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Estimating the bus user time benefits of implementing a median busway: Methodology and case study

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ABSTRACT

This paper presents a general framework to estimate the bus user time benefits of a median busway including the effects on travel time and access time. Unlike previous models, we take into account the effects of geometry and the interaction with the demand structure. Models for predicting the bus in-vehicle time benefits of a median dual carriageway busway against mixed traffic condition on 2 and 3 lanes roads are estimated using data from a case study in Santiago (Chile), using a bus travel time model empirically estimated and considering different base case situations, including mixed traffic operations and bus lanes. Results of the application show that the expected in-vehicle time savings of a median busway might be reduced by access time losses due to increased walking distances and road crossing delays. Also, that net time benefits can vary significantly according to the base situation and the structure of demand considered. These findings point out to the need of including a wider set of impacts when studying the benefits of median busways, beyond in-vehicle time savings only. The empirical work presented here is completely based on passive data coming from GPS and smartcards, what makes easier and cheaper to conduct this type of analysis as well as to do it with a comprehensive scope at an early stage of the development of a BRT project. This framework can be extended to other types of dedicated bus lanes provided that a corresponding bus travel time savings model is available.

1. Introduction

Many growing cities around the world share the perspective of a future scenario of high congestion, rapid motorization growth, and difficult traffic conditions. Within this context, bus rapid transit (BRT) systems are viewed as an alternative for improving travel conditions because they can provide high-standard public transport services at a lower capital cost and with shorter construction times than rail-based systems, such as train or metro systems (Wright and Hook, 2007) with more flexibility to adapt to a rapidly changing environment (Cervero, 2013).

Segregated bus lanes (busways) are a key component of BRT systems because these lanes isolate the bus flow from the congestion caused by private cars and other vehicles, reducing travel time. Many segregated bus corridors, curbside lanes, and other types of segregated busways have been constructed around the world (Hensher and Golob, 2008; Wirasinghe et al., 2013). Within a BRT project, the infrastructure for dedicated bus lanes is typically the most expensive and most controversial component because these lanes affect other vehicles and the urban environment near the corridor. There are different approaches to implement dedicated bus corridors, which can vary from a painted bus lane to a specially built tunnel or

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elevated structure. Other elements such as stations, vehicles, fare collection systems, and operation control systems, are typically compatible with any type of dedicated bus lane infrastructure and can be evaluated independently.

Given the increasing interest in BRT systems around the world, it is timely to count with comprehensive approaches to estimate benefits and costs of such systems, that can be used as input to guide design decisions. In this article, we focus on median (central segregated) busways only, which have been implemented in several cities (e.g., Jakarta, Beijing, Seoul, Cleveland, Vancouver, Nantes, Bogotá, Curitiba, Santiago and many others). Central segregated bus corridors are a clear concept but can be implemented with varying features, including the number of bus and private vehicle lanes, and the presence of overtaking lanes at stations. These corridors are typically considered the best option for dedicated bus lanes because the private vehicle movements at intersections or property entrances do not affect bus operations and vice versa. Empirical evidence on the running time savings accrued by segregated busways abound (see, e.g., TRB, 2007; Wright and Hook, 2007).

Impacts of segregated busways on other stages of the users travel time, such as access and waiting times, are less apparent. In particular the impact of median busways on access times has not been properly assessed with numeric methods and have not been estimated in well-known BRT design guidelines, such as the guides by the Transportation Research Board (TRB, 2007) and by the Institute of Transportation and Development Policy (Wright and Hook, 2007). Moving a bus stop from the curbside to the median does increase access distance as users need to cross a number of road lanes to reach the stop, and extra sources of delays are present if a traffic signal is in place.

In the literature, there are several analytical models that optimize bus stop spacing by studying the tradeoff between access and in-vehicle time, that is introduced by increasing the number of bus stops (e.g., Mohring, 1972; Kuah and Perl, 1988; Chien and Schonfeld, 1998; Furth and Rahbee, 2000; Chien and Qin, 2004; Ibeas et al., 2010). It has been shown that with segregated busways optimal bus stop spacing increases, due to the increase in acceleration/deceleration delays at bus stops when buses reach a larger cruising speed, as is the case on segregated busways as compared against mixed-traffic operations (Tirachini, 2014). More sophisticated works on access time modeling go beyond the traditional framework that assumes demand uniformly distributed along bus corridors or urban areas, to incorporate information from Geographic Information System (GIS) platforms, that makes possible to identify more precise walking distances to bus stops that can be embedded in models to optimize bus stop location (Furth et al., 2007; El-Geneidy et al., 2010). However, all bus stop spacing optimization models do not estimate or analyze the effect of median busways on access time from the sidewalk to the median, which is introduced and estimated in this article.

Another issue that has been disregarded in the literature is that to build up a median busway in an existing road section may often imply a variation (likely an increase) of the signalized intersections density. It arises from the need to protect crossing pedestrians that will have to walk longer distances, the bus passenger movements between bus-stops and sidewalks and, in some cases, buses exiting the busway to make a turn in a nearby intersection. Also, traffic signal timing will be affected by changes in road geometry. These impacts may reduce the benefits in running time of the median busway especially in off-peak periods where signal cycle times will be longer than those needed without the busway.

