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DYNAMIC MODEL OF A VEHICLE MOVING IN THE URBAN AREA

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Abstract. The peculiarities of constructing a model of an individual vehicle moving along the urban street are investigated. The aim of the study is to construct a dynamic vehicle-environment-driver model, which enables to implement the situation 'an individual vehicle moving along urban streets', taking into consideration a concrete type of a vehicle, its loading, driver's behavior, peculiarities of external characteristics of internal combustion engines run on traditional or alternative fuel as well as the use of hybrid power plants.

Keywords: dynamics of a vehicle, dynamic model, environmental impact, driver.

1. Introduction

To solve transport system problems, complex studies that cover the areas of vehicle efficiency increase, transport flow management, environmental protection and transport operation safety as well as an effective system, which meets financial capabilities, of installing hardware and revaluating human values are required.

Transport system is one of the biggest users of energy resources; therefore a lot of attention has been paid to energy saving aspects recently (Baublys *et al.* 2003). Energy consumption evaluation as well as the solution of environmental pollution problems when studying a vehicle moving in urban and suburban areas are hindered by numerous systematic and random obstacles related with the dynamics of a vehicle itself, street infrastructure, drivers and pedestrians' behavior, transport flow peculiarities and the level of traffic organization. To simplify the solutions, various methodologies are used to describe the regularity of the vehicle's movement. Models related with the dynamics of an individual vehicle's regularity enable to describe the behavior of a vehicle under concrete movement conditions precisely; however, in this case specific data about the vehicle's structure as well as the road infrastructure down to the type of the road pavement, quality and meteorological conditions are required (Dragčević *et al.* 2008; Gužys *et al.* 2006; Kapski *et al.* 2008; Liu 2007; Prentkovskis *et al.* 2010; Antov *et al.* 2009; Vansauskas, Bogdevičius 2009; Pečeliūnas, Prentkovskis 2006; Sokolovskij *et al.* 2007; Sokolovskij, Pečeliūnas 2007; Šliupas 2009; Viba *et al.* 2009). Transport flow models usually use generalized characteristics identified through statistical analysis, which do not reflect the peculiarities of vehicles in a transport flow. Due to this reason, it is difficult to prognose the changes of movement conditions by prognosing possible flow structure or road infrastructure changes. Moreover, flow models do not present the data necessary to evaluate a real situation of an individual vehicle moving along an urban street to evaluate energy consumption or environmental pollution through the use of digital methods and to make assumptions for the prediction of the development of transport flows comprised of various types of vehicles. Lack of digital models is problematic when preparing environment-friendly driving recommendations: general not intensive speeding up recommendations do not meet the recommendations how to increase the street's carrying capacity, which gives doubts about its efficiency when reducing pollution.

The dynamics of individual vehicles has been investigated quite thoroughly; however, studies have been restricted by speeding up, braking and continuous driving tasks (Jazar 2008). The aim of the study is to construct the dynamic vehicle–environment–driver model, which would enable to implement the situation 'an individual vehicle moving along urban streets', taking into consideration a concrete type of a vehicle, its loading, driver's behavior, internal combustion engines run on traditional or alternative fuel, peculiarities of external characteristics as well as the use of hybrid power-plants. Taking the factors above into consideration, dynamic characteristics of a vehicle, engine or engine's working modes are identified and the composition of exhaust gas, fuel consumption, noise level and other parameters related with the automobile movement in an urban area are prognosed more accurately. The use of this dynamic model also enables to plan the improvement of over ground vehicles' ecological characteristics, to evaluate the efficiency of power plants run on alternative fuel, to develop energy saving algorithms of the vehicle's movement (Mockus *et al.* 2006). In the next stage, it is planned to select sample individual vehicle models, to modify them according to the changing composition of a transport flow thereby reducing the number of factors in the flow model and to present more accurate generalizing characteristics.

When constructing the model, the vehicle's dynamic characteristics, infrastructure elements, influencing on the vehicle's movement conditions, driver's behavior description methods were investigated by selecting the ones which reflect the impact of the transport system component on the characteristics under investigation with the minimum number of parameters best.

