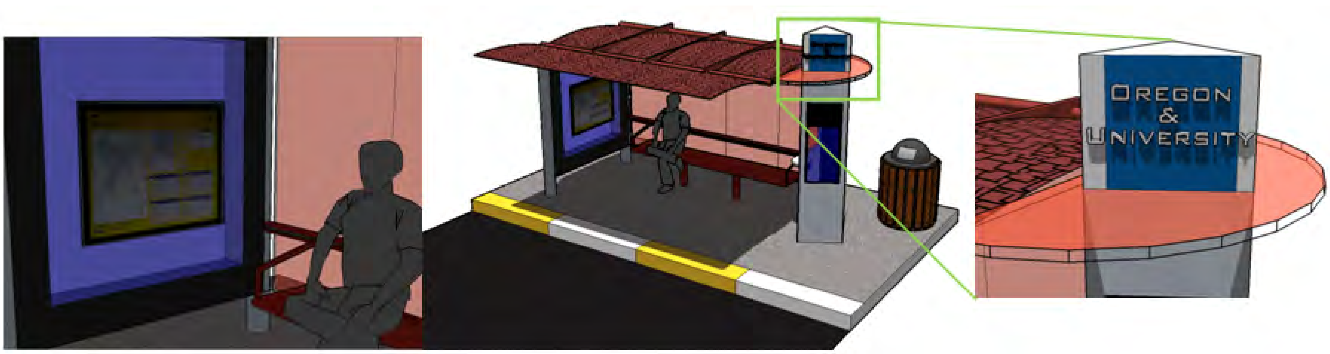



*Figure 9.24: BRT Station model for the limited phase*

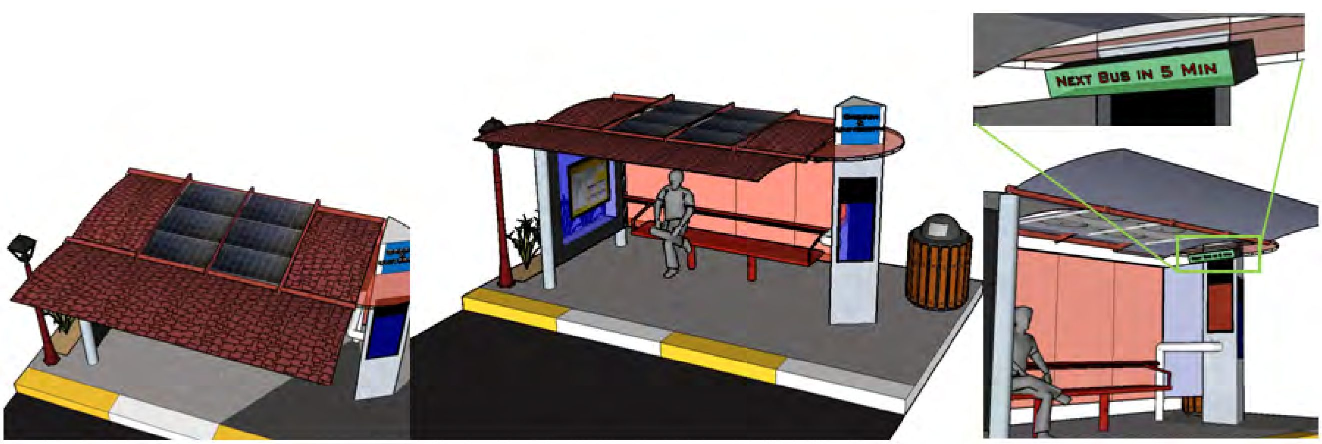



*Figure 9.25: BRT station design for the moderate phase*

### 9.1.14 BRT Station-Third Phase (Aggressive)

For the aggressive phase, the concept of infrastructure and operational design is the most advanced of the three phases. This stage includes off-board fare equipment and controlled access to the stops and stations. Figure 9.26 shows a BRT stop at Bogota's system similar to those in rail or subway systems. For N Mesa Corridor, a similar option can be implemented using either lateral or median road stations/stops.


*Figure 9.26: BRT station design for the Aggressive phase*

### 9.1.15 Park-and-Ride Facilities

Park and ride services are convenient for commuters because it provides the option to decrease travel time as well as to avoid any possible delays. In addition, a parking incentive could increase the ridership among the whole Mesa Street corridor.

After thorough analysis, the intersections considered to potentially include park-and-ride facilities along the Mesa Street corridor are Mesa Street/Main Street (Terminal 1), Mesa Street/Festival Drive, Mesa Street/Resler Drive, and Mesa Street/Doniphan Drive (Terminal 2). Availability of space for commuters to park plays a vital role in the implementation of the park-and-ride amenities as well as the ridership. At Terminal 1, ridership is relatively high, but there is no available space at the moment, however, with the restructuring of Downtown El Paso, Texas, a park-and-ride parking lot should be feasible. At the next intersection of Mesa Street /Festival Drive the ridership is moderate and parking space (land acquisition) could be available. Furthermore, it is surrounded by apartment complexes and single family homes that might become potential BRT riders as the walking distance overpass the 0.25 miles recommended by the TCQSM (Kittelson & Associates et al., 2003). The next intersection at Mesa Street and Resler Drive currently has a high ridership because it is surrounded by schools, commercial shops, and parking space is extensive. Finally, it would be recommended that a park-and-ride facility be added to the second terminal. The main reasons are that this point is located at the edge of the BRT route, and the ridership coming from northern El Paso neighborhoods would be attracted by the BRT system as local transit routes might not be available to those locations.

At any of the above recommended locations, commuters can park and have multiple destination choices along with transfers to other exterior routes along Mesa Street corridor. This would allow commuters to have efficient transportation at a reasonable expense as well as shorter travel times.

### 9.1.16 Estimated Cost

BRT development consists of a group of features that vary according to the planning phases and the complexity of the project. Similarly, the cost of implementing such features varies depending on the capital costs (infrastructure and land cost); operational costs; design and implementation considerations; performance; and economic, social, and environmental impacts (Wright et al. 2007).

One of the remarkable advantages of BRT compared to other public transportation systems is the relatively low infrastructure cost (Kittelson & Associates 2007) (Wright et al. 2007). In order to estimate these costs, the research team used a practical tool included as a part of a study that includes several cities developing-nation BRT systems and inputs from BRT experts (Wright et al. 2007). Table 9.4 presents basic features in every phase as analyzed in Chapter 5, and also the corresponding estimated cost for every feature. Even though the actual cost will depend on local conditions, BRT estimates are a useful instrument for planners and project developers to have an approximate initial value of the system (Wright et al. 2007). Note that all costs were estimated in 2007 U.S. dollars (Institute for Transportation and Development Policy 2008).

## Table 9.4: Implementation Phase Basic Features

| GUIDEWAY AND LANE IMPROVEMENT | PHASE 1 | PHASE 2 | PHASE 3 |
|---|---|---|---|
| Mixed Flow | x | x | |
| Dedicated guideway | | | x |
| Contra-flow way | | | |
| Grade separated exclusive guideway – Below grade | | | |
| Grade separated exclusive guideway – At grade | | | |
| Grade separated exclusive guideway – Aerial | | | |
| Queue jumpers | | x | x |
| Overpass lane | | | |
| Median lane runway | | | |
| Curb lane | | | |
| Curb extension | | | |
| **STATIONS** | | | |
| Enhanced Shelters | x | x | x |
| Level Platforms | | | |
| Other Amenities & Services (route & schedule, vending machines, telephones) | x | x | x |
| Automatic passenger counter | | | x |
| Intermodal and transfer facilities | | | |
| Pedestrian crosswalks with signals | x | x | x |
| Pedestrian Bridge | | | |
| Station air conditioning/heater | | | x |
| Passing lanes (express services) | | | x |
| **PARK-AND-RIDE FACILITIES** | | | |
| Open lot parking | | | x |
| Multi-Level Parking | | | |
| Transfer areas (buildings) | | | |
| Bicycle parking | | | x |
| Taxi stands | | | |
| **SURROUNDING LAND USE** | | | |
| Transit-Oriented Development (surrounding land use) | x | x | x |
| High-quality transit services | | | |
| Sidewalk condition improvements | | | |
| Security systems near stations | | | x |
| Clustered business facilities | | | |
| **VEHICLES** | | | |
| 40'-60' Diesel articulated | | | x |
| 80' double articulated (2007) | | | |
| Standard Diesel Buses | | | |
| CNG fuel vehicle | x | x | |
| Electric (trolley-like) vehicle | | | |
| Hybrid vehicle | | | |
| On-board fare collection | x | x | |
| On-board real-time information | | | |
| Wi-Fi service | | | |
| 40'Low-floor vehicles | | | |
| Multiple entrance-exit doors | x | x | x |