Regarding the effect on waiting time, segregated busways in general reduce running times, which, depending on operational decisions, may be translated in an increase of service frequency and therefore a reduction of waiting times, or may be used by the operator to reduce fleet size, keeping frequency constant. However, even if the bus frequency is kept constant after the introduction of a busway, there is a likely effect of bus segregation on reducing travel time variability (Diab and El-Geneidy, 2013), which in turn induces a reduction of headway variability and therefore a reduction of average waiting times (Osuna and Newell, 1972; Eberlein, 1995; Hickman, 2001).

The objective of this paper is to provide a general framework to estimate the benefits of any type of median busway project and any base-case scenario in terms of bus user time, including both in-vehicle and access time costs, under reasonable assumptions and using easily accessible information that is likely to be available at the early stages of the planning process. The base case only assumes that buses use curbside lanes, in which even other types of bus priority, such as bus lanes, may exist.

We generalize traditional analyses that focus on running times, to include impacts on access distance and access time due to the implementation of median busways, which have been disregarded in the previous literature. The benefits of median busways are overestimated if their impact on increasing access time is ignored, as previously done in the BRT design and research literature. The main contribution of this paper is the developing of a formal model to quantify impacts of median busways not only on in-vehicle times but also on access times and the inclusion of effects derived from changes in road geometry.

The model is applied to a real median busway in Santiago, Chile, in which we show that the effects on access times are far from marginal. We account for the fact that in central corridors, passengers must access bus stops located at the center of the road from the location where their activities occur, which may imply some additional walking time and delay. The access time costs also depend on the type of infrastructure implemented.

The application relates to a dual carriageway median busway, where the base situation is mixed traffic (MT) on two or three lanes per traffic direction. A detailed model of the bus travel time for such a case has been estimated in Santiago, Chile, developed in Gibson et al. (2015), from which we derive a model to estimate in-vehicle time benefits.

The remainder of this article is organized as follows. A general model to estimate user benefits of a median busway is presented in Section 2. Section 3 presents a model to estimate in-vehicle time benefits derived from the case study of Santa Rosa. Section 4 presents the results from the application of the modeling framework proposed in Section 2 to the case study. Section 5 presents the conclusions of this study.

2. Model for bus user time benefits due to a median busway

2.1. Basic assumptions

Consider a road segment where buses currently operate under any arrangement at curbside lanes (e.g., Fig. 1a), and there is the possibility of implementing a median busway, as illustrated in Fig. 1b. In the current situation, the median drawn in Fig. 1a may or may not exist, and the number of lanes per direction in each situation may vary. Depending on these parameters, some changes to the geometric variables as defined below may be necessary.

Such a project will have effects on all right-of-way users (car and other vehicles, passengers, pedestrians); however, in this paper, we will focus only on bus passenger time. A full benefit assessment must consider other users and operating costs as well as potential effects on the urban setting and environment. Additionally, any possible effects on the demand will not be considered at this stage, assuming that its amount and structure remain unchanged.[1] Therefore, passenger and bus flows are assumed to be constant.

The most relevant time-related effects of a busway are reductions in cruising time and intersection delays, affecting the level of service perceived by users via the in-vehicle-travel time and the system operation through a decrease in bus cycle time. We will assume that the latter is employed by the operator in reducing the fleet size such that the service frequency and passenger waiting time remain unchanged.[2]

Passenger service time (boarding and alighting) should not be affected by the busway *per se*; this time could be affected if different bus stop designs or fare collection methods were devised (Wright and Hook, 2007; Tirachini and Hensher, 2011); however, these changes can be made irrespective of the existing type of right of way. The same can be assumed regarding bus queuing delays that occur at bus stops in high-frequency high-demand markets; in principle these delays do not change if a busway is implemented, unless bus flow is also increased or reduced. On the other hand, the time required for a bus to decelerate to or accelerate from a complete stop is greater if a bus is moving at a higher speed, as is usually the case in segregated busways. This effect must be considered. Finally, access time to/from the bus stop may also be affected by a median busway, as illustrated on the right side of Fig. 1b. The magnitude of this effect depends on the geometry and the interaction with the traffic control system (signal settings). In the next section we develop a model that accounts for the aforementioned effects of segregated median busways.

2.2. Discounted travel time

We conduct the analysis of bus circulation on a road stretch of length L, which can be used only by buses or shared with multiple modes (e.g., buses, cars, trucks, motorcycles, bicycles), at a disaggregate level. As bus passenger demand and vehicle flows vary both temporally and spatially, a proper characterization of in-vehicle time and access time should also account for differences in space and time. Therefore, a division of the relevant road stretch into sections is performed, together with the consideration of different time periods that account for temporal differences in demand and flow. The size of the sections and periods should warrant internal homogeneity. The type of day (e.g., working, weekend, holiday) may also be differentiated.

Given that passenger service times (boarding and alighting) are not affected by a median busway by itself, this component of the bus travel time is isolated and disregarded to perform a fair comparison of time savings and losses due to the implementation of busways, if the impact is measured in relative terms. Therefore, to analyze the effect of the median busway on the speed profile of vehicles, isolated from the passenger operations at bus stops, we define and use a *discounted in-vehicle time*, calculated as the time to traverse a given road section, minus the time required for passengers to board and/or alight plus any additional delays due to bus stop congestion within that road section. Formally, we define $DIVTB^{ijk}$ as the discounted in-vehicle time for segment i, period j, and day k, normalized by distance (s/km). $DIVTB^{ijk}$ can be estimated if a bus travel time model is available, as done in Section 3.