2. Vehicle's Model

The dynamic model of a vehicle moving under restricted conditions is constructed for a concrete vehicle with its mass distribution, internal combustion engine characteristics, transmission transfer relations and chassis. Road characteristics which may influence on the resistance movement forces are set: road alignment; on horizontal curves: turn radii, road cross section, conditions of the wheel adhesion with the road pavement, road pavement quality and maximum speed limits (Nagatani 2005; Verhoef, Rouwendal 2004). These characteristics are sufficient to prognose possible accelerations in working and extreme modes as well as fuel consumption. Motion parameters are calculated according to the automobile's force balance equation.

The methodology of identifying the terms of the equation is known; however, its solution is restricted by the peculiarities of vehicles with ICE (internal combustion engine): the equation may be written for a concrete gear and a concrete engine working mode. When shifting gears, the motion is described by dividing the process into the stages of throwing out of gear, shifting gear and throwing in the clutch. Traction force is restricted not only by the moment created by ICE, but by the conditions of driving wheels' adhesion with the road. The constituents of traction and resistance forces contain terms which depend on the speed (air resistance, losses in transmission and road-tyre contact). Moreover, parts of dependences are non-linear; therefore the equation is usually solved through the use of digital methods based on linear dependences. The factors mentioned above do not have considerable impact on a vehicle moving on a suburban road when shifting gears is occasional; road sections with identical movement conditions are rather long and ICE's work in transition modes makes up an inconsiderable part. Movement along an urban street is related with changing modes; thus, to simulate fuel consumption digitally, it is compulsory to identify and evaluate the part of ICE's work in transition modes. Therefore, the model is even more related with a concrete vehicle, which reduces the model's value when making general conclusions. To substantiate the expedience of applying the dynamic model, the possibilities of identifying a typical sample automobile were investigated.

It is impossible to evaluate the peculiarities of all vehicles; therefore, in the initial stage of the study we used a slightly modified vehicle classification proposed for flow investigations. The analysis showed that to formalize the description of engines' external characteristics, three groups of trucks shall be distinguished. The peculiarities of the dynamics (carriage of people) as well as movement restrictions (compulsory braking at bus stops) makes the simulation of the bus movement a specific task. Due to the reasons enumerated above, the following classification was used:

- cars;
- small trucks and small buses;
- medium-size loading capacity trucks;
- motorway trucks and motor train trailers;
- buses.

According to further investigations, the accepted classification reflects both the specificity of vehicles' movement in urban areas (vehicles with larger dimensions move slowlier along narrow streets) and their acceleration/deceleration characteristics.

A vehicle's movement algorithm when the vehicle's motion is not restricted by additional obstacles is presented in Table 1. The parameters that take into consideration the losses and resistance to movement forces are taken from experimental data. Equations of identifying traction, loss and resistance forces are presented in Table 1.

The structure of the automobile's dynamic model (Fig. 1, block 7) is presented in Fig. 2.

Table 1. Constituents of the vehicle's movement resistance and traction

$\sum F_i = F_k + F_s + F_a$ F_k – motortrain movement/ rolling resistance force F_s – ascending resistance force F_a – aerodynamic resistance force
$F_k = fmg$ $f = f_0 + K_f v$ $F_s = \pm mg \sin\alpha$ $F_a = K_O A v^2$
$F_\tau = \dfrac{M\,ICE\,u_{tr}\eta_{tr}}{r_d}$

