INFLUENCE OF THE TREND OF MODERN VEHICLES MAXIMAL SPEED AND ACCELERATION INCREASING ON THE TRAFFIC SAFETY

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INTRODUCTION

Speed represents the most significant exploitation parameter of motor vehicles which can be used to most completely express their efficiency. The need to reduce the travel time and goods transport issued a demand – to increase the speed of vehicles. Therefore, the tendency to increase the maximum speed was always present, which reaches around 200km/h for passenger vehicles. On the other hand, maximum speed increase has – for a consequence – a number of negative effects:

- the reduction of traffic safety for vehicles, due to an increase of risk of traffic accidents,
- greater consequences in case of traffic accident, due to the increased kinetic energy of the vehicles,
- increase in fuel consumption and in emission of toxic materials,
- increasing the strength of the drive aggregate,
- construction changes of vital vehicle parts and joints, in order to increase their hardiness, functionality, and reliability.

The main and limiting factor of maximum speed increase is certainly its negative effect on traffic safety. Thus, law limits of maximum speed are induced, and its values depend on traffic conditions: residential zones, local and main roads, highways. Although the maximum speed limits differ, in most countries they stand at 120km/h on highways. Contemporary passenger vehicles have far higher maximum speed, which can be seen on a graph on *Figure 1*.

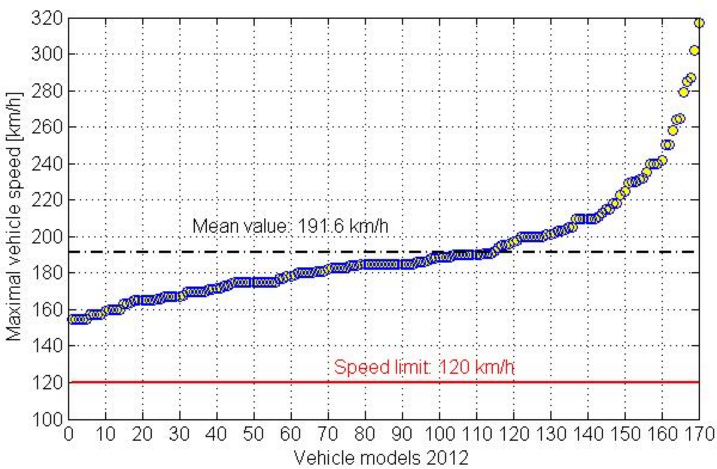

***Figure 1** Maximum speed of contemporary passenger vehicles (170 models from different manufacturers)*

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The condition shown by the graph on *Figure 1* indicates potential dangers regarding speeding, considering that the kinetic energy of the vehicle changes with the square of speed. In order to gain a more real evaluation of that energy's value, graph on *Figure 2* represents the comparative graph of the "Bofors" cannons of different caliber, with different masses and different projectile speeds, and of a vehicle weighting one ton, whose speed is 120 (MV120) and 200km/h (MV200). This comparison can be illustrated via concrete data that the energy of the vehicle MV200 equals energy of the 5 kg projectile, fired with initial speed of 800 m/s, which represents 70-100mm cannon caliber. Given facts support the attitude that the motor vehicle can be considered <u>a weapon of murder with devastating power</u>!

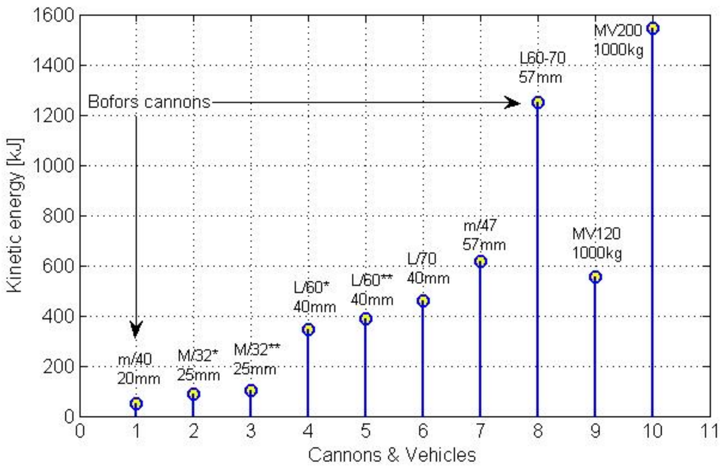

Figure 2 *Kinetic Energy of cannons and vehicles*

Due to before shown facts, main goals of this research are:

