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Economic and social modelling of urban traffic controlling

Adam TOROK*. Raimundas JUNEVIČIUS** Ferenc MESZAROS*

*Budapest University of Technology and Economics, Department of Transport Economics
Budapest, Hungary H1111
(Tel: +3614631037; atorok@kgazd.bme.hu).
**Vilnius Gediminas Technical University, Department of Transport Technological Equipment,
Vilnius, Lithuania, LT10223
(raimundas.junevicius@vgtu.lt)

Abstract: Road traffic flows in intersections in inner city environment are modeled in this article. Cost of CO_2, CO, CH, NOx, PM and value of travel time have been used in order to estimate the economical and social costs arising at the intersections. The article presents assumptions for constructing the mathematical model. It describes the mathematical model and gives simulation results. Traffic flow parameters, as traffic flow concentration and traffic flow speed are presented as based on real traffic data. Different controlling policies are demonstrated.

Keywords: Traffic Light Control; Modeling, Control and Optimization of Transportation Systems; Freight Transportation: Control, Optimization, Routing etc

1. INTRODUCTION

Road transport is one of the main inland transport modes providing door to door services all over the world. Each inland territory is criss-crossed by interurban road and street networks. Vehicles carry people and distribute industrial freight on these network elements. Majority of these road vehicles are driven by internal combustion engines; therefore beside practical use they also produce air pollution and particulate matter, noise, vibration. Cars consume a lot of energy; therefore when solving problems caused by them engineers and scientists have to solve a wide range of problems starting from vehicle manufacturing to their use. A lot of burning problem arise when cars are used and the main problems to be solved by both engineers and scientists are to reduce pollution and to save energy. By saving energy, cars may become more environment friendly. Various problems caused by vehicles are discussed in article (*Makaras et. al, 2011*). *Wang et. al. in 2008* present various methods of fuel consumption and engines' emission measuring as well as coefficients of efficiency are also introduced. *Tanczos, Torok, in 2007* investigate climate fluctuation changes and energy consumption in Hungary. *Janulevičius et. al. in 2010* present the methodology of determining energy consumption taking into account the engine's capacity and its specific fuel consumption. *Wu and Liu in 2011* in their article present the methodology of calculating fuel consumption by taking into account such criteria as aerodynamic and rolling resistance. *Smit et. al. in 2008* present and generalize three emission models, where the impact of congestions on motor vehicles' emission is evaluated differently and present indicators to identify transport congestions. The article also presents congestion identification models. *Jovi and Doric in 2010* use the programming package PTV Visio to model traffic flows on the urban street network and based on that present vehicle emissions. *Jakimavičius and Burinskienė in 2010* investigate vehicle flow optimization methods and their application possibilities examining the effect of information traffic users receive about the situation in the city, whereas in their subsequent article they present a rating system of the residential areas of the city Vilnius by using expert methods and pointing out the residential areas with the highest traffic volumes (*Jakimavičius, Burinskienė, 2009*). This article gives an example of applying mathematical models to traffic flows to simulate ICE emission and to estimate the arising social cost. Although the article of *Torok and Zoldy in 2010* does not investigate combustion reactions of ICE, it calculates ICE emissions as a function of the vehicle's speed, which are developed by using the values of emissions.

2. METHODOLOGY

An intersection can be characterized by the traffic flow in the different directions and lanes. To describe traffic flows, a traffic lane is used as a basic unit. It is assumed that cars can drive only in one direction in each lane; therefore, the road surface is split into separate traffic lanes and two-way roads are described in the mathematical model as two separate one-way roads with one or more traffic lanes (*Torok, Berta, 2009*). In this model a traffic lane segment is taken as a finite-length line that ends at the intersection. As the results were gained from a real intersection the model need to be modified in order to satisfy the real data. That is why pollution factors are more elaborated compared to other factors. Traffic flow based social cost was calculated as follows:

$$TSC = \sum_{i=1}^{n} TSC_i \tag{1}$$

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where,

TSC [HUF] is the total social cost of traffic flows at the intersection that should be minimalised by the control system;

TSC_i is the total social cost of traffic flow in one direction (authors have first assumed that each direction has only one lane. In case of multiple lanes total social cost in [HUF] should be derived from the sum of the TSCs of the individual lanes),

$$TSC_i = EC_i + TTS_i \tag{2}$$

where,

EC_i is the estimated environmental cost of traffic flow in direction i, [HUF];