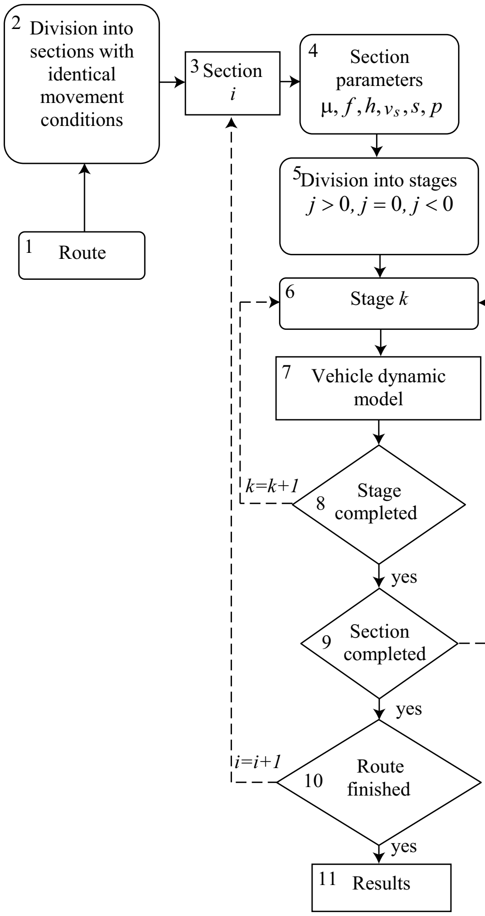

Fig. 1. Algorithm of movement on the city route: μ – frictional coefficient; f – rolling resistance coefficient; h – uphill; v_s – maximum permitted speed; s – mark at the end of the traffic lights' section (s = 1 or s = 0); j – acceleration; p – pedestrian crossing mark (p = 1, p = 0)

3. Formalization of Engine's External Characteristics and Fuel Consumption

To solve traditional dynamic tasks, comprehensive external engine characteristics are required. However, producers present the dependences of torque moment $M(n)$, capacity $N(n)$ and relative fuel consumption $g_e(n)$ on the engine rotation frequency only at the full loading of an engine. Therefore, when constructing the model we paid more attention to the generalization of the distinguished automobile group engine characteristics. The analysis confirmed that serial production engine exploitation characteristics for the same group of automobiles depend more on their production period, not on the producer (Jakštas 2010). More attention was paid to $M(n)$. The data $M = f(n)$ and $N = f(n)$ of vehicles' engines frequently used on the Lithuanian roads as well as inert characteristics may be calculated according to the information submitted by companies-producers (Janulevičius *et al.* 2010).

When investigating $M(n)$ dependences, we identified that it is more convenient to use relative coordinates $M^*(n^*)$, where $M^*=M/M_{max}$; $n^*=n/n_{max}$; M – torque moment (Nm) at engine rotation velocity n (rpm); $M_{\max}$ – maximum torque moment; n_{max} – maximum engine rotation frequency. In our opinion, when n_{max} is used for reduction, engine characteristics are generalized more accurately than using the largest capacity rotation frequency $n_{N.}$ When the largest torque moment frequency n_M is used for reduction, it is more difficult to compare various engines as the specificity of the engine is reflected better.

Characteristics of the engines used in the serial general-purpose automobiles in coordinates $M^*(n^*)$ fall into several groups. The study showed that besides diesel and Otto engines, engines with turbo compressors shall be distinguished. Moreover, the engine's working volume