- research of the effect of vehicle speed on cause and severity of the traffic accident [1],
- determining a method for controlling and limiting the vehicle speed [2],
- research of the effect of vehicle speed on fuel consumption and toxic materials emission [3],

Research in this field, so far, did not have for a goal the evaluation of the maximum speed increase on demands placed during the project phase of the vehicle and its subsystems. Namely, the increase of maximum speed demands the change in engine performances (power, torque, maximum rpm, dynamics) transmission (number and layout of transmission degrees), vehicle itself (chassis aerodynamics, characteristics of pneumatics, mechanical hardiness and vital parts reliability). Fulfilling these demands increases the production costs of the vehicle. This study researches the tendency to increase the maximum speed in order to provide a conclusion regarding its requirements.

1. THE EFFECT OF SPEED IN THE CHARACTERISTIC REGIMES OF VEHICLE MOVEMENT

General characteristic of all vehicle movement in real regimes of exploitation is the change of speed caused by traffic flow. Based on statistical analysis of real regimes of the vehicle, it is possible to define a typical curve of speed changes during the exploitation (*Figure 3*).

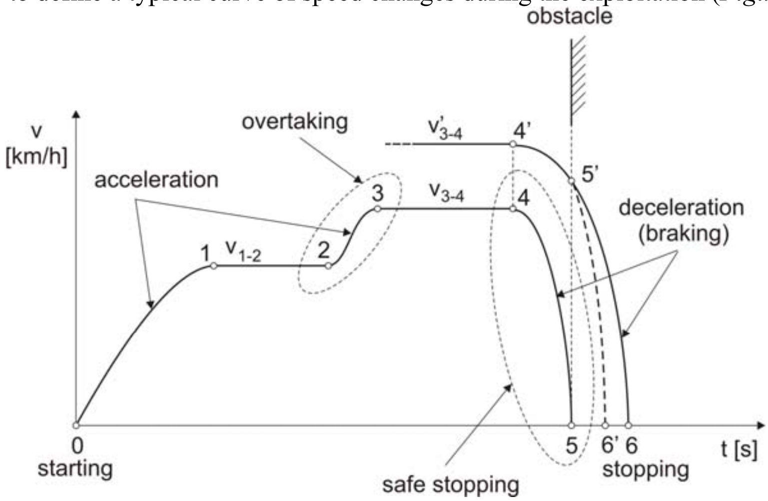

Figure 3 *Characteristic curve of speed changes during vehicle movement*

Of all regimes of the vehicle movement, highest risk comes, certainly, from maneuvers: overtaking (2÷3) and braking in case of the sudden appearance of another traffic participant or immobile obstruction on vehicle course(4÷5). Basic parameters which affect the safe conducting of these maneuvers, apart from driver reaction time and proper evaluation of the situation are: the intensity of vehicle acceleration (overtaking) and the efficiency of the braking process (safe stop).

However, from graph on *Figure 3* we can notice that the successfulness of these maneuvers is affected by constant values of speeds v_{1-2} i $v_{3-4.}$ Specifically, in the case of safe stop, with an increase in speed value from v_{3-4} to $v_{3-4.}$, under the same braking process efficiency, braking time is lengthened, which leads to an increase risk of traffic accident. On the other hand, increase in speed v_{3-4} leads to the increase of vehicle kinetic energy, leading to more severe consequences in the case of traffic accident.

