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Personal Rapid Transport System Compatible With Current Railways and Metros Infrastructure

Efrén Díez-Jiménez, Miguel Fernández-Muñoz, Rubén Oliva-Domínguez, David Fernández-Llorca, *Senior Member, IEEE*, and Miguel Ángel Sotelo, *Fellow, IEEE*

***Abstract*— We present an innovative personal rapid transit technology compatible with current metro infrastructures, named OPTIMOTUS. The key of this technology is that passengers can travel without stops, thus multiplying several times the effective travel speed. In metro lines with shorter separation between stations (< 1000 m) and for long travels (> 5 stations), passengers travel speed could be up to 3.5 times faster with OPTIMOTUS than with conventional metro trains. In addition, its implementation costs would be relatively low since the vehicles are designed to be compatible with current metro railways. However, there are still many open issues to be engineered before claiming the full viability of the technology.**

***Index Terms*— Person rapid transit, underground, subway, individual transport.**

I. Introduction

METRO networks have increased their quality, improved their service and extended their range in cities significantly during last years, contributing towards worldwide environmental objectives and optimizing public transport systems.

Although trains technologies are in continuous enhancement, the concept of a railways system has not changed too much since the very first passenger railways in 19th century in spite of its significant limitations. Despite enjoying a separated infrastructure, passengers of metro trains do not usually have very high effective travel speed. In lines with many stations, the actual passenger speed is very slow, typically in the range of 20-30 km/h, mainly due to the continuous stops for passengers boarding. One main disadvantage is associated with the predetermined destinations when travelling within a single metro line. Other destinations can be reached, but only with one or more transfers from one line to another. In addition, metro trains usually circulate partially empty out of the peak hours, which is very inefficient in terms of operation, energy and cost.

There have been different essays facing and trying to solve this speed limitation imposed by consecutive stops. Some studies have proposed techniques to skip stops by scheduling trains with direct travels without intermediate stops combining with trains stopping at each stop within the same line [1]. Other optimizations propose train scheduling according to passenger demand or through adaptive optimal control [2], [3]. Although, all those previous methods offers good enhancements on the average passenger travel speeds, they are limited by the railway system concept itself.

In order to relieve the inconveniences of trains transport, but enjoying the advantages of transport in separate infrastructure, other transport systems have been proposed as for example Personal Rapid Transit (PRT) systems. Personal Rapid Transit (PRT) is defined as an automated transport system wherein vehicles are used to transport a batch of passengers on demand to their destinations without stops and transfers [4]. These systems are based on a fleet of self-propelled vehicles, generally with autonomous driving, and capacity for one or several persons. In these systems, the vehicle synchronizes its schedule with the demand of the passenger, as well as it plans the itinerary reducing unnecessary stops.

In 1978, the book "Fundamentals of personal rapid transit" [5], introduced the fundamentals of PRT, based on research conducted in the USA. These authors defined PRT as a public transport system of small vehicles that automatically travel in exclusive lanes, separated from the street and pedestrian traffic. Carnegie et al., in 2007 defined PRT as a private space vehicle that is not shared with strangers and that makes a trip without stops and without transfers from the departure station to destination, anywhere in a large urban area [6]. The quality of the service would be comparable to a car driver and far superior to conventional public railway transport.

Between the 1960s and the 1990s, many PRT [7] research projects were carried out in the United States, Japan, Australia and Europe. Since 2001, several European projects like CityMobil (2009) [8], Cybercars2 (2006) [9] and Cybermove (2004) [10] have reviewed the concept of transport on demand, including PRT. In terms of commercial applications, the most developed systems are SkyWeb Express (2009) [11], and Mister (2009) [12], which are complete solutions for PRT. Also, Skytran (2013) [13] and Shweeb (2010) [14] presents ideas for PRT but most of them stayed in the experimental phase, due to technical difficulties or excessive implementation cost. There have been several theoretical approaches showing the benefits of PRT, but again they rest in the theoretical level [4], [15]–[18]. As far as we are concerned, there are only two PRT systems in real operation: the Morgantown

Manuscript received December 27, 2018; revised April 1, 2019, October 19, 2019, and December 18, 2019; accepted February 24, 2020. The Associate Editor for this article was W. Fan. *(Corresponding author: Efrén Díez-Jiménez.)*

Efrén Díez-Jiménez, Miguel Fernández-Muñoz, and Rubén Oliva-Domínguez are with the Mechanical Engineering Area, Signal Theory and Communications Department, Polytechnic School, Universidad de Alcalá, 28805 Alcalá de Henares, Spain (e-mail: efren.diez@uah.es; miguel.fernandezmuno@uah.es; ruben.oliva.89@gmail.com).

David Fernández-Llorca and Miguel Ángel Sotelo are with the Computer Engineering Department, Polytechnic School, Universidad de Alcalá, 28805 Alcalá de Henares, Spain (e-mail: david.fernandezl@uah.es; miguel.sotelo@uah.es).

Digital Object Identifier 10.1109/TITS.2020.2977387

PRT system designed by the University of West Virginia [19], operative since 1975 and the London Heathrow airport PRT ULTRA [20] operative since 2009 and used to transport people from a remote parking area to the central terminal.

In patent literature, PRT systems can be found. The patents applications US4061089A [21] and US8950337B1 [22] claim the invention of self-propelled vehicles as PRT but not being compatible with double flow in current infrastructure, key point of OPTIMOTUS as described next. In patents: DE19546694A1 [23], DE102006020338A1 [24], ES405430A1 [25], ES2370705T3, US5219395A [26] and US5778796A [27], DE4029571A1 [28] PRT systems, mostly based on monorail, with possibilities of double flows are claimed, but again not compatible with current infrastructures, needing their own infrastructure.

All the PRT listed above offer common advantages in respect to conventional metros. However, they have a main drawback for their implementation: all of them need separate and custom-made infrastructure. This requires a very high investment and a need for additional space, both things are difficult to obtain in today's large cities. That is why most of them have not been implemented beyond an experimental level and only two of them are operative for short travels.

With the development of autonomous cars, new PRT systems are being mainly developed to share the space with conventional cars or light trains [18], [29], [30]. But while the road infrastructure is still shared with manually driven cars, congestions, accidents and other limiting issues may appear.