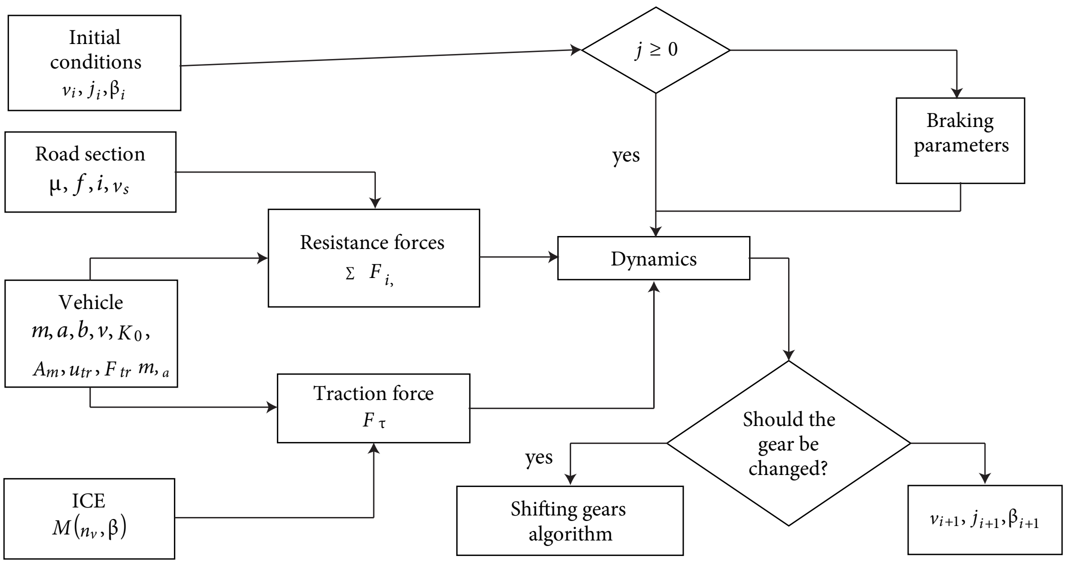

Fig. 2. The structure of the vehicle's dynamic model: v_s – maximum speed limit; ΣF_i – empty travel resistance force; m – mass; a, b – coordinate of mass centre; M – torque; n_v – RPM of motor; β – load coefficient; F_τ – traction force; *ICE* – internal combustion engine; K_0 – streamlining coefficient; A_m – motor train model area; u_{tr} – transmission transfer number

impacts on the characteristics (Fig. 3). When investigating the dependence of the torque moment on the load, two dependence groups had to be distinguished. Diesel engines, especially those produced 10–15 years ago, change their characteristics when fuel supply amount is changed, without any essential changes of their form (Fig. 4a). The characteristics of petrol engines change more considerably when fuel supply varies (Fig. 4b). Here the shift of the torque moment maximum towards smaller rotation frequencies is observed. Therefore, we presented the analogy method for a generalized description. The method points out how to obtain the engines' torque moment dependences on different loads. For this reason, the known torque moment dependence is shifted horizontally and vertically in logarithmic coordinates. The method may be applied when essential variations do not occur if the fuel supply is changed. The essence of the method lies in the universal moment dependence occurrence. A more detailed analysis showed that it is possible; however, the expression of the generalized curve is complicated and the method loses the advantage of its simplicity. Supposing that flow models take into consideration only modes when the engine's traction force is required, dependences are divided into 3 groups: working ($\beta = 0.3 \div 1$), transition processes ($\beta = 0.05 \div 0.3$) and braking ($\beta = 0$) (Fig. 4). In such case dependence *M(n)* for separate mode groups is described by 2÷3 degree polynomials.

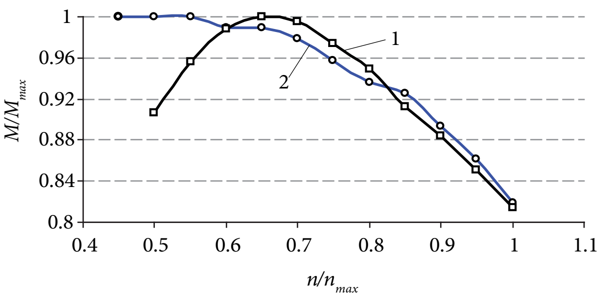

Fig. 3. Torque moment dependences on the rotation frequency for Diesel engines of different working volumes and different generations: 11.1 *l* – old generation engine (1); 1.9 *l* – new generation engine (2)

In a general case, the dependence is described as follows:

$$M(n) = M_{\max} \cdot k_{\beta m} \cdot \Big(a_0 + a_1 \left(k_{\beta n} \cdot n^*\right) + a_2 \left(k_{\beta n} \cdot n^*\right)^2 + a_3 \left(k_{\beta n} \cdot n^*\right)^3\Big), \tag{1}$$

where: $k_{\beta m} = \exp(\Delta V(\beta))$; $k_{\beta m} = \exp(\Delta H(\beta))$; $\Delta V(\beta)$; $\Delta H(\beta)$ – vertical and horizontal, respectively, $M(n)$ – movement of dependences in logarithmic coordinates from basic dependence.

The characteristics of transition and braking modes are described by the third degree polynomials and that of the working mode by the second degree polynomials

4. The Impact of Infrastructure

In dynamic models, a street description differs from an ordinary road description in that besides traditional parameters required to evaluate the vehicle's dynamic characteristics, possible obstacles, such as intersections, pedestrian crossings, their passing conditions, for buses: bus stops and entering them conditions, shall be additionally taken into consideration in the vehicle–street model (Boumediene *et al.* 2009; Ilgakojytė-Bazarienė, Jablonskytė 2009; Junevičius, Bogdevičius 2009; Wen 2008; Beljatynskij *et al.* 2009; Chunchu *et al.* 2010; Akgüngör 2008a, 2008b; Berezhnoy *et al.* 2007).

