MIXED TRAFFIC WITH DIFFERENT PERCENTAGE RATES OF ELECTRIC VEHICLES AND ITS ENVIRONMENTAL INFLUENCE IN URBAN AREAS

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Abstract: *The development of high power electronics, improvement of existing and emerging of new battery technologies and optimization of electric motors over the last decade are some of the issues that have raised the interest in electric vehicles. Based solely on tank to wheel analyses, electric vehicles are regarded as zero emission vehicles. Regarding these facts, the research presented in this paper is focused on mixed traffic with different percentage rates of electric vehicles and its environmental influence in urban areas. A model of a mixed traffic stream comprised of conventional and electric vehicles was built upon a microscopic single lane urban traffic simulator. Through number of parallel simulations of solely conventional and mixed traffic stream and analysis of the results, we have evaluated the influence that certain presence rates of electric vehicles in the mixed traffic stream have on the exhaust emission. The results that we have obtained are constrained by the assumption that the electric energy used by the electric vehicles originates from renewable energy sources.*

Keywords: MIXED TRAFFIC STREAM, ELECTRIC VEHICLES, URBAN ENVIRONMENT, EMISSION

1. Introduction

The newest ecological and economical trends provide solid foundation for clean, efficient and sustainable vehicles for urban transport. Besides the fact that vehicles represent integral part of everyday life, they are one of the main pollutants because of the exhaust emission of the internal combustion engines which is highly responsible for the greenhouse effect and global warming. Vehicle dependence of fossil fuels as main energy source has economical and political implication. The diminishing oil reserves implies on crises with wider proportions. In the last decade the number of vehicles has doubled and is over one billion. Everyday, new vehicles are introduced in the traffic and contribute to the pollution problem. Furthermore, the internal combustion engines have low energy conversion efficiency that brings ahead some economical issues. From this point of view, neither electric vehicles which are on the market can achieve much greater efficiency within the well to wheel analyses, but they still make a significant difference. Under the assumption that the energy which is used by these vehicles comes from clean energy sources, like water, wind, sun, ocean, nuclear etc., then these vehicles are considered as zero emission vehicles even within the well to wheel analyses and represent a base for clean, efficient and green urban traffic system. On the other hand, if the energy comes from thermal power plants which use coal as primary energy source, then these vehicles are zero emission vehicles only within tank to wheel analyses. Moreover, well to wheel analyses show that the pollution in these cases can be even higher than the pollution that is made by the internal combustion engines. However, the thermal power plants are usually out of urban areas and are subjects of less complicated control than motor vehicles which are widely spread and individually maintained.

Electric vehicles were introduced on the market in the middle of the 19th century, even before the conventional vehicles (vehicles with internal combustion engine). Because of some technological discoveries, like the starter, and improvements in the mass production of conventional vehicles as well as the problems with battery charging, the electric vehicles have lost the first battle with the conventional vehicles and have disappeared from the market at the beginning of the 20th century. The interest in electric vehicles has revived in the 1960es as a result of ecological movements and uncomfortable dependence on fossil fuels. The development of high power electronics, improvement of existing and emerging of new battery technologies and optimization of electric motors over the last decade are some of the issues that have intensified the interest in electric vehicles. Regarding these facts, the research presented in this paper is focused on mixed traffic with different percentage rates of electric vehicles and its environmental influence in urban areas.

The remainder of the paper is organized as follows. The structure of the virtual model of traffic stream is presented in section 2. Parallel simulations of conventional and mixed traffic stream are presented in section 3. Section 3 also shows the results of performed comparative analyzes regarding the impact that certain presence rates of electric vehicles in the mixed traffic stream have on the emission. Finally, the conclusions are drawn in section 4.

