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Commercial bus speed diagnosis based on GPS-monitored data

Cristian E. Cortés [a], Jaime Gibson [a], Antonio Gschwender [b], Marcela Munizaga [a,*], Mauricio Zúñiga [a]

[a] Department of Civil Engineering, Universidad de Chile, Casilla 228-3, Santiago, Moneda 975, Santiago, Chile
[b] Coordinación Transantiago, Moneda 975, Santiago, Chile

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ABSTRACT

Commercial bus speed is a key factor in the operation of public transport systems because it represents a direct measure of the quality of service provided to users and also considerably affects system costs. By commercial speed, we are referring to the average speed of buses over stretches, including all operational stops. Evaluating system performance by monitoring the commercial speed provided by bus services is highly desirable; however, in dense networks, it becomes a difficult task because of the amount of information required to implement such a monitoring procedure. The introduction of GPS technology in buses can overcome this difficulty in terms of information availability, although it presents the challenge of processing huge amounts of data in a systematic way. Here, we present a method based on GPS-generated data to systematically monitor average commercial bus speeds. The framework can be applied to each bus route as a whole, as well as over segments of arbitrary length, and can be divided into time intervals of arbitrary duration. The results are presented as matrices and graphs that can be read and interpreted easily. We discuss the potential of this methodology to provide useful insights for bus system planners and operators. The method and its applications are illustrated with data coming from the Santiago–Chile public transport system (Transantiago), where GPS observations of more than 6000 buses operating on over 700 different routes are available every 30 s.

1. Introduction

In operational terms, commercial bus speed is a key variable in the operation of public transport systems because it is related to both the level of service provided to users and the system cost. By commercial speed, we are referring to the average speed of buses over stretches, including all operational stops (bus stops, terminals, and traffic lights). This definition of commercial speed is different from what is defined as running speed, which only considers moving buses. Monitoring the status of commercial speed (hereinafter referred to as speed) is important, although it becomes very difficult in cases of dense route networks, mainly because of the amount of information required for such a process. Currently, vehicles are equipped with GPS technology, which allows us to overcome this difficulty by means of proper interpretation and handling of the data provided by GPS devices.

In this study, we present a method based on GPS-generated data to systematically monitor average bus speeds. The framework can be applied to each bus route as a whole, as well as over segments of arbitrary length, and can be divided into time intervals of arbitrary duration. The proposed methodology is able to capture and process valuable information, such as system performance based on bus movement data using GPS devices. In addition, the described methods facilitate the use of

* Corresponding author. Tel.: +56 2 9784380; fax: +56 2 6894206.
E-mail addresses: ccortes@ing.uchile.cl (C.E. Cortés), jgibson@ing.uchile.cl (J. Gibson), antonio.gschwender@transantiago.cl (A. Gschwender), mamuniza@ing.uchile.cl (M. Munizaga), mzuniga@gmail.com (M. Zúñiga).

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tools to depict speed indicators in a useful way for diagnostic purposes, even for intricate bus networks. These results are presented as matrices and graphs that can be read and interpreted easily. We discuss the potential of this methodology to provide useful insights for bus system planners and operators.

Some typical difficulties faced in the daily operation of a bus system can be caused by unexpected traffic conditions in cases where buses are mixed with other vehicles in most routes, which increases travel time uncertainty and delays at bus stops. In cases of severe congestion, it may be advisable to propose the construction of exclusive bus-ways and specialized infrastructure for fare collection outside of buses or traffic light optimization to improve bus circulation. The development of a tool that is able to provide a diagnosis of bus speed is useful for planners and operators to make decisions regarding the implementation of major projects and management measures. The analysis can be performed at different disaggregation levels, starting from a global picture of the situation and moving to a detailed description of a specific bus route over a specific segment of interest.

Broadly speaking, the literature concerning the applications of GPS information for improving bus system operations can be classified into three major areas. First, there is an area of study that utilizes real-time GPS pulses for the design and development of online control algorithms, management measures and real-time information systems for users and operators. Second, several studies have proposed to estimate travel time of general traffic by using offline GPS data of buses as probes. Finally, some studies have used offline GPS data for speed monitoring to evaluate system conditions or improve transit service by managing schedules or creating timetables.

With regard to the first area of study (online GPS data for operational control strategies), the most popular real-time control strategy for buses is holding, where vehicles are held at certain bus stops to homogenize headways. Eberlein (1995) showed that holding strategies could reduce the variance of passenger waiting times as well as the expected values of both waiting and travel times. Several authors have explored holding models that rely on real-time vehicle location information (Eberlein et al., 2001; Hickman, 2001; Sun and Hickman, 2004; Zolfaghari et al., 2004). Another attractive real-time strategy is known as stop-skipping. Stop-skipping involves speeding up buses by skipping (one or more) bus stops so that vehicles may recover their planned schedules after disruptions or unexpected delays. Khoat and Bernard (2006) showed that this strategy would effectively reduce in-vehicle travel time for passengers; however, the decision maker must be aware of the increase in waiting times experienced by passengers whose stops were skipped. This strategy has been studied by Lin et al. (1995), Eberlein (1995), Eberlein et al. (1999), Fu and Liu (2003), and Sun and Hickman (2004), among others. Recently, Cortés et al. (2010) and Sáez et al. (2010) designed and evaluated a predictive control strategy that integrated the two strategies (holding and stop-skipping) to solve a real-time predictive control problem with uncertain passenger demand.

In a second area of research, some studies used buses as probes to characterize and evaluate arterial performance. Tantiyanugulchai and Bertini (2003) used information of one corridor from both AVL and GPS data and found that the maximum instantaneous bus speed achieved between stops was the most reliable output to represent general traffic movement (i.e., non-bus traffic). Pu and Lin (2008a) reviewed five cases of using buses as probes and highlighted the limitations of the methodology in the following situations: the understanding of the bus-car interaction in urban traffic streams, the uncertainty of bus operations, the lack of traffic data and the difficulty of handling and processing massive AVL data. Pu and Lin (2008b) studied a short segment of a bus route to compare the use of archived driven space, AVL (fixed position at certain points along bus routes) and online time-driven data (data provided by a GPS). They concluded that both types of data have a similar capacity to estimate travel time, although time-driven information is able to better describe the bus operation phenomena. Berkow et al. (2007) also discussed the possibility of using buses as probes to evaluate arterial performance.