1.1 Analysis of the effect of vehicle speed on dynamic processes in the case of traffic accident

The most basic way to prevent a traffic accident is to safely stop a vehicle before it comes into contact with an obstacle in its trajectory. The process of stopping the vehicle includes the speed reduction, which is obtained by lowering the drive moment and by applying the braking system. The movement equation for this type of a vehicle movement regime has the following shape:

$$m\frac{dv}{dt} = -F_r \tag{1}$$

Whereas F_r is the total resistance force which causes the vehicle braking. In this case, we assume the fact that during intensive braking, drive force of the vehicle is equal to zero. By adding a substitution: $dt = ds/v$ equation (1) gains the following shape:

$$m\,v\,dv = -F_r\,ds \tag{2}$$

By integral of equation (2) we gain an evaluation of speed change during the vehicle braking:

$$v = \sqrt{v_o^2 - \frac{2(s - s_o)}{m} F_r} \tag{3}$$

Whereas v is the current vehicle speed, s – distance passed by vehicle so far, m – vehicle mass, v_o i s_o speed and distance passed at the beginning of the braking process.
In case of intensive braking, the vehicle braking resistance force is equal to:

$$F_r = F_{bmax} = mg\varphi \tag{4}$$

Whereas $F_r = F_{bmax}$ is the maximum braking force the base can take, g – acceleration provided by gravity, φ the coefficient of adherence of the base.
Graph on *Figure 4* represents the changes of the speed given by equations (3) and (4), under different initial speeds at the beginning of the braking process, for a vehicle weighting one ton, and the coefficient of adherence $\varphi=0.8$.

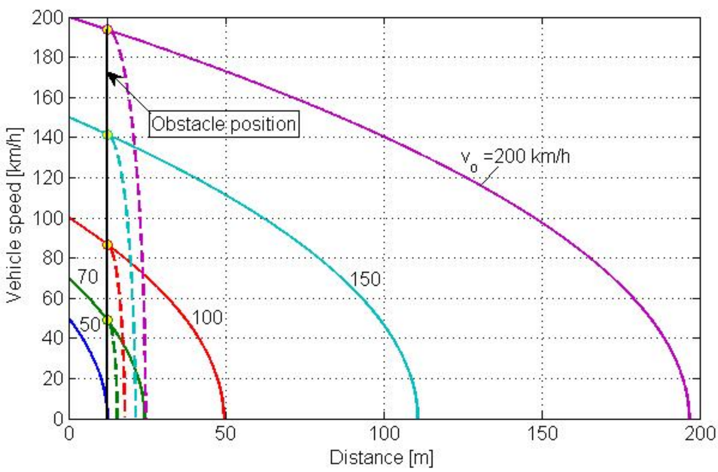

***Figure 4** Changes of speed during the braking process and obstacle impact at different speeds*

Safe stop is concluded only at initial speed v_o*=50 km/h*, considering that the obstacle is located at the position adequate to braking distance for this initial speed: s_b*=12.29 m*. At higher initial speed, braking distance is longer, so vehicle reaches the obstacle with different speed values which can be read from graph. The relation of Kinetic energy from the point when braking starts E_{ko}, and the one related to the obstacle E_{k2}, is shown by a graph on *Figure 5*. Graph also represents the change in kinetic energy which is absorbed by the braking system under the different initial speeds: $DE_k=E_{ko}-E_{k2}$. As it can be seen from the graph, that is a constant value which is adequate to the absorbed kinetic energy at the initial speed of *50 km/h*: $Ek_{50}=96.45$ *kJ*.

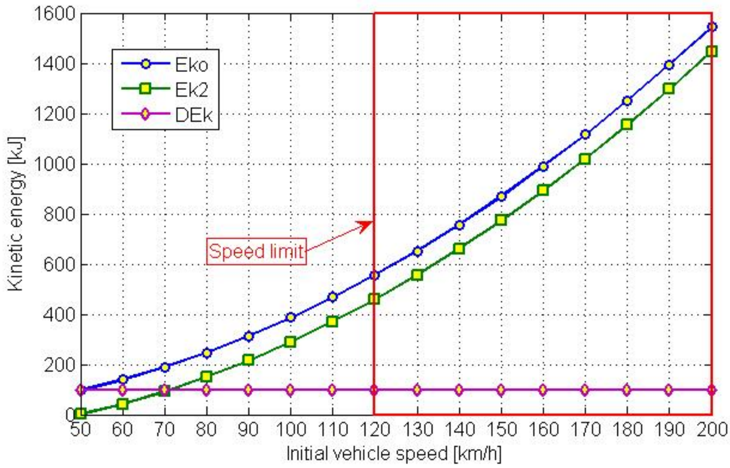

Figure 5 *Values of kinetic energy absorbed the braking system and kinetic energy on obstacle*