The robustness and reliability of metros combined with the fact that their infrastructure was firstly built have prevented their replacement by other innovative smarter personal rapid transport systems developments. Nevertheless, we are proposing an innovative personal intelligent rapid transport, named OPTIMOTUS, with the versatility and high-speed of PRT while being compatible with current railway infrastructures. This new system is currently under patent evaluation [31].

In this work, we present the description of this emerging intelligent transportation system. Preliminary mechanical design of the vehicles and vehicle performance estimation are described. The travel speed improvement potential has been analyzed by using the vehicle performance. Travel speed enhancement estimations provided by OPTIMOTUS in a generic metro line are given, showing a significant speed multiplication. However, there are still many open issues to be engineered before claiming the full viability of the technology. We describe and initiate the discussion of those open issues giving conceptual solutions and preliminary analysis to solve them.

This article is organized as follows: section II presents a description of this new transport system. The system's vehicles preliminary design and their expected cruise speed are shown and calculated in sections III and IV. Theoretical application of OPTIMOTUS in a generic metro line is described in section V. Section VI deals with open issues, focusing mainly on management of passenger demand at rush hours and other open questions. Conclusions are summarized in section 7.

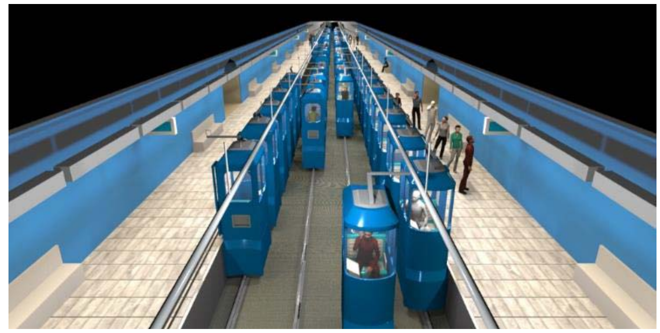

Fig. 1. Render of Metro station with OPTIMOTUS system.

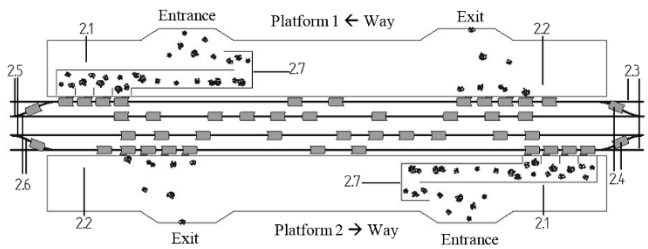

Fig. 2. OPTIMOTUS Metro station diagram description.

II. OPTIMOTUS System Description

OPTIMOTUS is a smart on demand passengers rapid transport system based on a fleet of self-propelled autonomous vehicles, supported and stabilized laterally on a single rail. Vehicles can transport one or several persons. Its design is compatible with the circulation of at least two parallel flows of vehicles on the same railway track, see figure 1. The benefit of having two parallel flows of vehicles is that one rail can be used as a continuous cruise flow rail and the other rail can be used as an acceleration and deceleration lane for the vehicles. This allows a continuous flow of vehicles between the origin and destination station in cruise speed, without the need to make intermediate stops and, therefore, multiplying the actual effective travel speed of the passengers. Potentially, the socio-economical impact of this approach is enormous.

Rolling stock is designed to be compatible with current railway infrastructures. OPTIMOTUS can be used in all kind of infrastructures with electric or diesel engines, indoor or outdoor, almost any type of rails, in lines with more or less density of stations and greater or smaller demand of transport.

Figure 2 shows a top view of the platforms of a current metro station with the vehicles. The entry (2.1) and exit passenger areas (2.2) of passengers from at the platforms are indicated. Current metro stations normally have two railway tracks in, one per way-direction. Then, there are four rails in total. The two outer rails (2.3), those closer to the platforms, serve as acceleration or deceleration lane for the vehicles (2.4) allowing passengers to enter or exit from the transport. The two inner rails (2.5) serve as cruise speed lanes, enabling the uninterrupted flow of vehicles. The rail track switches (2.6), which make the change of rail, are also shown conceptually.

Each vehicle has a width ranging between 1 m and 0.8 m. This makes it compatible with most of the current railway track gauges. The maximum geometric width of the vehicle is

Fig. 3. Render of OPTIMOTUS from platform.

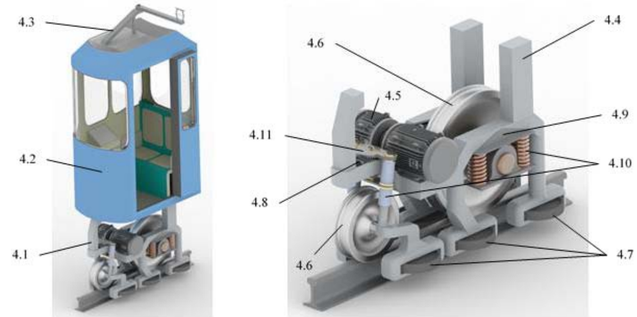

Fig. 4. Preliminary design of a single vehicle of OPTIMOTUS system. Up–isometric compete view, down–rolling stock.

the separation gauge between rails, however margins must be kept for safety reasons. With the proposed width, the vehicle could host on adult and one child. Moreover, longer vehicles for special needs (wheelchairs, baby trolleys, large persons, etc.) can circulate. Wider vehicles could also be created for those lines with large track gauges as metros using international gauge (1435 mm). Vehicles are composed of a passenger cabin, a pantograph system for electrical connection, a support and stabilization system against lateral roll, a motor, brakes, suspension and an air conditioning system. In addition, the vehicle must have an autonomous driving system, as well as the necessary sensors for it, together with communication systems for traffic coordination. Moreover, each vehicle must include a buttons panel, an automatic voice recognition software or mobile applications connection for setting the destination station of the passenger, figure 3.

III. Vehicle Preliminary Design

The rolling stock, shown isolated in figure 4 right, is composed of a chassis (4.4) and the mechanical elements that make possible the movement of the vehicle: motor (4.5), front and rear wheels (4.6), lateral anti-roll wheels (4.7) (three on each side of the rail), transmission systems (4.8), axle boxes (4.9) and suspensions (4.10). The vehicle suspension system is based on motorbikes layout including a steering mechanism (4.11) on the front wheel to self-guide the vehicle along the rail. Wheels can be done in metal-metal contact but also another option is to mount pneumatic tires.