Finally, the third line of research, which has grown recently, deals with the use of GPS data of varying coverage levels that provide a reliable source of information with great potential for speed monitoring. For example, Storey and Holtom (2003) presented a United Kingdom application that uses historical data from different types of vehicles and concluded that GPS speed measurements are more accurate than moving car observer measurements. Jiang (2001) studied the effect of road work areas (on the Indiana freeway) on speed using a test vehicle equipped with a GPS. They estimated acceleration and deceleration rates based on one-second time intervals. They affirmed that GPS data are more accurate than data obtained using traffic counters. Greaves and Figliozzi (2008) used a GPS survey of commercial vehicles in Melbourne, Australia to obtain profiles of truck speeds. Furthermore, Gurushinghe et al. (2002) reported the result of an empirical study made on a probing field, which concluded that the accuracy of the data obtained using GPS technology was superior to that of the same data obtained using conventional measurements.

With regard to potential applications for vehicle dispatch and schedules, Berkow et al. (2007) studied the potential uses of information available from Tri Met transit operators in Portland, Oregon. They developed aggregate measurements that focused on determining schedule adherence. They analyzed the speed/time-of-day relation for buses on one particular route. Moreover, in a web page application, Strathman et al. (1999) proposed a new bus dispatch scheme based on a system that captured vehicle position and passenger boarding data. Four service reliability indices were optimized (headway ratio, run time ratio and a coefficient of variation associated with both). They showed the benefits of such a system compared to the current automatic dispatch implementation. Dueker et al. (2003) used the same information system to determine the dwell time and alighting time of passengers; they performed a sensitivity analysis with respect to conditions such as the type of route and the height of the bus floor. Finally, Kimpel (2007) developed a methodology for visualizing passenger boarding data at bus stops as scaled circles on a whole-city map. Finally, Quiroga and Bullock (1998) proposed a method to estimate the speed over a segment of a bus route using GPS data points emitted by buses when they are close to either the entrance or exit of the defined segment.

The new public transport system for Santiago, Chile, called Transantiago, brought technological advances such as a smart-card payment system and GPS-equipped buses. These advances facilitated the automated collection of detailed information such as bus positions and passenger boarding data. GPS observations of more than 6000 buses are available online every 30 s. The current status of Transantiago provides an ideal scenario to apply the proposed method because the route system was completely modified from the previous scheme.

In the present paper, we propose the use of offline GPS data to construct a broad picture of the performance of the Santiago bus system operation over space and time. This methodology is based on speed computations that allow the detection of segments and periods with poor circulation conditions.

In the next section, we describe the information that is available from GPS devices supplied in Transantiago. Then, a description of the methodology used to obtain representative mean speed estimates over time and space is presented. Next, we describe the tools that we devise to produce diagnostics of bus routes based on those estimates. Finally, some relevant conclusions and further research directions are discussed.

2. Data description and processing

2.1. Original data

With regard to the availability of data, we focused our analysis on the information available from the Transantiago bus system. Although information exists for the entire operational period from March 2007, we extracted data from a single week (09/01/2008-09/07/2008).

The database was structured into tables. The bus position table contains geo-coded bus information (latitude, longitude and time). The GPS device provided bus positions at regular, 30-s intervals when the bus was moving (the buses were moving for 80% of the observations). If the driver pressed the panic button (which was sometimes pressed accidentally), then the position was registered every 10 s (this interval was found in approximately 15% of the sample observations). If the bus was not moving, then a control register was taken every 5 min (5% of the data in our 1-week sample). In total, 6178 different buses (determined by license plates) were observed in the system. An additional table contains bus assignments and provides information about each bus route over a certain period. There were 737 different routes in the system, including variations such as express or short services. The route assignment information was provided by Transantiago. Linking both tables, we obtained 44,476,637 observations of bus positions that were assigned to known routes.

In this section, we describe the two major procedures of data management employed for the proper computation of commercial speed. First, we describe the path rectification methodology. Second, we describe the method that allows us to project the locations of the GPS pulses onto the rectified bus paths.

The data corresponding to the GPS pulses was stored in a database using PostgresSQL8.3 (Stonebraker, 1987). The performance was optimized by adding proper indices that organized the information and privilege specific queries for service and time periods. Processing the data for all services took approximately 1 day of computation. The processes to obtain the speeds and the interface in Google Earth were coded in the language C++.

2.2. Path rectification

Storey and Holtom (2003) discussed the need to represent routes in the simplest way possible by using the road center line and fitting each data point to the center line of the most appropriate section of road. Based on such recommendations, we simplified the representation of the information available from the defined paths for each route. The paths are identified in the form of a shape that is translated into geocoded points. The original data contained regularly separated points (at very short distances) and showed some disturbances at intersections with other routes. We transformed the original data into a more manageable and precise path definition using the Douglas and Peucker (1973) procedure. We were then able to identify the minimum number of points required to define the route path within an error bound ε. Douglas and Peucker's method started with the original multiple points definition of the path and recursively selected the points that generate new segments that are sufficiently close to the original line.

A representation of the procedure is depicted in Fig. 1a, where the original curve is given by the ordered set of points shown in part 0, and the final curve is shown in part 4. This figure shows that the algorithm recursively split the line. Initially, all points between the first and last point were considered. We then marked the first and last points to be retained. The procedure found the point that was furthest from the line segment using the first and last points as end points. If a point were closer than ε to the line segment, then any points not currently marked should be discarded without the smoothed curve being worse than ε. If the furthest point from the line segment was greater than ε, then that point should be retained (marked) in the set that defined the modified curve. The algorithm is used recursively considering the first point and the worst point and then with the worst point and the last point. When the recursion was completed, a new output curve was generated consisting of all (and only) those points that were marked as kept. We used $\varepsilon = 4$ m as a threshold.

The visualization of the paths and GPS points in Google Earth shows that the procedure provided reasonable results. Fig. 1b illustrates the method and results that were obtained for one particular route.

