Bus Corridor Operational Improvement with Intelligent Transportation System based on Autonomous Guidance and Precision Docking

Leopoldo R. Yoshioka, Claudio L. Marte, Mauricio Micoski, Renato D. Costa, Caio Fontana, Cledson A. Sakurai, Jose R. Cardoso

Abstract— It is important to bring to Urban Transportation, in specific of medium capacity, solutions that allow it to increase efficiency. This article shows functionalities associated to Intelligent Transportation Systems that can contribute to the increase in efficiency of Urban Collective Transportation. In particularly, the automation of a conventional bus by way of Autonomous Guidance Technology, which consists of magnetic sensing, computational intelligence and electro-mechanical actuator. The automation of the lateral guidance provides for docking maneuvers with better precision at the stops, in addition to allowing the vehicle to travel on narrow routes quickly and safely. One application of this technology is presented in Expresso Tiradentes bus corridor in São Paulo, where the achieved results demonstrate improvements in the efficiency of bus operations.

Keywords— Autonomous Vehicle, Bus Rapid Transit (BRT), Intelligent Transportation Systems (ITS), Magnetic Sensing.

I. INTRODUCTION

IN the medium and large cities it is notorious the increasing difficulty in displacing its citizens, which entails in an increasing loss of mobility. This is felt by longer times necessary for displacement, transfers and waits [1]. In part, this is a result of the competition among modes of transportation in utilizing a shared network.

In the rail mode, it is noticed a lesser case of competition because different types of services can share the same track, as well as the existence of railway junctions with traffic lights that restrict flow and increase travel time [2]. But, both, (different types of services and railway junctions with traffic lights) are uncommon.

Now on the road mode exists a sharper competition among vehicles responsible for Collective Transportation (High Occupancy Vehicle) and Individual Transportation. This competition enhances the occurrences of congestions. These imply in a longer wait time at intersections and on displacement, as well as, a decrease on the Collective Transportation quality of services [3].

The attempt of resolving these difficulties (longer travel times and congestion) by increasing the infrastructure of the routes and allowing a larger capacity offered to vehicles of Individual Transportation has been exhaustively put into practice, not only in Brazil, but also in other countries. And this is a path that runs out in short time, having a consensus that priority should be given to Collective Transportation in relation to Individual Transportation.

Therefore there is a necessity that migration from Individual Transportation to Collective Transportation should be stimulated. And, for that to occur in a Collective Transportation that associates larger capacity and differentiated services, that is of better quality, it should be sought.

In Brazil it is common the offer of Collective Transportation Systems of low capacity and frequently of lower quality. When enquired, the population declares a strong preference for systems of high capacity, like the metro. However, it is necessary a high level of investment and a long time of implementation, what makes its quick dissemination unviable.

Obviously, when it comes to meet a high/medium demand with solutions of low capacity, the result is a provision of a service of low quality.

Brazil lives in a phase where transportation solutions of medium capacity may meet, at least in part, the desire of the population to enjoy a service of better quality. Because of that, it is positive the experiences of the Monorail in São Paulo and Bus Express Corridors . i.e. Bus Rapid Transit (BRT) under implementation in most cities hosting the World Cup in 2014 [4].

BRT is a mode of public transportation on tires, fast and flexible, that combines stations, vehicles, services, routes and intelligent transportation systems (ITS) elements in an integrated system with a strong positive identity that evokes a unique image.

This choice for the BRT is based on the volume of investment required [5], time of implementation and the possibility of incremental improvements during operation. What can be difficult to observe on systems above rails, in more critical points or of bigger impact, evolving over time

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until it reaches its fullness [6].

The BRT has potential to revolutionize the current situation, presenting itself as one of the most recommended options for transportation systems of medium capacity, because it is widely favored for the cost-benefit relations and time versus complexity of implementation.

For the BRT to reach the highest levels of efficiency (lower cost and greater reliability), safety and comfort – for users of Collective Transportation it is fundamental the utilization of the advances in the Information and Communication Technology (ICT) area. The BRT is a concept that presents itself in a clear manner to the evolutions of Collective Transportation services can with the combined application of ITS technologies and more efficient use of urban space.