2. Virtual model of traffic stream

The model of the traffic stream is built upon the single lane urban traffic simulator that we have previously developed, calibrated and validated [5, 7]. The simulator comprises an infrastructural model, i.e. a model of the arterial road that is selected for observation and a general acceleration model. The infrastructural model reflects real life traffic conditions, regarding the length of the road, number of intersections, their positions along the road, duration of traffic lights on each intersection and phase differences between certain traffic lights on consecutive intersections. These parameters are classified as infrastructural input parameters in the model [1]. The general acceleration model is a modified form of the model used in the MITSIM traffic simulator [8]. This submodel is built upon the infrastructural submodel. It defines the vehicles behavior within the infrastructural submodel regarding the current vehicles conditions. A vehicle in the model can be found in two primary conditions and several secondary conditions. Primary conditions are:

- free-flow condition, and
- car following condition.

At free flow condition the driver tries to obtain and attain driver's desired speed. On the other hand, in the car following condition the driver or the adaptive stop&go cruise control system reacts to the relative speed of the leader. The transition between these two primary vehicle conditions is defined by the time headway to the vehicle predecessor. This means that if the time headway is bigger than the defined threshold then the driver i.e. the vehicle is in the free flow condition, otherwise the vehicle is in the car following condition. The applied acceleration depends on the current condition.

The following mathematical model defines the acceleration at free-flow condition:

$$a_n^{ff}(t) = a_{n\,max}(V_n(t))\left[V_n^{ff} - V_n(t-\tau_n)\right] \quad (1)$$

Where: $a_{n\,max}(V_n(t))$ is the maximum acceleration of the vehicle n in relation with its current speed, $V_n(t-\tau_n)$ is the speed of the vehicle n at time $t-\tau_n$, V_n^{ff} is the desired speed of driver n, and τ_n is the total reaction time.

At car following condition the acceleration is defined with the following mathematical model:

$$a_n^{cf}(t) = f\left[V_n(t-\Delta t), \Delta X_n(t-\Delta t), k_n(t-\Delta t)\right] g\left[\Delta V_n(t-\tau_n)\right]$$

$$f\left[V_n(t-\Delta t), \Delta X_n(t-\Delta t), k_n(t-\Delta t)\right] = \alpha \frac{V_n(t-\Delta t)^{\beta}}{\Delta X_n(t-\Delta t)^{\gamma}} k_n(t-\Delta t)^{\delta}$$

$$g\left[\Delta V_n(t-\tau_n)\right] = \left|\Delta V_n(t-\tau_n)\right|^{\rho}$$

$$a_n^{cf}(t) = \alpha \frac{V_n(t-\Delta t)^{\beta}}{\Delta X_n(t-\Delta t)^{\gamma}} k_n(t-\Delta t)^{\delta} \left|\Delta V_n(t-\tau_n)\right|^{\rho} \quad (2)$$

Where: $f\left[V_n(t-\Delta t), \Delta X_n(t-\Delta t), k_n(t-\Delta t)\right]$ is a sensitivity function, $g\left[\Delta V_n(t-\tau_n)\right]$ is a stimulus function, $V_n(t-\Delta t)$ is subject vehicle speed at time $(t-\Delta t)$, $\Delta X_n(t-\Delta t)$ is space headway at time $(t-\Delta t)$, $k_n(t-\Delta t)$ is density of traffic ahead of the subject vehicle within its driver view at time $(t-\Delta t)$, $\Delta V_n(t-\tau_n)$ is relative speed between the subject vehicle and its predecessor at time $(t-\Delta t)$, Δt is the sampling time, and α, β, γ, δ, ρ are model parameters [12].

The model exerts positive or negative response upon positive or negative stimulus. In other words, a vehicle accelerates if the leader has higher speed, and decelerates if the leader has lower speed. The model behaves differently at positive and negative stimulus. This is obtained with different model parameters for acceleration and deceleration [5, 12].

The safety in the model is ensured by a boundary condition that guaranties minimal safe distance between vehicles in motion. This minimal safe distance is rigidly set as the braking distance with maximum deceleration to full stop, increased by the basic intervehicle spacing. In this way the model covers the

so called emergency condition.