| INTELLIGENT TRANSPORTATION SYSTEM | PHASE 1 | PHASE 2 | PHASE 3 |
|---|---|---|---|
| Automatic vehicle location – AVL | | x | x |
| Close circuit cameras | | | |
| Passenger information system | | x | x |
| Transit signal priority | | | |
| Collision warning | | | |
| Precision docking | | | |
| Lane assist system | | | |
| Automatic steering- guidance system | | | |
| Automatic speed and spacing control system | | | |
| Voice and video monitoring | | | |
| Signal coordination | | | |
| **FARE COLLECTION** | | | |
| Pre-board fare | | | |
| Cash payment | x | x | |
| Smart cards | | | x |
| Magnetic strip cards | | | |
| **SERVICE AND OPERATION** | | | |
| Large route coverage | | | x |
| High service frequency | x | x | x |
| Feeders system | x | x | X |
| Reduced number of stations | x | x | x |
| On-time performance monitoring | | | x |
| Multiple routes | | | x |
| Route length extension | | | |
| Marketing identity | x | x | x |
| **OPERATING SPEED** | | | |
| Operating Speed <20 mph | x | | |
| Operating Speed >20 and <30 mph | | x | x |
| Operating Speed >30 mph | | | |

Tables 9.5 through 9.7 show the estimated amount for each item as well as the corresponding unit and quantity for the three different phases along the N Mesa Street Corridor. Phases 2 (Limited) and 3 (Moderate) have relatively similar cost being the main difference the accomplishment of ITS amenities and stop/stations improvements in phase number 3 (Moderate). Phase 3 (Aggressive) was identified as the most expensive phase, with a total of $53,522,500. As stated in previous chapters, this phase represents a “full” BRT system becoming the most complete but expensive deployment phase alternative.

## Table 9.5: Estimated Cost for Limited Phase

| Item | Cost per Unit | Unit | Quantity | Cost |
|---|---|---|---|---|
| ***Phase 1*** | | | | |
| ***Busway construction / roadway reconfiguration*** | | | | |
| Use existing asphalt on busway / new concrete at stations | $150,000 | US$ per kilometer | 30 | $4,500,000 |
| ***Lane separators*** | | | | |
| 10 cm separator blocks | $5,000 | US$ per kilometer | 0.1 | $500 |
| ***Station construction*** | | | | |
| Enhanced Stop | $30,000 | US$ per station | 20 | $600,000 |
| ***Station air conditioning / heating*** | | | | |
| Full air conditioning / heating | $100,000 | US$ per station | 2 | $200,000 |
| ***Station identification - sign post*** | | | | |
| Station identification post | $800 | US$ per station | 20 | $16,000 |
| ***Maps and information*** | | | | |
| Maps at stations | $3,000 | US$ per station | 24 | $72,000 |
| ***Station security*** | | | | |
| Emergency callbox | $1,500 | US$ per station | 2 | $3,000 |
| Security cameras | $8,000 | US$ per station | 2 | $16,000 |
| ***Fare collection readers*** | | | | |
| Smart card system (4 readers per station) | $10,000 | US$ per station | 6 | $60,000 |
| ***Fare collection turnstiles*** | | | | |
| Rotating turnstile (4 turnstiles per station) | $7,000 | US$ per turnstile | 6 | $42,000 |
| ***Fare registering unit / vending machine*** | | | | |
| Smart card system | $15,000 | US$ per machine | 6 | $90,000 |
| ***Fare media*** | | | | |
| Smart card system with microprocessing ability | $4 | US$ per card | 10000 | $40,000 |
| ***Fare system software*** | | | | |
| Smart card system | $500,000 | US$ per software | 1 | $500,000 |
| ***Trunk vehicle technology*** | | | | |
| Stylized standard | $330,000 | US$ per bus | 10 | $3,300,000 |
| ***Feeder vehicle technology*** | | | | |
| Air conditioning in bus | $2,500 | * | 99 | $594,000 |
| ***Terminals and depots*** | | | | |
| Terminal facilities | $3,000,000 | US$ per terminal | 2 | $12,000,000 |
| Restrooms at terminals | $15,000 | US$ per terminal | 2 | $60,000 |
| | **Sub-total** | | | $22,093,500 |
| | **Contingency** <br> *10% contingency* | | | $2,209,350 |
| | **Total** | | | $24,302,850 |

*Cost was estimated using 2007 U.S. Dollars (Institute for Transportation and Development Policy 2008)

## Table 9.6: Estimated Cost for Moderate Phase

| Item | Cost per Unit | Unit | Quantity | Cost |
|---|---|---|---|---|
| ***Phase 2*** | | | | |
| ***Busway construction / roadway reconfiguration*** | | | | |
| Use existing asphalt on busway / new concrete at stations | $150,000 | US$ per kilometer | 26 | $3,900,000 |
| New asphalt on single lane busway / concrete at stations | $700,000 | US$ per kilometer | 4 | $2,800,000 |
| ***Lane separators*** | | | | |
| 10 cm separator blocks | $5,000 | US$ per kilometer | 0.1 | $500 |
| ***Station construction*** | | | | |
| Enhanced Stop | $40,000 | US$ per station | 20 | $800,000 |
| ***Station air conditioning / heating*** | | | | |
| Full air conditioning / heating | $100,000 | US$ per station | 2 | $200,000 |
| ***Station identification - sign post*** | | | | |
| Station identification post | $800 | US$ per station | 20 | $16,000 |
| ***Maps and information*** | | | | |
| Maps at stations | $3,000 | US$ per station | 24 | $72,000 |
| ***Recycling receptacles at stations*** | | | | |
| Receptacles at station | $1,000 | US$ per station | 20 | $20,000 |
| ***Station security*** | | | | |
| Emergency callbox | $1,500 | US$ per station | 2 | $3,000 |
| Security cameras | $8,000 | US$ per station | 2 | $16,000 |
| ***Fare collection readers*** | | | | |
| Smart card system (4 readers per station) | $10,000 | US$ per station | 6 | $60,000 |
| ***Fare collection turnstiles*** | | | | |
| Rotating turnstile (4 turnstiles per station) | $7,000 | US$ per turnstile | 6 | $42,000 |
| ***Fare registering unit / vending machine*** | | | | |
| Smart card system | $15,000 | US$ per machine | 6 | $90,000 |
| ***Fare media*** | | | | |
| Smart card system with microprocessing ability | $4 | US$ per card | 15000 | $60,000 |
| ***Fare system software*** | | | | |
| Smart card system | $500,000 | US$ per software | 1 | $500,000 |
| ***Intelligent Transportation Systems (ITS)*** | | | | |
| Queue Jumper | $100,000 | US$ per mile | 0.12 | $12,000 |
| Real-time information displays | $7,500 | US$ per station | 22 | $165,000 |
| ***Trunk vehicle technology*** | | | | |
| Stylized articulated | $730,000 | US$ per bus | 8 | $5,840,000 |
| ***Feeder vehicle technology*** | | | | |
| Air conditioning in bus | $2,500 | * | 99 | $594,000 |
| ***Control centre (including software)*** | | | | |
| GPS system (equipment) | $1,000,000 | US$ | 1 | $1,000,000 |
| ***Terminals and depots*** | | | | |
| Terminal facilities | $3,000,000 | US$ per terminal | 2 | $12,000,000 |
| Restrooms at terminals | $15,000 | US$ per terminal | 2 | $60,000 |
| | **Sub-total** | | | $28,250,500 |
| | **Contingency** | | | |
| | *10% contingency* | | | $2,825,050 |
| | **Total** | | | $31,075,550 |

