

URBAN PUBLIC TRANSPORT SPEED INFORMATION SYSTEM FOR ENERGY CONSUMPTION OPTIMIZATION

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In this paper it is presented a solution for optimizing the energy consumption of urban public transport electric vehicles (EV) by real-time modelling of speed. ISOTEC (Information System for Optimizing Tram/Trolley Energy Consumption) intelligent transport system calculates the vehicle's run profile, based on information received for the Traffic Management and Control Centre (TMC) and from the Public Transport Management Center (PTMC). ISOTEC creates fluid runs, without unnecessary stops at signalized intersections or before entering passenger platforms, when these are occupied by other vehicles. The proposed solution presents novelty elements regarding the real time modelling of urban public vehicle run profile with the help of computing techniques.

Keywords: urban public transport, electric vehicles, energy consumption, real-time speed modelling

1. Introduction

It is a certain fact that the world is changing, transport demand and traffic are constantly increasing. Municipalities all around Europe encourage the usage of Public Transport instead of private cars, but in order to be effective, they must offer a service with good quality parameters: increased transport capacity, good frequency and connections, fast trips, HVAC (heating, ventilation, air conditioning) systems, passenger information systems, etc. As a result, urban public transport vehicles (EV) are longer, wider and heavier than back 20 years ago, their dynamical properties have changed, commercial speed and frequency have increased. Energy consumption has followed the same ascending trend.

Urban public transport is a heavy user of electric energy. Energy efficiency and energy savings are two keywords that describe the latest preoccupation of transport researchers [1, 2, 3]. Several measures have been proposed and taken by Transport Authorities: the usage of regenerated energy resulted from braking [4], energy storage devices [5], reduction of resistances to motion and processing losses [6], Traffic Management related measures (efficient driving, the usage of coasting regimes, priority at intersections, etc.) [7, 8],

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implementing intelligent systems for controlling the transport process [9, 10]. The so called “Green Wave” program is successfully used in big cities in order to give green light at the passing of a public transport vehicle through an intersection. But in some cases, for busy lines with increased running frequency, in rush hours, it leads to traffic jams on perpendicular directions.

This paper presents a proposal for a new intelligent transport system, ISOTEC (Information System for Optimizing Tram/Trolley Energy Consumption), a tool for real-time speed modelling and energy consumption optimization. The system indicates to the EV driver the speed advised to be followed between two passenger stations and the point on the track where coasting and braking should start in order to get minimum energy consumption but without disregarding customer (passenger) orientation issues.

Correlating the information from Transport Management Centers (TMC) and Public Transport Management Centers (PTMC), real time determination of traffic lights status (red or green) and the position and number of EVs that move on the same section is possible. Knowing what status has the traffic light when the vehicle approaches, it helps to model the speed in order to avoid stopping. If two or more EVs circulate on the same section, real time modelling of each one's speed improves traffic fluidity and the usage of recuperated energy through braking. It also limits the voltage drops on the network.

2. Modelling an electric vehicle's run profile and its energy consumption

Energy consumption is a function of power and time, power is a function of voltage and current. Voltage is a function of distance (related to the feeding point) and current is a function of speed. That means the energy consumption W of an EV depends on the run profile and the power supply configuration. The objective function of the optimization process computed in ISOTEC, is:

$$W = f(P, \Delta t) = f(U, I, \Delta t) = f(v, d, t) \quad (1)$$

The modelling of a vehicle's run profile is resumed to adapting and solving Newton's second law, presented in equation (2) and considering the forces that act on the vehicle's movement, shown in fig. 1. Due to the fact that the EV's wheels store kinetic energy during movement, in calculus the total mass of the EV is multiplied with the rotating masses coefficient.