II. Intelligent Transportation System for Public Transportation

In the Urban Collective Public Transportation (UCPT) exists the necessity to explore the potential of utilization of ITS technologies in the BRT systems [7], hereinafter referred to as ITS4BRT.

Recent studies show that ITS functions could improve BRT systems [4] [8] [9]. In the following we present a summary of concepts of ITS4BRT, including main *Actors* and relevant *ITS Functionalities*.

Actors

We show in Fig 1 a hierarchical representation of the actors involved in the ITS4BRT. One cans see below a summarized description:

1. *Conductor:* operates a licensed vehicle;
2. *Operational Controller*: is responsible for monitoring and controlling the hourly schedule of the UCPT route. The activities include: monitoring, controlling, measurements of congestion, route modifications and provision of public transportation;
3. *Operator:* is responsible for the management of fleets conditioned to rules defined by Transportation Regulatory Agency;
4. *Passenger*: represents an individual (or group) not part of the crew, inside of a vehicle, when the trip is taking place;
5. *User*: represents all human entities that utilize, directly or indirectly, the transportation services. In accordance with the moment and situation, this actor can be a pedestrian, Traveler, Passenger, Conductor, or any other that benefits with provide services;
6. *Traveler*: represents any individual that utilizes transportation services.

A. Intelligent Transportation Functionalities for Bus Rapid Transit System (ITS4BRT)

As shown in Fig. 2 we can organize main service groups of the ITS4BRT into seven groups (or service domains), which are described in the following:

1. *Planning and Programming*: detailed in the next section;
2. *Management*: detailed in the next section;
3. *Electronic Ticketing (Fare)*: set of services responsible for the commercialization of credits, from the issuance, passing by distribution, validation e effective collection (billing) to the compensation (“clearing”), allowing the integration between different modes of transportation;
4. *Information to Users:* services: set of services responsible for distributing, in an extensive manner, up to date and effective static and dynamics information about the transportation network and services to Users;
5. *Prevention and Safety:* set of services responsible to provide greater safety to Traveler/ Passenger/ Conductor, in the aspect to avoid action by a third parties (“security”), as to prevent against operational risks (“safety”);
6. *Multimodal Coordination*: set of services responsible for the coordination between transportation and traffic system, aiming at improving the intermodal transfer and prioritize Public Transportation at signalized intersections; and
7. *Infrastructure*: focuses on the continuity of the operation, maintaining the infrastructure and auxiliary services, as electric energy supply, telecommunications, data processing and others.

III. Planning, Programming, Management and Critical Autonomous System

These groups of services involve definition and establishment of services standards and quality indicators. This set of services also addresses the Critical Autonomous System

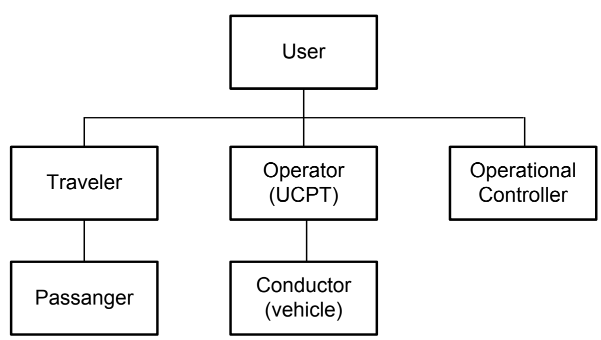


Fig. 1 Hierarchical Representation of the Actors involved in the Intelligent Transportation System focusing in BRT system..

that includes the Precision Docking and Autonomous Guidance features.

A. Planning

Functionality utilized to establish *service quality* and define *resources* and *infrastructure* necessary. In the service standards and quality of the services established, for example: degree of accessibility, levels of comfort, levels of service integration, maximum wait times (minimum frequency and commercial speed), quality/performance indicators e levels of prevention. And, as far as resources and infrastructure are defined, for example: bus line and route planning, and service offers.

B. Programming

Based on *Planning* and in function of the resources available, the Service Programming of the UCPT takes place, searching for a better relation between supply and demand, with the issuance of Operational Service Orders (daily schedule), detailing, for example: allocation of vehicles per route, frequency, travel time, itineraries, hourly schedules (grid) and allocation of human resources (*Conductor*).