2.3. Access time modeling

For the analysis of access time, we make two further assumptions: (i) the bus-stop platform is located at the same distance of pedestrian crossing in the situations with and without median busway and (ii) all passenger (pedestrian) crossings are controlled by traffic signals in both situations. Then, the following cases can be identified:

a. For buses operating at curbside lanes either in mixed traffic (MT) or dedicated bus lanes, as illustrated in Fig. 1a, passengers who access/leave the bus stop platform from/toward a location along the same sidewalk (X in Fig. 1a) do not experience any delay due to the traffic signal, and the walking time to/from the bus stop can be neglected. Therefore, their total access time can be assumed to be zero. Passengers who access/leave the stop from/toward the opposite

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[1] TRB (2003) suggests that when allocating road space to segregated busways, total time savings to bus users should be larger than total time losses to car users. However, more generally, a cost–benefit analysis of segregated busways should include short and medium term effects on modal demand. A recent economic model for the analysis of road space allocation combined with other urban transport policies is provided by Basso and Silva (2014).

[2] If a reduction in running time is only partly absorbed by decreasing the number of buses operating, bus frequency also increases which will reduce waiting time costs and scheduling delays for users.

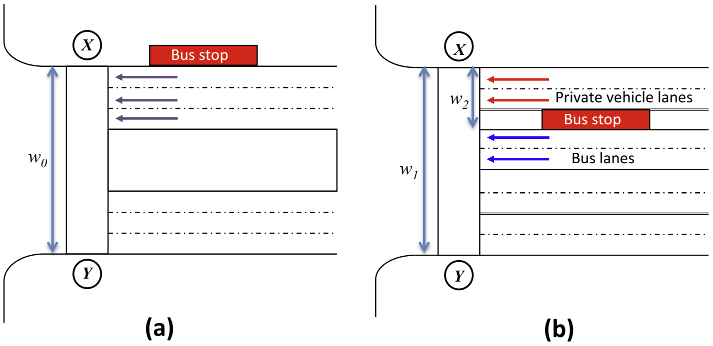

Fig. 1. Simplified layout before and after median busway.

sidewalk (Y in Fig. 1a) require some time to cross the street. That time has two components: the walking time required to cross the entire road that will be equal to the road width w_0 (m) divided by the pedestrian walking speed ps (m/s) and the delay associated with the traffic signal. The passengers may require one or two stages to cross, depending on w_0, ps, and the signal settings. Therefore, the delay associated with the traffic signal in the case without the median corridor can be written as $(1+\beta)d_0$, where d_0 (s) is the delay associated with crossing in one stage and β is a parameter that can vary from zero to two depending on the geometry of the intersection and signal settings for the pedestrian crossing stage(s).

b. For a median busway, as illustrated in Fig. 1b, passengers coming from/going toward both sides of the road will require some time to access the bus stop platform. Passengers who come from/go toward location X in Fig. 1b will experience a walking time equal to the distance from the sidewalk to the platform w_2 (m) divided by the average pedestrian crossing speed ps (m/s) plus a delay d_2 (s) due to the signal settings associated with crossing w_2. Passengers coming from/going to location Y in Fig. 1b will experience a walking time required to cross from/to the central platform $(w_1 - w_2)/ps$ and a delay due to the signal settings d_1 (s). We consider that in the situation with a median busway, all relevant passengers crossings are performed in one stage.

Next we calculate the net effect of implementing a median busway on access time. Let us consider section i, period j, and day k. Defining α as the proportion of transferring passengers that come/go from/to a location on the same side of the bus stop platform (X in Fig. 1), the average time benefits due to the access time denoted by ATB and calculated as the difference between the total time required for a passenger to access the bus stop in the situations without and with the median busway are given by

$$ATB^{ijk} = (1-\alpha^{ijk})\left(d_2^{ijk} - d_1^{ijk} + (1+\beta^{ijk})d_0^{ijk}\right) - (2\alpha^{ijk}-1)\frac{w_2}{ps^{ij}} - (1-\alpha^{ijk})\frac{w_1 - w_0}{ps^{ij}} - d_2^{ijk} \qquad (1)$$

This equation can be evaluated with average values for all bus stops in a route section or separately for each of them and then make a summation. ATB^{ijk} represents the average time gains (losses if negative) per passenger accessing the bus stop platform in one direction, in seconds (s). Although the first two terms in (1) may have any sign, ATB^{ijk} is expected to be negative, i.e., there will be losses to bus users in this respect, when accessing buses on median busways relative to curbside circulation.

2.4. Total time benefits

Once discounted in-vehicle time and access time benefits and costs are identified, the total time benefits for bus users on day k, TB^k in (h/day) are estimated as:

$$TB^k = \sum_{ij} TB^{ijk} = \sum_{ij}\left(DIVTB^{ijk}\,LF^{ijk} + ATB^{ijk}\frac{NTP^{ijk}}{L^i}\right)\frac{NB^{ijk}\,L^i}{3600} \qquad (2)$$

where

LF^{ijk}: average load factor for section i, period j and day k (pass/bus).
NTP^{ijk}: average number of transferred passengers for section i, period j, and day k (pass/bus).
L^i: length of section i (km).
NB^{ijk}: average number of buses traveling in section i during period j and day k (bus).