$$F_t(v) - R(v, r, p) - F_f(v) = m \cdot k \cdot \frac{dv}{dt} \quad (2)$$

where,

v – EV's speed

$F_t(v)$ – EV's traction force

r – curve radius

p – gradient

R (v, r, p) – resistances to motion

$F_f(v)$ – EV's braking force

m – total mass of the EV

k – rotating masses coefficient

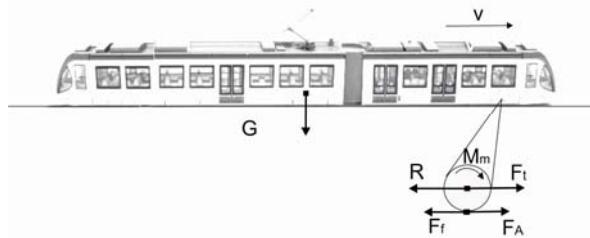


Fig. 1 – Forces that act on the EV's movement

Taking into account that the configuration of the power supply network is hard to change and the track has a finite determined length, distance is not subject to our optimization. Time is a hard controllable variable, without an automatic drive system the time needed to travel from one point to another can vary considerably. It all depends on the driver's behavior which is hard to predict. As a result, in this article, the optimization variable of the objective function is speed. Variables time and distance can be calculated using the following formulas:

$$t = \int_{v_i}^{v_{i+1}} \frac{1}{a} \cdot dv = \lim_{\Delta v_i \rightarrow 0} \sum_i \frac{\Delta v_i}{a_i} \quad (3)$$

$$d = \int_{v_i}^{v_{i+1}} \frac{v}{a} \cdot dv = \lim_{\Delta v_i \rightarrow 0} \sum_i \frac{\bar{v}_i \cdot \Delta v_i}{a_i}$$

Due to the difficulty of analytically solving equations (2) and (3), ISOTEC's software uses an approximation iterative method. The speed increment Δv is chosen small enough so that other variables (traction force F_t , braking force F_f , adhesion force F_a , resistive force R , acceleration a , deceleration a_f) can be considered constant in the chosen speed span $[v_i, v_{i+1}]$.

$$\begin{aligned}
 v_{i+1} &= v_i + \Delta v \\
 a &= \frac{F_t - R}{m \cdot k} \\
 t_{i+1} &= t_i + \frac{\Delta v}{a} \\
 d_{i+1} &= d_i + \frac{v_i \cdot \Delta v}{a} = d_i + v_i \cdot \Delta t
 \end{aligned} \tag{4}$$

Acceleration is influenced by traction equipment, mechanical design characteristics, topographic layout and operation control indicators. The braking operation mode is based on a virtual backwards run calculation. From the next stopping point or from a point where the speed limit is lower than the actual speed of the vehicle, a backwards trajectory is projected. Acceleration to actual speed is done using the braking force instead of the tractive one. When the vehicle reaches the next stopping point braking distance, the braking mode is initiated. Deceleration will be equal to the calculated acceleration, but taken from the end to the beginning.

ISOTEC's software has been created based on dynamic programming, in Matlab environment. The objective function – finding the optimum run with respect to minimum energy consumption – is divided into small functions. Modules for computing acceleration, braking, cruising and coasting are used. They are tested to check in which case scenario they fit, and then they are combined to obtain the most efficient speed profile. Limitations given by track, signaling, passing through junctions are always taken into account.

Dynamic programming has proven to be an efficient tool for EVs runs simulation. Its small computing time is useful also for the presented application, real-time optimization being a real quick changing process.

Determining the energy consumption, the current absorbed and the voltage at the pantograph/collector for EVs that run on a given route, resumes to finding the equivalent electric scheme of the electric traction system, shown in fig. 2:

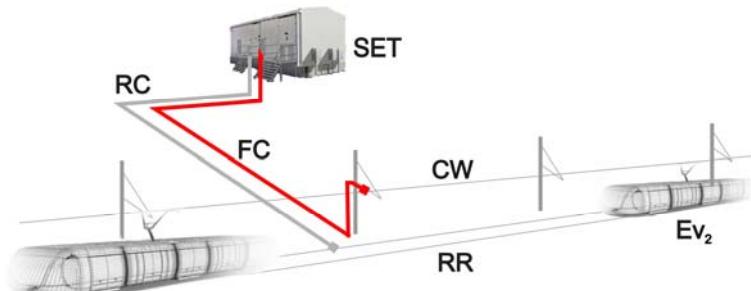


Fig 2: Electric traction system of urban public transport

The electric traction substation SET feeds the contact wire CW through feeder cables FC. The current is absorbed at the level of the pantograph/collector, it is converted inside the EV to satisfy the needs of the traction motors and it is returned via running rails RR and return cables RC to the substation SET.