The cabin is composed by a floor, front, rear, left and right side panels, automatic doors, and ceiling. Inside the cabin, there is a seat for two medium size persons, room for baggage and an interactive screen for the selection of the destination station, general information and/or entertainment applications. Seats have a common safety belt that will be mandatory to use. The pantograph is shown on the top.

Main dimensions of this preliminary design are depicted in figure 5. The volumetric size of the vehicle is 1500 x 950 x 3230 mm, excluding the pantograph. Provided that the maximum width of the vehicle must allow double flow of vehicles in a single rail track, the rest of design parameters are as free as in any machine design from zero.

Weights and materials of the different parts and subsystems are listed in table I. At this point weight estimations have been done in a very conservative way taken into account that structural, fatigue and manufacturability analysis should be

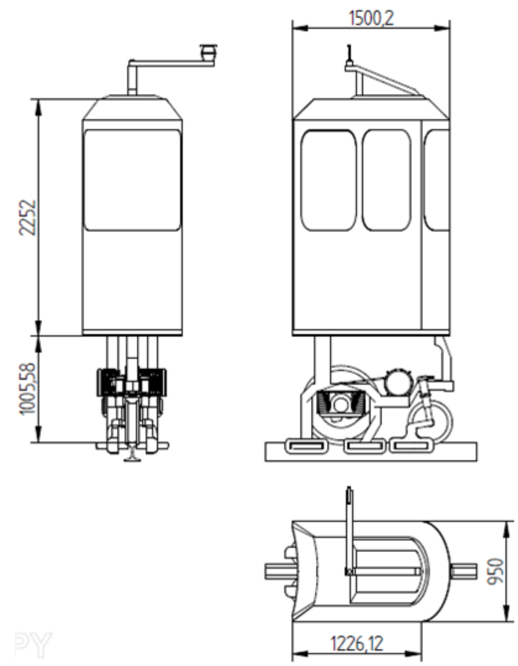

Fig. 5. Front, lateral and top view of the preliminary design.

TABLE I

List of Weights and Materials for the Different Parts

Part / Subsystem	Weight (kg)
Rolling stock	
54 kW DC Motor + transmission	50
Wheels and Anti-roll wheels	80
Chassis	80
Suspensions and steering fork	70
Cabin	
Walls + interior elements	80
HVAC, Computer and Electronic system	40
Battery	80
Pantograph	20
TOTAL	**500 kg**

done in a detailed final design. The total empty weight of the vehicle has been estimated in 500 kg. Laterally, the weight distribution must be done in order to keep the centre of gravity as closest as possible to the middle section. This reduces the loads due to roll torque on the structural elements.

TABLE II

RESISTANCE TO MOTION CALCULATION

Resistances	Value	Comments / Justification
Aerodynamic drag (N)	$0.373 \cdot v^2$	$R_a = \frac{1}{2} \cdot \rho \cdot A_{front} \cdot C_d \cdot v^2$
- ρ, density (kg/m^3)	1.225	at sea level and at 15 °C
- A_{front}, front area (m^2)	3.068	From CAD drawing, figure 4
- C_d, drag coefficient	0.392	Estimated conservatively as half semi-sphere coefficient [34]
Gradient force (N)	317.83	$R_{gradient} = W \cdot \sin(\theta)$
- θ slope (degrees)	2.86	5% of slope, maximum slope allowed in some metro systems.
- W, weight (N)	6370	Including 500 kg of vehicle and 150 kg of passenger / load
Rolling resistance (N)	6.37	$R_{rolling} = f_r \cdot W$
- f_r, friction coefficient	0.001	Rolling friction of wheel-rail clean and made in steel
- W, weight (N)	6370	Including 500 kg of vehicle and 150 kg of passenger / load
Total Resistance (N)	$\mathbf{0.737 \cdot v^2}$ **+ 324.2**	

IV. VEHICLE CRUISE SPEED AND ACCELERATION ESTIMATION

An estimation of the maximum cruise speed can be done by equalizing the resistance to motion at a certain speed with the maximum traction force provided by the motor. The maximum traction force will be limited and applicable at the wheel-rail contact. In terms of power, the maximum speed will be achieved at the instant where the necessary motion power is equal to the maximum power provided by the motor. This can be expressed as:

$$P_{motion} = P_{motor}$$
$$R_{motion} \cdot v = M_{motor} \cdot \omega_{motor}$$

where v is the cruise speed, M_{motor} is the total output torque from the motor and ω_{motor} is the rotational speed of the motor.

R_{motion} is the total resistances that a vehicle faces while attempting to keep a constant speed and/or accelerate from one speed to another. Resistances can be categorized in: aerodynamic drag, gradient resistance, rolling resistance and inertia forces. Tractive force must be greater than or equal to the resistive forces in order to maintain a sustainable motion [32]. We can balance them as:

$$R_{motion} = R_{aerodynamic} + R_{gradient} + R_{rolling} + R_{inertia}$$

The specific expression for each of the resistive force is given in table II. Those expressions are common formula used in transport engineering. In the case of OPTIMOTUS, expressions, parameters and resistances calculations are listed in table II:

If we consider a DC electric motor of $P_{motor} = 54$ kW as the model GVM210-100-SPW from Parker Hannifin Corporation in normal operation [34], a achievable cruise speed can be:

$$P_{motion} = \left(0.737 \cdot v^2 + 324.2\right) \cdot v = 54000v \cong 140\ km/h$$

The peak power provided by the motor is 82 kW, thus the maximum cruise speed could reach even 162 km/h. Therefore a reasonable and very conservative cruise speed for the vehicle can be set in $v_{cruise} = 100$ km/h using just 24 kW. This cruise speed will be used for travel speed improvement factor calculation.