* Air conditioning in bus assumes 1.2 buses per km and is based on number of kilometers of feeder services
*Cost was estimated using 2007 U.S. Dollars (Institute for Transportation and Development Policy 2008)

## Table 9.7: Estimated Cost for Aggressive Phase

| *Phase 3* | | | | |
|---|---|---|---|---|
| **Item** | **Cost per Unit** | **Unit** | **Quantity** | **Cost** |
| ***Busway construction / roadway reconfiguration*** | | | | |
| Use existing asphalt on busway / new concrete at stations | $150,000 | US$ per kilometer | 26 | $3,900,000 |
| New asphalt on single lane busway / concrete at stations | $700,000 | US$ per kilometer | 4 | $2,800,000 |
| ***Lane separators*** | | | | |
| 10 cm separator blocks | $5,000 | US$ per kilometer | 0.1 | $500 |
| ***Busway colouration*** | | | | |
| Busway with fully colourised lanes | $50,000 | US$ per kilometre | 30 | $1,500,000 |
| ***Passing lanes at stations (i.e. express services)*** | | | | |
| Express services | $50,000 | US$ per station | 6 | $300,000 |
| ***Station construction*** | | | | |
| 5 metre wide stations | $350,000 | US$ per station | 20 | $7,000,000 |
| ***Station air conditioning / heating*** | | | | |
| Full air conditioning / heating | $100,000 | US$ per station | 2 | $200,000 |
| Air conditioned / heated shelter inside station | $30,000 | US$ per station | 20 | $600,000 |
| ***Automatic sliding doors at boarding interface*** | | | | |
| Sliding doors (8 doors per station) | $40,000 | US$ per station | 10 | $400,000 |
| ***Station identification - sign post*** | | | | |
| Station identification post | $800 | US$ per station | 20 | $16,000 |
| ***Maps and information*** | | | | |
| Maps at stations | $3,000 | US$ per station | 24 | $72,000 |
| ***Recycling receptacles at stations*** | | | | |
| Receptacles at station | $1,000 | US$ per station | 20 | $20,000 |
| ***Station security*** | | | | |
| Emergency callbox | $1,500 | US$ per station | 24 | $36,000 |
| Security cameras | $8,000 | US$ per station | 24 | $192,000 |
| ***Fare collection readers*** | | | | |
| Smart card system (4 readers per station) | $10,000 | US$ per station | 24 | $240,000 |
| ***Fare collection turnstiles*** | | | | |
| Rotating turnstile (4 turnstiles per station) | $7,000 | US$ per turnstile | 24 | $168,000 |
| ***Fare registering unit / vending machine*** | | | | |
| Smart card system | $15,000 | US$ per machine | 24 | $360,000 |
| ***Fare media*** | | | | |
| Smart card system with microprocessing ability | $4 | US$ per card | 20000 | $70,000 |
| ***Fare system software*** | | | | |
| Smart card system | $500,000 | US$ per software | 1 | $500,000 |
| ***Intelligent Transportation Systems (ITS)*** | | | | |
| Broad-band service at stations/terminals | $750 | US$ per station | 2 | $1,500 |
| Real-time information displays | $7,500 | US$ per station | 24 | $180,000 |
| ***Bicycle integration*** | | | | |
| Bicycle parking at stations | $8,000 | US$ per station | 5 | $40,000 |
| ***Park-and-ride facilities*** | | | | |
| Park-and-ride facility (open lot parking) | $1,500,000 | US$ per facility | 1 | $1,500,000 |
| ***Trunk vehicle technology*** | | | | |
| Stylized articulated | $730,000 | US$ per bus | 10 | $7,300,000 |
| ***Feeder vehicle technology*** | | | | |
| Air conditioning in bus | $2,500 | * | 99 | $594,000 |
| ***Feeder system*** | | | | |
| Feeder busway/station improvements | $75,000 | US$ per kilometre | 99 | $7,425,000 |
| ***Control centre (including software)*** | | | | |
| GPS system (equipment) | $1,000,000 | US$ | 1 | $1,000,000 |
| ***Terminals and depots*** | | | | |
| Terminal facilities | $3,000,000 | US$ per terminal | 2 | $12,000,000 |
| Restrooms at terminals | $15,000 | US$ per terminal | 2 | $60,000 |
| | **Sub-total** | | | $48,475,000 |
| | **Contingency** | | | |
| | *10% contingency* | | | $4,847,500 |
| | **Total** | | | $53,322,500 |

* Air conditioning in bus assumes 1.2 buses per km and is based on number of kilometers of feeder services
* Cost was estimated using 2007 U.S. Dollars (Institute for Transportation and Development Policy 2008)

## 9.2 Case Study 2: Lamar Boulevard Corridor Austin, Texas

### 9.2.1 Background

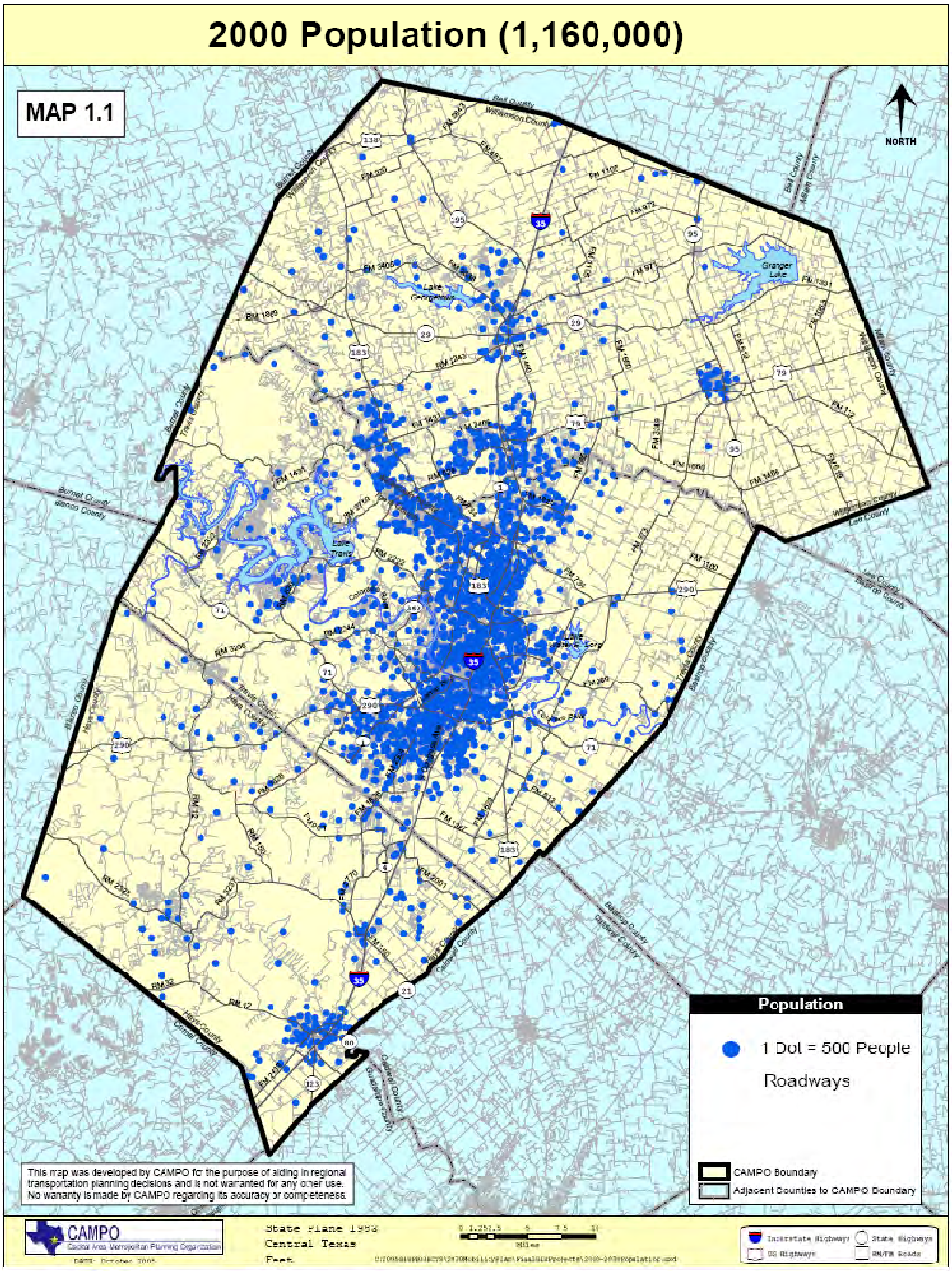
Capital Metropolitan Transportation Authority (Capital Metro) announced a plan to implement BRT service in the Lamar Boulevard corridor through a series of public meetings in Austin, Texas during August 2008. The research team had chosen the Lamar corridor for a case study application of the BRT months before the Capital Metro announcement. In order to avoid any appearance of conflict with the proposed service, the following case study provides an overview of the corridor and its potential, but does not suggest detailed design concepts for the proposed service.

