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Mass Correlation Between Real Vehicle and Vehicle Laboratory Simulation Model

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The problem how easily to scale down real object of simulation to laboratory simulation model, thus simplify equations to the extent of only one scaling factor that correlates between the real object and model, is always present in laboratory simulations. This paper presents a simple way to scale down real vehicle to the model level and also how to determine the acceptable range of real vehicle that can be simulated by laboratory model. The problem started when all field measurements on real vehicle ended, and laboratory simulation model, smaller than real vehicle, had to simulate that vehicle (drive machine had less rated power than a vehicle engine, and a load machine can create less load that of a real vehicle).

Korelacije masa realnog vozila i laboratorijskog simulacijskog modela vozila

Izvornoznanstveni članak

Problem jednostavnog umanjivanja realnog modela kako bi se mogao simulirati na laboratorijskom simulacijskom modelu, pogotovo tako da se jednadžbe pojednostave do razine promjene samo jednog faktora, uvijek je prisutan u laboratorijskim simulacijama. Ovdje se govori o jednostavnom načinu da se parametri realnog vozila smanje na razinu modela kao i o prihvatljivim granicama takovog smanjivanja. Naime problem je nastupio kada su obavljena mjerenja na realnom vozilu i ono je trebalo biti simulirano na laboratorijskom simulacijskom modelu koji je manji od vozila (pogonski motor je manje snage, a opteretni stroj može stvoriti manje opterećenje pogonskom motoru).

1 Introduction

Vehicle laboratory simulation models are an essential part of most researches on vehicle behaviour [1] to [5]. Since laboratory models are usually smaller than real vehicles, there is a problem of representation of real vehicle with a model.

The initial task was to create a laboratory model (Fig.1) for traction load simulation that includes drive (DC electrical machine), transmission (gearbox), inertia (flywheel) and DC machine representing other losses (rolling resistance, air resistance…)[6], [7].

The model basic parameters are following:

- the inertia $\boldsymbol{J}$ = 25 kgm^2 (flywheel plus load machine rotor)
- the drive machine power $\boldsymbol{P}$ = 20 kW
- the load machine power $\boldsymbol{P}$ = 40 kW
- rated model rotation speed (rated flywheel and load machine rotation speed) $\boldsymbol{n_n}$=1500 r/min

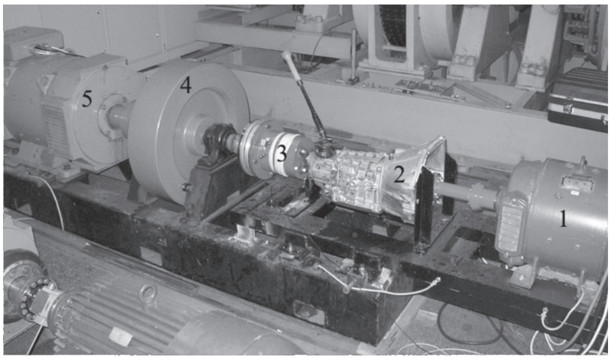

Figure 1 Realized laboratory simulation model with drive (1), transmission (2), torque sensor (3), flywheel (4) and load machine (5)

Slika 1. Ostvaren laboratorijski simulacijski model s pogonskim motorom (1), prijenosom (2), mjeračem momenta (3), zamašnjakom (4) i opteretnim strojem (5)

After creating a laboratory model, the following problem occurs: how to represent real vehicle (in our

Symbols/Oznake

J	– inertia, kgm^2 – moment inercije	m	– vehicle mass, kg – masa vozila
P	– power, W – snaga	g	– Earth gravity acceleration, m/s^2 – ubrzanje Zemljine gravitacije
n_n	– rated rotation speed, r/min – nominalna brzina vrtnje	a_1	– empirical factor, 1 – empirijski faktor
T_W	– air resistance load torque, Nm – moment uzrokovan otporom zraka	T_α	– road slope load torque, Nm – moment uzrokovan nagibom puta
c	– air resistance factor, 1 – faktor otpora zraka	α_0	– road slope, ° – nagib puta
A	– vehicle superficial front area, m^2 – površina prednje strane vozila	T_a	– inertia torque, Nm – moment uzrokovan ubrzanjem masa
ρ	– air density, kg/m^3 – gustoća zraka	e	– equivalent vehicle mass factor, 1 – faktor ekvivalentne mase vozila
v	–vehicle velocity, km/h – brzina vozila	m_e	– equivalent mass, kg – ekvivalentna masa
w	– wind speed towards vehicle, km/h – brzina vjetra prema vozilu	z	– number of wheels on the vehicle, 1 – broj kotača na vozilu
r	– drive wheel radius, m – radijus pogonskog kotača	T_{tot}	– total load torque, Nm – ukupni opteretni moment
T_R	– rolling resistance load torqur, Nm – moment otpora kotrljanja	i	– transmission ratio, 1 – prijenosni omjer transmisije
f_0	– empirical factor, 1 – empirijski faktor	k	– simulation factor, 1 – simulacijski faktor