The general acceleration model is capable of handling interruptions of the traffic stream, which are common in urban environments. As a result of an interruption of the traffic stream, a vehicle in the model might be in a certain secondary condition. Each secondary vehicle condition is defined by separate algorithm that controls appropriate vehicles in the model. So, the secondary vehicle conditions appear because of violation of primary vehicle conditions under the boundaries implemented by the infrastructure i.e. the traffic lights signalization. The model handles the following secondary

vehicle conditions:

• Crossing the intersection during the yellow traffic light

before the red traffic light,

• Stopping at the intersection due to the red traffic light,

• Stationary condition of the vehicle at the intersection

during the red traffic light or because of the stationary

condition of the leader,

• Start at initialization of the green traffic light or because

of start of the leader.

Besides the infrastructural parameters, the virtual model of mixed traffic stream also controls a set of vehicular dependent input parameters and a set of driver dependent input parameters [1]. The vehicular set of parameters covers the total number of vehicles in the model, number of conventional vehicles, number of electric vehicles, vehicle category (according to EC 2007/46) [10], presence rate of each vehicle category, inlet traffic flow, acceleration and braking performances, masses and dimensions.

As for the driver dependent set of input parameters, it contains the drivers desired speed, time headway threshold, total reaction time and intervehicle spacing when the vehicles are stationary.

The basic output parameters of the model, obtained as a result of simulation of real traffic stream in urban environment, are: vehicle acceleration, speed, traveled distance and intervehicle spacing. Besides these basic output parameters the model is able to give additional information like number of vehicles stopped at certain intersection, vehicle flow through certain intersection during the green light, outlet traffic flow, travel time, energy and fuel consumption and CO2 emission.

All of these ensure flexibility of the model and possibility to be adjusted to different types of arterial roads.

3. *Parallel simulations of conventional and mixed traffic stream and comparative analysis of the results*

The evaluation of the environmental impact of certain presence rates of electric vehicles in the mixed traffic stream is based on number of parallel simulations of real and mixed traffic stream. The real traffic stream contains only conventional vehicles, and the mixed traffic stream, besides the conventional vehicles, contains certain percentage of electric vehicles. Each traffic stream in the simulations comprises 100 vehicles. The simulations are conducted on one of the most frequent arterial roads in the city of Skopje. The selected arterial road is 5.1 km long, and has eight consecutive intersections. All infrastructural parameters, vehicle and driver dependent input parameters are experimentally obtained and implemented in the model [1, 2, 3, 4, 6, 8, 9, and 11]. The simulations of real and mixed traffic stream within a parallel simulation are performed with identical input parameters. On the other hand, each parallel simulation (pair of simulations) has different initial setup. It means that they have different arrangement of vehicle categories, different presence rate and different arrangement of electric vehicles, different initial time headways and different vehicles masses and dimensions. Furthermore, conventional vehicles show additional differences in the desired speed, acceleration and deceleration performances, reaction time and basic intervehicle spacing when vehicles are stationary, regarding different parallel simulations. Electric vehicles in the model are considered to be vehicles of category M1.

The basic output parameters of the model, within a simulation, are presented on Fig. 1, Fig. 2, Fig. 3 and Fig. 4. (Figures show the parameters of only three vehicles in the traffic streams in order to obtain appropriate perception about the acceleration, speed, traveled distance and intervehicle spacing profiles.)