Acceleration time from 0 to 100 km/h is a second important parameter for the vehicle kinematic performance. Vehicle acceleration can be obtained as:

$$a(v) = \frac{F_{aa}(v)}{m}$$

where F_{aa} is the available force to accelerate and m is the mass. The available accelerating force is the traction force provided by the motor and applied in the wheel-rail contact minus the resistances to the motion. Thus, previous expression can be written as a function of the speed as:

$$\frac{dv}{dt} = \frac{F_{tract} - 0.737 \cdot v^2 + 324.2}{650}$$

Motor speed has to be reduced in order to adequate it to wheel speed. This implies that a speed reducer gearhead should be included between motor and wheel. In this case, a speed reducer with a reduction ratio of 1:7 is considered. Inversely, output torque from the motor is multiplied by a factor of 7. The output torque of the selected motor is 78.6 Nm, thus the torque applied in the wheel will be 550.6 Nm. C Traction force is the torque applied in the wheel divided by the radius of the wheel (0.39 m). Traction force is 1410 N. This traction force could be applied between wheel and rail if the adherence is higher. Maximum adherence has been estimated considering a 75% of the total weight on the rear wheel and a friction coefficient in sliding between wheel and rail of 0.3. Then, maximum adherence is 1433 N, higher than the maximum traction force applied in the wheel. Finally, the acceleration time can be obtained by solving the defined integral:

$$t_{0-100} = \int_0^{27.7} \frac{650}{1086 - \left(0.737 \cdot v^2 + 324.2\right)} dv = 20.9\ s$$

With this 0 to 100 time, an average value for the acceleration from 0 to 100 km/h can be obtained as:

$$a_{avg0-100} = \frac{\Delta v}{\Delta t} = \frac{27.7}{20.9} = 1.3 m \cdot s^{-2}$$

This acceleration 0.13g is adequate for passenger comfort. Deceleration from 100 to 0 km/h for the stops can be in a similar range.

The specific consumption of a transport system is defined as the energy consumed per passenger-km (pkm). OPTIMOTUS vehicle requires a power of 24 kW to move a person traveling at 100 km/h. Therefore, 24000 J/s per passenger travelling at 0.025 km/s. i.e 0.96 MJ/pkm. Other railway systems consumption are: the regional rail passenger transport in Germany needs 0.90 MJ/pkm [10], the US intercity Amtrak rail needs

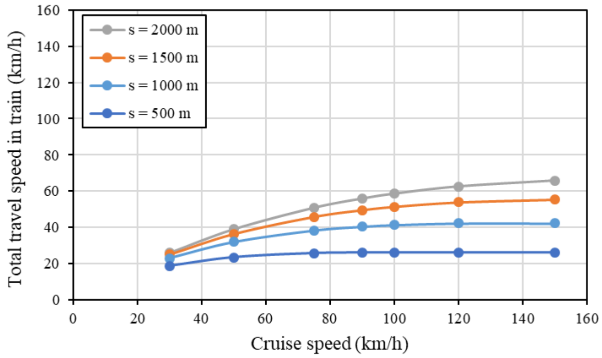

Fig. 6. Total travel speed when travelling in train as a function of the cruise speed reachable by the train between stations.

1.5 MJ/pkm [11] and the European transport efficiency including all modes is 1.12 MJ/pkm [11]. Thus, OPTIMOTUS specific consumption is at least in the same order of magnitude, even lower than other railways systems.

V. Enhancement of Travel Speed Analysis

With previous values, we can estimate the multiplication of the travel speed that OPTIMOTUS provides. The potential improvement has been done for a generic metro line in a simplified manner.

This generic line has been defined with the parameters: n_{total} as the total number of stations and s as a constant distance between stations. It has been compared the travel speed that a train would offer in this generic line with respect to the travel speed that OPTIMOTUS shows. For the train travel speed, a 30 seconds stop has been considered and the acceleration and deceleration of the train is constant and equal than for OPTIMOTUS, a $= 1.323$ m/s^2.

Thus, the total travel speed of the train v_{train} after travelling a certain number of stations n can be expressed as:

$$v_{travel\ in\ train} = \frac{s}{(t_{stop} + t_{acc} + t_{cruise} + t_{dec})}$$

where $t_{acc} = \frac{v_{cruise}}{a}$, $t_{dec} = t_{acc} = \frac{v_{cruise}}{a}$, $t_{stop} = 30\ s$ and $t_{cruise} = \frac{s_{atcruise}}{v_{cruise}} = \frac{s - \frac{v_{cruise}^2}{a}}{v_{cruise}} = \frac{a \cdot s - v_{cruise}^2}{a \cdot v_{cruise}}$.

Therefore, travel speed of the train is:

$$v_{travel\ in\ train} = \frac{s}{(t_{stop} + \frac{a \cdot s - v_{cruise}^2}{a \cdot v_{cruise}} + 2 \cdot \frac{v_{cruise}}{a})}$$

At this point it is interesting to analyse the influence of cruise speed and separation in the final total travel speed of the train, i.e. the final travel speed of the passengers (excluding departure waiting time, train acceleration / braking a $= 1.323$ m/s^2, and $t_{stop} = 30\ s$), figure 6. It can be appreciated that for lines with closer stations, the real travel speed can never be very high, even if the trains could provide larger cruise speeds. Therefore, for lines with closer stations it is recommended to downsizing trains cruise speeds and increase trains acceleration and braking capacity. Those lines

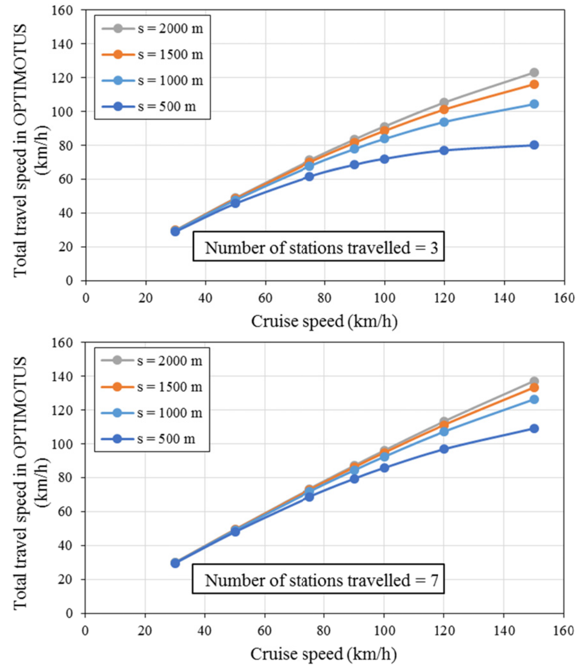

Fig. 7. Total travel speed when travelling in OPTIMOTUS as a function of the cruise speed reachable by the vehicle when travelling 3, or 7 stations.

with larger distances between stations can achieve higher cruise speeds and hence, to obtain faster total travel speeds. For trains operating at 100 km/h cruise speed and with the most convenient case, s $=$ 2000 m, the total travel speed is only 59% percent of the cruise speed achievable by the trains. This is because there is a great waste of time in stops and in acceleration and deceleration phases and this always happens between consecutive stations. This description can be generalized for any current metro system taking into account their particular parameters of acceleration, stop time and station separation.