case 1993 Fiat Tempra 1,9D) with a laboratory model. A further problem is how to simulate other vehicles (motorcycles, other cars, vans…) and what are the limitations of this laboratory model. And, of course, it will be ideal to represent the difference between the real vehicle and simulation model with one scaling factor.

2. Vehicle in motion torque equations

In order to solve those problems, basic equations of vehicle in motion were set.

The drive of the vehicle in motion "feels" four major loads: air resistance, rolling resistance, road slope resistance, inertia mass resistance [9].

The equation for the load torque, on drive wheels, caused by air resistance is:

$$T_W = c \cdot A \cdot \rho \cdot \frac{(v+w)^2}{3{,}6^2} \cdot r \quad [Nm], \tag{1}$$

For winds coming directly from the rear side of the vehicle and when wind speed exceeds vehicle velocity, the equation is not valid any more; this can also be caused by a different rear side air resistance factor.

The equation for the load torque, on drive wheels, caused by rolling resistance is:

$$T_R = f_0 \cdot m \cdot g \cdot r \cdot \cos\alpha + \\ + f_0 \cdot m \cdot g \cdot a_1 \cdot v^2 \cdot r \cdot \cos\alpha \, [Nm]. \tag{2}$$

The equation for the load torque, on drive wheels, caused by road slope is:

$$T_\alpha = m \cdot g \cdot \sin\alpha \cdot r \quad [Nm]. \tag{3}$$

This equation is valid for $\alpha > 0$ for ascending road and $\alpha < 0$ for descending road as well.

The equation for the load torque, on drive wheels, caused by inertia masses is:

$$T_a = \frac{e \cdot m \cdot r^2 \cdot \pi}{30} \cdot \frac{dn}{dt} \quad [Nm], \tag{4}$$

where: n [r/min] is drive wheel rotation speed and e [1] is equivalent vehicle mass factor from:

$$m_e = m + \frac{J_{drive\ wheel}}{r^2_{drive\ wehicle}} \cdot z = e \cdot m \quad [kg]. \tag{5}$$

The equivalent mass will, in further text, be presented as a product of the vehicle mass and ***equivalent mass factor e***. Thus, for example, the vehicle FIAT Tempra, which will be the test object in this research, has 1520 kg, while its equivalent mass is 1576,8 kg and factor ***e*** is 1,037.

The total drive machine torque is:

$$T_{tot} = \frac{c \cdot A \cdot \rho \cdot w^2 \cdot r}{3,6^2 \cdot i} + \frac{f_0 \cdot m \cdot g \cdot r \cdot \cos\alpha}{i} + \frac{m \cdot g \cdot r \cdot \sin\alpha}{i} + \\ + \frac{2 \cdot c \cdot A \cdot \rho \cdot w \cdot r^2 \cdot \pi}{3,6 \cdot 30 \cdot i} \cdot n + \\ + \left(\frac{c \cdot A \cdot \rho \cdot r^3 \cdot \pi^2}{30^2 \cdot i} + \frac{f_0 \cdot m \cdot g \cdot a_1 \cdot r^3 \cdot \pi^2 \cdot \cos\alpha}{30^2 \cdot i} \right) \cdot n^2 + \\ + \frac{e \cdot m \cdot r^2 \cdot \pi}{30 \cdot i} \cdot \frac{dn}{dt} \,. \tag{6}$$

If the torque is expressed generally (with the constant road slope α), it results in the following:

$$T_{tot} = k_1 + k_2 \cdot n + k_3 \cdot n^2 + k_4 \cdot \frac{dn}{dt} \,. \tag{7}$$

3. Influence of vehicle mass change to simulation

3.1. Simulation of different vehicle masses

Load simulation of the vehicle traction system requires an analysis of the mass change influence on the simulation process because of its total mass the drive units loading depend on (5). Some of them accumulate kinetic energy in kinetic states and others irreversibly change energy into surface or air friction. The total vehicle mass consists of its base (factory) mass and masses of all the passengers and cargo. In order to simulate different vehicle masses, the equations (1), (2), (3) and (4) should be fulfilled. In all those equations, except (1), the simulation process depends on parameter *m*, which represents total vehicle mass. Since this parameter changes, i.e. it depends on passenger and cargo mass, the possibility of simulation with only one rotating mass should be found.