Figure 3 shows the equivalent simplified electric scheme of the above described electric traction system, with two accelerating EVs in the same supply section. Each EV is characterized by known specific power consumption P_{EV} .

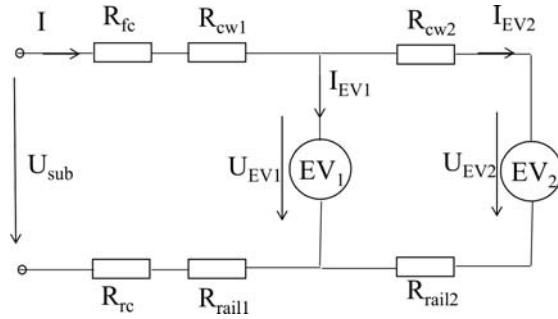


Fig 3: Simplified electric scheme of two EVs in the same supply section

The traction substation bus-bar voltage U_{sub} is dependent of the load current of the rectifier sets and the equivalent resistance of the substation. The resistances of the feeder cables R_{fc} , contact wires R_{cw} , running rails R_{rail} and return cables R_{rc} depend on the resistance of the material used and their length. The current I , flowing from substation via contact system to the EVs collector, the voltage drops U_{EV1} and U_{EV2} and the energy consumption W are calculated solving the following systems of equations:

$$\begin{aligned}
 U_{EV1} &= \frac{P_{EV1}}{I_{EV1}}; U_{EV2} = \frac{P_{EV2}}{I_{EV2}}; \\
 I &= I_{EV2} + I_{EV1}; \\
 U_{sub} &= I \cdot (R_{fc} + R_{cw1} + R_{rail1} + R_{rc}) + U_{EV1}; \\
 U_{EV1} &= U_{EV2} + I_{EV2} \cdot (R_{cw2} + R_{rail2}); \\
 W &= P_{EV1} \cdot \Delta t_1 + P_{EV2} \cdot \Delta t_2;
 \end{aligned} \tag{4}$$

The above electric circuit can be easily enlarged and resolved if there is more than two vehicles on the same supplied sector and if regenerative braking is applied. The generalization is not necessary due the limited number of vehicles on the same supply sections (around 3-5 vehicles).

3. ISOTEC system for real-time modelling of speed

ISOTEC intelligent transport system combines communication, computation and control technologies with the purpose of reducing energy consumption and improving the performance, safety, efficiency and mobility of urban public transport system. Its main purpose is to eliminate unnecessary obstacles between two passenger stations. The system can be used both for trams and trolleybuses.

Standing at traffic lights and waiting to enter the platform in stations or at the end of the line are unnecessary time and energy consuming elements of a vehicle's run. In most cases, priority at intersections given to public transport vehicles (PTV) has been declared complicated and a big trouble generator due to the long queues generated on the perpendicular way. This happens because PTVs arrive at stops right after the green sequence finishes or shortly before it starts again and it asks for another. So, the green time is increased with a certain percentage. This system is not feasible on a line with high vehicles frequency. If real-time modelling of speed would be implemented, such situations would be avoided.

ISOTEC is synchronized and always ready to exchange information with the TMC to receive the status of the traffic lights and with the PTMC for the position of other vehicles on the track. Communication with the two centers is bi-directional, using GPRS/GSM technology. The data transfer is made on short or medium distances, at certain periods of time. In fig. 4, the communication architecture of ISOTEC is shown.