On the other side, the expression for the total travel speed in OPTIMOTUS can be written:

$$v_{travel\ in\ OPTIMOTUS} = \frac{n \cdot s}{(t_{acc} + t_{dec}) + t_{cruise}} = \frac{n \cdot s}{2\frac{v_{cruise}}{a} + t_{cruise}}$$

where n the number of stations travelled and s is the distance between stations, t_{acc} is the time in acceleration, t_{dec} the time braking and t_{cruise} is the time at cruise speed. This cruise time can be expressed as function of n, $v_{cruise}a$ as:

$$t_{cruise} = \frac{s_{atcruise}}{v_{cruise}} = \frac{n \cdot s - 2 \cdot s_{accelerating}}{v_{cruise}} = \frac{n \cdot s - \frac{v_{cruise}^2}{a}}{v_{cruise}}$$

All calculations have been done using 100 km/h as conservative cruise speed for OPTIMOTUS vehicles and an constant acceleration /deceleration of $a = 1.3\ m/s^2$

One main difference of the speed in OPTIMOTUS is that it is dependent on the stations travelled, unlike in conventional trains. We have also analyzed the influence of cruise speed, number of stations travelled and separation between, figure 7.

In figure 7, it can be seen that total travel speed is several times larger than for trains. Even in the case of just three

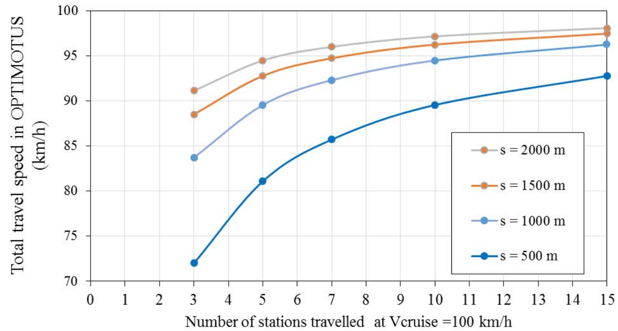

Fig. 8. Total travel speed when travelling in OPTIMOTUS as a function number of travelled stations at 100 km/h cruise speed.

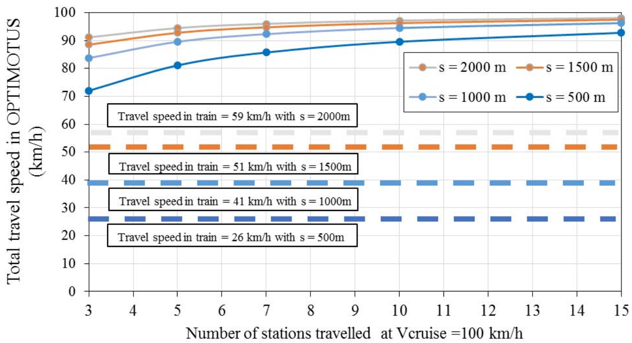

Fig. 9. Comparison of total travel speed in OPTIMOTUS (full lines) and conventional trains (dashed lines) as a function number of travelled stations at 100 km/h cruise speed.

stations travel, the lack of stop in the intermediate stations provides faster speeds for OPTIMOTUS. Most of the curves in figure 7 are almost straight lines, this means that the vehicles are almost always travelling at their cruise speed. Since the vehicles does not have to stop, they have enough time to reach their cruise speed and maintain it along the trip.

Figure 8 represents the total travel speed when travelling in OPTIMOTUS as a function number of travelled stations at 100 km/h cruise speed. It is clear that the larger is the number of travelled stations, the less significant are the acceleration and deceleration time in respect to the time circulating at cruise speed.

We can compare the behavior of a conventional train system with the OPTIMOTUS' s behavior. This comparison has been done for the case of 100 km/h cruise speed. Figure 9 presents the total travel speed in OPTIMOTUS with respect to the number of stations and the total travel speed in trains, which is independent on the stations travelled. It can be seen that OPTIMOTUS system is clearly more efficient.

To end the analysis, travel speed improvement factor has been calculated by dividing the travel speed in OPTIMOTUS by the travel speed in conventional trains. Results are presented in figure 10. For lines with shorter distance between stations and for long travels, the improvement factor can be up to 3.5 times better with OPTIMOTUS. In those lines with further separation between stations, the improvement is smaller but still significant and worthwhile.

Therefore, it is clear that developing a stops-free PRT system compatible with current metro railways infrastructures could mean a huge time and energy saving of public transports networks besides offering a more comfortable and agreeable of urban mobility.

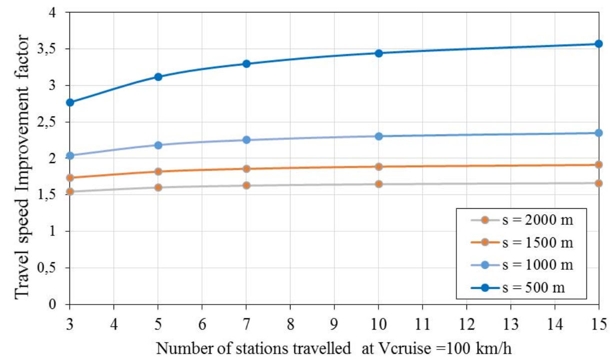

Fig. 10. OPTIMOTUS total travel speed improvement factor as a function number of travelled stations at 100 km/h cruise speed.

VI. Open Issues and Questions

Although OPTIMOTUS technology shows great potential for enhancement of travel times, there are many open issues that must be deeply treated and developed. In this section, we list most of those open issues, analysing them preliminarily and proposing some initial approaches for their solution.

A. Detailed Mechanical Design Issues

Stresses, fatigue and wear of all the mechanical elements must be analyzed. Regarding the vehicle design, no significant issues have been detected since the vehicle elements can be custom-designed for compliance with all the mechanical requirements.

Wheel-rail contact analysis is essential for the correct design of the mechanical rolling stock and so, to anticipate and predict the maintenance operations and their associated costs. For railway operations, Wear Rate (WR) is a common parameter to predict maintenance actions. This parameter is the amount of vertical wear of a rail per cumulative million gross ton (MTon) circulating at a certain speed. This index can be used to classify the wear as mild (WR<0.06 mm/MTon), medium (0.06 mm/MTon<WR<0.2 mm/MTon) and severe (WR>0.2 mm/MTon), [35]. As a design objective, rail wear due to OPTIMOTUS has been set in lower than 0.05 mm/MTon at 100 km/h cruise speed.