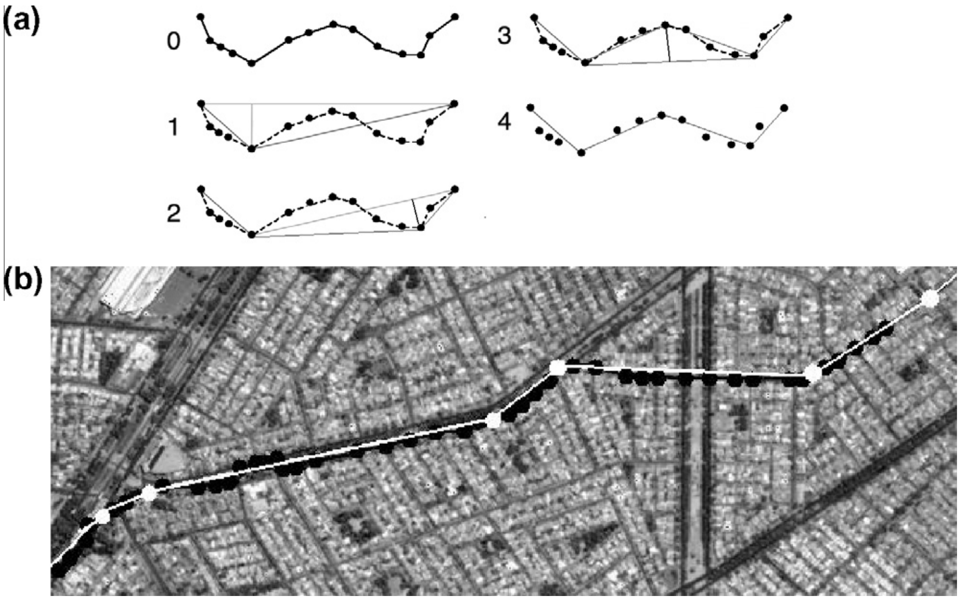

Fig. 1. Path rectification method.

The path rectification method was used to deal with problems that arose close to the junctions and to simplify the path definition. This rectification was accomplished by reducing the number of redundant nodes that did not contribute to the definition of the route path within a predefined error bound. With regard to the final goal of computing commercial bus speeds, the rectification of paths through the Google Earth tool allowed for the correct computation of route distances.

Apart from this practical issue, there were certain problems with the path definition. For example, some routes used reversible roads (a common practice in Santiago), and in other cases, there were traffic deviations. We defined a procedure to identify those GPS points that were far from the corresponding path so that those outlying points could be eliminated from the analysis.

2.3. Projection of GPS pulses to rectified paths

One important issue is the projection of the GPS locations onto the path definitions. These points were properly rectified using the methodology described previously (computing the orthogonal projection of the GPS points into the path line that is defined by the segmentation points). In Fig. 2, we show the projection process in the following two interesting cases: a straight path and a 90° turn.

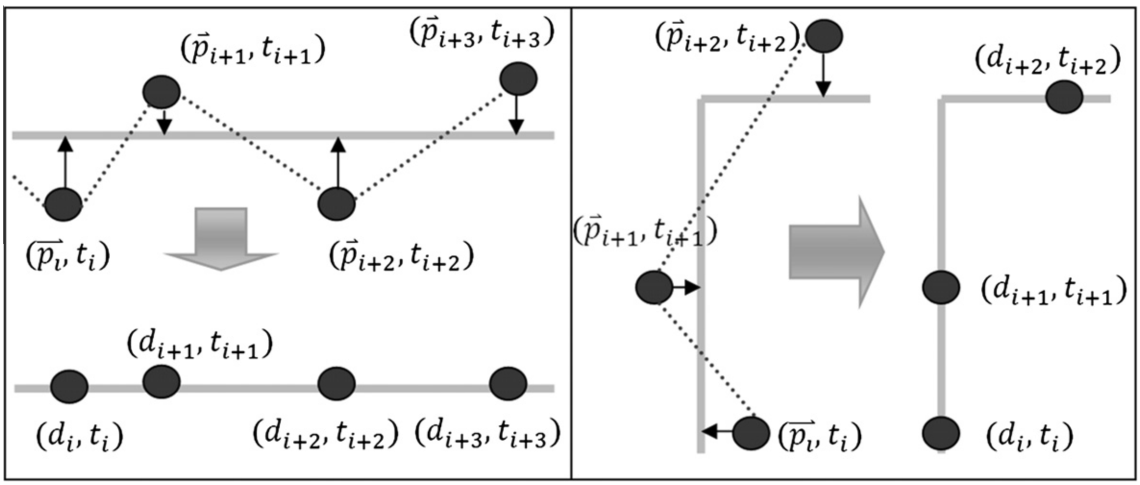

Fig. 2. GPS pulse projection onto paths.

In Fig. 2, each pair $(\bar{p}_i, t_i)$ denotes the position (in two-dimensional coordinates) that is instantly recorded by a GPS pulse i. The pair (d_i, t_i) corresponds to the new description of a GPS pulse i in which the position is translated into a distance measurement relative to the origin of the pulses' associated route path.

3. A methodology to compute representative speed values

The computation of a representative speed for the Transantiago buses is a major challenge, mainly due to the amount of information and the degree of data disaggregation. To obtain reliable speed values, a crucial issue is the proper management, processing and estimation of the required inputs for the calculations (distance and lapses based on interpolations in time and space).

The monitoring system provides information regarding GPS pulses that register bus positions every 30 s. As GPS devices automatically generate instantaneous speed data, a natural initial analysis is to compute the average of those observations, which are directly available in the database. However, instantaneous speeds are unstable in urban conditions because buses are constantly accelerating and decelerating, and the information is considered unreliable by system operators.

The objective is to devise a flexible and representative methodology that would allow a decision maker to manage different disaggregation levels in space and time. Based on that objective, we define a typical time–space diagram grid for each given route, where each element of the grid is defined by a rectangle of edges D and T.

Fig. 3 shows the proposed grid and highlights a basic grid element. The gray dots represent the GPS pulses that are already projected to the rectified paths.