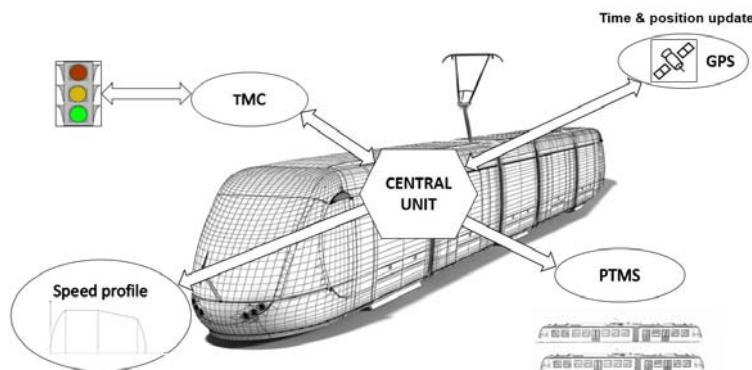


Fig 4: ISOTEC communication architecture

At every station, the system generates a new speed profile that is advisable to be followed until next station for energy saving reasons. During the time spent

in station, using GPS technology, the system updates its positions and time reference. Also, it evaluates which are the next possible stopping points until next station. If there are no obstacles on its route, ISOTEC uses the pre-established circulation program, with maximum allowable speed, maximum acceleration and deceleration (without taking in consideration emergency braking) and minimum travel time. With the help of new technologies maximum acceleration and deceleration can be limited to certain values. Coasting instead of cruising may be used to gain extra savings. It depends on how the timetable and the circulation program are initially designed.

The system determines the best point to start coasting and where to end it. Because the distances between two stations are relatively small in urban public transport (250 – 500m) only one coasting section is advisable. And for driver's comfort, after coasting braking is applied in order to reach the next station. Other situations (various coasting, accelerating, braking points) can be taken into consideration if an automatic driving system is implemented.

The system also takes into consideration the speed limits or variations due to track's topography (curves, gradients, switches, and special equipment). It eliminates any increase of speed for small distances.

When the next possible stopping point is a traffic light, first the system evaluates the necessary time for the EV to reach this point using maximum allowable speed. Then, it gets information from the TMC about the status of the traffic light at the estimated arrival time.

If the traffic light will be green, maximum speed is permitted. For a prudent drive, two measures can be taken:

- Configure the speed so that the EV never arrives at the traffic light at the beginning of the green color sequence or at the end of it.
- Decrease recommended speed to 20km/h in the area close to the junction. The time needed to brake from that speed to zero and the distance are small enough to avoid accidents.

If the traffic light's color is red, the system decreases the speed so that the EV will arrive at the junction when the green light is on. To avoid passengers' frustration, the resulted speed cannot be less than 15 km/h. Even if moving at a speed of 15km/h the EV still has to stop at the traffic light because of a big red time sequence, an important energy consumption saving is made.

ISOTEC can be installed and computed in the central unit of each EV, as a distributed system or in the central software of PTMC, as a centralized system. In order to handle the situation of several EVs on the network and to use the regenerative braking on the same supply section (or traction substation), the second choice is advisable. A centralized system would globally real-time model the speed of each EV, correlating the braking of one with the acceleration of other.

4. Simulation results: case study for Bd. Iuliu Maniu – Pod Grozavești tram track

To prove that implementing ISOTEC would bring improvements to the fluidity of the run and significant decrease of energy consumption, simulation of a tram track is shown below. The line from Bd. Iuliu Maniu (Politehnica) to Pod Grozavești stations has been chosen for presentation.

The distance between the two considered stations is 995m. A traffic light is positioned at Econom Cezărescu Street, at 835m distance from Bd. Iuliu Maniu station. The timing and sequence of Econom Cezarescu traffic light is: green light for 30s, yellow Light for 3s, red light for 50s.

For calculating resistances to motion, the horizontal and vertical profiles of the line have been measured and presented in table no. 1 and 2. All curves have progressive radius so the maximum admissible speed is increased compared to circular ones.