From the moment of obstacle contact, further change of vehicle speed depends on the character of the obstacle: mobile/immobile, crude/deformable. Resistance force which in this case stops the vehicle can be shown by a following formula:

$$F_r = - c_r\, x \tag{5}$$

Whereas c_r represents the resulting stiffness of the structures of vehicle and the obstacle, x- the amount of moving (deforming) after the contact.
Equation of the vehicle movement in this case is:

$$m\frac{dv}{dt} = -c_r\, x \tag{6}$$

That is:

$$m\,v\frac{dv}{dx} = -c_r\, x \tag{7}$$

Whose solution provides the change of vehicle speed after the contact with obstacle:

$$v = \sqrt{v_2^2 - \frac{c_r}{m}\left(x^2 - x_o^2\right)} \tag{8}$$

Whereas v_2 is vehicle speed at the moment of contact with the obstacle, x_o initial value of movement ($x_o=0$). According to equation (8), amount of speed reduction of the vehicle at the same value of initial movement speed V_2 , depends on the stiffness of the system vehicle-obstacle (C_r), which is taken into consideration during the design of the frontal structure of the chassis. It is obvious that larger values of this crudeness lead to higher decelerations, and thus to potentially higher consequences of the traffic accident.

1.2 Effect of vehicle speed on cause and consequences of traffic accidents

The analysis to follow presents the effect of vehicle speed on dynamic processes during the case of traffic accident is conducted under the assumption that reactions of drivers and effects of other conditions (caraway and weather conditions) are the same. In real traffic conditions all of these factors are present, so their effect on traffic accident is very complex. The most objective evaluation of this effect can be gained by statistic analysis of results gained by expertise of the higher number of traffic accidents, which does represent the most common method of research. However, there is often a need to form models based on results of statistic analysis, whose usage allows more efficient research of this effect.
From all the models which can be found in literature, in this study we'll show Power Model of G.Nilsson [1].
This model is defined with a basic formula:

$$\frac{Fatal\ accidents\ after}{Fatal\ accidents\ before} = \left(\frac{Speed\ after}{Speed\ before} \right)^n \qquad (9)$$

Whereas „before" and „after" are related to the values of speed vehicle has before and after the change from its mean value. The value of power of *n*, determined by statistic analysis of real data for different types of traffic accidents, are shown at *Table 1* [1].

Table 1 *Values of power of n [1]*

Accident or injury severity	exponent	interval
Fatalities	4.5	(4.1 – 4.9)
Seriously injured road user	3.0	(2.2 – 3.8)
Slightly injured road user	1.5	(1.0 – 2.0)
All injured road users (severity not stated)	2.7	(0.9 – 4.5)
Fatal accidents	3.6	(2.4 – 4.8)
Serious injury accidents	2.4	(1.1 – 3.7)
Slight injury accidents	1.2	(0.1 – 2.3)
All injury accidents (severity not stated)	2.0	(1.3 – 2.7)
Property-damage-only accidents	1.0	(0.2 – 1.8)

By using an equation (9) and values of power of n given in *Table 1*, we reached graphs shown on *Figure 6* for three basic categories of traffic accidents. From graph we can directly gauge the effect of change of average speed of the vehicle on the cause of studied types of traffic accidents.