TTS_i is the estimated cost of travel time savings in direction i, [HUF],

$$TSC_i = \sum_{i=1}^{r}\left[\sum_{j=1}^{m}\left(\varepsilon_{ij}\tau_{ij}\rho_i\right) + \sum_{k=1}^{p}\left(v_{ik}\tau_{ik}\right)\right] \tag{3}$$

where,

$\varepsilon_{i,j}$ is the environmental emission factor of vehicle category j in directtion i, [g/s];

$\tau_{i,j}$ is the waiting time of the traffic flow in the lane at direction i, for vehicle category j [s];

$\rho_{i,}$ is the cost of environmental emission for pollutant i [HUF/g];

$v_{i,k}$ is the value of travel time for passenger k at direction i, [HUF/s];

$\tau_{i,k}$ is the waiting time in the lane at direction i, for passenger k [s].

The estimated cost calculation requires the environmental categorization of the traffic flows as well. The classification of vehicle fleet should be simplified compared to the real life, to adjust the input parameters to the mathematical function. Since actually there is no available database about such composition of parameters about the vehicle fleet, a "second-best" solution has been approached. We started to analyse the horizontal data of the vehicle fleet of each year, while the age of vehicles determines their environmental category applicable at the time of registration (*Meszaros et al., 2012*). This approached led us to the share of EURO emission classes among different vehicle classes and propulsion systems. EURO emission classes are standards for environmental pollutions. These standards are maximising the emission of road vehicle. They are getting stricter and stricter with years (Fig. 1-6.).

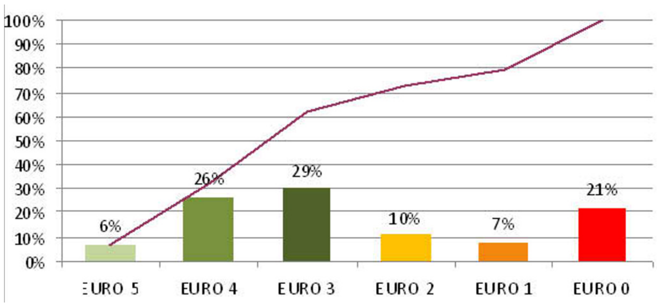

Fig. 1. **Share of EURO emission classes among diesel driven passenger cars** *(Meszaros et al., 2012)*

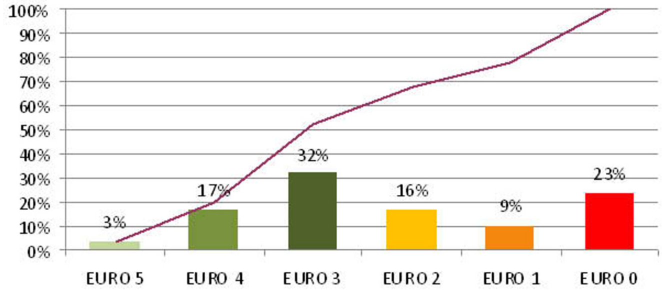

Fig. 2. **Share of EURO emission classes among gasoline driven passenger cars** *(Meszaros et al., 2012)*

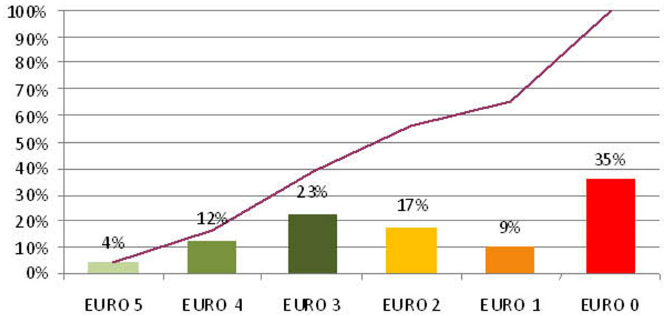

Fig. 3. **Share of EURO emission classes among diesel driven buses** *(Meszaros et al., 2012)*

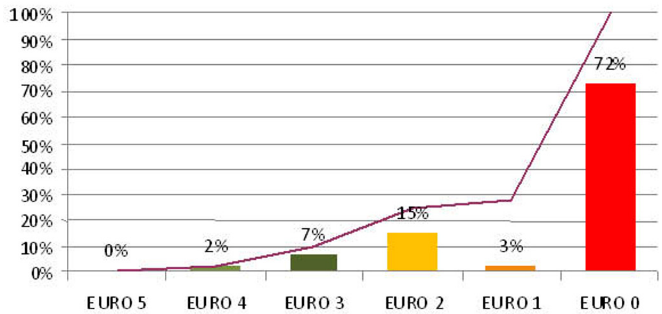

Fig. 4. **Share of EURO emission classes among gasoline driven buses** *(Meszaros et al., 2012)*