C. Management

This is a group of functionalities that performs monitoring and control in real time of parameters and events of the UCPT system, through the comparison with the programmed, intervening, when necessary, aiming to suit the operation to the defined standards. In the following we describe the functions that compose this group.

c1) Measurements

Functions associated to collection, processing and visualization of information (parameters) around the vehicle and of the infrastructure (stations, terminals and routes), necessary to the operation. Are examples of information shipped in the BRT vehicles: monitoring of the state (safety devices, opening/closing of doors) and measurements of continuous variables (positioning, speed, acceleration, occupation and functions of engine/vehicle structure). Examples of information associated to infrastructure (stations, terminals and routes): *User/Traveler* count (at terminals and platforms) and on the routes – count and identification of vehicles, measurement of speed, red light crossing and unwarranted occupation.

c2) Fleet Management

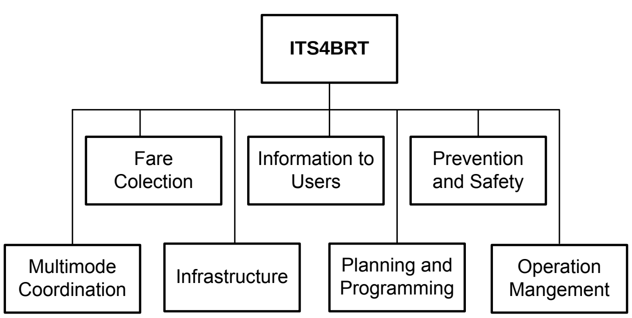


Fig. 2 ITS for BRT service groups (domain)

Functions referred to the capacity of generating the main inputs involved in the service provision of the UCPT, aiming to manage the Maintenance and Control and the Quality of Services Provided. As far as the functionality of following maintenance and control of input, like examples: information about fuel consumption and conservation, ware of parts and accessories. To measure the quality of services will be necessary information that allow it to evaluate the conduction of the vehicle, seeking to capture dada that reflect traffic safety, Passenger comfort and the form of integration between vehicle and the Conductor.

c3) Management of Services Provided

Functions that allow it to monitor the trip performance of the UCPT and perform the Management Operation, monitoring and controlling, in real time, the elements of the UCPT's system, with the purpose to provide an operation within the parameters pre-established in Planning and Programming the operation. These parameters refer to the conditions that the system should operate and that are subject to interference of the processes that could be originated for various factors like: climatic conditions, events, works and actions of the Conductor among others. Are examples of functions: maintain the regularity and reliability of services; confront the scheduled planed (programmed) versus the scheduled executed (actual); adjust dynamically the supply and demand and adjust the operation to a situation not expected, considering the resources available.

D. Critical Autonomous System

This is group of functionalities to assist, in an automatic or semi-automatic way, operations that need a greater degree of safety, precision or speed, aiming at the optimization of the operation. The objective of this group is to turn the operational performance of the BRTs close to the systems on rail. Following are described the functions that compose this group.

d1) Control of Routes and Stations Doors

Function referred to the capacity of automatic opening and closing of doors of the stations and monitoring of the corridor routs of the UCPT.

As for Automatic Door Opening Control, this could contribute to increment safety, the commercial speed and the operational flow, maintaining the synchronization of the door opening at the stations with the UCPT vehicles.

d2) Monitoring of the use of corridor routes

Function referred to monitoring of the use and to reprimand the utilization of the BRT lanes by non-authorized vehicles.

d3) Precision Docking

This function is utilized in the alignment of the vehicle with the platform, at the stops or stations, for passenger embarking and disembarking operations. In these operations, in accordance with the characteristics of the systems, it could exist the necessity to perform it with more agility and precision, aiming to eliminate variations from the different levels of ability of the Conductor.

d4) Autonomous Guidance

This function allows, in isolated and straight routes, a more precise and secures driving, without the necessity of intervention by the *Conductor*, except in emergency situations. The application of this functionality can provide an increase of the commercial speed.