A rough calculation of the million gross ton per year for OPTIMOTUS can be done. The estimated weight of a vehicle is 650 kg with passenger; the expected daily operation time is 19 hours. Assuming that a rail section bears with a vehicle each 10 seconds in average and considering than only half of the passenger will pass in through the rail section, the daily load is 2223 Tons; thus 0.81 MGTon per year. By assuming that OPTIMOTUS will operate in similar tribological conditions than trains in [35]; the WR of the rail section would be 0.04 mm, something reasonable for any metro maintenance service.

B. Electrical Engineering: Pantographs

Electrical DC or AC energy will have to energize OPTIMOTUS vehicles as in most of metro networks.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

This means that each single vehicle will need a pantograph system for the electrical connection. In addition, OPTIMOTUS pantograph has a special requirement: the head must retract when the vehicle is at the stations. In common infrastructures, there is only one catenary located in the middle plane between the rails. Thus, those vehicles resting at the stations must retract their pantograph in order to avoid collisions with the pantographs of the vehicles circulating in the cruise rail. This implies two important considerations. Firstly, the pantograph will have to provide a large number of actuations. A good design objective is to bear with at least 0.5 million cycles in a 10 years period. This is can be achieved with conventional machine elements. Secondly, an auxiliary connection system is needed for the vehicles while they are in the stations. The solution can be to add a small battery package in the vehicles or to implement an auxiliary connection system at the stations.

C. Rail Switchers

The change from one rail to the other during acceleration and deceleration is one the most difficult challenge for OPTIMOTUS. The switch of rail track has to be fast enough to permit the incorporation of new vehicles to the cruise rail without reducing the speed of those vehicles already in the cruise rail. In addition, the system has to be very reliable and long-lasting since the number of actuation will be very large. The objective for the rail track switch can be to bear with more than 15 million cycles in 3 years period.

Two design approaches can be explored. First one is to design a rail track switch using rail tracks and linear actuators as usual, (as an example see the monorail track switch from Osaka, Japan [36]). A second approach will be to create an actuation system on the auxiliary lateral wheels of the vehicles. This system will retract and extent the lateral wheels at the right moment for guiding the vehicle. The main advantage of this second approach is that no change will be necessary in the infrastructure so total implementation costs can be cheaper. The major drawback is that it enhances the complexity of the vehicle and its unitary cost.

D. Traffic Management, Communications and Control

Automatic driving in railways has not presented severe difficulties since only one degree of freedom must be controlled. There are multiple automatic metro lines all around the world operating normally. Such automatic systems are typically controlled by general Traffic Management Systems (TMS).

However, in OPTIMOTUS, traffic management and control must be extended to a different level because many vehicles have to circulate very close to each other. In addition, OPTIMOTUS vehicles acceleration / braking capacities are far different from ordinary trains because the moving mass is smaller. Considering these two characteristics a new approach should be explored.

The scheme for the TMS proposed is depicted in figure 11. This scheme is applicable if no transfers between lines is implemented. Then, each line direction way will have a general TMS system whose network is connected to a set of TMS controllers corresponding for each station. The whole line

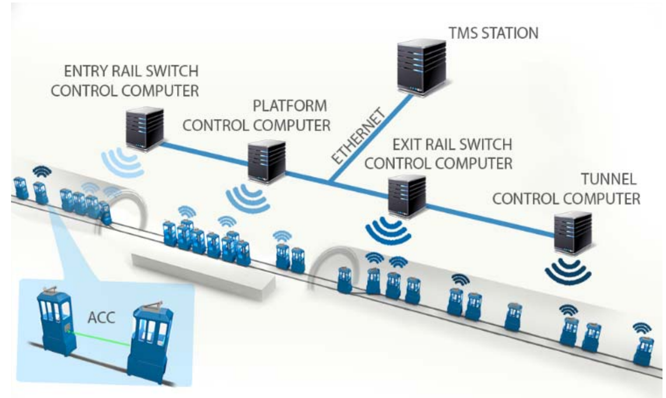

Fig. 11. Control and communication system proposed for OPTIMOTUS.

track will be split in fixed cells managed by each TMS Station. Each cell will manage the vehicles during the circulation inside the cell.

Then, the control cell is divided in four sections lengths corresponding to: tunnel track before the station, exit rail switch, track through the station platform and entry rail switch. Each Station TMS will have four slave controllers for each section. Those controllers are in charge of the vehicle driving instructions until they leave the section. Four controllers are in permanent communication through Ethernet connection with Station TMS. Redundant system may be considered for safety reasons. Communications with vehicles will be done through RF systems, preferably on 4G platforms.

Additional rail switches must be installed along the tunnels to allow reallocation of traffic flux in case of vehicle failures or emergency, to keep the vehicle flux and to reach the interruption point to solve the issue.

Each vehicle will have an own on board control unit and a set of sensors to measure speed and separation distance with the previous vehicle. We propose that speed control in the cruise travel lane should be based on Adaptive Cruise Control (ACC) system commonly present in cars. ACC are based on a radar or laser distance sensors. The idea is to include an on board ACC system on each vehicle that measures the distance from the previous vehicle and sets the travel speed accordingly. ACC speed and separation distance values will be set by external TMS.

TMS must be in charge of all the vehicles incorporation and exit from the cruise speed rail. It has to manage passengers' destinations, to manage traffic and parked vehicles in the station, to deal with asymmetrical demands between stations and also to provide good and safe response against emergency events. TMS strategy may follow recent developments for vehicle-infrastructure connected environments [37]. TMS can proceed as follows: the passenger gets on the vehicle, the vehicle automatically closes its doors. Then, the vehicle sends an OK signal to TMS. TMS analyses the right moment for the incorporation to the cruise lane according to the rest of traffic, TMS sets the vehicle speed and separation distance values and the acceleration initiates. At the right moment, TMS activates the rail track switch for passing from one rail to the other. In the meanwhile, the passenger has set the destination by means of tactile screen interaction, voice recognition or mobile app. Cruise speed travel can be controlled internally by the vehicle on board controller, in any case continuous information of the vehicle location has to be sent to TMS. When travelling in the cruise lane, vehicles do not communicate between themselves. They simply try to travel at the set cruise speed like cars with ACC + traffic jam assist try to do in traffic jams. Once the destination is almost reached, TMS sets a different speed parameter for the vehicle, activates rail switch and the vehicle brakes and opens its doors.