The unit time saving per traveling bus passenger, expressed in (s/km), resulting from dividing the right-hand side of (2) by $NB^{ijk}\,L^i\,LF^{ijk}/3600$ is

$$UTB^{ijk} = DIVTB^{ijk} + ATB^{ijk}\,PR^{ijk} \tag{3}$$

where PR^{ijk} is defined as the passenger renewal rate per km for section *i*, period *j* and day *k* $\left(PR^{ijk} = \frac{NTP^{ijk}}{L^i\,LF^{ijk}}\right)$. In (3) the same weight for access and in-vehicle times is assumed. Depending on the use given to the results of the formula, it may be necessary to penalize ATB, as many studies report that the walking and waiting times have a higher value of travel time savings than in-vehicle time. If the objective is to use these figures for project appraisal, then the use of different weights for access and in-vehicle time depends on the approach used by the local authorities. In Chile, only one social value of time is used to evaluate any time benefits of an urban transport project (independent of the type of user, activity at the destination, or type of time) (Ministerio de Desarrollo Social, 2012).

3. Case study: a model to estimate in-vehicle time benefits

This section demonstrates how to obtain a model to estimate user benefits in terms of in-vehicle travel time with the high degree of space–time disaggregation required by Eq. (2). A model for the estimation of bus travel time (s/km), disaggregated into its main components, under different priority conditions is used as an input (see Gibson et al., 2015). The analysis case is a 9.6 km segment of Santa Rosa Avenue (Santiago, Chile) that has a dual carriageway median busway along half of its length and mixed traffic (MT) in two or three lanes of 2.4 km each. The interest of this case study is that quite different conditions for bus circulation are found along the same avenue. The first condition will be considered the "with project" scenario, whereas the second will be considered the "without project" situation.

This model is based on passive data only (bus GPS records, smartcard fare transactions and signal settings); therefore, similar models can be easily generated for other roads with different bus priority schemes provided that such data is available. Detailed data were obtained for five working days of one week of April 2011 between 7:30 and 21:00. The road segment under analysis was divided into seven sections of 1–2 km. In sections 1 and 2, there was MT in two lanes per direction; sections 3–5 contained the median busway; and in sections 6 and 7, there was MT in three lanes one-way. The time disaggregation used for the analysis was 30 min. The average travel time observed per section–period varied from 100 to 440 s/km, equivalent to a variation on average commercial speed between 8 and 36 km/h.

The model of the travel time components distinguishes the cruising time, uniform delay (including the effect of the traffic signal coordination), and overflow delay at intersections and delays (stop lost time and passenger service time) at bus stops. This decomposition allowed the differences among each of these elements to be captured according to the bus circulation condition. As no information from private vehicle flows was available, overflow delay in the MT sections was incorporated through dummy variables. The model is highly reliable according to statistical indicators.

In summary, the model results indicate that a median busway allows all of the overflow delay, a significant part of the cruising time and a variable (depending on the degree of saturation in the MT section) percentage of the uniform delay to be eliminated. However, passenger service time is not affected, and the time lost per stop at bus stations increases in the busway because of its higher cruising speed. Such a combination of effects leads to a variety of values for the net bus travel time savings.

In search of an integrated picture, we decided to employ the calibrated model to estimate the bus travel time that would result from implementing a dual carriageway median busway in the MT sections. To achieve this, the travel time model was applied to the latter using the busway parameters and their own values for the explanatory variables with an adjustment.

The adjustment is needed for the value of the explanatory variable related to the delay at intersections to recognize the effect on traffic signal settings of the geometrical changes involved in setting up a median busway. For instance, it is not possible to maintain short cycle times with the median busway because it implies an increase in the pedestrian minimum green time due to a wider crossing distance as well as an increase in intergreen times where there are turns crossing the busway. This adjustment is made using factors derived from the comparison of the timing plans of the busway and those of the MT segments. This procedure avoids producing an overestimation of busway savings.

A means of validation for the devised method arises from considering that the characteristics of the two-lane MT segment (MT2) are in between those of two existing busway sections (3 and 4). The relevant variables are the number of signalized intersections (SI), the number of detentions at bus stops per bus (ST), and the number of passengers transferred per bus (TP). Table 1 lists the values of the aforementioned variables, normalized by section length, and the average travel time (ATT) observed in the existing busway sections and estimated for the simulated busway in MT2. The estimated ATT for a busway in MT2 is in between those of busway sections 3 and 4 and closer to 4, maintaining the same relation observed in the relevant variables. Such analysis cannot be performed for the three-lane MT segment, as the values of the variables related to stops and passenger demand are far beyond those observed on the busway.

Thus, we obtained estimates of the average travel time with the busway for each section–period–day of the MT sections. However, the variable $DIVTB^{ijk}$ included in the model presented in Section 2 is the discounted in-vehicle time; it is necessary to subtract the time devoted to passenger service from both the estimated time with the busway and the observed time with MT in the MT2 and MT3 segments coming from the data. The passenger service time is given by the product of the number of passengers transferred per km on each section–period and the passenger service time obtained by Gibson et al. (2015): 1.386 (s/pass). No bus stop congestion was observed; therefore, no additional discount was required.

Table 1
Validation of the travel time estimation procedure.