IV. Autonomous Guidance and Precision docking

The purpose of the Autonomous Guidance System (AGS) is to replace the action of the conductor in the steering control of the vehicle. It allows the bus to perform approach and docking maneuvers at the stops with a lot more

Fig. 3 pictures sequence showing the conductor switching from manual to automatic guidance (Expresso Tiradentes bus corridor – Sao Paulo

Fig. 4 picture sequence of precision docking maneuver at a stop (Expressp Tiradentes bus corridor – Sao Paulo)

precision and quickness. The vehicle could also travel in straight routes quickly and safely. It consists of sensor, signals processors, on-board computer and actuator. It can be installed in any type of vehicle. It is capable of automatic positioning and alignment of the vehicle on the road, with precision and reliability.

As it is shown in the photos sequence in Fig. 3, the vehicle can operate in the manual mode or automatically being that the conductor continues present, still being responsible for the control of the speed, stops and departures. The set of photos in Fig.4 shows details of the precision docking maneuvers at a stop.

The autonomous guidance system is composed of four main segments: Position Sensing; Signal Processing; Guidance Control; and Steering Wheel Actuator. In the following you will find a brief description for each of these segments:

A. Position Sensing

It is a fundamental part of the AGS, since, based on the information obtained by the position sensing is what determines the lateral positioning of the vehicle in relation to the road. There are basically five types of reference of positioning applicable for AGS, including magnetic lane, lane marking on the route (optic), Differential Global Positioning System (DGPS), electromagnetic and the magnetic marker [14].

Fig. 5 pictures of magnetic markers (permanent magnet of ferrite, dimension: 25x100 mm)

Evaluation the applicability for the BRT, from each of the reference types based on criteria of safety, robustness, flexibility, durability, and cost of implementation arrived at the conclusion that the two more adequate types are the magnetic marker and the optic [15]. In this article it will be addressed only the sensing by magnetic marker. Fig. 5 illustrates a magnetic marker used in Expresso Tiradentes Corridor (São Paulo).

B. Signal Processing

It is responsible for extracting information of the lateral deviation from the signals captured by the sensing system.

Through the signal processing it is determined the position of the profile peak of the magnetic field generated by the magnet. From this information the lateral deviation of the vehicle is calculated [16] [17]. Fig. 6 illustrates the tridimensional view of the magnetic field profile generated by a magnetic track. It can be observed that the peaks follow the polarity (north or South) of the magnets, which can be utilized to code geometry information of the route.

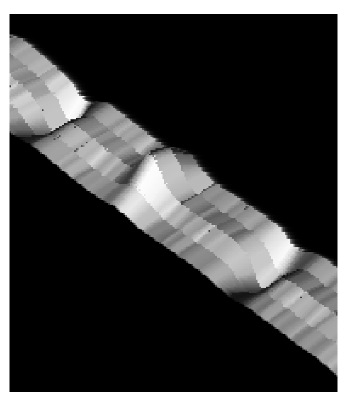


Fig. 6 3D view of the magnetic field profile generated by a track of magnets installed in the bus corridor

C. Guidance Control

The guidance control is responsible for the maintenance of the correct lateral position of the vehicle on the route. From the information of the lateral deviation of the vehicle obtained through the signal processing, the control generates the command for the actuator to apply the right steering angle to correct the lateral deviation of the vehicle [18]. Fig. 7 shows a representation of the vehicle utilizing the bicycle model [19].

In the following we describe some of the components utilized in guidance control.

c1) Kalman Filter

The state of the vehicle is composed of the following variables:

- ***x***: lateral distance measured from the track to the vehicle, in the direction perpendicular to the body of the vehicle;
- ***y***: position of the vehicle measured along the route;
- **Ψ**: angle between the body of the vehicle and the track.
- **α**: steering of the front wheel, which is the angle between the body of the bus and the direction to where the front wheel is pointed;
- **ρ**: curvature of the reference to be followed. The curvature is defined with the variation in the angle of the tangent to the reference in relation to the traveled distance.