### 9.2.2 Overview

The Lamar corridor serves as one of the major high-intensity multimodal transportation corridors in Austin. This case study includes descriptions of corridor transportation and land use characteristics as well as its central location and existing connections, and the need to increase corridor transportation system capacity.

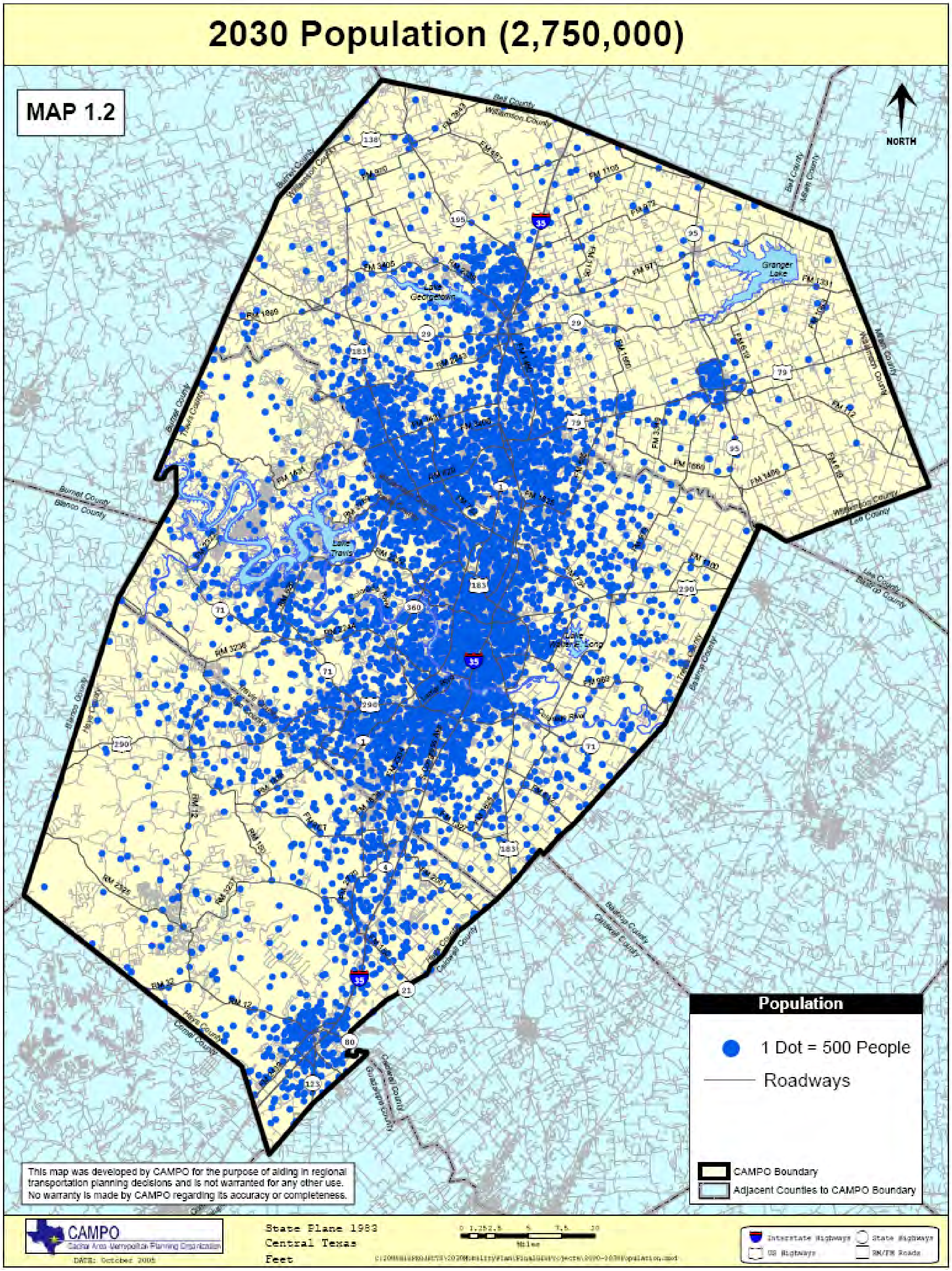
The Austin Metropolitan region has been growing rapidly; the population has almost doubled in the last twenty years. Between 1990 and 2000, the population of Austin Metropolitan Statistical Area (MSA) increased 47.7%. The growth has increased demand for the already over-stressed roadways and transit services in the region. Ranked as one of the most congested midsize cities in the United States, the Austin downtown Interstate 35 (IH 35) section is regarded as one of the top ten most congested freeway segments in the region and the parallel Loop 1 (Mopac freeway) has reached capacity during peak hours for years. There is no doubt that enlarging transportation capacity in the Lamar Boulevard corridor could help alleviate congestion problems.

Figures 9.27, 9.28, and 9.29 illustrate the current and projected future population distributions for the Austin area, as well as, levels of congestion on area transport facilities.