A representative measure for the average bus speed within a grid element g is calculated. This average speed s is equal to the summation of the total distance traveled by all buses inside a given grid element divided by the summation of the total time spent by each bus in that given element. Analytically, for grid element g,

$$\bar{s}_g = \frac{\sum_i D_i^g}{\sum_i T_i^g} \tag{1}$$

where D_i^g and T_i^g represent the distance and time interval that bus i was within grid element g. Note that we only include those buses that are observed in the time–space grid element. The lengths of the element edges are exogenous parameters through which the scale of analysis can be specified. When there is no bus registered in a grid element, a null value is conventionally assigned to $\bar{s}_g$.

To define the grid, each simplified route path is divided into segments of length D in space, measured along the path, and time periods of duration T. We define an automatic procedure to generate such segments exclusively dependent on D and T. In the spatial dimension, the division is conducted by means of an algorithm that provided a set of points on the path separated by a distance equal to D. The next step in computing the speed associated with each grid element is to determine the intersection of the bus trajectories with the boundaries of each element. We use the GPS information corresponding to the positions of the buses registered at fixed time intervals and projected onto the paths. From these data, we need to interpolate either the instant or position at which each bus entered and exited a specific segment, as the GPS information does not necessarily match such boundaries. The procedure, shown in Fig. 4, is described below.

In this figure, each pair $\left(d_i^k, t_i^k\right)$ denotes the position and instant recorded by a GPS pulse i transmitted from bus k. From these GPS data, we can compute the coordinates associated with the path-boundary intersections of the grid element (represented by stars in Fig. 4). In the example in Fig. 4, the grid element (with vertices d_0, d_1, t_0, t_1) contains two bus trajectory segments. The shape of the trajectory segments implies one interpolation in space and three in time. In addition, the shape

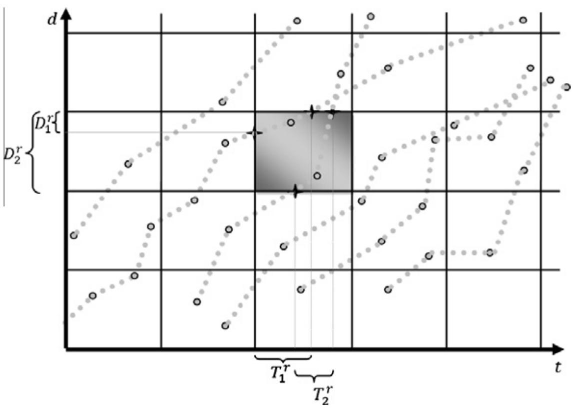

Fig. 3. Time–space diagram for a bus system.

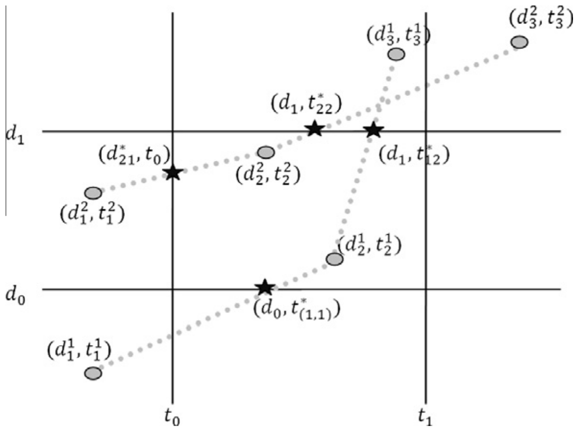

Fig. 4. Interpolation procedure based on GPS data.

generates the coordinates highlighted with an asterisk in the figure. The limits are computed analytically as shown in Eqs. 2–5:

$$t_{11}^* = t_1^1 + \frac{\left(d_0 - d_1^1\right)}{\left(d_2^1 - d_1^1\right)} * \left(t_2^1 - t_1^1\right) \tag{2}$$

$$t_{12}^* = t_2^1 + \frac{\left(d_1 - d_2^1\right)}{\left(d_3^1 - d_2^1\right)} * \left(t_3^1 - t_2^1\right) \tag{3}$$

$$t_{22}^* = t_2^2 + \frac{\left(d_1 - d_2^2\right)}{\left(d_3^2 - d_2^2\right)} * \left(t_3^2 - t_2^2\right) \tag{4}$$

$$d_{21}^* = d_1^2 + \frac{\left(t_0 - t_1^2\right)}{\left(t_2^2 - t_1^2\right)} * \left(d_2^2 - d_1^2\right) \tag{5}$$

Finally, from Eq. (1), the estimate of the average speed associated with this specific grid element g is given by:

$$\bar{s}_g = \frac{D_1^g + D_2^g}{T_1^g + T_2^g} = \frac{\left(d_1 - d_{21}^*\right) + \left(d_1 - d_0\right)}{\left(t_{22}^*\right) + \left(t_{12}^* - t_{11}^*\right)} \tag{6}$$

Note that in some cases, we require extrapolation instead of interpolation. These cases are carried out with an analogous procedure.

Quiroga and Bullock (1998) also determined mean speed as the total distance over the total time. On the one hand, because they estimated the time taken by each bus to cover fixed length segments, they calculated the harmonic mean of individual bus speeds (i.e., space mean speed). On the other hand, if time is fixed for each bus, and the distance traveled by each bus is estimated, then an arithmetic mean of individual bus speeds (time mean speed) could have been calculated. This is not the case in our methodology because neither the distance traveled nor the time spent by buses within a given grid element is fixed. The use of either a harmonic or an arithmetic mean results in a biased mean speed estimation for this context.

In the next section, we present the development of a methodology to implement a diagnosis tool that utilizes diagrams and matrices as indicators to represent the aforementioned calculations.

4. Diagnosis tool based on average speed

4.1. Framework and definitions

With the aforementioned procedure, we can directly obtain a matrix S_{ij} for each service, where each element s_{ij} is the average speed for segment i and period j. As each bus route has an associated specific space definition, the procedure must be conducted separately for each bus route. The extension of this methodology to the aggregation of different bus routes sharing the same segments requires further processing; this analysis is a subject of ongoing research.

From the obtained speed information, one is able to perform a diagnosis by route, which does not allow for a comparative analysis among different routes. Public transport systems usually serve a large number of routes (in our study, over 700 one-direction routes). It is important for planners and operators to have a broad picture of the overall speed situation before going into the details of each route.