Table 1

Horizontal profile of Bd. Iuliu Maniu – Pod Grozăvești tram line

No.	Kilometer curve beginning	Kilometer curve end	Radius [m]	Maximum admissible speed [km/h]
1	0+003,000	0+360,000	500	50
2	0+845,000	0+925,000	120	26
3	0+925,000	0+995,000	315	50

Table 2

Vertical profile of Bd. Iuliu Maniu – Pod Grozăvești tram line

No.	Kilometer	Elevation	Length [m]	Level difference	Slope [% ₀]
5.	0+000,000	87,0	-	-	-
6.	0+130,000	83,0	130	4,0	-30,76
7.	0+280,000	78,0	150	5,0	-33,33
8.	0+360,000	77,6	80	0,4	-5,00
9.	0+515,000	77,1	155	0,5	-3,23
10.	0+995,000	75,4	480	1,7	-3,54

The considered EV is a Siemens Combino tram, a famous low floor vehicle. Its bare weight is 32.5t and a load of 13.1t; meaning 2/3 of its total capacity has been taken in calculation. Speed is limited to 50km/h, cruising and coasting are considered. The maximum acceleration available is 1,8m/s but due to passenger comfort it is limited to 1,3m/s. The maximum deceleration is also limited to 1,1m/s.

Two power supply points are feeding the line: one is placed 100m before Bd. Iuliu Maniu station and the other one at kilometer 0+650,000. The supply

voltage is 750V (-30%, +20%). The substation is placed in the nearby of the tram track, the feeder and return cables are 500m long. The internal resistance of the substation is $R_a = 0,02\Omega$. The overhead contact lines and running rails are typical for trams. Auxiliary services are approximated to 75 kWh.

Figure 5 shows the actual run between the two considered passenger stations with a stop at the traffic light. The tram arrives after 72s at the traffic light where it stays for 50s. The total journey time is 150s, the effective travel time is 100s and the average speed is 23.85km/h. Figure 6 shows the trend of the current absorbed by the tram and the voltage at the pantograph. The total energy consumption is 5.15 kWh meaning a specific energy consumption of 0.11 kWh/km*t.

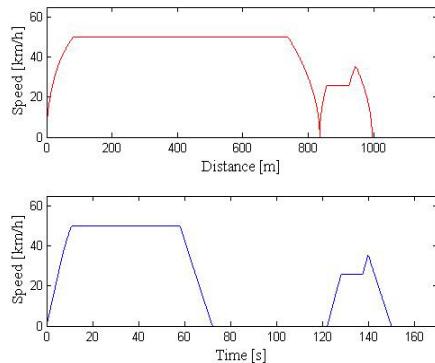


Fig.5: Speed vs distance and time between Bd. Iuliu Maniu and Pod Grozăveşti stations, with a stop at Econom Cezarescu traffic light

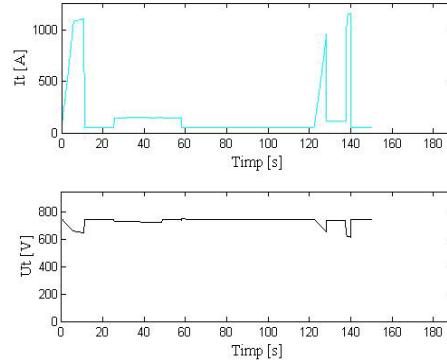


Fig. 6: Current absorbed and voltage at the pantograph

Table 3 presents the main parameters that describe the tram run profile between Bd. Iuliu Maniu and Pod Grozăveşti stations. The time spent at Econom Cezarescu traffic light varies from 0s (no stop) to 50 s (maximum stop).

Table 3

Main parameters of Bd. Iuliu Maniu – Pod Grozăveşti tram run profile

Traffic light stop time [s]	Average speed [km/h]	Total travel time [s]	Average absorbed current [A]	Total energy consumption [kWh]	Specific energy consumption [kWh/txkm]
0	39,35	91,00	213,69	4,05	0,098
10	32,51	110,15	206,21	4,73	0,101
20	29,81	120,15	193,24	4,83	0,105
30	27,52	130,15	182,26	4,94	0,109
40	25,52	140,15	172,84	5,04	0,112
50	23,85	150,15	164,6	5,15	0,119

As it is expected, any additional stop generates an increase of the energy consumption, to the detriment of Transport Authorities. The commercial speed decreases proportional with the stop time period, to the detriment of passengers.

Figure 7 shows the speed profile when the software ISOTEC is used to avoid the 50s red time at the traffic light. The stopping point is transformed into a speed limitation point. So, until the traffic light is reached the speed is limited to 25km/h. The tram arrives at the traffic light in 123s.