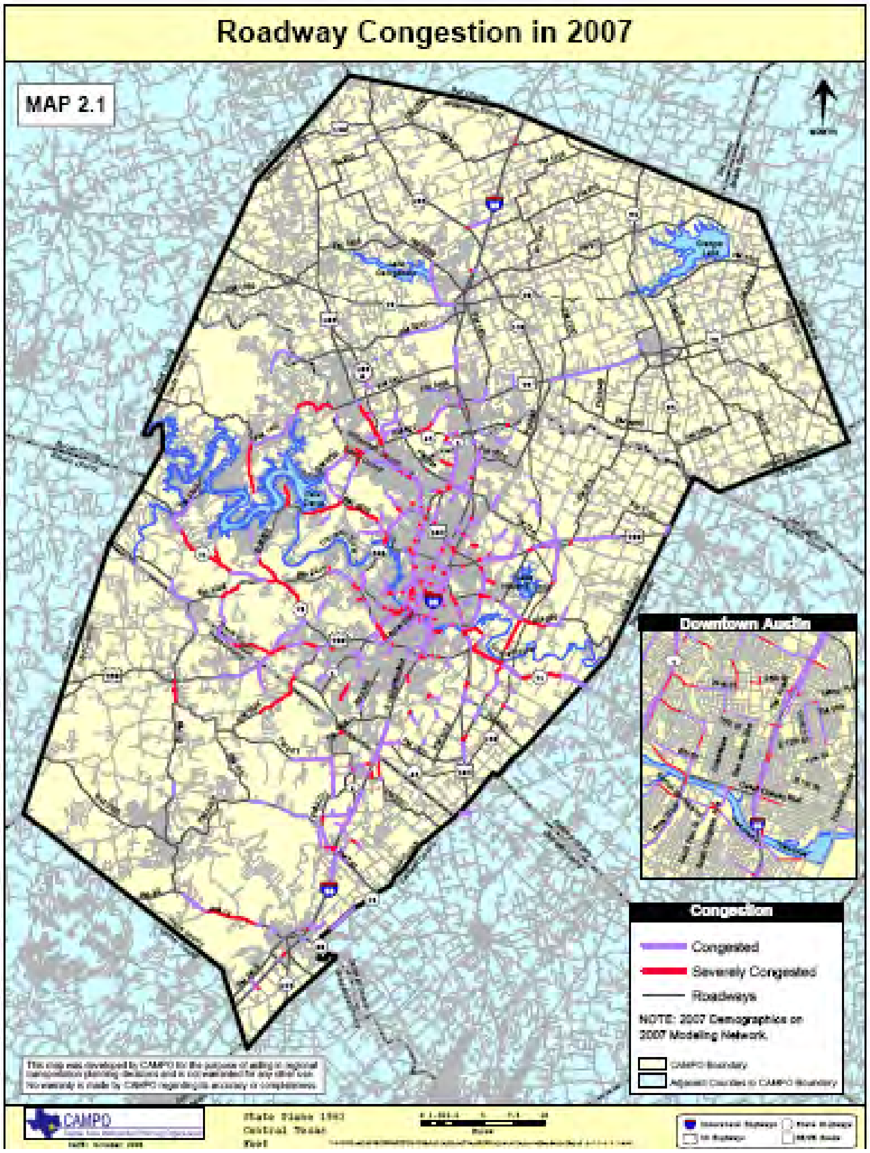

*Source: CAMPO*

*Figure 9.27: Year 2000 Austin area population distribution*




*Source: CAMPO*

*Figure 9.28: Projected Austin area population distribution for year 2030*




*Source: CAMPO*

*Figure 9.29: Austin area congested transportation facilities*

Operating BRT service in the Lamar corridor may achieve the following contributions:

- Improve transportation capacity and efficiency of the corridor and better utilize the existing infrastructure
- Relieve IH 35 congestion, or at least contribute to that congestion relief
- Create a new regional transit route
- Convert the corridor to a more sustainable form that is more transit- and pedestrian-friendly.

Building on its central location and existing connections, bus rapid transit service and economic development on Lamar Boulevard could together create a corridor more representative of the active and diverse communities it runs through.

### 9.2.3 History and Context

Lamar Boulevard has quite a colorful history. After much of Lamar was widened and expanded in 1959, the number of lanes continued to vary from four to six, and continuous two-way left-turn lanes are provided on much of the central city parts of the facility. Figure 9.30 presents a vision of its future.

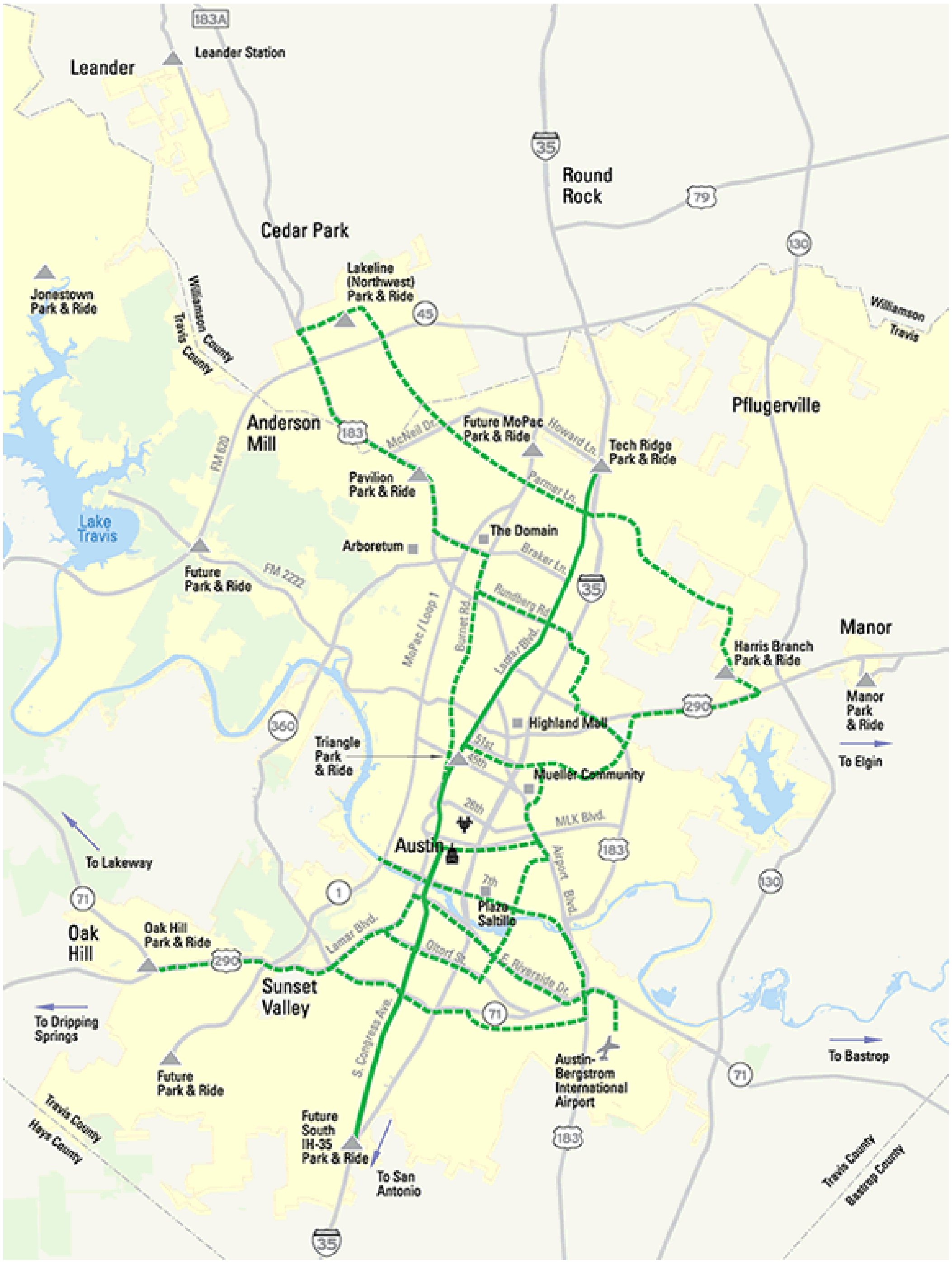



*Figure 9.30: Capital Metro proposed BRT route pattern along Lamar Boulevard (north end) connecting to Congress Avenue (south end)*

### 9.2.4 Lamar Corridor Today

Lamar Boulevard is a major north-south roadway. Between West 45th Street and West 51st Street, Lamar Boulevard is divided into two major roadways; North Lamar Boulevard eventually changes to South Lamar and Guadalupe Street, connecting to The University of Texas at Austin campus and state government offices. The segment where Lamar splits from