An indicator to describe the status of a route in each period is needed. To build such an indicator based on a common grid, a speed should be found that is representative of each route in each period. We then calculate the total time it would take for a bus to traverse an entire path in a certain period by summing each path segment traversal time, under the conditions observed on each segment during that period. This is an average commercial speed that is "representative" of the period for each route and, by construction, its value is the harmonic mean of s_{ij} over each segment for a given route and period.

To complete the diagnosis tool, it is necessary to assign a meaning to the computed aggregate or disaggregate values. To this end, it is useful to take into account a referential speed, denoted by S_R. This value, S_R, can be interpreted as the minimum acceptable speed.

Therefore, as aggregate indicator, we propose the index I_{jk} for service k in period j, given by:

$$I_{jk} = \frac{S_R \sum_i \frac{1}{s_{ijk}}}{N_{jk}} \quad \text{for } s_{ijk} \neq 0 \tag{7}$$

where N_{jk} is the number of segments of service k, with $s_{ijk} \neq 0$ in period j.

If the index is a value close to one, then the global speed of the route will be close to the reference speed S_R. When the index is greater than one, the service condition becomes poorer; the opposite is valid for indicators smaller than one (i.e., reflecting good performance services).

This indicator allows for cross-comparisons between routes, in the same period or along periods as well as within a specific route during different time periods. To this end, any set of routes can be taken together to build a matrix of elements I_{jk}.

Finally, it is necessary to introduce some type of appraisal for both s_{ijk} and I_{jk} values that describe a route's performance. This appraisal is achieved by defining ranges for those variables that are related to S_R and another "high standard" speed.

4.2. Conditions for application

To be applicable in the real world, the methodology described in the previous section requires the specification of segment and time period ranges based on reference speeds.

In search of representative values, the size of the segments must be adequate to limit variability and the influence of singularities. In this case, the major singularities are the bus stops, junctions and turns. We considered X = 500 m as a reasonable segment size, given that in Santiago, this distance corresponds to approximately four blocks, which meant that each segment would contain one or two bus stops. With regard to the time dimension, the key is to define periods within which traffic and passenger demand conditions do not vary considerably. However, it is desirable to have a reasonable number of buses recorded within each grid element. Because we were mainly interested in working days and could aggregate all buses over the five working days of a week, we considered periods of T = 30 min. For non-working days, longer periods are advisable, because traffic and passenger demand patterns are less variable on such days.

The reference speed S_R was set at 20 km/h, a standard widely used in Latin America for bus system design. Though there is no equally recognized value for "high standard" speed, we believe that 30 km/h is appropriate because it is close to efficient Metro systems' commercial speeds. The ranges chosen to characterize the service conditions are listed in Table 1.

Considering the magnitude of the information available, we developed visualization tools based on color codes assigned to the defined condition scale. We used red for very bad, orange for bad, yellow for barely acceptable, light green for fair, dark green for good and blue for excellent. White was used when no information was available. Each matrix gave rise to a two-dimensional diagram, with each element colored appropriately.

Another visualization tool was devised to facilitate the recognition of the defined segments along a bus route's actual path. This tool was developed within Google Earth, and in addition to showing the path segmentation on this platform, basic information regarding computed commercial speeds for each segment was deployed. Pre-processing the data takes around 2 days, and then approximately five minutes per route are required to generate all the graphics and Google Earth representations of speeds.

To illustrate the proposed diagnosis tool, results obtained in Santiago for the working days of a week in September 2008 are shown.

Table 1
Service condition range definition.

Condition	s_{ijk} (km/h)	I_{jk}	Color
Very bad	$\leqslant 15$	$\geqslant 1.333$	Red
Bad	>15 to $\leqslant 19$	<1.333 to $\geqslant 1.053$	Orange
Barely acceptable	>19 to $\leqslant 21$	<1.053 to $\geqslant 0.952$	Yellow
Fair	>21 to $\leqslant 25$	<0.952 to $\geqslant 0.80$	Light green
Good	>25 to $\leqslant 30$	<0.80 to $\geqslant 0.667$	Dark green
Excellent	>30	<0.667	Blue

4.3. Example

Fig. 5 shows the diagram corresponding to the global indicator defined in Eq. (7). The diagram axes are time period and route. Each diagram cell's color represents the service condition for a route during a particular time period. In this example, the indicator was computed for buses registered through the five working days of the week (September 1–7, 2008) from 6 am to 11 pm, using 30-min periods. Fig. 5 was built for a group of services belonging to a specific bus company.

Routes are identified by their service codes, which include the letters "I" or "R" for the inbound and outbound trips and occasionally the letters "e" or "c" to denote express or short variants of a certain service. These variants operate mainly on a part-time basis.

The wide variation in service conditions throughout the day is clearly depicted in the diagram. Although light green (fair performance) is predominant, most services experience unsatisfactory conditions (orange and red cells) during certain times of the day. Morning and afternoon peaks can be recognized (around 7:30 am and 6:30 pm), but there are significant differences among routes in both the number of congested periods and the start and end times of decreased speeds.

As expected, express services show high speeds throughout the day. They travel mainly on expressways or exclusive busways and travel long distances between stops for passenger transfers. Routes 113 and 115 (both inbound and outbound) also show consistently remarkable performances because they use an expressway for parts of their routes. In contrast, Route 103 (both inbound and outbound) show poor conditions for 12 consecutive hours.