When the magnetic sensor is used, the variables read are *x*, *y*, Δα and ρ (the value of ρ is obtained from the desing of the track and from the position measurement in which the vehicle is found) and the Kalman filter is used to estimate the values of *x*, α and Ψ [20] [21].

c2) State of the Vehicle Estimator:

The State Estimator reads the information form the sensors, applies it to the Kalman filter and decides how to use the results. One important decision of this module is define if the actual state is trustworthy of not. In the magnetic track case, the approximation between the estimate and the state actually measured is used in this decision.

c3) Control Algorithm:

The function of a Control Algorithm is to calculate the steering that should be applied to cancel the lateral deviation at a certain point ahead. When the reference comes from a optic sensor is necessary to consider two differences in relation to the use of the magnetic sensor:

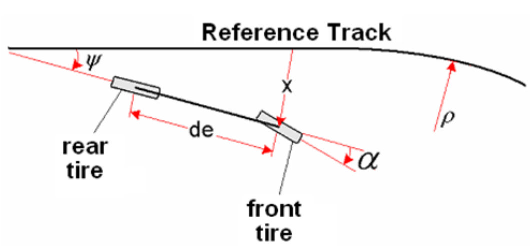


Fig. 7 vehicle dynamics of the BRT bus representation based on bicycle model.

the separation between samples and use of the curvature. In the case of the magnetic sensor, the separation between the samples is given by the distance between the magnets, usually of 2 meters. As the speed of the vehicle varies, the time between samples also varies, which brings

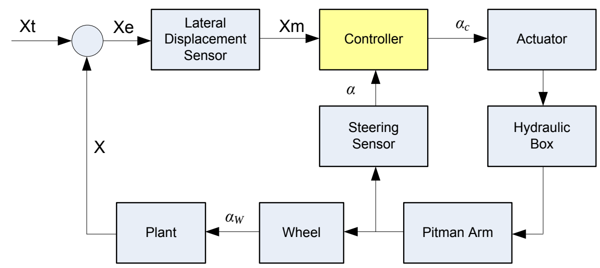


Fig. 8 functional block diagram of the magnetic guidance system

stability problems during high speeds. The use of the curvature of the reference depends of the system being capable of determining with precision in which point of the track it is found. In the case of magnetic sensors, this is done by the creation of binary codes based on the polarity of the magnets installed. Between the codes, the simple counting of the magnets detected provides one information of position. With the position information, the law of control can take into account the actual curvature and of the segment ahead, anticipating the steering at the entrance of curves. Fig. 8 shows the block diagram of the guidance control system.

c4)Steering Wheel Actuator

The actuator is an electro-mechanical component that has the function of transforming the output of the guidance control system in triggering the steering wheel system, in order to provide adequate steering of the directional wheels of the vehicle, which are necessary to produce the correction of the lateral deviation of the vehicle. It is composed of controller, motor and mechanic coupling with the steering system of the vehicle. The controller is responsible for the communication with the guidance computer that processes the guidance algorithm. The engine in conjunction with the mechanic coupling produces the mechanic movement necessary for the triggering of the steering system of the vehicle. The block diagram in Fig. 9 shows components of the wheel steering actuator.

At each 50 milliseconds the guidance computer calculates a new angular position assumed by the steering bar. This information is passed by Controller Area Network (CAN) for the engine controller. The controller commands the engine in a closed loop, that is, it commands electrically the position of the axle and reads, through an internal sensor, if the axle reached the desired position. This causes that angular position of the axle follows with great precision the values determined by the Guidance's Central Processing Unit (CPU). The axle of the engine is coupled mechanically to reduction box, which amplifies the momentum of 2Nm (servomotor capacity) to 20Nm on the steering bar. This configuration was sufficient to control the vehicle steering in all situations tested in real condition in the bus corridor. The exit axle of the reducer is connected to the clutch, which is the element of control of the engine coupling to the steering bar. The clutch is controlled electronically by the Auto/Manual button on the driver panel. When the system is in Automatic mode,