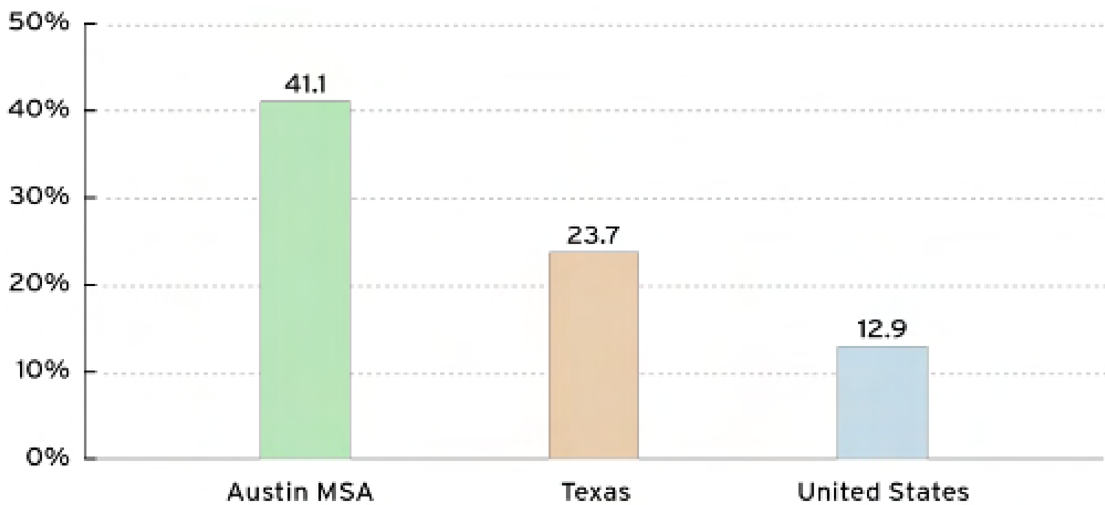
Guadalupe to 45th Street is the so-called "triangle area." Paralleling the name changes are changes in character and roadside development throughout these segments. While the north segment is characterized by multifamily apartments and single-family homes with nodes of denser development as the major ridership generator, the middle segment from 38th Street to downtown is dominated by office buildings and university facilities with strip shopping areas at key intersections. The downtown segment is dominated by office buildings and strip malls.

Some major findings from the investigation of Lamar Boulevard today are:

- The Austin downtown region is expected to continue to grow, placing pressure on the current transportation system and affordable housing.
- Current bus ridership may be below BRT planning thresholds, but has an opportunity to increase.
- The IH 35 corridor is congested and in severe need of relief.
- In the Lamar Boulevard corridor, a Capital Metro commuter bus service (Flyer #101) has been in operation for several years and has significant patronage.
- State, regional, and local transportation planners in the region have been conceptually planning transit elements for this corridor.

### 9.2.5 Austin Regional Growth

Between 1996 and 2006, the population of Austin increased 41.1% to about 1.5 million (Figure 9.31). Experts have predicted that between 2010 and 2020, the Austin region will grow by 30% more in population and experience a continuous increase in jobs. Because the region has a diverse economic base in government, education, and the high tech industry, its economy has been one of the nation's strongest in recent years. Economic prosperity breeds growth in many areas, including travel.




*Source: U.S. Bureau of the Census.*

*Figure 9.31: Austin population growth compared to Texas and U.S. rates (1996-2006)*

For several years in a row, the Texas Transportation Institute has ranked the Austin urbanized area as one of the most congested mid-size cities with vehicular traffic. With no significant roadway facilities on the horizon, other than a few toll lane projects, this trend is likely to continue. At the same time, the region's transit system, Capital Metro, is facing capacity constraints.

Based upon expert interviews and data analysis, factors preventing bus ridership from being higher along the Lamar corridor include:

- Relatively low residential and commercial density;
- Development and road architecture that is auto- and not pedestrian-oriented;
- Lack of facilities that cater to bus riders and pedestrians including few shelters, primitive stop conditions, difficult pedestrian access, and a lack of bus user information sources.

### 9.2.6 Corridor Commuting Patterns

The majority of those residing within one-half mile of Lamar Boulevard, between Tech Ridge Park Center and 38th Street, are students or workers employed by The University of Texas at Austin or state government. With the existing known characteristics of Lamar Boulevard, an analysis was conducted of possible BRT route patterns, stations, and opportunities and challenges.

### 9.2.7 Potential Development Nodes and Stations

Usually nodes serving as existing activity centers that could be redeveloped to transit-supportive densities along the proposed BRT route are regarded as new BRT stop candidates. In general, these sites are primary centers of commercial, retail or employment activities that generate significant daily travel demand. These nodes include:

- **Parmer Lane**. The Parmer Lane corridor is a major harbor of Austin's IT companies. Companies such as IBM and Dell cluster around this area. Also, many strip malls are located around this area, which makes Parmer Lane a very busy traffic corridor.
- **Highland Mall**. Highland Mall, close to Lamar Boulevard and accessible by several arterial streets, was the second mall built in Austin. The mall hosts retail and restaurants, and is classified as a special attractor.
- **The University of Texas at Austin**. The intersection of 26th and Guadalupe Street lies closest to the main campus of The University of Texas at Austin, a major student travel destination and employment center. The single-university campus enrollment has approximately 50,000 undergraduate and graduate students, and 21,000 faculty and staff. It currently holds the largest enrollment of all colleges in the state of Texas.
- **Texas State Government** The Texas State Government complex includes the State Capitol on 11th Street northward to MLK Boulevard generally adjacent to and east of Guadalupe Street. It is a major employment center providing office facilities for more than 20,000 Texas state employees.

- **Oltorf Street, Riverside Drive** The two intersections of Oltorf Street and Congress Avenue, and Riverside Drive and Congress Avenue, are primary activity nodes for the southern extension of the Lamar corridor. Like the middle segment of the BRT route, the southern segment generates major traffic volumes that currently use IH 35, Congress Avenue, and South Lamar Boulevard.

### 9.2.8 Vehicle Characteristics

The vehicle proposed by Capital Metro for use on this BRT line is an articulated vehicle (two short buses connected by an accordion-like device), allowing one driver to drive more passengers per vehicle. This vehicle's length is limited by the geometry of this corridor (and there are no plans to acquire any property even in tight spots such as Guadalupe at 29$^{th}$ Street). Operating larger vehicles could achieve a slightly lower operating cost from the existing Flyer Route101 bus. Passenger comfort might be slightly improved with a larger vehicle.

### 9.2.9 Opportunities of the Corridor

Several opportunities and challenges exist for BRT along the Lamar Boulevard corridor. An integrated land use and transportation plan for the corridor can be visualized:

- BRT has been widely accepted as an effective tool to improve transit efficiency, sustainability, and pedestrian friendliness.
- The initial BRT implementation will use lower-cost, short-term bus improvements, which may enhance bus ridership quickly and help to spur transit-related development in the corridor.
- Certain bottleneck segments, such as the Triangle section, have great potential for widening without significant right-of-way requirements and can greatly improve the current traffic situation.

### 9.2.10 Stations

After choice of the termini, a conceptual plan was developed for the Lamar corridor including the following eight locations for potential primary BRT stations:

**Lamar Corridor (north end of corridor)**

- Tech Ridge park and ride
- Parmer Lane
- Highland Mall
- The University of Texas at Austin
- Texas State Government Complex

**Congress Avenue (south end of corridor)**

- Riverside Drive
- Oltorf Street

- Riverside Drive, and
- Ben White-Congress park and ride
- Future I 35-Slaughter Lane park and ride

These stations would serve as transfer stops between local bus/circulator service and Lamar Boulevard. In addition, each station would offer passenger amenities similar to a Metrorail station such as real-time transit information and pedestrian improvements.

A limited number of stops provide longer distances between stops than on a typical city bus route. Limiting stops would provide higher speeds and is commonly thought of as a necessary prerequisite for BRT.

#### 9.2.11 Summary

The proposed BRT service along the Lamar Boulevard corridor is an appropriate application of the BRT concept. The corridor has excellent potential for becoming a good demonstration of BRT as a corridor capacity improvement that is very cost effective.