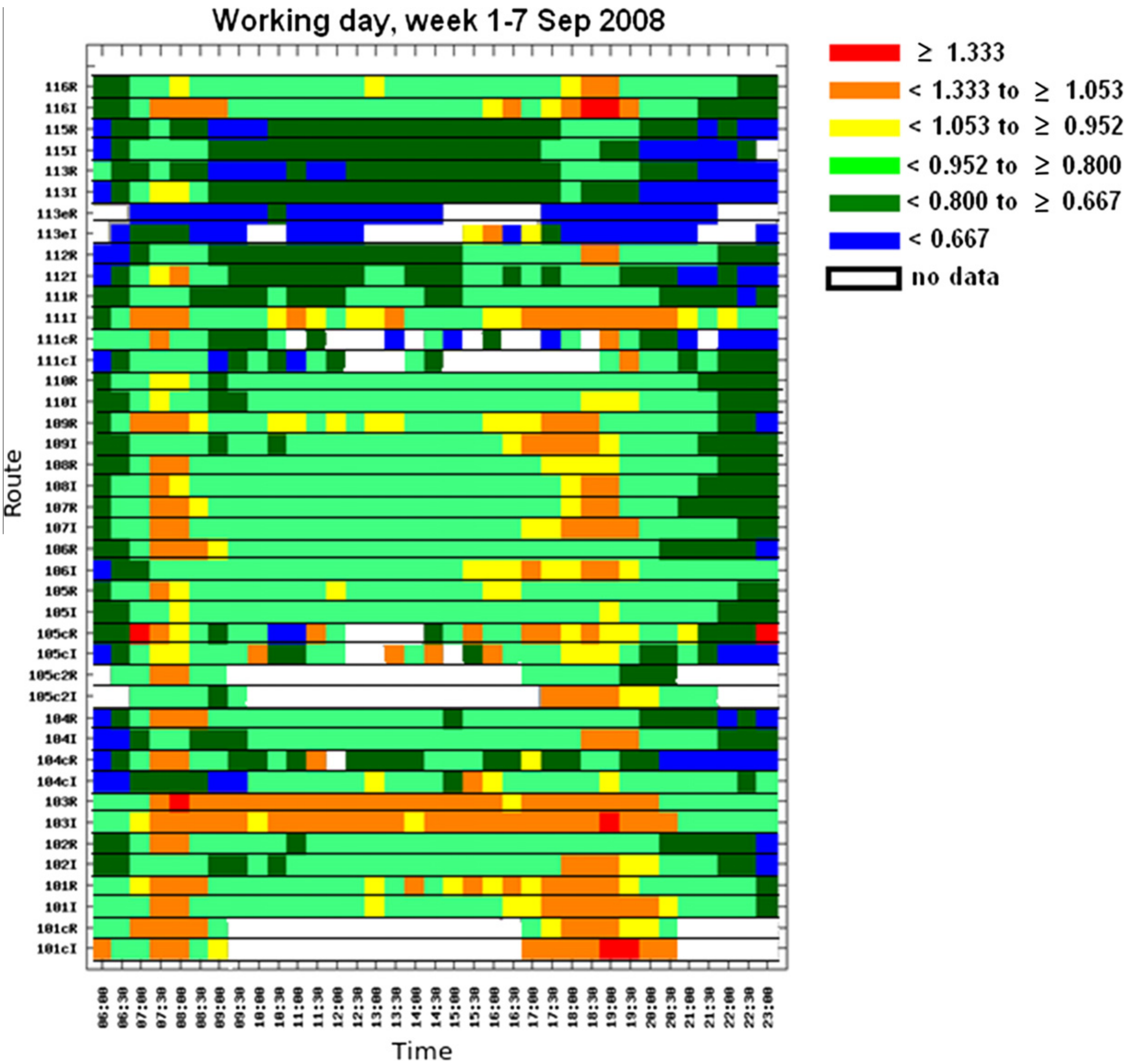

Fig. 5. Global speed indicator diagram for a group of bus routes.

The scope and potential results of route improvement measures are likely to be quite different. For instance, one can assume that only heavy investments will enable a route such as Route 103 to reach an acceptable service condition. However, it seems that Route 112 is a good candidate for low-cost improvements because its service condition is good (except for a 1-h period in each direction that occurred at different times of the day).

An in-depth analysis of the second diagram, showing the average speed for a particular route by segment and period, is useful. Figs. 6 and 7 display this information for Route 112, inbound and outbound, respectively.

Because both services follow more or less the same path in opposite directions, diagrams were built with segments in the reverse order so that the actual segment locations remained approximately the same. These diagrams offer a picture that is more complex than the one suggested by the global indicator. The predominant satisfactory conditions in the latter are often a mix of excellent and poor segments. In particular, there is a broad stretch (segments 12–28 in the outbound trip and 52–38 in the inbound trip) where unsatisfactory conditions prevail most of the time.

The next step in the analysis is to identify such a stretch in the actual road network. The representation of the route path on Google Earth is shown in Fig. 8. One map was generated for each time period, where the nodes correspond to segment extremes. The color between each pair of nodes was assigned according to the service condition of the segment in that period. Clicking on a node provides detailed corresponding segment speed information (Fig. 9).

In our example, the low-speed stretch of road is the most congested part of Santiago's ring road. There is currently a project to build a tunnel in this location to accommodate long-distance car trips and relieve surface traffic. Furthermore, based on previous analyses, it may be worth considering the implementation of bus-only lanes during the morning peak period along the inbound direction and during the evening peak period in the opposite direction. In addition, improvements could be made in other congested segments, such as 26 and 35 for the inbound trip as well as 39 and 52 for the outbound trip.

To further diagnose the problems in these low-speed segments, a more detailed visualization of a specific segment was developed that shows the exact time and position of each GPS pulse for a single bus. Analyzing the successive positions of a bus in a low-speed segment enables the determination of the exact location of severe congestion problems for a given seg-