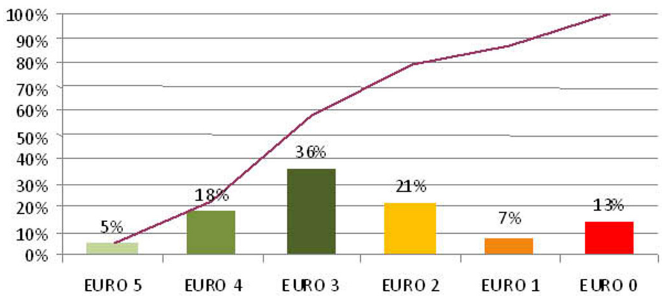

Fig. 5. **Share of EURO emission classes among diesel driven lorries** *(Meszaros et al., 2012)*

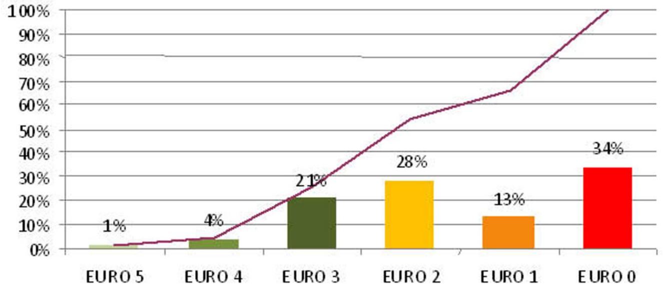

Fig. 6. **Share of EURO emission classes among gasoline driven lorries** *(Meszaros et al., 2012)*

In macroeconomical sense we modelled the lanes as competing products that are competiting for the time of green signals. We build up a model based on competition and analyzed the results. Practical uses of supply and demand analysis often centre on the different variables that compete – in our case green signal of different lanes are competing. In the literature both affine and nonlinear approximations of the demand and supply curves are in use. We could have a left-ward shift in supply that decreased traffic quantity. With increas of time of red signal the traffic is decreasing. That could lead to use the free capacity in green signal in other directions. Mathematically the demand function can be described as:

$$x_t = a_t \cdot p_t + \alpha_t \tag{4}$$

where:

- x_t: the demand for the road
- p_t: price in time t
- t: time period
- $a_t<0$ and $\alpha_t>0$, these parameters are determined by tools of econometry

Mathematically the supply function can be described as

$$y_t = \beta_t + b_t \cdot p_{t-1} \tag{5}$$

where

- y_t: the supply of road
- t-1: time period before time period t
- $b_t>0$ and $\beta_t<0$, these parameters are determined by tools of econometry

It is well known that market equilibrium is when demand x_t and supply y_t are equal for the green signal. The demands for green signal are competing but the supply is limited. For every time period t there is an equilibrium that can be described with

$$\begin{aligned} a_t \cdot p_t + \alpha_t &= b_t \cdot p_{t-1} + \beta_t \\ a_t \cdot p_t &= b_t \cdot p_{t-1} + (\beta - \alpha)_t \end{aligned} \tag{6}$$

We reach the final market equilibrium when $p_t=p_{t-1}$. Therefore, we get

$$\hat{p}_t = \left(\frac{\beta - \alpha}{a - b}\right)_t \tag{7}$$

where

- $\hat{p}_t$: final market equilibrium price

On this basis Eq.(6) is the determination of the equilibrium at which the demand for green signal exactly meets the supply. The actual price differs from the market equilibrium price with

$$\tilde{p}_t = p_t - \hat{p} = p_t - \left(\frac{\beta - \alpha}{a - b}\right)_t \tag{8}$$

where

- $\tilde{p}_t$: difference between price in time t and final market equilibrium

At this time the market equilibrium can be described as:

$$\begin{aligned} a_t \cdot \tilde{p}_t &= b_t \cdot \tilde{p}_{t-1} \\ \tilde{p}_t &= \left(\frac{b}{a}\right)_t \cdot \tilde{p}_{t-1} \end{aligned} \tag{9}$$

where

- $\tilde{p}_{t-1}$: difference between price in time period before time period t and final market equilibrium

With the above mentioned model authors have tried to analyze the effects of concurring green signals urban intersections (*Fig. 7.*).