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# Appendix A: BRT System Data

- Table A1: BRT System Characteristics for the 22 U.S. Cities Included in the Cross Sectional Analysis
- Table A2: Components of Los Angeles, Pittsburgh, Phoenix, Chicago, and Honolulu BRT Systems

**Table A1: BRT System Characteristics for the 22 U.S. Cities Included in the Cross Sectional Analysis**

| | **Boston** **Silver Line** | **Chicago** **Express (overall)** | **Charlotte** **(Planning)** | **Honolulu** **City Express (overall)** | **Las Vegas** **North Las Vegas Max** |
|---|---|---|---|---|---|
| **Running Way** | | | | | |
| **Exclusive Lanes** | **NO** | **NO** | **YES** | **NO** | **YES** |
| Mixed Flow Lanes(miles) | 0.2 | 36.7 | 0 | 56.6 | 2.9 |
| Dedicated Lanes (miles) | 2.2 | 0 | 28 | 0 | 4.7 |
| **Vehicles** | | | | | |
| Vehicle Type | Specialized BRT Vehicle | Conventional Standard (40') | Conventional Standard (40') | Conventional Articulate (60') | Specialized BRT Vehicle |
| Aesthetic Enhancements | Specialized Lively | Specialized Lively | Specialized Lively | Specialized Lively | Specialized Lively Large Windows |
| Passenger Circulation Enhancements | Additional Door Channels | Additional Door Channels | Additional Door Channels | Additional Door Channels | Alternative Seat Layout, Internal Bicycle Racks |
| Propulsion System | Diesel ICE | Diesel ICE | Diesel ICE | ICE- Ultra-Low Sulfur Diesel | Diesel Electric Hybrid |
| **ITS** | | | | | |
| Transit Signal Priority | YES (in 2004) | YES | YES | YES | YES |
| **Stations** | | | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | | | |
| Fare Collections Process | Pay on board | Pay on board | Pay on board | Pay on board | Pay on board |
| **Service Plans** | | | | | |
| Service Frequency (Peak Headway in Minutes) | 4 | 9 | 9 | 11 | 12 |

*Table A1: BRT System Characteristics for the 22 U.S. Cities Included in the Cross Sectional Analysis (continued)*

| | **Los Angeles** **Metro Rapid (Overall)** | **Miami** **BUSWAY** | **Oakland** **Rapid Bus** | **Orlando** **LYMMO** | **Phoenix** **RAPID (Overall)** |
|---|---|---|---|---|---|
| **Running Ways** | | | | | |
| **Exclusive Lanes** | NO | YES | NO | YES | YES |
| Mixed Flow Lanes(miles) | 115.3 | 0 | 14 | 0 | 31.6 |
| Dedicated Lanes (miles) | 0 | 8 | 0 | 3 | 43.8 |
| **Vehicles** | | | | | |
| Vehicle Type | Standard | Standard, Articulated, Minis | Stylized Standard (40.5') | Standard, Articulated, Minis | Stylized Standard |
| Aesthetic Enhancements | Specialized Lively Large Windows | Specialized Lively Large Windows | Specialized Lively Large Windows | Specialized Lively | Specialized Lively |
| Passenger Circulation Enhancements | Alternate Seat Layout | Alternate Seat Layout | Additional Door Channels; Enhanced Wheelchair Securement | Alternate Seat Layout | Alternate Seat Layout |
| Propulsion System | ICE-CNG | ICE-Diesel | ICE-CNG | ICE-Diesel | LNG |
| **ITS** | | | | | |
| Bus Signal Priority | YES | YES | YES | YES | YES |
| **Stations** | | | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | | | |
| Fare Collections Process | Pay on board | Pay on board | Pay on board | Pay on board | Pay on board |
| **Service Plans** | | | | | |
| Service Frequency (Peak Headway in Minutes) | 14 | 10 | 12 | 5 | 10 |

*Table A1: BRT System Characteristics for the 22 U.S. Cities Included in the Cross Sectional Analysis (continued)*

| | **Pittsburgh**<br>**BUSWAY (Overall)** | **Seattle**<br>**RapidRide** | **Eugene**<br>**EMX** |
|---|---|---|---|
| **Running Ways** | | | |
| **Exclusive Lanes** | YES | YES | YES |
| Mixed Flow Lanes(miles) | 20.8 | 36.7 | |
| Dedicated Lanes (miles) | 3.0 | 0 | 4 |
| **Vehicles** | | | |
| Vehicle Type | Standard, Articulated, Minis | Standard | Articulate |
| Aesthetic Enhancements | Specialized Lively | Specialized Lively | Specialized Lively |
| Passenger Circulation Enhancements | Level of boarding | Level of boarding | Level of boarding |
| Propulsion System | ICE-CNG | ICE-Diesel | Hybrid-Electric |
| **ITS** | | | |
| Bus Signal Priority | YES | YES | YES |
| **Stations** | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | |
| Fare Collections Process | Pay on board | Pay on board | Pay on board |
| **Service Plans** | | | |
| Service Frequency (Peak Headway in Minutes) | 15 | 10 | 11 |

*Table A1: BRT System Characteristics for the 22 U.S. Cities Included in the Cross Sectional Analysis (continued)*

| | **Alameda**<br>**San Pablo Rapid** | **Montgomery**<br>**(Planning)** | **Santa Clara**<br>**VTA Rapid 522** | **Louisville**<br>**(on Hold)** |
|---|---|---|---|---|
| **Running Ways** | | | | |
| **Exclusive Lanes** | NO | YES | YES | |
| Mixed Flow Lanes(miles) | 7.0 | 0 | N/A | |
| Dedicated Lanes (miles) | 0 | 6.0 | N/A | |
| **Vehicles** | | | | |
| Vehicle Type | Van Hool Bus | Standard | Articulate | |
| Aesthetic Enhancements | Specialized Lively | Specialized Lively | Specialized Lively | |
| Passenger Circulation Enhancements | Third rear door | Level of boarding | Level of boarding | |
| Propulsion System | Diesel, Hybrid | ICE-Diesel | ICE-Diesel | |
| **ITS** | | | | |
| Bus Signal Priority | YES | YES | YES | |
| **Stations** | | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter | |
| **Fare Collections** | | | | |
| Fare Collections Process | Pay on board | Pay on board | Pay on board | |
| **Service Plans** | | | | |
| Service Frequency (Peak Headway in Minutes) | 10 | 10 | 15 | |

*Table A1: BRT System Characteristics for the 22 U.S. Cities Included in the Cross Sectional Analysis (continued)*

| | **Dulles (Early Planning)** | **Cleveland (Under Construction)** | **Albany (Planning)** | **Kansas City MAX** |
|---|---|---|---|---|
| **Running Ways** | | | | |
| **Exclusive Lanes** | **YES** | **YES** | **YES** | **YES** |
| Mixed Flow Lanes(miles) | 0 | 1.2 | 0 | 5.5 |
| Dedicated Lanes (miles) | 23 | 5.5 | 16.5 | 3.5 (peak hour) |
| **Vehicles** | | | | |
| Vehicle Type | Articulated Buses | Articulated Buses | Articulated Buses | Standard |
| Aesthetic Enhancements | Specialized Lively | Specialized Lively | Specialized Lively | Specialized Lively |
| Passenger Circulation Enhancements | Level of boarding | Level of boarding | Level of boarding | Level of boarding |
| Propulsion System | Hybrid-Electric | Hybrid Diesel -Electric | Hybrid-Electric | Diesel |
| **ITS** | | | | |
| Bus Signal Priority | YES | Yes | YES | Yes |
| **Stations** | | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | | |
| Fare Collections Process | off- board Payment | off- board Payment | off- board Payment | off- board Payment |
| **Service Plans** | | | | |
| Service Frequency (Peak Headway in Minutes) | 9 | 9 | 9 | 9 (peak hour) |

*Table A1: BRT System Characteristics for the 22 U.S. Cities Included in the Cross Sectional Analysis (continued)*

| | **Minneapolis (Planning)** |
|---|---|
| **Running Ways** | |
| **Exclusive Lanes** | YES |
| Mixed Flow Lanes(miles) | |
| Dedicated Lanes (miles) | 22.0 |
| **Vehicles** | |
| Vehicle Type | Articulated Buses |
| Aesthetic Enhancements | Specialized Lively |
| Passenger Circulation Enhancements | Level of boarding |
| Propulsion System | Hybrid-Electric |
| **ITS** | |
| Bus Signal Priority | YES |
| **Stations** | |
| Station Type | Enhanced Shelter |
| **Fare Collections** | |
| Fare Collections Process | Pay On-Board |
| **Service Plans** | |
| Service Frequency (Peak Headway in Minutes) | 7 |