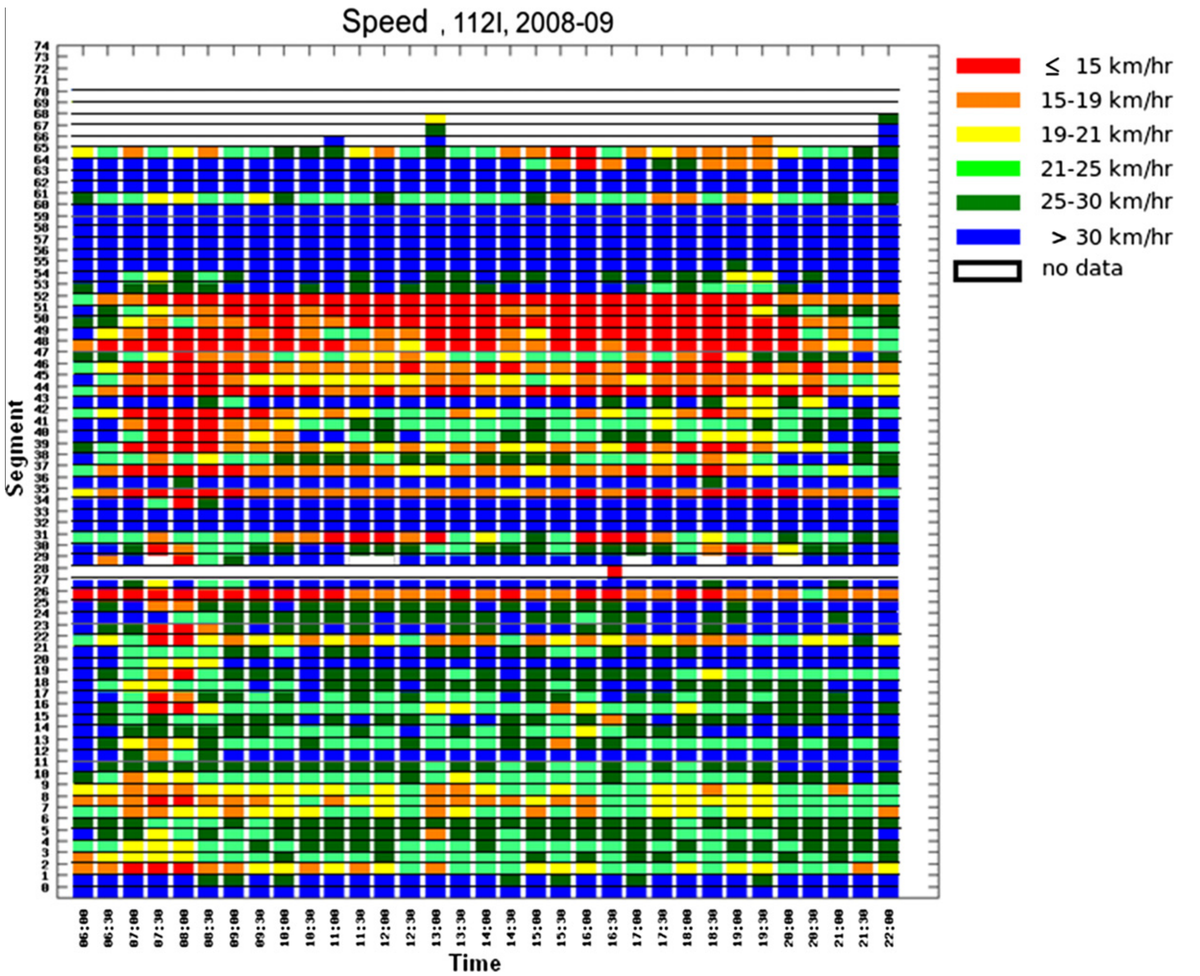

Fig. 6. Global speed indicator diagram for Route 112 inbound.

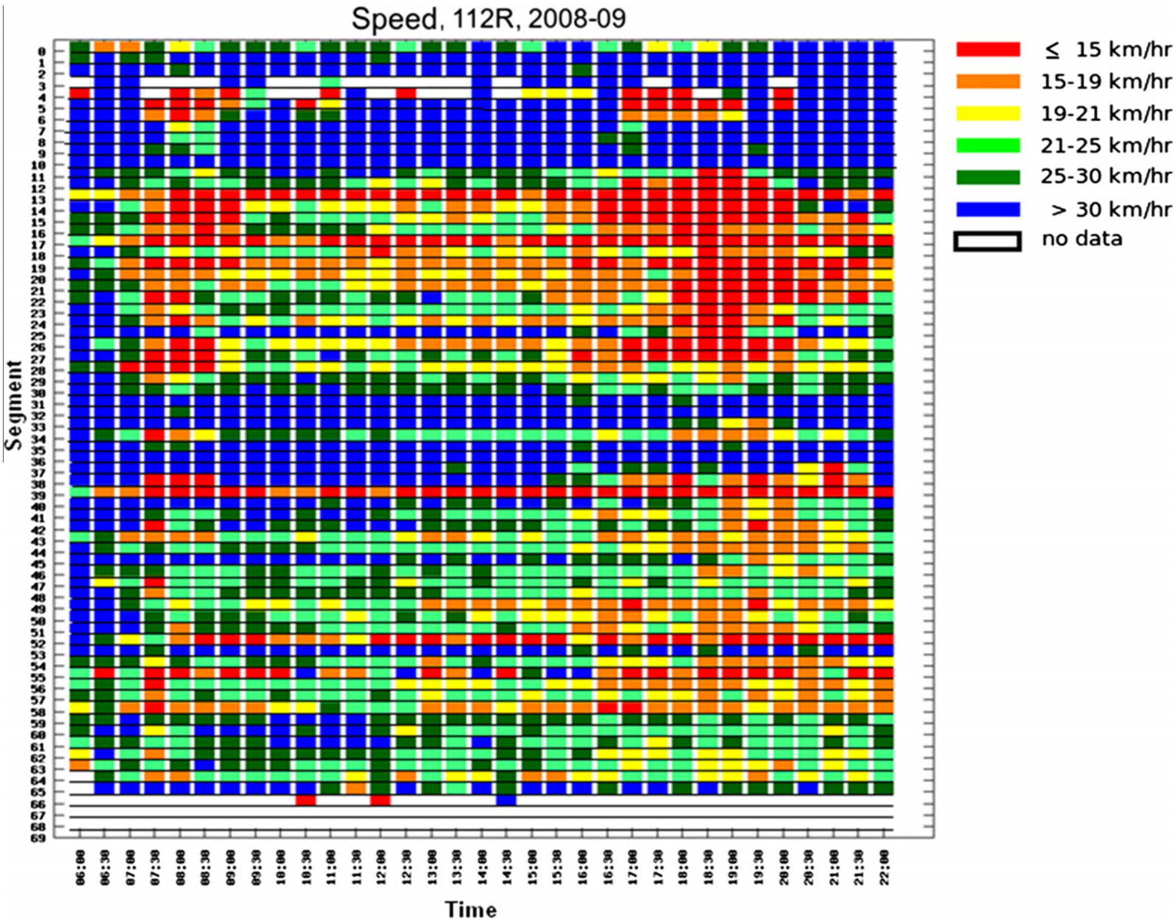

Fig. 7. Global speed indicator diagram for Route 112 outbound.