Section	SI (per km)	ST (per km)	TP (per km)	ATT (s/km)
3	2.54	0.63	1.284	112.7
4	3.68	1.10	2.993	122.2
Busway in MT2	3.34	1.01	2.526	119.8

The benefit derived from implementing a busway is then the difference between the discounted in-vehicle times observed (without busway) and estimated (with busway) for each mixed traffic section–period–day available in the database. We had 264 observations for the MT2 case and 257 for the MT3 one. The calculated values for $DIVTB^{ijk}$ vary from 0 to 252 s/km with an average of 62 s/km. In Fig. 2, these benefits and the discounted observed bus travel times are plotted, and a strong linear relationship is observed. It should be noted that all these values are computed for one travel direction.

This relationship remains stable in the entire range, with no concentration of points that could be linked to particular periods (peak-off/peak, for example). Furthermore, the benefits for two lanes tend to be slightly above those of the three-lane case. Therefore, different linear models are estimated for each one of the following form:

$$DIVTB^{ijk} = \gamma + \delta\, DOT^{ijk} \quad (\mathrm{s/km}) \tag{4}$$

where DOT^{ijk} is the average discounted observed travel time with MT in section i, period j, and day k (s/km) and γ and δ are parameters to be estimated. The regression was performed using SPSS (IBM Corporation), and the results are presented in Table 2. The goodness-of-fit indicators are quite satisfactory. These models shall be valid over the range of values and conditions considered for the calibration process, which for the case presented here are described in Gibson et al. (2015).

Although the magnitude of the benefits vary over a wide range, as shown in Fig. 2, these models allow for a synthetic formulation: this type of busway generates travel time savings of about 90% of the discounted travel time with mixed traffic in excess of 111 s/km if in two lanes and in excess of 117 s/km if in three lanes, for one traffic direction. The difference in parameters between both cases is mainly due to the geometric changes involved, which has been considered here in the aforementioned adjustment procedure.

These models are a relevant result, as they can easily be applied, requiring only the average discounted travel time per section–period–day as the input. Also, because the passenger service time is excluded from the analysis, these times are independent of the fare collection system and bus characteristics, such as the floor height or number and width of doors, which can vary significantly from one place to another.

A potential problem of any model based on demand information obtained from the fare collection system is the existence of fare evasion or the use of different payment methods. In Santiago, smartcard bip! is the only payment system available on buses; thus, all payment transactions are recorded. However, there is a problem of fare evasion, the magnitude of which has been variable, reaching levels over 20%, according to Santiago transport authorities (DTPM, 2012). As discussed in Gibson et al. (2015), a careful treatment of the other components of bus travel time, constrains this problem to the true value of passenger service time. If the amount of passengers transferring is underestimated, then this parameter will be overestimated; however, the product of both should be correctly captured. As it is this product which is involved in generating the discounted observed and estimated times, the model parameter values are not affected by fare evasion.

4. Case study: estimation of bus user time benefits

4.1. Situations to be compared

To illustrate the use of the model presented in Section 2, we will evaluate the potential bus user time benefits of implementing a dual carriageway median busway in parts of the road that currently operate under three-lane MT conditions. We assume that the busway to be implemented has the same design of the existing busway along Santa Rosa Avenue. Two base case situations will be considered: mixed traffic in three lanes (MT), which is the current situation, and a small improvement that would be to reserve one lane exclusively for buses (BL). All of the calculations are made for one working day, between 7:30 AM and 8:30 PM, in the South–North direction only, using data from one week in April 2011, as reported in Gibson et al. (2015).

The in-vehicle time benefits for the MT base case are directly obtained from Eq. (4), applied using existing data on the discounted observed time for the three-lane segment. For the BL case, neither such a model nor field data are available; thus, the benefits must be derived from disaggregate estimates of travel time with a busway and with a bus lane. For the former situation, we use the values already produced in the simulation of the busway, as explained in the preceding section.

For the latter situation, travel times per section–period are generated with the help of the aforementioned travel time model. Values are assigned to each travel time component making conservative assumptions about the change that a bus lane would undergo with respect to the MT condition. In particular, the bus lane is assumed to have sufficient capacity to accommodate bus flows and a certain number of invading cars without giving rise to overflow delays at intersections. To

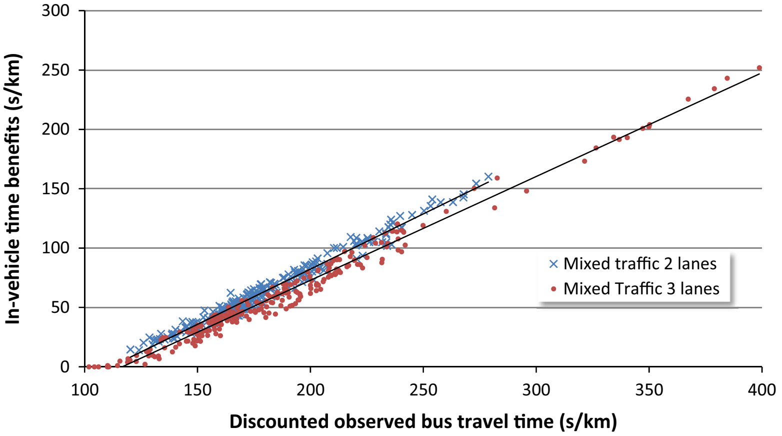

Fig. 2. Relationship between in-vehicle time benefits and discounted observed travel time.