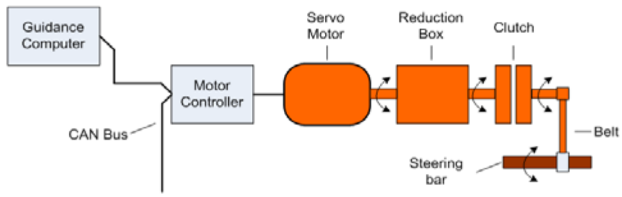


Fig. 9 functional block diagram of wheel steering actuator

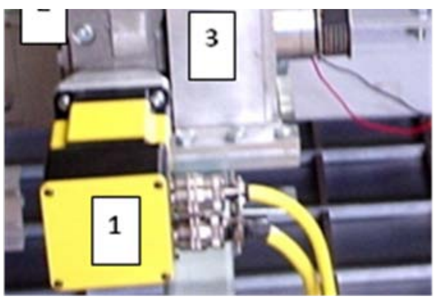


Fig. 10 assembly of wheel steering actuator. (1) servomotor; (2) reduction box; (3) magnetic clutch; (4) steering bar

the clutch transfers the movement of the exit axle of the reducer to the steering bar. When the system is in Manual mode, the clutch decouples both axles, and the steering bar turns freely in relation to the exit of the reduction box. As illustrated in Fig.9, the clutch is connected to the steering bar by way of a belt coupled to a pulley installed on the exit axle of the clutch and other installed on the steering bar.

V. Experimental Results

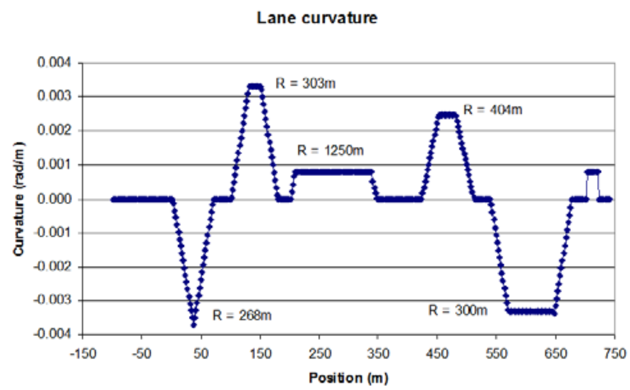
The graphs (a) and (b) in Fig.11 shows the radiuses of the curves from the route and the respective lateral deviation of the vehicle (in relation of the magnetic track) of a segment of 750 meters of the Tiradentes Express between the Mercado and Pedro II Stations.

It should be noted that autonomous guidance given following operational precisions:

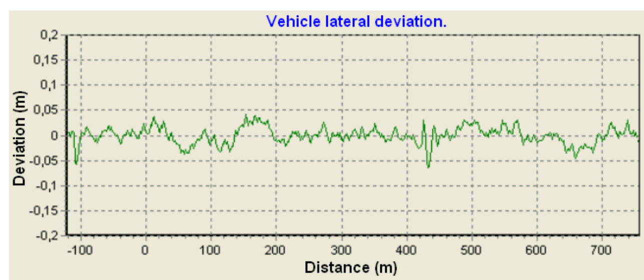
- Guidance Precision at the stops: 1.0 cm;
- Guidance Precision throughout the route;

This result creates the following perceptiveness for the Bus Corridor operational improvements:

1. Reduction of passenger boarding and deboarding time;
2. Increase in accessibility for users with disabilities, children and the elderly;
3. Possibility of eliminating access ramps for wheelchairs;
4. Possibility of operation on straight routes, enabling the implementation of exclusive routes in urban centers;
5. Cost reduction of the corridor construction. It is estimated that the road width could be reduced from 3.50 to 2.90 meters.
6. Time reduction in the bus approach and exit at the stops.
7. Increase on the passenger comfort based on the standardization of the vehicle's path along the route.
8. Driver's stress reduction, which with the automatic guidance can concentrate on the acceleration and breaking control.



(a)



(b)

Fig. 11 (a) radius of curvature of the route segment between Mercado and Pedro II Stations in Expresso Tiradentes bus corridor (b) lateral deviation of vehicle along the same segmen

VI. Conclusion

Through the ITS4BRT when the denominated Critical Autonomous System, more specifically the Docking Precision and Autonomous Guidance functions, implemented on the

Expresso Tiradentes bus corridor in São Paulo, it was possible obtain an operational improvement of the BRT. As shown: lateral deviation, on the docking maneuver at the stops, less than one centimeter and lateral precision guidance, throughout the route, less than five centimeters. In addition to the performance improvement, the magnetic sensing alternative was chosen based, among other criteria, of a smaller investment necessary for implementation and maintenance.

VII. Acknowledgements

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