Moreover, the model shall take into account a considerable variation of maximum speed limits on separate road sections from the maximum speed limits in an urban area (50 km/h): drivers usually pass intersections and pedestrian crossings slowlier if, according to the route, they have to turn at the road intersection, the speed is reduced, etc. All mentioned above shall be taken into consideration when dividing the section into stages and when moving along the urban route algorithm (Fig. 1).

The regulated intersections are evaluated simply. If they are not connected into the common traffic management system, their working cycle consisting of the green, yellow and red signal duration is known. When simulating, the following initial conditions of the section before the intersection are known: automobile speed entering the section, maximum permitted speed in the section

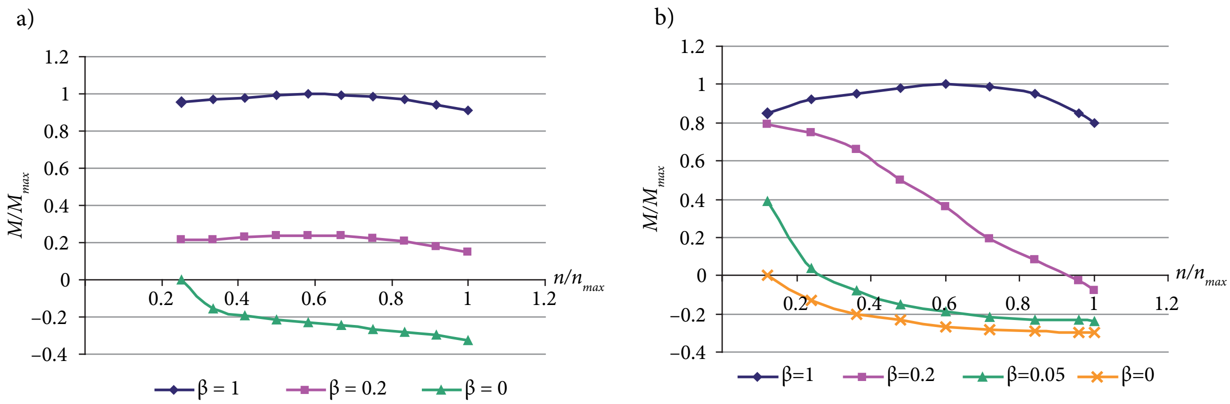

Fig. 4. Dependence of torque moment on rotation frequency when different fuel is supplied: for Diesel (a) and Otto (b) engines

and section length; therefore, the duration of covering the section may be prognosed. If the automobile's arrival time at the intersection is known, it may be estimated at which signal the automobile will approach the intersection. In a general case, the vehicle's movement cycle between intersections will be described as follows (Fig. 5):

1. the vehicle speeds up to the maximum speed limit on the given section;
2. the vehicle drives at a constant speed;

3a. the vehicle slows down as it was prognosed that it will manage to pass the green signal on the condition that the speed shall be reduced down to the accepted speed on the given intersection (variant 1);

3b. the vehicle slows down as it was prognosed that it would not manage to pass the green signal and would have to stop (variant 2);

3c. due to certain reasons initial requirements were not satisfied. Standing too long in the section one should stop: a situation which is typical for driving in a column (variant 3).

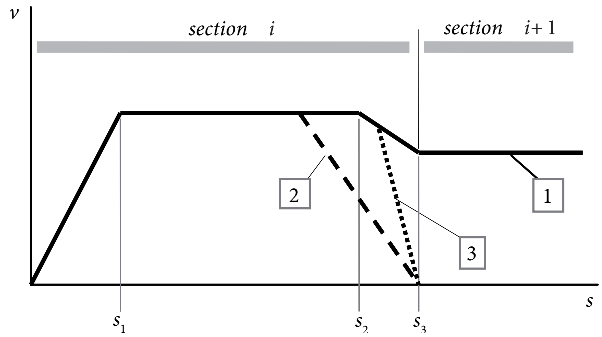

Fig. 5. The scheme of driving along the street section (Different driver's behaviour variants 1–3 depending on the signals of traffic lights. The end of stages $s_1 - s_3$ if the section covering algorithm contains all three stages)