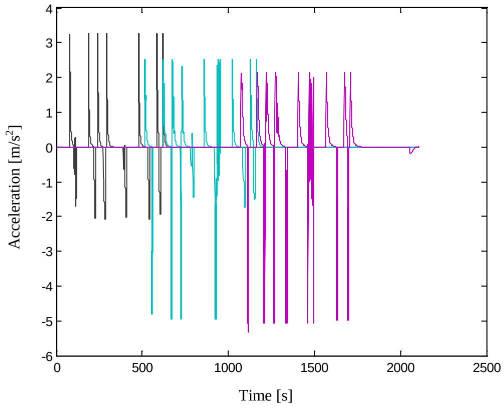

Fig. 1 *Acceleration profile*

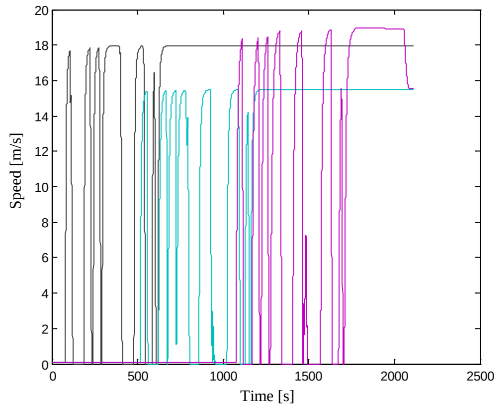

Fig. 2 *Speed profile*

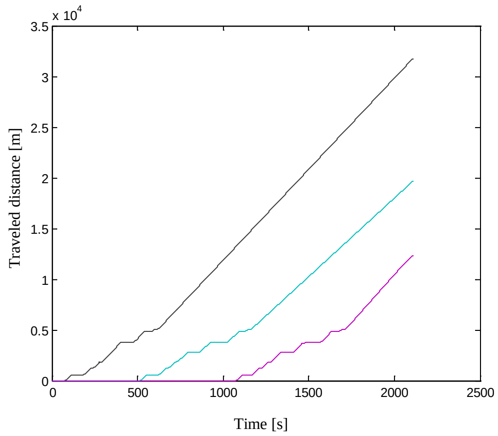

Fig. 3 *Traveled distance profile*

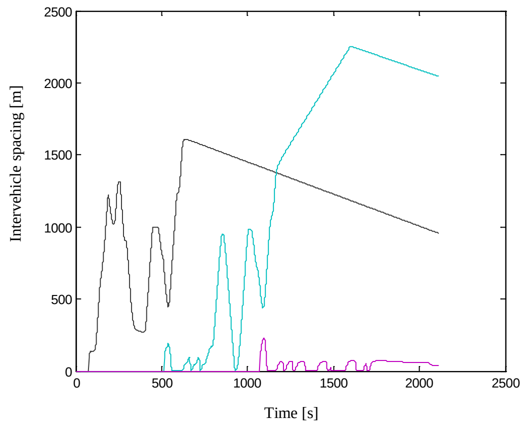

Fig. 4 *Intervehicle spacing profile*

The amount of energy that is required for vehicle movement on the observed arterial road in relation to the traveled distance, within a simulation, is shown on Fig. 5. This energy does not count the portion of energy which is spent during vehicle deceleration and when vehicles are stationary.