At the station, TMS must handle passenger demand to move vehicles in order to get new passenger loads. A buffer of empty vehicles can be stored in the external rail along the tunnels for the case of asymmetrical demands (between arrivals and departures). Previous optimization studies of PRT empty vehicles management could be applied to OPTIMOTUS [38]–[40]. For emergency cases, TMS could use additional rail track switchers located along the tunnels to readdress the cruise flow and permit to solve the emergency.

E. Transport Efficiency, Service Conditions and Safety

Two parameters can be calculated in order to analyse the transport efficiency and the service conditions of such a new transport system like OPTIMOTUS: departure rate, i.e. how many passengers can leave from a certain station per hour and passenger flow, i.e. how many passengers can travel in the cruise lane per hour.

The general idea for OPTIMOTUS is that vehicles travel in sets of 10 units with vehicles very close to each other, approximately 1 m of separation. This distance can be accurately controlled by ACC system. By departing and travelling in sets of 10 vehicles, the departure rate and passenger flow can be maximized. Thus, 10 vehicles will depart simultaneously from the station and will travel together all the time, until the vehicles reaches each corresponding final station. At this moment, the set will be broken and the vehicle willing to leave will have larger headway from previous and next vehicle. The estimated headway ahead is 4 m and after is 15 m, hence the rail switch must actuate within one second. So, the rail switcher must be very fast to have enough time to switch out the vehicle and switch in again to maintain the rest of the set in cruise lane. Once the vehicle has left the cruise lane, the set can be merged again and continue its travel but with a lower number of vehicles.

During routine operation, passengers will wait their turn in a single queue with a certain number vehicles available at each turn, as shown in figure 2. Travelling in set of 10 vehicles will permit to delivery 10 passenger, or even more if the vehicle is shared, at once. The vehicles necessary reload time to bring ten empty vehicles into load zone, has been estimated in 10 seconds. The necessary load time for a passenger to get into the vehicle safely from the waiting line, has been estimated in 4 seconds. This leads to a reasonable vehicle departure rate for OPTIMOTUS of 10 vehicles each 14 seconds, i.e. 2500 passenger/h per platform. This rate has been calculated in routine operation of a station with one acceleration rail and its corresponding rail track switch. Although this vehicle departure rate could be fast enough for more than 90% of the operation time, one of the main challenge for OPTIMOTUS is to provide efficient service also at peak hours.

Just for comparison, the demand at peak hours can be as high as 7000 passenger/h per station in large cities metros at peak-hours (Metro de Madrid statistics, Moncloa Station, 8 a.m [41]). By assuming an asymmetrical, 65%-35%, demand between ways, 4550 passenger/h per platform. Important to notice that passenger demand would be much lower if no transfers between lines were needed, as OPTIMOTUS could provide. Therefore, optimization solutions must be researched for peak hours. Some ideas to be explored are: increase the number of simultaneously vehicles, multiple rail track switchers, vehicle sharing for the same destinations, increasing accelerations, shortening load time. In the worst of the case, passengers will have to wait longer in the platform but the save in travel time can still be worthy.

The general idea for OPTIMOTUS is that vehicles travel in sets of 10 units, in this way, passenger flow can be maximized. In order to calculate the maximum passenger flow, the limiting factor is the braking capacity of the vehicles. It is proposed to add emergency locking brakes in rear and front wheels but also in antiroll-wheels. In this way, the emergency brake time can be reduced to 4 seconds from 100 km/h to full stop. This leads to a maximum braking acceleration of 6.9 m/s^2. Considering this emergency deceleration and taking into account that metro railways are controlled and separated, a reasonable safety distance between vehicle sets of 40 m can be defined. The total time that 10 vehicles need to travel 70 m (40 m safety plus 15 m vehicles length plus 15 m headway) at 100 km/h is 2.52 s. Therefore, a reasonable maximum passenger flow through the cruise rail is 14285 passenger/h. Just for comparison, Metro de Madrid line serie 8400 trains can load 1272 passenger at maximum capacity and faster schedule frequency is one train each 4 minutes, this leads to 19080 passenger/h, not far from what OPTIMOTUS could deliver.

F. Implementation and Operation Cost

One of the main and unique characteristic of OPTIMOTUS is that vehicles, and thus the whole system itself, are compatible with the great majority of existing urban and suburban railway infrastructures. Therefore, the initial investment required for its implementation is several orders of magnitude lower than that for any other rapid transport system previously proposed. Likewise, the impact on the territory of the cities would be minimal since it does not require additional space.

An implementation cost estimation has already been done from preliminary design, see table III. The calculation has been done for a generic line with 20 stations with a passenger demand of 10000 passenger traveling simultaneously which means an estimation of 14000 vehicles per line. A comparison with the cost of Washington Metro rolling stock is also presented [42].

The total cost for a single OPTIMOTUS vehicle is estimated in 7675 €/vehicle, considering large scale cost reduction factor. The infrastructure adaptation cost are split as: local TMS – 40k€, rail switches (at least four) - 400k€, acoustic and protection panels in stations between rails – 20k€. This means a total cost per station adaptation of 460k€. In addition,

TABLE III
IMPLEMENTATION COST COMPARISON FOR OPTIMOTUS VERSUS WASHINGTON METRO TRAIN RENEWAL

Implementation Cost comparison – for 10000 passengers.			
OPTIMOTUS			Washington Metro Series 7000 cars
	Units	Cost (M€)	528 cars were purchased by 1265 M€ (1460 M$)
Vehicles(7675 €/ud)	14000	108	200 passengers / car
Station adaptation (460k€/station)	20	9.2	Proportionally
Line adaptation	1	8.5	52 cars = 10400 pax
Total cost		**126 M€**	**Total cost** **126 M€**

line adaptation costs are calculated as: cost of the master TMS (0.9M€) and 76 rail track switches distributed along the tunnels for flows changes (7.6M€).

At first approach, the conclusion is clear: it can be convenient to install OPTIMOTUS instead of renew current trains since the cost will be similar and the performance will be several times better.

Regarding operation costs, it is hardly to calculate, even to estimate operation cost at this point of the development. In any case, similar considerations than for automatic metros may be valid. There is no need of drivers since all the transport is done automatically, thus, there will be a great difference with the operation cost of a conventional metros. On the other hand, it will be necessary extra personnel on the platforms to monitor, control and help during passengers boarding and getting off. This need will be especially intense during the first years of operation. It will be required a certain adaptation time to this different way of mobility.