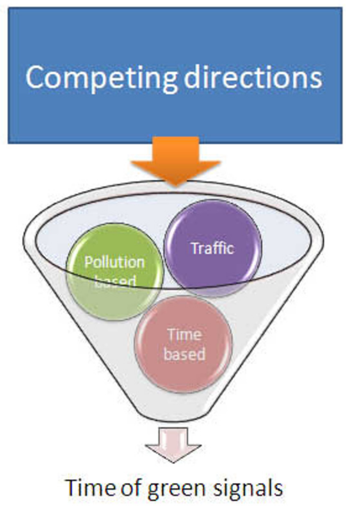

Fig. 7. **Model of competing directions** *(source own edition)*

3. RESULTS

Authors have tested the above mentioned methodology on an intersection with 6 directions each with single lane. The 6 direction can run in 4 phase intersection. The following cost results were calculated for the directions:

Table 1. Page Estimated cost of direction

	Cost of estimated environmental pollution	Cost of travel time saving	Total
	[HUF]	[HUF]	[HUF]
1st direction	9932	1344	11276
2nd direction	9420	1180	10600
3rd direction	4818	1724	6542
4th direction	5329	1868	7197
5th direction	1535	69	1604
6th direction	5114	221	5335

(source: own calculation)

Excel spreadsheet model had been designed for calculate the green signals in case of different intersection controlling policy for the different phases (*Fig. 8.*). Length of green signal has been calculated based on the proportion of the phase compared to the total. In case of traffic volume the current volume of the phase was compared to the total. In case of emission based controlling the emission of one phase was compared to the total emission of the intersection. In case of social cost the travel time increasement was compared as a basis of calculation.

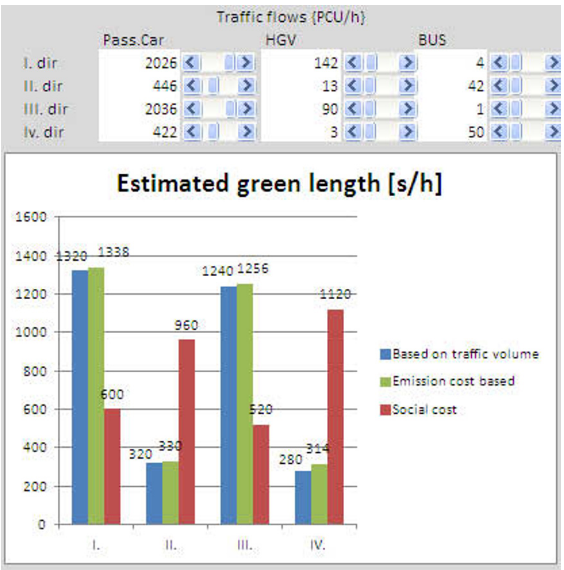

Fig. 8. **Estimated green length**
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4. ANALYSIS AND DISCUSSION

Furthermore authors are planning to design a complex function that will be able to handle and balance between the control types. Yet it is only shows the difference between control strategies (*Fig. 9.*).

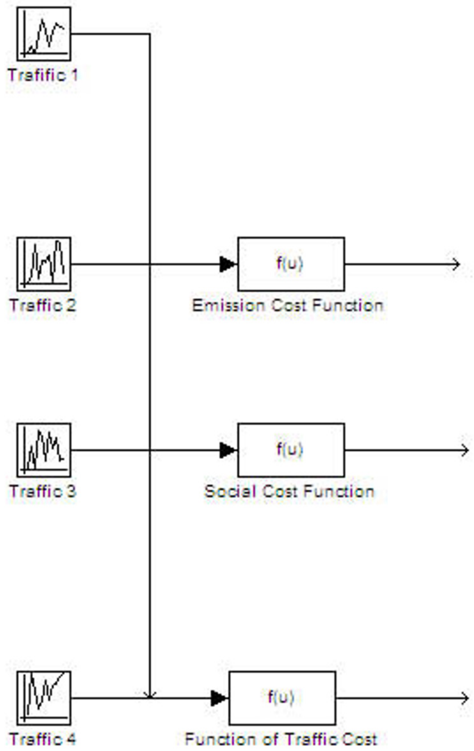

Fig. 9. **Schematic arrange of model components**
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Further on authors are planning such system that could deal with mixed strategies. Such system has not yet been investigated (*Fig. 10.*).