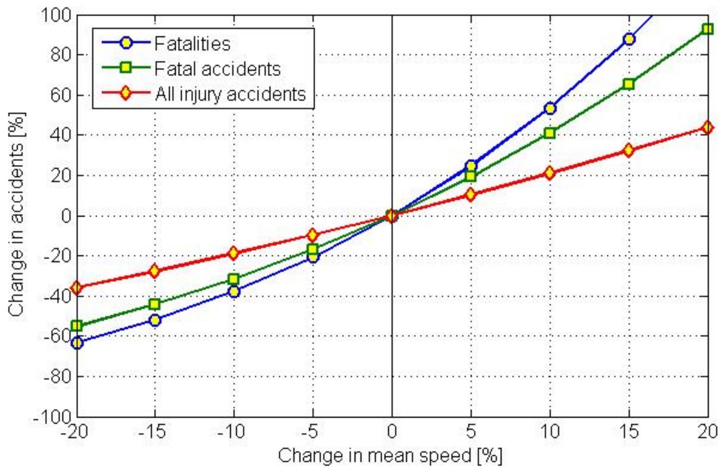

Figure 6 *The effect of vehicle speed on risk and severity of traffic accident*

In the same manner, we can gain the graphic dependency and gauge the effect of average speed for all other types of traffic accidents stated in *Table 1*.

2. TECHNOLOGICAL, ECONOMIC AND ECOLOGICAL ASPECTS OF INCREASING THE MAXIMUM SPEED OF CONTEMPORARY VEHICLES

Based on analysis done in previous chapters, we can come to following conclusions:

- the tendency to increase the maximum speed is present for all manufacturers,
- the average value of maximum speed of contemporary passenger vehicles reaches around 200km/h which is far higher then maximum speed allowed in most countries (120km/h),
- increase of average speed of the vehicles directly influences the risk and severity of the traffic accidents.

Bearing in mind the given conclusions, there is a need to analyze the need for such tendency under the criteria of requirements during the project phase of such vehicles as well as during exploitation and manufacturing.

2.1 Basic characteristics of the vehicles with higher maximum speed

Movement speed represents, definitely, the most exploitation parameter of the motor vehicles, with whose increase we directly shorten the travel time and goods transportation time, as long as its maximum value is corresponding to the limited regime which rarely occurs in public transportation. The value of maximum speed of the vehicles can be determined by the analytic method through basic movement equations [5]:

$$m\frac{dv}{dt}=\frac{M_e\, i_m\, i_o}{r_d}\eta-F_r \qquad (10)$$

$$v_{max} = \frac{2\pi r_f\, n_{max}}{i_m\, i_o} \tag{11}$$

In this equations, following values are used: M_e – the effective engine momentum, i_m transmission ratio, i_o –transmission of main differential, η – degree of transmission usage, r_d – dynamic radius of the wheel, , r_f radius of radius of wheel tumbling, n_{max} -maximal engine revolutions.

Force of resistance F_r, , in equation (10), deals with forces: resistance of air F_v and tumble resistance F_f, , considering that the maximum speed of vehicle is determined on flat road, so the ascent resistance of the road is equal to zero. The vehicle movement regime which is adequate to maximum speed is gained from condition: *dv/dt=0 ,* that is:

$$M_e(n_{max}) = \frac{r_f\left(F_v + F_f\right)}{i_m\; i_o} \tag{12}$$

Where there is an assumption that there wont be pneumatic slip, ($r_d \approx r_f$), or losses in transmission ($\eta=1$). The equation (12) defines the value of the engine momentum which is supposed to provide the number of revolutions n_{max} under the effect of resistance force: F_v+ F_f, in the highest gear (for contemporary vehicles its i_m=i_V). The resistance to the movement of the vehicle is given by following formulas [5]:

$$F_v = \frac{1}{2} c_x\, \rho\, A\, v_{max}^2 \tag{13}$$

$$F_f = f\; G \tag{14}$$

Whereas c_x - aero dynamical coefficient of air resistance, ρ – air density, A – front vehicle surface, f – coefficient of tumbling resistance, G – vehicle weight. By replacing the form for movement resistances into an equation (12) it gains the following final shape:

$$M_e(n_{max}) = \frac{r_f\left(f\, G + 0.5 c_x \rho\, A\, v_{max}^2\right)}{i_V\; i_o} \tag{15}$$