In terms of maintenance cost, it is expected that much more maintenance operations will be required since all the vehicles will have to pass revisions and controls. However, as vehicles are small each maintenance operation will be less expensive. Railways maintenance costs could be lower since, even if there will be more elements rolling on the railways, the load of each vehicles is much smaller, thus fatigue limits of railway materials may not be overpassed.

G. Societal Technology Embracement

The adoption of a new transportation technology is always one of the main barriers for a new system to overcome. It is indeed something to be considered since this is a new transport system and of course, people will need some time to trust it. This may take some years, as it currently happens with new semi-autonomous vehicles or ridersharing platforms or as it happened with automatic metro systems (which nowadays people use commonly). In our opinion, safety is the key point for a good technology embracement. The second key point is to create a great level of comfort within the cabin. If the system demonstrates that it is safe and comfortable, the time saving will be determinant for its competitiveness against other types of public road transport. Indeed, metro systems are still one of the type of transport more used, and the targeted passenger market for our system is the same as the one of current metro systems. Thus, we consider that system can attract a lot of passenger due to it time-saving capacity and comfortability.

Throughout this section, we will to open new interesting work fields for researchers interested in this emerging technology.

VII. CONCLUSION

Despite enjoying a separate infrastructure, passengers of metro trains do not usually have very high effective travel speed. In lines with many stations, the actual passenger speed is very slow, typically in the range of 20-30 km/h, mainly due to the continuous stops for boarding of passengers.

In this work, we have presented a PRT system which avoid the needs of stops in consecutive stations. This system, named OPTIMOTUS, has the versatility and high-speed of non-stops PRT while being compatible with current railway infrastructures.

OPTIMOTUS designed to be compatible with the circulation of at least two parallel flows of vehicles on the same railway track. This permits one rail to be used as a continuous cruise flow rail and the other rail can be used as an acceleration and deceleration vehicle lane. This allows a continuous flow of vehicles between the station of origin and destination in cruise speed, without the need to make intermediate stops and, therefore, multiplying the actual passengers' effective travel speed.

Vehicles' preliminary mechanical design and vehicle performance estimation have been described. OPTIMOTUS vehicles can reach reasonably 100 km/h of cruise speed and a 0-100 km/h acceleration time in 20.93 s.

Enhanced travel speed estimations provided by OPTIMOTUS in a generic metro line are given. We demonstrate a significant speed multiplication. For metro lines with shorter separation between stations ($<$ 1000 m) and for long travels ($>$ 5 stations), OPTIMOTUS travel speed can be up to 3.5 times faster than in conventional metro trains. In those lines with further distances between stations, the improvement is smaller but still significant and worthwhile.

We have also analysed other issues like fatigue and stress behaviour of most critical parts showing that values are bellow critical limits. Special requirements for the pantograph and rail switch have been discussed.

To end, we have presented a possible traffic management system layout, including the communication systems needed. We have also defined some safety criteria and we have estimated that OPTIMOTUS system could handle safely up to 14285 passengers/h in a track section. In terms of cost, rough numbers indicate that it can be economically affordable.

This innovative emerging vehicular technology presented in this article do show a great potential for enhancement of travel times while its implementation is relatively easy since the vehicles are compatible with current metro infrastructures. However, there are still many open questions that must be deeply treated before we can claim the total viability of the system.

ACKNOWLEDGMENT

The authors would like to recognize the work of David Álvaro Martín and Alba Martínez Pérez in figures preparation.

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Efrén Díez-Jiménez received the bachelor's degree in industrial engineering, with specialization on vehicles and structures, in 2008, the M.Sc. degree in machines and transport engineering in 2010, and the Ph.D. degree in mechanical engineering and industrial organization in 2012. He is currently an Associate Professor of transport engineering at the mechanical engineering area with the Universidad de Alcalá. Some of his research interests are railways engineering system, vehicles design, and transport system design. He has received the Extraordinary Award for the Best Thesis in Mechanical Engineering and also several national and international recognitions for his research work.

Miguel Fernández-Muñoz received the degree in electronic and industrial automation engineering from the Universidad de Alcalá (UAH) in 2019. He has experience in 3D mechanical design and analysis of mechanical systems. He has followed several specialization courses on AutoCAD, MSC Adams, Solid Edge ST10, and in C programming. He is currently collaborating in several projects related to machine mechanics. He is the co-inventor of OPTIMOTUS technology. His main research interests are mechanical design, as well as mechanical machine testing.

Rubén Oliva-Domínguez received the master's degree in mechanical engineering from the Universidad Carlos III de Madrid in 2012. He is currently pursuing the Ph.D. degree with the Universidad de Alcalá. He is also a Co-Inventor of OPTIMOTUS technology. His main research interests are vehicle design, vehicle performance calculation, and vehicle testing.

David Fernández-Llorca (Senior Member, IEEE) received the Ph.D. degree in telecommunications engineering from the University of Alcala (UAH), Madrid, in 2008. He is currently an Associate Professor with UAH. He is the author of over 90 refereed publications in international journals, book chapters, and conference proceedings. His research interests are mainly focused on computer vision and intelligent transportation systems. He received the IEEE ITSS Outstanding Application Award in 2013, the Best Young Researcher Award from UAH in 2013, and the Best Ph.D. Award by UAH in 2008. He is currently an Associate Editor of the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS.

Miguel Ángel Sotelo (Fellow, IEEE) received the Ph.D. degree in electrical engineering from the University of Alcalá (UAH), Madrid, Spain, in 2001. He is currently a Full Professor with the Department of Computer Engineering, UAH. His research interests include computer vision and control systems for autonomous vehicles, and vehicle-infrastructure cooperation. He has served as a Project Evaluator, a Rapporteur, and a Reviewer for the European Commission in the field of ICT for Intelligent Vehicles and Cooperative Systems in FP6 and FP7. He is a member of the IEEE ITSS Board of Governors and Executive Committee. He has served as an Editor-in-Chief of the *IEEE Intelligent Transportation Systems Magazine*, an Editor-in-Chief of *ITSS Newsletter*, an Associate Editor of the IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS, and a member of the Editorial Board of *The Open Transportation Journal*. He is currently the President of the IEEE Intelligent Transportation Systems Society on Intelligent Transportation Systems.