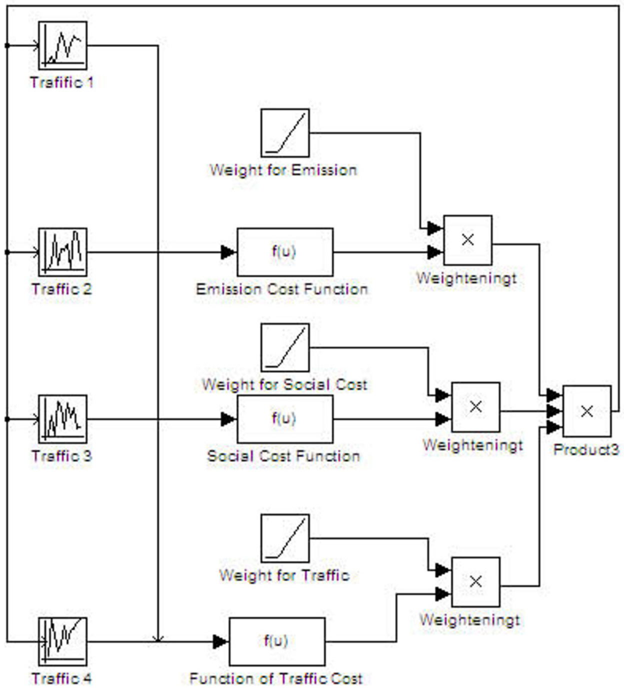

Fig. 10. **Schematic overview of planned control** *(source own edition)*

Authors have investigated the possibilities of cost based intersection control and found that, there are possibilities for increasing throughput efficiency of the intersection, minimising total cost. Furthermore authors have calculated the green times for the directions in the intersection and have built up a block diagram of the system for further analysis.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Jakimavičius, M.; Burinskienė M. 2009. **A GIS And Multi-Criteria-Based Analysis And Ranking Of Transportation Zones Of Vilnius City**, *Technological And Economic Development Of Economy* 15(1): 39 – 48

Jakimavičius, M.; Burinskienė M. 2010. **Route Planning Methodology Of An Advanced Traveler Information System In Vilnius City**, *Transport* 2010 25(2): 171 – 177

Janulevičius, A.; Juostas A.; Pupinis G. 2010. **Engine Working Modes During Tractors Operational Period**, *Mechanika* 3(83): 58 – 63

Jovic, J.; Doric, V. 2010. **Traffic And Environmental Street Network Modelling**: **Belgrade Case Study**, *Transport* 25(2): 155 – 162

Makaras, R.; Sapragonas, J.; Keršys A.; Pukalskas S. 2011. **Dynamic Model Of A Vehicle Moving In The Urban Area**, *Transport* 26(1): 35 – 42

Meszaros, F., Markovits-Somogyi, R., Bokor, Z. 2012. **Modelling and Multi-Criteria Optimization of Road Traffic Flows Considering Social And Economic Aspects**, *Scientific Journal on Transport and Logistics 3*(1): 70 – 82

Smit, R.; Brown A.L.; Chan Y.C. 2008. **Do Air Pollution Emissions And Fuel Consumption Models For Roadways Include The Effects Of Congestion In The Roadway Traffic Flow?** *Environmental Modelling & Software* 23: 1262 – 1270

Tanczos, K.; Torok, A. 2007. **The Linkage Between Climate Change And Energy Consumption Of Hungary In The Road Transportation Sector**, *Transport* 22(2): 134 – 138

Torok, Berta, 2009: **Layout Effect Of Roadway On Road Vehicle Speeds**. *Pollack Periodica*: An International Journal For Engineering And Information Sciences 4: p115-120. DOI: 10.1556/Pollack.4.2009.1.12

Torok, Zoldy, 2010: **Energetic And Economical Investigation Of Greenhouse Gas Emission Of Hungarian Road Transport Sector**. *Pollack Periodica* 5:(3) p123-132, DOI: 10.1556/Pollack.5.2010.3.10

Wang, H.; Fu, L.; Zhou, Y.; Li, H. 2008. **Modelling Of Thefuel Consumption For Passenger Cars Regarding Driving Characteristics**, *Transport Research Part D* 13: 479 – 482

Wu, J.; Liu J. 2011. **Development Of A Predictive System For Car Fuel Consumption Using An Artificial Neural Network**, *Expert Systems With Application* 38: 4967 – 4971