The amount of power, which engine reaches in the regime of maximum speed, is provided by the known formula:

$$P_e(n_{max}) = M_e(n_{max})\,\frac{\pi\, n_{max}}{30} \tag{16}$$

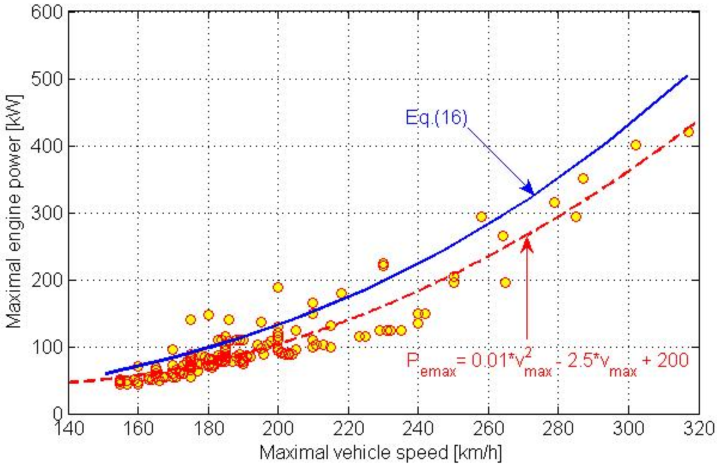

***Figure 7** Dependency between the maximum engine power and maximum vehicle speed*

Graph on *Figure 7* shows the dependency between maximum engine power of maximum vehicle movement speed, provided by equations (15) and (16), and using the catalogue base of 170 contemporary vehicles which are approximated by the interpolating polynomial of 2nd degree. We can notice how the law of change of given curves goes together, which leads to a conclusion that by increasing the maximum vehicle speed, under all other remaining conditions being same, maximum power increases by the law of square parabola.

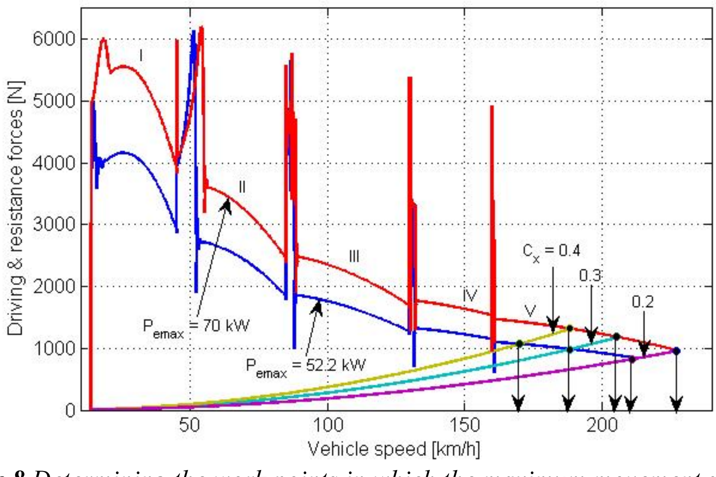

***Figure 8** Determining the work points in which the maximum movement speed of the vehicles is reached*

From equations (15) and (16) we can notice that all other parameters which have effect on the maximum vehicle speed. The direction of their effect is illustrated on *Figure 8*, which shows the dependency of forces of drive and of resistance of the vehicle on the movement speed in certain gears. As it can be seen from graph the increase of maximum speed of the vehicle can be reached by an optimal combination of increase in power of the engine and by lowering the movement resistance and the transmission ratio. The effect of maximum number of engine revolutions n_{max} on the value of maximum speed is provided by equation

(11). Irrelevant that the maximum number of engine revolutions does not coincide with number of revolutions during the maximum power (especially at otto engines) due to relatively small different we are taking them as coinciding by an agreement.