**Table A2: Components of Los Angeles, Pittsburgh, Phoenix, Chicago and Honolulu BRT Systems**

| | Los Angeles | | | |
|---|---|---|---|---|
| | **Metro Rapid Broadway** | **Metro Rapid Florence** | **Metro Rapid Wilshire** | **Metro Rapid Ventra** |
| **Running Ways** | | | | |
| **Exclusive Lanes** | NO | NO | NO | NO |
| Mixed Flow Lanes(miles) | 10.5 | 10.3 | 25.7 | 16.7 |
| Dedicated Lanes (miles) | 0 | 0 | 0 | 0 |
| **Vehicles** | | | | |
| Vehicle Type | Standard | Standard | Standard | Standard |
| Aesthetic Enhancements | Specialized Lively Large Windows | Specialized Lively Large Windows | Specialized Lively Large Windows | Specialized Lively Large Windows |
| Passenger Circulation Enhancements | Level of boarding | Level of boarding | Level of boarding | Level of boarding |
| Propulsion System | ICE-CNG | ICE-CNG | ICE-CNG | ICE-CNG |
| **Bus Signal Priority** | | | | |
| Bus Signal Priority | YES | YES | YES | YES |
| **Stations** | | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | | |
| Fare Collections Process | Pay on board | Pay on board | Pay on board | Pay on board |
| **Service Plans** | | | | |
| Service Frequency (Peak Headway in Minutes) | 30 | 11 | 9 | 30 |

*Table A2: Components of Los Angeles, Pittsburgh, Phoenix, Chicago and Honolulu BRT Systems (continued)*

| | **Los Angeles** | | |
|---|---|---|---|
| | **Metro Rapid Vermont** | **Metro Rapid Crenshaw** | **Metro Rapid Van Nuys** |
| **Running Ways** | | | |
| **Exclusive Lanes** | NO | NO | NO |
| Mixed Flow Lanes(miles) | 11.9 | 18.8 | 21.4 |
| Dedicated Lanes (miles) | 0 | 0 | 0 |
| **Vehicles** | | | |
| Vehicle Type | Standard | Standard | Standard |
| Aesthetic Enhancements | Specialized Lively Large Windows | Specialized Lively Large Windows | Specialized Lively Large Windows |
| Passenger Circulation Enhancements | Level of boarding | Level of boarding | Level of boarding |
| Propulsion System | ICE-CNG | ICE-CNG | ICE-CNG |
| **Bus Signal Priority** | | | |
| Bus Signal Priority | YES | YES | YES |
| **Stations** | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | |
| Fare Collections Process | Pay on board | Pay on board | Pay on board |
| **Service Plans** | | | |
| Service Frequency (Peak Headway in Minutes) | 4 | 13 | 15 |

*Table A2:Components of Los Angeles, Pittsburgh, Phoenix, Chicago and Honolulu BRT Systems (continued)*

| | **Pittsburgh** | | |
|---|---|---|---|
| | **East Busway** | **South Busway** | **West Busway** |
| **Running Ways** | | | |
| **Exclusive Lanes** | NO | NO | YES |
| Mixed Flow Lanes(miles) | 10.5 | 10.3 | 0 |
| Dedicated Lanes (miles) | 0 | 0 | 3.0 |
| **Vehicles** | | | |
| Vehicle Type | Standard | Standard | Standard |
| Aesthetic Enhancements | Specialized Lively Large Windows | Specialized Lively Large Windows | Specialized Lively Large Windows |
| Passenger Circulation Enhancements | Level of boarding | Level of boarding | Level of boarding |
| Propulsion System | ICE-CNG | ICE-CNG | Diesel |
| **Bus Signal Priority** | | | |
| Bus Signal Priority | YES | YES | YES |
| **Stations** | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | |
| Fare Collections Process | Pay on board | Pay on board | Free Fare |
| **Service Plans** | | | |
| Service Frequency (Peak Headway in Minutes) | 30 | 11 | 5 |

*Table A2:Components of Los Angeles, Pittsburgh, Phoenix, Chicago and Honolulu BRT Systems (continued)*

| | **Phoenix** | | | |
|---|---|---|---|---|
| | **RAPID I-10 East** | **RAPID I-10 West** | **RAPID SR-51** | **RAPID I-17** |
| **Running Ways** | | | | |
| **Exclusive Lanes** | YES | YES | NO | NO |
| Mixed Flow Lanes(miles) | 6.5 | 4.8 | 10.3 | 11.5 |
| Dedicated Lanes (miles) | 14.0 | 8.0 | 0 | 0 |
| **Vehicles** | | | | |
| Vehicle Type | Stylized Standard | Stylized Standard | Stylized Standard | Stylized Standard |
| Aesthetic Enhancements | Specialized Lively | Specialized Lively | Specialized Lively | Specialized Lively |
| Passenger Circulation Enhancements | Level of boarding | Level of boarding | Level of boarding | Level of boarding |
| Propulsion System | LNG | LNG | LNG | LNG |
| **Bus Signal Priority** | | | | |
| Bus Signal Priority | YES | YES | YES | YES |
| **Stations** | | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | | |
| Fare Collections Process | Pay on board | Pay on board | Pay on board | Pay on board |
| **Service Plans** | | | | |
| Service Frequency (Peak Headway in Minutes) | 10 | 10 | 10 | 10 |

*Table A2:Components of Los Angeles, Pittsburgh, Phoenix, Chicago and Honolulu BRT Systems (continued)*

| | **Chicago** | | |
|---|---|---|---|
| | **Western Avenue Express** | **Irving Park Express** | **Garfield Express** |
| **Running Ways** | | | |
| **Exclusive Lanes** | **NO** | **NO** | **NO** |
| Mixed Flow Lanes(miles) | 18.3 | 9.0 | 9.4 |
| Dedicated Lanes (miles) | 0 | 0 | 0 |
| **Vehicles** | | | |
| Vehicle Type | Conventional Standard (40') | Conventional Standard (40') | Conventional Standard (40') |
| Aesthetic Enhancements | Specialized Lively | Specialized Lively | Specialized Lively |
| Passenger Circulation Enhancements | Level of boarding | Level of boarding | Level of boarding |
| Propulsion System | Diesel ICE | Diesel ICE | ICE-Diesel |
| **Bus Signal Priority** | | | |
| Bus Signal Priority | NO | NO | NO |
| **Stations** | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | |
| Fare Collections Process | Pay On-Board | Pay On-Board | Pay on Board |
| **Service Plans** | | | |
| Service Frequency (Peak Headway in Minutes) | 12 | 12 | 11 |

*Table A2:Components of Los Angeles, Pittsburgh, Phoenix, Chicago and Honolulu BRT Systems (continued)*

| | **Honolulu** | | |
|---|---|---|---|
| | **City Express A** | **City Express B** | **City Express C** |
| **Running Ways** | | | |
| **Exclusive Lanes** | **NO** | **NO** | **NO** |
| Mixed Flow Lanes(miles) | 19.6 | 7.0 | 30.0 |
| Dedicated Lanes (miles) | 0 | 0 | 0 |
| **Vehicles** | | | |
| Vehicle Type | Conventional Standard (60’) | Conventional Standard (60’) | Conventional Standard (60’) |
| Aesthetic Enhancements | Specialized Lively | Specialized Lively | Specialized Lively |
| Passenger Circulation Enhancements | Level of boarding | Level of boarding | Level of boarding |
| Propulsion System | Ultra Low Sulfur Diesel | Ultra Low Sulfur Diesel | Ultra Low Sulfur Diesel |
| **Bus Signal Priority** | | | |
| Bus Signal Priority | YES | YES | YES |
| **Stations** | | | |
| Station Type | Enhanced Shelter | Enhanced Shelter | Enhanced Shelter |
| **Fare Collections** | | | |
| Fare Collections Process | Pay on board | Pay on board | Pay on board |
| **Service Plans** | | | |
| Service Frequency (Peak Headway in Minutes) | 11 | 30 | 30 |