Depending on the maximum speed limit on road sections *i*-1, *i* and *i*+1, all three (speeding up, driving at a constant speed and slowing down) or one or two stages are prognosed in the algorithm. When dividing the section, it is supposed that drivers strictly observe traffic regulations: do not exceed the speed limit until they leave the section at a lower speed limit and brake at the end of the section so that they enter the next section at a lower speed without exceeding the speed limit. Division into stages is performed when lengths of sections required for speeding up and slowing down are estimated according to the set ones, which depend on the driver's behavior and accelerations. In case of short sections, it is possible that the automobile does not reach the speed limit set for the given section. Non-regulated intersections and pedestrian crossings were simulated according to the same principle. When constructing the model of the vehicle driving on the non-regulated pedestrian crossing, it was supposed that drivers observe traffic regulations and stop when a pedestrian is on the pedestrian crossing. The time required to cross the street is calculated according to the following formula (Nagatani 2006):

$$t_p = 5 + B/V_p, \tag{2}$$

where: t_p – duration of crossing the pedestrian crossing for pedestrians; B – width of the carriageway, crossed by pedestrians in cycle; V_p – pedestrians' speed (1.3 m/s).

Experimental data on the probability of pedestrian occurrence on the pedestrian crossing were used for the description through the use of the pedestrian crossing index *p*.

5. The Driver's Model

In general, the driver, the vehicle and the environment are connected by complicated relations (Fig. 6). The road–vehicle model is comprised of separate dynamics and speed limiting blocks, which are combined by the driver's model. The dynamic model describes a concrete automobile with its mass distribution, engine characteristics, transmission transfer degrees, rotating mass inertia moments. The subsystem of speed limiting combines information on the road geometric parameters and signs and describes the automobile stability in cases of turnover, sliding and cross rolling as well as the impact of external and random obstacles on the automobile's stability. This subsystem may also take into consideration information on the speed of other automobiles and their position at a given moment of time, treating them as moving obstacles. The driver follows all information obtained from the speed limiting subsystem and carries out the functions of fuel supply, braking, and gear shifting in the dynamic model.

When driving in an urban area, the focus is changed. As the speeds are lower, the driver may pay less attention to the stability of the automobile's direction; however his attention is distracted more than on the roads as there are more objects to be watched by the driver.

Therefore, under urban conditions, the driver's behavior in typical situations may be described typically: it is supposed that the driver is disciplined and observes traffic regulations, is not tired and knows the route, is able to choose the engine's working mode according to the traffic conditions. Therefore, the driver's choices in the model are restricted in the following three cases:

- Sports-like driving style. When braking, 90% of friction conditions are used. When speeding up, 50% of friction conditions are used. Gears are shifted when engine's rotation frequency complying with the maximum power capacity is reached. An internal combustion engine is not turned off.
- Normal driving style. The speed is increased and reduced according to usual accelerations under urban conditions 3÷3.5 m/s^2, if engine characteristics and friction with pavement conditions allow. A modification was introduced for heavy vehicles and buses, by gradually reducing accelerations to 2.5÷3 m/s^2 for 15 ton trucks. Gears are shifted at the engine rotation frequency com-

plying with the maximum torque moment. The internal combustion engine is not turned off at intersections.

- Economic driving style. Accelerations are restricted to 1÷1.4 m/s^2, for trucks and buses 1 m/s^2; at intersections the internal combustion engine is turned off if idling time exceeds 5 s.

The driver's behavior is reflected in the gear shifting duration as well. Gear shifting duration set in the model is divided into three equal duration stages: throwing out of gear A, shifting gear B and throwing in the clutch C.