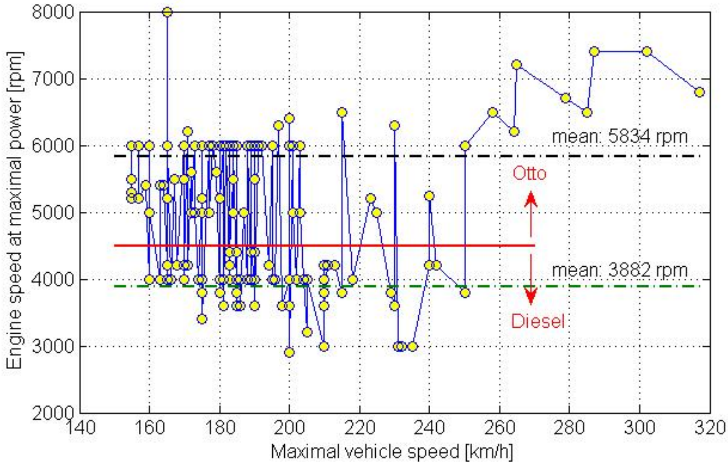

Figure 9 *Engine speed under which the maximum power is reached*

According to equation (11) under the same values: wheel radius and transmission ratio, by increasing the maximum number of revolutions per minute maximum speed is increased as well. However, from the graph on *Figure 9*, contemporary engines of passenger vehicles have fairly similar constants for number of revolutions under maximum power, to the value of 250km/h. The average values of those number of revolutions are: ≈6000 o/min, at otto engines and ≈4000 o/min for diesel engines. Thus, the vehicles with diesel engines under the same maximum speed need to have lesser values of transmission ratio and thus higher torque ratio under the number of revolutions n_{max} in relation to vehicles with otto engine. Vehicles which acquire maximum speed over 250km/h, are in the category of sport vehicles, at which their maximum speed increase is followed by the adequate increase in number of revolutions, as it can be seen on the graph on *Figure 9*.

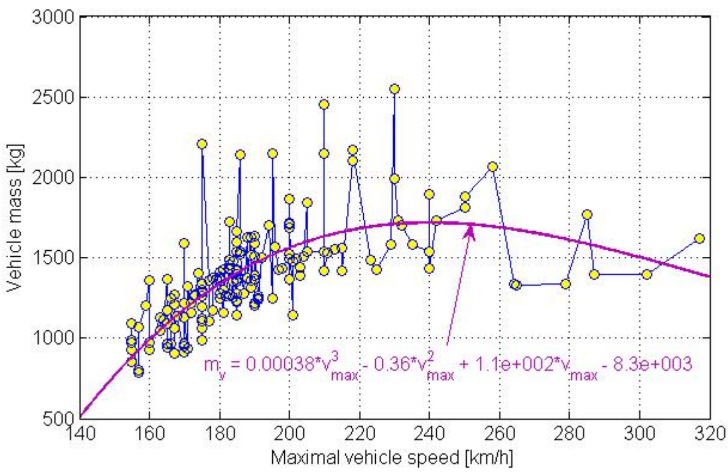

Figure 10 *Effect of the vehicle mass*

The effect of mass on vehicle movement can be gauged by an equation (10) from which follows that, under the same conditions, by reduction of vehicle mass leads to increase in vehicle speed. However, graph on Figure 10 shows a value increase tendency for serial vehicles up to the maximum speed of ≈ 240 km/h. This phenomena can be explained by the fact that maximum speed increase of serial vehicles is followed by category increase, and thus with vehicle dimensions. Only in category of sport vehicles v_{max}□*250 km/h*), the tendency to reduce the vehicle mass is present.

According to research available in the literature (3), the increase of maximum vehicle speed over some other values affects the consumption of fuel and emission of harmful components of the vehicle negatively, which also has to be taken into consideration in analysis such as this one.

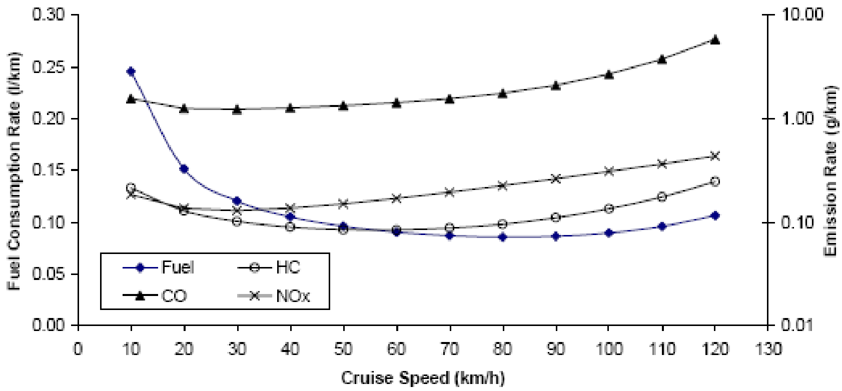

Figure 11 *Effect of movement speed on fuel consumption and emission of toxic materials [3]*

Graph on *Figure 11* shows exactly such dependencies, for which we need to mention that under the same movement speed value, the amounts of fuel consumption and toxic material emission depend on vehicle acceleration, so with the increase of acceleration value , those values increase as well.