Table 2
Models for in-vehicle time benefits of a dual carriageway busway.

Base situation	Estimated parameters		
	γ	δ	R^2
Mixed traffic, 2 lanes	−103.739	0.930	0.975
t-Statistic	−61.9	101.3	
Mixed traffic, 3 lanes	−102.172	0.875	0.981
t-Statistic	−69.8	115.7	

appraise the result of this procedure, a comparison of the estimated average bus commercial speeds is performed. In the current situation with MT the observed value is 18.2 km/h; the value estimated with the busway is 25.5 km/h whereas the simulated value for the bus lane case is 20.7 km/h.

The access time benefits are obtained from Eq. (1) using the average values of the variables for each road section. There are three types of variables related to the passenger demand, crossing time, and traffic signal delay. Given the assumptions made, the first group of variables remains constant; the second exhibits differences between the busway and MT/BL, but not between the latter; and the third class of variables can be different for all three cases.

The demand-related variables are the average number of passengers transferred per bus *NPT*, the load factor *LF*, and the proportion α of passengers coming from/going to a bus stop to/from the same side of the road. The first two variables are determined from passive data using the methods developed by Munizaga and Palma (2012) and Gschwender et al. (2012). As we do not have information for α, we will assume a neutral value of 0.5. The values of the variables related to the geometry of the before/after situations are $w_1 - w_0 = 13$ m and $w_2 = 7$ m. The average pedestrian speed *ps* is assumed to be 1.2 m/s in both cases.

To calculate d_0, d_1, and d_2, we verified that in all of the situations considered, it is feasible for passengers to cross to/from the bus stop in one signal stage. Therefore, the average delay can be calculated as $r_p^2/2c$, where r_p (s) is the pedestrian red time, c (s) is the signal cycle time, and $\beta = 0$ (100% one-stage crossing). To be consistent, r_p must be equal to the summation of the buses' green time and the pedestrian crossing time to the platform. This last term is given by the quotient between the corresponding distance and *ps*. These distances are 19 m for MT and BL and 25 m for the busway. The cycle time and buses' green time are obtained from the MT data and the assumptions made to generate the BL and busway scenarios.

4.2. Estimation of bus user time benefits

Now, we are able to calculate the discounted in-vehicle time benefits $DIVTB^{ijk}$, the average time gains (losses) per passenger accessing the bus stop platform ATB^{ijk}, the unit time savings per traveling bus passenger UTB^{ijk}, and the total time benefits for bus users TB^k of building a median busway compared with a base situation of MT or a bus lane. As the load factor comes from smartcard data a 1.2 multiplier is applied to TB^k to account for underestimation due to fare evasion.

Fig. 3 presents the estimated unit time benefits per period for each case considered. The average load factor is also displayed for reference. Additionally, the discounted observed travel time in the segment varies from 116 to 424 s/km, with a temporal pattern similar to the one depicted in Fig. 3 for the MT case. The unit time benefits of the median busway compared with MT are quite different according to the time of day, with a clear maximum occurring during the morning peak, reaching values up to 140 s/km; however, a level between 40 and 60 s/km is maintained during most of the remainder of the day. On

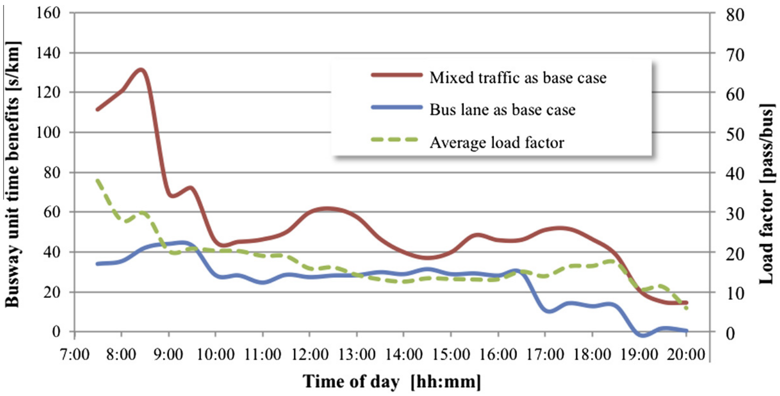

Fig. 3. Unit time benefits of the busway versus two base-case situations.

average, these figures indicate that in this case the busway saves 31% of in-vehicle travel time, reaching a remarkable 42% during the morning peak. However, if the comparison is made against an improved base situation with a bus lane, the unit benefits are more modest, with a maximum slightly over 40 s/km at around 9 AM and a plateau near 30 s/km from 10 AM to 4.30 PM. A strong decline is observed after 6 PM for both base-case scenarios.

The access time benefits are always negative, i.e., part of the benefits in the in-vehicle time are counterbalanced by losses in the access time. In Fig. 4, we present the ratio between both parameters. During most of the day, this ratio remains at approximately 10% in the MT scenario and close to 20% in the bus lane scenario. However, in the evening, when passenger renewal rate increases and in-vehicle time benefits decrease, this ratio sharply grows in both cases.

The total bus user time benefits of the busway were computed by applying Eq. (2). Due to a lack of data, a value of 0.5 was assumed for the parameter α, and a sensitivity analysis was performed. The results indicate that α has a limited effect: a 10% increase/decrease in α implies only a 1% increase/decrease in total time benefits. This assumption holds in what follows.