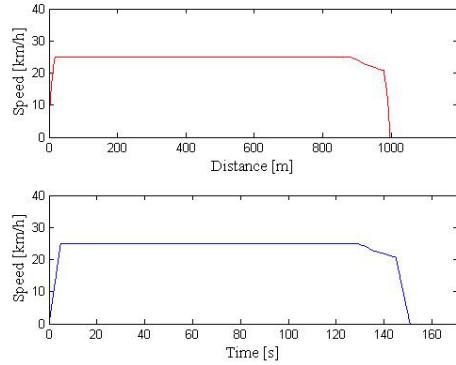


Fig.7: Speed vs distance and time between Bd. Iuliu Maniu and Pod Grozavesti stations, using ISOTEC to avoid stops

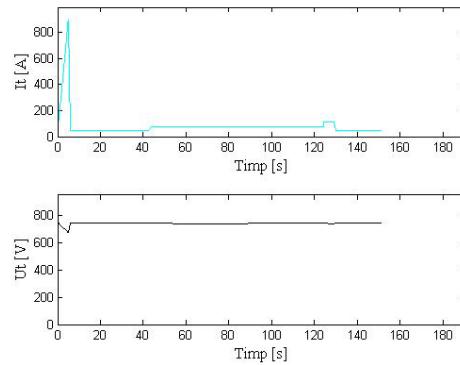


Fig. 8: Current absorbed and voltage at the pantograph using ISOTEC to avoid stops

After passing the intersection, ISOTEC optimizes the run profile, eliminating speed increases for small distances and adding coasting regime. Coasting starts at kilometer 0+880.000 and braking at kilometer 0+975.000. For this run, there is a total of 2.49 kWh energy consumption with 0.05 kWh/km*t specific energy consumption.

Table 4 summarizes the values of the main parameters for the above tram run profile, using ISOTEC system, with real-time speed modelling and unnecessary stops elimination.

Table 4

Main parameters of the tram run profile using ISOTEC

Traffic light stop time to avoid [s]	Average speed [km/h]	Total travel time [s]	Speed used until traffic light [s]	Average absorbed current [A]	Total energy consumption [kWh]	Specific energy consumption [kWh/txkm]
0	37,88	94,00	50	173,56	3,41	0,075
10	31,92	112,01	38,5	118,37	2,76	0,061
20	29,27	121,84	33,75	101,70	2,59	0,057
30	27,25	131,41	30	92,66	2,53	0,055
40	25,37	141,07	27	84,43	2,48	0,054
50	23,7	150,8	25	79,26	2,49	0,054

The energy saving rate using ISOTEC varies from 18% to 50%, for the above described example. The smaller the time travel and the speed are, less electric energy is used. A very small speed would bring frustration to passengers and would increase too much the time travel. For these reasons, the minimum speed must be limited to a certain value, established by each Transport Authority. Even if stopping in front of the traffic light can't be avoided due to a big red light time or a short distance between the station and the intersection, the EV must run at a small speed until it reaches the traffic light. In this manner, still an important energy reduction is made, worthy of taking into consideration.

5. Conclusions

The proposed intelligent transport system is a tool for real-time modelling of speed and energy consumption optimization. The novelty brought by the presented research is the idea of regulating speed based on the information received from Traffic and Public Transport Management Centers about traffic light's status and about the presence of other vehicles on the same section.

Implementing ISOTEC system has the following advantages:

- It reduces energy consumption by:
 - eliminating unnecessary stops at signalized intersections;
 - eliminating speed increases on small distances;
 - indicating the point where coasting should start without affecting the travel time;
 - indicating the point where braking should start in order to use only electric braking and to have a smooth deceleration;
- It improves the traffic frequency and fluidity;
- It eases the driver's work by assisting him;
- It prepares the implementation of a semi-automated driving system;
- It prepares the implementation of a system that will permit the usage of a big percentage of regenerated energy by synchronizing the braking of one EV with the acceleration of other.

Real-time optimization of an electric vehicle's speed can bring important advantages to each Transport Authority willing to implement such a system.

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