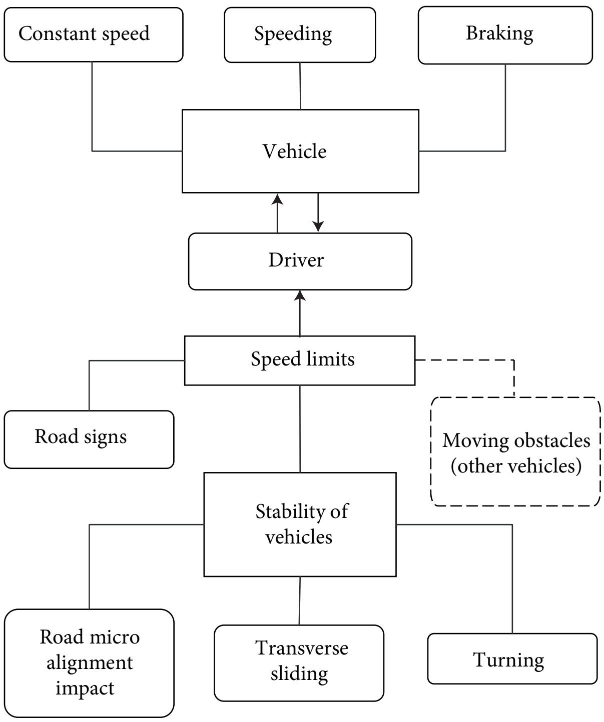

Fig. 6. Principle scheme of the system *driver–vehicle–road* when constructing a complex model of a vehicle's motion on a road

6. Results and Discussions

The model's efficiency was verified when simulating various situations of movement in an urban area. Therefore, the route in the Kaunas city was selected. Its length is 4.2 km with 7 intersections regulated by traffic lights.

To avoid collision with the upcoming traffic, the selected driving direction was straight or turning right. The route contains 8 degree steep uphill. Therefore, driving in two directions was set. The road and the automobile are described according to the methodology discussed in Chapters 2–5.

When simulating an individual vehicle driving on the route, the model's efficiency was confirmed: information about the speed, engine mode and gear was obtained (Fig. 7).

Road alignment (uphill–downhill) has impact on an average speed. When moving on the set route by setting different speed limits on separate sections, from 40 km/h speed limit starts to depend on the route covering direction (Fig. 8).

The algorithm of the automobile movement along a street section enables to analyse the following aspects in detail:

- to identify how much the movement mode under conditions approximate to real ones, taking into consideration regulated intersections, differs

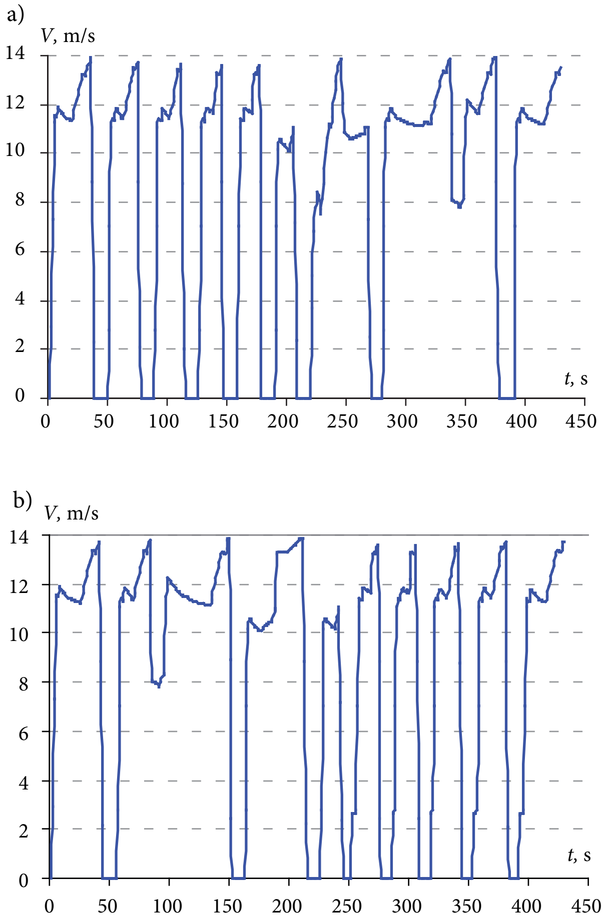

Fig. 7. The results of driving along a set route in an urban area (speed – V): a – forward; b – back

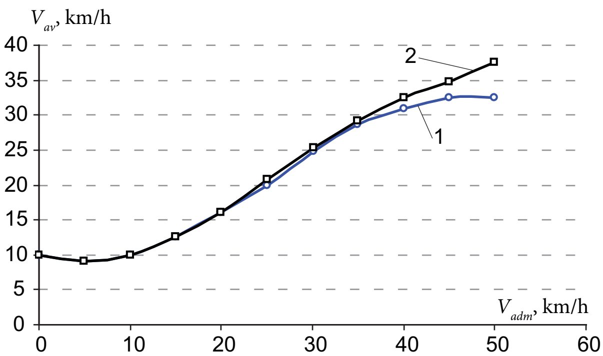

Fig. 8. Dependence of average speed V_{av} on the speed limit V_{adm} when driving along the set route in an urban area: 1 – forward; 2 – back

from the movement at a normal speed compared with the movement in the EURO city cycle;
- to obtain data for the increase of vehicle operational costs (number of stops, number of gear shifting) (Fig. 9);
- to identify the variations of travel duration rather accurately when simulating vehicles of different types and driving styles.