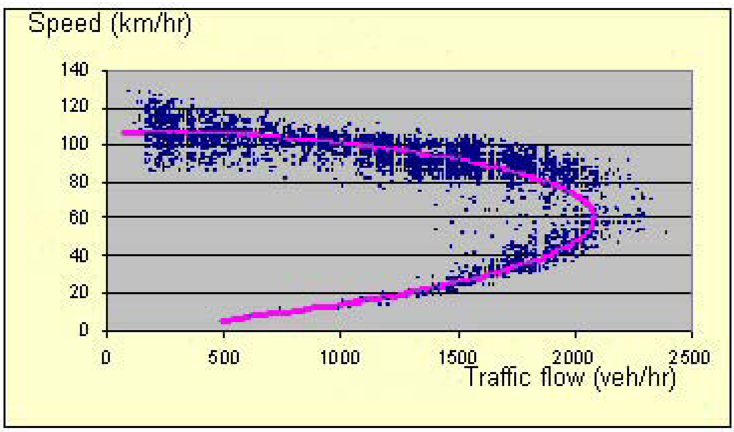

Figure 12 *The effect of average speed on vehicle flow (number of vehicles per hour) [2]*

Early stated fact that with an increase of average speed we reduce travel time and goods transportation time can not be generalized for all speed values. Graph on *Figure 12* shows exactly that for urban traffic line with 2x2 traffic tracks highest vehicle flow can be acquired for speeds averaging between 60 and 70km/h. Thus, with speeds above 70km/h, vehicle flow reduces and simultaneously traffic accident risk and severity of traffic accident consequences increase, which is exactly the reason to induce speed limits in the urban zones.

CONCLUSIONS

In the introduction part of the conclusions, we'll first quote two illustrative attitudes from document [2]:

- *"Speeding -- i.e. excessive and inappropriate speed -- is a widespread social problem as, typically, at any time 50 % of drivers are above the speed limits. It is the number one road safety problem in many countries, often contributing to as much as one third of fatal accidents and speed is an aggravating factor in the severity of all accidents".*
- *"Higher vehicle speeds also contribute to increased greenhouse gas emissions, fuel consumption and noise and to adverse impacts on quality of life, especially for people living in urban areas".*

Based on data analysis done in previous chapters we can add the following attitudes to quoted ones:

- tendency to increase maximum speed for contemporary vehicles has for a consequence an increase in production costs of vehicle and its components,
- in order to reduce the risk of traffic accidents it is necessary to include limits for values of maximum movement speed of vehicles and to apply complex measures of control of such regulations,
- rational solution to such problems is definitely to limit the maximum speed of serial vehicles based on the values which are closer to before stated limits,
- maximum speed of contemporary vehicles from the aspect of their manufacturers is practically a marketing move only, considering the fact that such speeds cannot be attained in the conditions of public transportation.

REFERENCES

[1] Elvik R., Christensen P., Amundsen A.: Speed and road accidents, An evaluation of the Power Model, TOI report 740/2004, Oslo 2004.
[2] Speed Management, Summary document, OECD, Europen Conference of Ministers of Transport, Januar 2004.
[3] Rakha H., Ding Y.: Impact of Stops on Vehicle Fuel Consumption and Emissions
[4] Garrard J.: Safe speed: promoting safe walking and cycling by reducing traffic speed, Safe Speed Interest Group, November 2008.
[5] Simić D.: Motorna vozila, II izdanje, "Naučna knjiga", Beograd 1977.
[6] Radonjić D., Janković A.: An influence of the internal combustion engine characteristics upon the traffic safety in the regimes of overtaking, Mobility & Vehicle Mechanics, Volume 36, Number 1, March 2010, p.7-26