The total estimated time benefits are shown in Fig. 5. The large differences between the morning peak and the remainder of the day observed in the unit time benefits are reinforced because the load factor is incorporated.

An amount of 1028.3 h/day is estimated if compared with the current situation (MT). Using standard parameters in local practice to expand daily benefits and for the value of time, the total time benefits in this scenario are estimated at approximately 400,000 USD/km-year per traffic direction, which appears consistent with justifying half of an investment cost of approximately 8 MM USD/km for this type of busway.

However, the daily benefits decrease by 57% to 438.9 h/day if compared with the bus lane scenario, the cost of which is almost negligible. Despite the fact that the median busway project might pass a stand-alone cost/benefit test as stated, in this case the introduction of a simpler alternative would lead to a different conclusion. Nevertheless, this result is conditional upon some of the particular features of this application. Two factors are of key importance: the assumptions made to determine the bus travel times in the bus lane scenario and the passenger demand structure. Regarding the first factor, bus lane performance is highly dependent upon enforcement. Here, it was assumed that a competent enforcement is in place; however, this assumption could be incorrect, and efforts can decline or become inefficient. In addition, passenger demand in the studied segment is characterized by a low load factor and renewal rate except during short periods, which again could be different.

To explore the potential effect of changes in both fields over the estimated benefits, we performed a simulation analysis whose results are reported below. Within this simulation analysis, we introduce a mild enforcement for the bus lane scenario and changes in the demand structure by varying the load factor to make it more even during the day and increasing the number of boardings/alightings in the segment, thus affecting the renewal rate. In Table 3, we present the results of a simulation with three demand scenarios: the same as that observed in the base case, a 50% increase in the off-peak upstream load factors and a 100% increase in the number of passengers transferred.

In terms of the bus priority condition for the base situation scenarios, three cases are also considered: the observed situation (MT), a bus lane with competent enforcement (same as BL above), and a modified bus lane scenario with mild enforcement. We assume that this last BL case implies that part of the overflow delays remain (50% versus 0% before) and that there is a smaller percentage of reduction in the uniform delay at section 7 (5% versus 15% before) and cruising time (5% versus 7% before). An increase in the passenger transfer rate imply additional detentions at bus stops. A logarithmic relationship was found between these variables and is used in this analysis to include this effect.

The new situations that are simulated by no means represent extreme cases. The resulting average and maximum load factors are far below the bus capacity, and the renewal rate is well under its theoretical maximum of 2. The bus lane mild enforcement case still makes it clearly superior to MT. However, Table 3 demonstrates that the estimated total user time benefits of implementing a median busway vary considerably among the situations. The same result was observed for the access/in-vehicle time ratios.

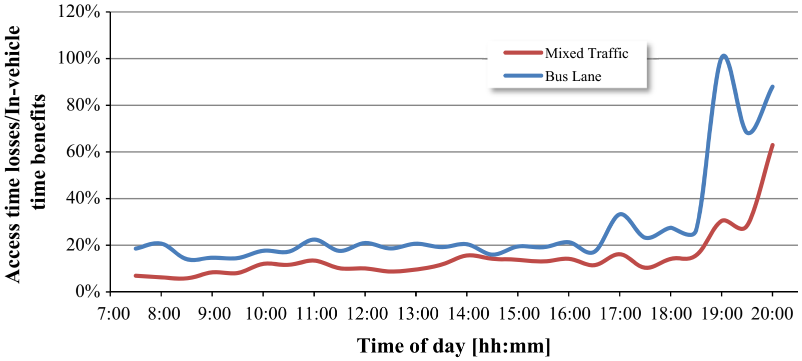

Fig. 4. Access time losses as a percentage of travel time benefits.

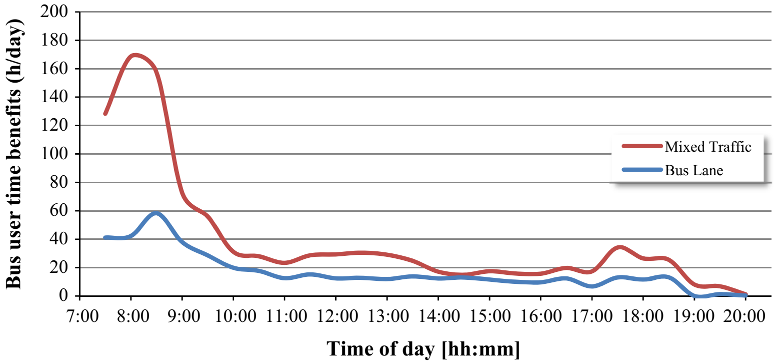

Fig. 5. Total time benefits – busway versus two base case situations.

Table 3
Simulated effects of changes on the median busway user time benefits.