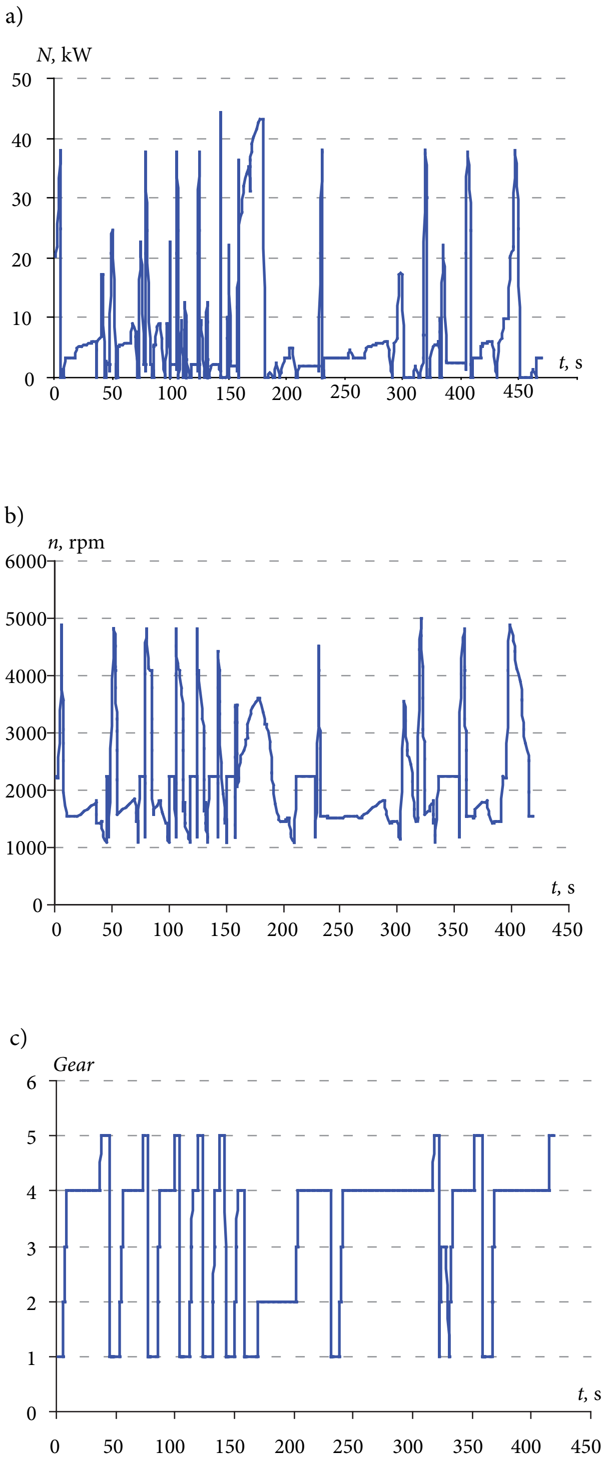

Fig. 9. The vehicle's engine capacity (a), torque frequency (b) and gear (c) variation when moving along a city route

7. Conclusions

1. The conducted study of an individual vehicle's movement in an urban area has confirmed that the use of analogy method enables to construct a digital model of the vehicle model representing a group of vehicles when a limited number of parameters is available.
2. Regular dynamic vehicle models shall be supplemented by the data of traffic restriction elements (intersections, pedestrian crossings, variation in the number of lanes) and traffic conditions as well as the description of the driver's behavior.
3. The vehicle's model enables to evaluate an average speed, delay, energy consumption and engine and machinery working conditions more accurately.
4. The vehicle's simulation model may expand the situations under analysis (changing lanes, flow dynamics at public transport stops when special traffic lanes are absent, bypassing obstacles) for more accurate evaluation of losses.

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