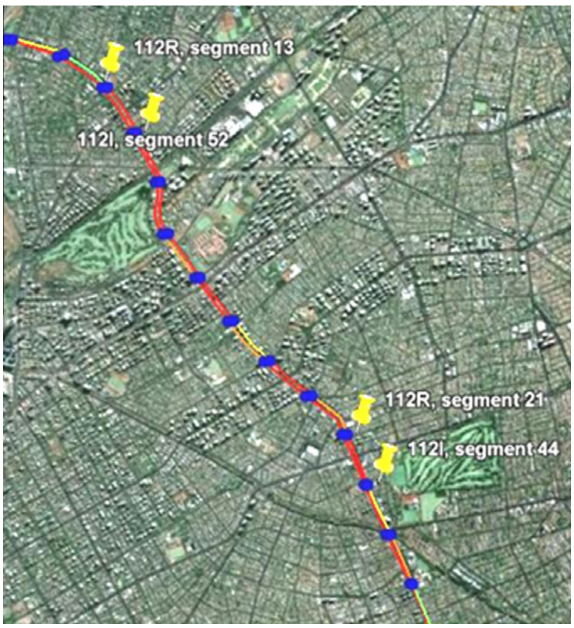

Fig. 8. Representation of route path and speeds on Google Earth.

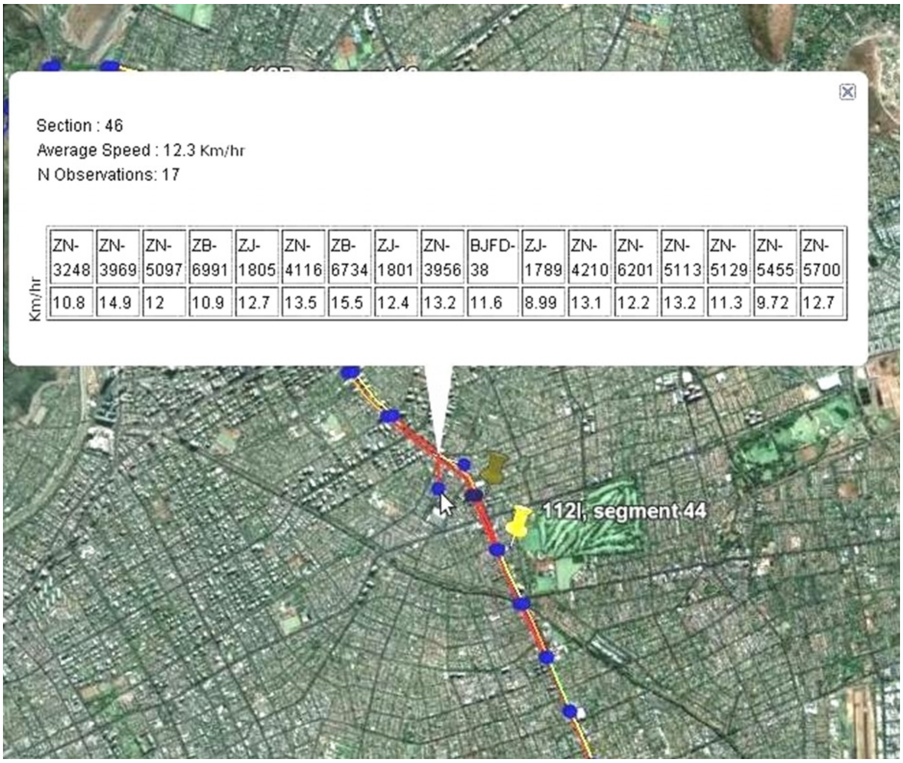

Fig. 9. Detailed information for any specific route segment.

Fig. 10. Detailed visualization of GPS pulses on a segment.

ment (e.g., before an intersection or at a bus stop). For example, Fig. 10 shows the position of the GPS pulses (purple points) of a south–north inbound trip of a bus on Route 112 that traveled on segment 26 during the 8:00–8:30 am period. The pulses were concentrated just before the intersection with a main avenue (Vespucio). Depending on the specific problems of this intersection, an ad hoc solution can be designed. For example, one solution may involve a modification of the traffic light times or the implementation of a short bus lane.

This example illustrates how the tools that we developed could be used to identify problems in bus operation and help focus efforts on the routes and segments with poorer performances.

5. Conclusions and further research

The information provided by the GPS records can be translated into reliable indicators that will allow decision makers to monitor commercial bus speeds over service networks, regardless of their size. The disaggregation capability of the proposed tool in both space and time is essential for generating and prioritizing projects by identifying operational problems at the required level of detail. As the supplied example shows, the situation can be very different among bus routes.

The diagnosis of operational conflicts starts with an overall view of the average speeds of a group of routes over time and proceeds by going stepwise into more detail. If needed, space and time resolution can be changed in the latter stages to provide more relevant information for specific service problems. In this study, we present a method based on GPS data that systematically analyze average bus speeds. The framework in this study can be applied to an entire bus route or to specific segments of any length, either for an entire day or for certain periods of time. The proposed methodology uses GPS devices to capture and process valuable information about system performance based on bus movement data. In addition, the proposed methodology provides tools to depict speed indicators in a way that can be used for diagnosis purposes, even in cases of non-traditional bus network configurations. The results are presented in the form of matrices and graphs that are simple to read and interpret.

We believe that this methodology has the potential to provide useful insights for bus system planners and operators. Moreover, for agencies that may not have viable GPS data tied to schedule points, this methodology represents a valid approach to looking at transit segment speeds and is flexible to accommodate any standard feed of GPS data. The proposed tool is currently being used by the Transantiago Authority. It is expected that the Transantiago Authority's experience will produce solid indications for refinements and expansions of the tool's components.

This tool can also be used to perform "before and after" evaluations and to compare routes that use roads with different infrastructure features. In this way, we foresee further research that incorporates automatic comparison techniques based on the matrix form of computed average commercial speeds. Another interesting line of research would be to study the passenger-demand/commercial-speed relationship by incorporating information from the payment system containing passenger demand data at a very detailed level.

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