Sensitivity analysis	Total time benefits TB (h/day)	% access time loss/ in-vehicle time benefits	Average load factor (pass/bus)	Passenger renewal rate PR
Scenario:	*Mixed traffic*			
Same demand as base case	1028.3	14.8	17.3	0.348
50% increase off peak upstream demand	1324.0	10.6	23.4	0.255
100% increase passengers transferred	917.9	26.7	18.4	0.642
Scenario:	*Bus lane with mild enforcement*			
Same demand as base case	623.1	21.7	17.3	0.348
50% increase off peak upstream demand	827.8	15.7	23.4	0.255
100% increase passengers transferred	520.5	36.3	18.4	0.642
Scenario:	*Bus lane with competent enforcement*			
Same demand as base case	438.9	27.6	17.3	0.348
50% increase off peak upstream demand	610.2	20.2	23.4	0.255
100% increase passengers transferred	340.6	45.2	18.4	0.642

The increase in the off-peak demand has a strong positive effect on busway benefits for all of the base-case scenarios in a range of 28–39%. In contrast, the increase in the passenger renewal rate significantly reduces these benefits due to a higher access time loss. Low-quality bus lane enforcement increases the busway benefits by 36–53%. The combination mild enforcement-higher off-peak demand makes the median busway almost as attractive as compared with MT in the base case, whereas a bus lane would be preferable in terms of the cost/benefit ratio for greater passenger renewal rates.

5. Concluding remarks

In BRT projects, a main concern is determining the best approach to provide dedicated lanes for buses. It is convenient to explore the options in the context of a cost/benefit analysis. Aiming at developing tools for this task, we present an innovative general framework to estimate the bus user time benefits of a median busway considering its effects on in-vehicle and access time components. The model is applied to a case study from Santiago (Chile), and the results demonstrate that there are several variables involved and that non-trivial conclusions can be obtained from this analysis.

As part of the general framework, specific models have been formulated to estimate the unit and total user time benefits. They require limited data that are increasingly available at low cost. The observed bus travel times, passenger boardings/alightings, and load factors can be derived from automatic vehicle location (AVL) and automatic fare collection (AFC) systems, respectively. This information enables the analysis to be performed at a highly disaggregate level in accordance with the presence of variables that may have different variation patterns in space and time. As GPS devices are increasingly common in public transit systems, disaggregate data for the total travel time are widely available, reducing the problem of obtaining on-site information to collect data on passenger boarding and alighting times and bus stop congestion delays, if any. Moreover, this type of information is necessary for any alternative procedure to estimate the savings of in-vehicle time.

A model for the bus in-vehicle time savings of a dual carriageway busway over mixed traffic circulation has been estimated, which only requires average discounted travel time per section–period–day as input. The result is that approximately 90% of the discounted travel time observed under mixed traffic condition in excess of 111 s/km for two lane roads and of 117 s/km for three lane roads can be saved. This model is one component of the general framework devised here but can be used on its own for predictive purposes in a wide range of situations, as it is independent of passenger service and bus-stop congestion times, which depend on many local features of bus systems.

Many alternative types of right-of-way for BRT projects can be analyzed using the aforementioned tool. We illustrate this possibility by calculating the bus user time benefits produced by a dual-carriageway median busway compared with three alternative bus circulation conditions: (i) mixed traffic, (ii) bus lane with mild enforcement, and (iii) bus lane with competent enforcement. The inclusion of access time in the analysis proved to be relevant in all the cases, as the median busway provides benefits in in-vehicle time but losses in access time. Depending upon the scenario, access time increase is between 10% and 45% of the in-vehicle time reduction due to the median busway. These scenarios are not extreme situations so in practice a broader range may be found. In fact, the magnitude of the difference for cases (ii) and (iii) depends on the level of enforcement. A poorly enforced bus lane can be similar to the mixed traffic situation.

A careful consideration of the impacts arising from the geometric changes involved by a busway project is indeed important in order to avoid overestimation of busway benefits. We have indicated in the case study presented here how to take them into account in the estimation of in-vehicle time benefits and shown that it leads to realistic results (see Table 1). We also described in the last paragraph of Section 4.1 the way in which geometric variables come into the computation of passenger delays associated with access time. Notice that as stated in Section 2.1 the specification of these variables may change in accordance with the lay-out of the situations considered.

From a practical point of view, our results show that the choice of how to provide dedicated bus lanes requires a detailed analysis, and the impact on access time to stations/bus stops should not be skipped or ignored. Compared to mixed traffic, a median busway can generate substantial in-vehicle travel time savings for bus users, especially under congested conditions in mixed traffic operation. These savings are proportional to the bus occupancy levels. However, both in-vehicle and access time for the busway increase as a function of the passenger renewal rate, which is proportional to the ratio between the number of passengers getting on and off in a section and the bus occupancy rate.

The case presented here suggests that a median busway is particularly appropriate for intermediate zones between the city center and the suburbs. In central zones (CBD), besides the difficulty of finding the appropriate space to accommodate a median busway, the density of bus stops and the passenger renewal rates are usually high. It is likely that curbside bus lanes perform better in this type of environment. In roads with two lanes serving one direction, where it is difficult to enforce car drivers to respect bus priority, it may work to preserve the whole road for buses, making it an exclusive way (for buses) during peak hours. On the other hand, in peripheral areas the congestion and passenger demand levels will likely be insufficient to warrant a bus corridor.

The empirical side of the work presented here relies on a detailed model of bus travel time developed by the same authors (Gibson et al., 2015) covering only the dual carriageway median busway and mixed traffic situations. If similar models for other cases are available, more comprehensive comparisons can be performed without making assumptions to build scenarios as we did here for the bus lane alternative. Interesting cases include busways with one lane per direction and overtaking lanes at bus stops and bus lane schemes of different size and segregation levels. We expect to conduct research in these areas. Also challenging issues that can be addressed in future empirical work are the effects of high passenger renewal rates, and demand elasticity.

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