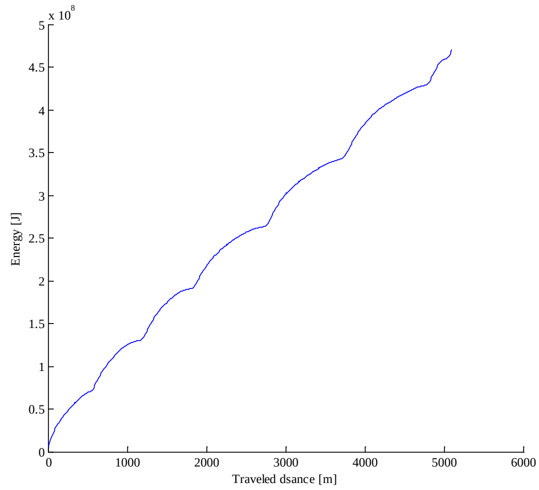

Fig. 5 *The energy required for vehicle movement on the observed arterial road*

As for the conventional vehicles, the fuel consumption is proportional to the energy which is required for vehicle movement. It depends on several parameters like fuel energy value, engine effective efficiency and transmition efficiency. During the calculations of the fuel consumption it is accepted that the fuel (gasoline or diesel) has average energy value of 44000 KJ/kg and average density of 0,795 kg/l, and the average engine effective efficiency with the transmition efficiency is 0,3 [13]. In order to obtain the total fuel consumption, eventually we have added the fuel that is consumed when vehicles are stationary to the calculated fuel consumption. It is assumed that during these actions the average fuel consumption is 2 l/h. The calculation of carbon dioxide emission is based on the average CO_2 emission obtained when burning one liter of fuel (2,46455kg/l). Table 1 shows the lower and upper limits of the required energy and fuel for vehicle movement, the total and average fuel consumption and CO_2 emission. The results are obtained within 35 simulations of real traffic stream i.e. traffic stream that is comprised of only conventional vehicles.

Table 1: *Energy demand, fuel consumption and CO2 emission*

Measure	*Min*	*Max*
Required energy [MJ]	421.93	535.34
Required fuel [l]	40.21	51.01
Total fuel consumption [l]	54.46	65.50
Av. fuel consum. [l/100km]	10.68	12.84
CO2 emission [g/km]	263.16	316.52

Based on these results we have determined the average fuel consumption and CO_2 emission on a yearly base regarding the observed arterial road (Table 2).

Table 2: *Fuel consumption and CO2 emission on a yearly base regarding the observed arterial road*

Measure	*Min*	*Max*
Av. fuel consum. [l/year]	17688 98.06	21275 87.17
CO2 emission [t/year]	4359.5 4	5243.5 4

A quantitative measure, about the impact that certain presence rates of electric vehicles in the mixed traffic stream have on the emission, is obtained through comparative analysis of the results of the parallel simulations. Therefore, we have performed eight sets of simulations. Each set has three independent parallel simulations. All simulations of mixed traffic stream, within a set, have identical presence rate of electric vehicles. The increment of the mentioned presence rate between consecutive sets is 10%. Table 3 shows the reduction of the fuel consumption and exhaust emission which is gained with different percentage rates of electric vehicles in the mixed traffic stream. It goes between 6.91% and 7.48% for only 10% electric vehicles in the traffic stream, up to 59.42% for 80% electric vehicles in the traffic stream.

Table 3: *Reduction of the fuel consumption and exhaust emission*

	Difference [%]			
Measure	*10% El. Veh.*		*20% El. Veh.*	
	min	*max*	*min*	*max*
Fuel consumption and exhaust emission	-6.91	-7.48	-13.54	-14.24
Measure	*30% El. Veh.*		*40% El. Veh.*	
	min	*max*	*min*	*max*
Fuel consumption and exhaust emission	-20.60	-21.49	-28.74	-30.57
Measure	*50% El. Veh.*		*60% El. Veh.*	
	min	*max*	*min*	*max*
Fuel consumption and exhaust emission	-33.61	-36.01	-40.01	-43.30
Measure	*70% El. Veh.*		*80% El. Veh.*	
	min	*max*	*min*	*max*
Fuel consumption and exhaust emission	-47.69	-50.43	-56.23	-59.42

4. Conclusion

The research presented in this paper covers a contemporary research area that deals with the reduction of fuel consumption and exhaust emission in urban environments. It also promotes the electric vehicles as zero emission vehicles.

The comparative analyses of the results of the parallel simulations lead towards some interesting conclusions, regarding the exhaust emission. Namely, the analysis showed that electric vehicles have positive influence on the fuel consumption and exhaust emission even at low percentage rates in the traffic stream. At higher percentage rates, the reduction of the subject parameters is more than 50%, which is extremely high. These findings could be acceptable only if the energy which is used by the electric vehicles comes from clean energy sources like water, wind, wave, solar or nuclear energy. In other words, the results that we have obtained are constrained by the assumption that the electric energy used by the electric vehicles originates from renewable energy sources and should not be taken for granted.

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