3.2. Base vehicle, base mass

Stated equations determine the simulation process. In order to use this model for different masses of the same vehicle, i.e. vehicle that does not change its shape and size (so the equation (1) does not change), the concept of ***"base vehicle"*** is introduced.

The base vehicle of some simulation model is the vehicle, for which, the simulation model, without any corrective coefficients, can perform simulation.

The base vehicle has "base mass" $\boldsymbol{m_1}$, which corresponds to inertia $\boldsymbol{J_{model}}$:

$$m_1 = \frac{J_{\text{model}}}{r^2_{\text{drive wheel}}} \quad [\text{kg}], \tag{8}$$

where: $r_{\text{drive wheel}}$ is simulated (base) vehicle drive wheel radius.

With this equation, the "base mass" $\boldsymbol{m_1}$ of all vehicles in Table 1, can be determined.

The model will, without any correction, simulate base vehicle drive modes (real vehicle with base mass), i.e. it will simulate vehicle torques, powers and energies according to following equations:

- base vehicle air resistance torque

$$T_{W-base\ vehicle} = \frac{c \cdot A \cdot \rho \cdot w^2 \cdot r}{3,6^2} + \frac{2 \cdot c \cdot A \cdot \rho \cdot w \cdot r^2}{3,6} \cdot \frac{n \cdot \pi}{30} + \\ + c \cdot A \cdot \rho \cdot r^3 \cdot \left(\frac{n \cdot \pi}{30} \right)^2 \; [Nm] \tag{9}$$

- base vehicle rolling resistance torque

$$T_{R-base\ vehicle} = f_0 \cdot m_1 \cdot g \cdot r \cdot \cos\alpha + \\ + \frac{f_0 \cdot m_1 \cdot g \cdot a_1 \cdot r^3 \cdot \pi^2 \cdot n^2 \cdot \cos\alpha}{30^2} \quad [Nm] \tag{10}$$

- base vehicle potential energy change torque

$$T_{\alpha-base\ vehicle} = m_1 \cdot g \cdot r \cdot \sin\alpha \quad [Nm] \tag{11}$$

- base vehicle acceleration torque

$$T_{a\_base\ vehicle} = \frac{e \cdot m_1 \cdot r^2 \cdot \pi}{30} \cdot \frac{dn}{dt} \quad [Nm] \,. \tag{12}$$

3.3. Simulation factor

The vehicle and its base mass ratio (i.e. ratio of corresponding inertia) is called simulation factor ***k***

$$k = \frac{m_{vehicle}}{m_1} \equiv \frac{J_{vehicle}}{J_{MODEL}} \,. \tag{13}$$

The simulation factor ***k*** represents a parameter that will be used when vehicle inertia $\boldsymbol{J_{vehicle}}$ is different from model inertia $\boldsymbol{J_{model}}$. Later on, with the aid of simulation factor ***k***, the possibility, that any vehicle (with mass different from base mass $\boldsymbol{m_1}$) can be simulated with the same model, will be shown.

In the case of base vehicle simulation, i.e. real vehicle with base mass (***k=1***), simulation is perform by equations (9) to (12).

3.4. Torque equations for vehicle with mass different from base mass m_1

In the case of ***k≠1***, a correction of simulation process should be made. A greater or smaller value of ***k*** (compared to base one), indicates the mass change without shape and size change. It also means that equation (9) does not change (air resistance torque), but parameter $\boldsymbol{m_1}$ in equations (10), (11) and (12) is changed with factor k. Therefore, those equations should be corrected according to base vehicle terms.

The equation (9) does not change, but, because of the clarity, it can be repeated:

- vehicle air resistance torque

$$T_{W-k}=T_{W-base\ vehicle}=\frac{c\cdot A\cdot\rho\cdot w^2\cdot r}{3{,}6^2}+\frac{2\cdot c\cdot A\cdot\rho\cdot w\cdot r^2}{3{,}6}\cdot\frac{n\cdot\pi}{30}+c\cdot A\cdot\rho\cdot r^3\cdot\left(\frac{n\cdot\pi}{30}\right)^2\ [Nm] \quad (14)$$

Equations (10), (11) and (12) should be changed by vehicle mass demands:

- vehicle rolling resistance torque

$$T_{R-k}=k\cdot T_{R-base\ vehicle}=f_0\cdot k\cdot m_1\cdot g\cdot r\cdot\cos\alpha+\frac{f_0\cdot k\cdot m_1\cdot g\cdot a_1\cdot r^3\cdot\pi^2\cdot n^2\cdot\cos\alpha}{30^2}\ [Nm] \quad (15)$$

- vehicle potential energy change torque

$$T_{\alpha-k}=k\cdot T_{\alpha-base\ vehicle}=k\cdot m_1\cdot g\cdot r\cdot\sin\alpha\ [Nm] \quad (16)$$

- vehicle acceleration torque

$$T_{a\_k}=k\cdot T_{a\_base\ vehicle}=\frac{e\cdot k\cdot m_1\cdot r^2\cdot\pi}{30}\cdot\frac{dn}{dt}\ [Nm]. \quad (17)$$

3.5. Simulation model torque equation

When torques are recalculated to model simulation level, all equations from (14) to (17) should be divided by factor k, which gives "simulation equation package" that is applied to the model:

- simulation air resistance torque

$$T_{W-model}=\frac{1}{k}\cdot T_W=\frac{c\cdot A\cdot\rho\cdot w^2\cdot r}{3{,}6^2\cdot k}+\frac{2\cdot c\cdot A\cdot\rho\cdot w\cdot r^2}{3{,}6\cdot k}\cdot\frac{n\cdot\pi}{30}+\frac{c\cdot A\cdot\rho\cdot r^3}{k}\cdot\left(\frac{n\cdot\pi}{30}\right)^2\ [Nm] \quad (18)$$

- simulation rolling resistance torque

$$T_{R-\text{model}}=\frac{1}{k}T_{R-k}=T_{R-base\ vehicle}=f_0\cdot m_1\cdot g\cdot r\cdot\cos\alpha+\frac{f_0\cdot m_1\cdot g\cdot a_1\cdot r^3\cdot\pi^2\cdot n^2\cdot\cos\alpha}{30^2}\ [Nm] \quad (19)$$

- simulation potential energy change torque

$$T_{\alpha-\text{model}}=\frac{1}{k}T_{\alpha-k}=T_{\alpha-base\ vehicle}=m_1\cdot g\cdot r\cdot\sin\alpha. \quad (20)$$

Table 1. ***Base mass m_1*** for different vehicles with J_{model}=25 kgm^2

Tablica 1. ***Bazna masa m_1*** za različita vozila s J_{model}=25 kgm^2

Vehicle / Vozilo	Mass / Masa $m_{vehicle}$ (kg)	Drive wheel radius / Radijus pogonskog kotača $r_{drive\ wheels}$ (m)	Inertia on drive wheels Moment inercije na pogonskom kotaču $J_{vehicle}$ (kgm^2)	Vehicle base mass Bazna masa vozila m_1 (kg)	$\frac{m_{vehicle}}{m_1}$ $\frac{J_{vehicle}}{J_{model}}$ $\frac{m_{vozila}}{m_1}$ $\frac{J_{vozila}}{J_{modela}}$
Motorcycle (Gilera NEXUS500)	216	0,27380	16,19	333	0,65
	306		22,94		0,92
Car (Fiat Tempra 1,9D)	1200	0,29155	102,00	294	4,08
	1520		129,20		5,17
Van (Ford Transit Van 430 LWB)	2255	0,36445	299,52	188	12,00
	4250		564,50		22,61
Truck (Mercedes Atego 10,5t)	3680	0,39850	584,39	157	23,44
	10500		1667,42		66,88
Bus (Volvo B12M)	6200	0,53775	1792,89	86	72,09
	19000		5494,33		220,93
Truck (Mercedes Actro 3241K)	9700	0,52175	2640,56	92	105,43
	32000		8711,14		347,83

- simulation acceleration torque

$$T_{a\_\mathrm{model}} = \frac{1}{k} T_{a\_k} = T_{a\_base\ vehicle} = \frac{e \cdot m_1 \cdot r^2 \cdot \pi}{30} \cdot \frac{dn}{dt} \, . \qquad (21)$$

The equation (21) describes the torque simulated with the flywheel, while equations (18), (19) and (20) describe load torques simulated by load machine (No. 5 on Figure 1).

And finally, each simulation model torque, multiplied with simulation factor k, represents the whole corresponding vehicle torque, reduced to its drive axis, i.e. its drive wheels, in static operation as well as in dynamics.

4. Confirmation by measurement on real vehicle

In order to prove stated, extended measurement on real vehicle (Fiat Tempra) was made (Figure 2 and 3) [8]. During those measurements vehicle torque and velocity and wind velocity were recorded.

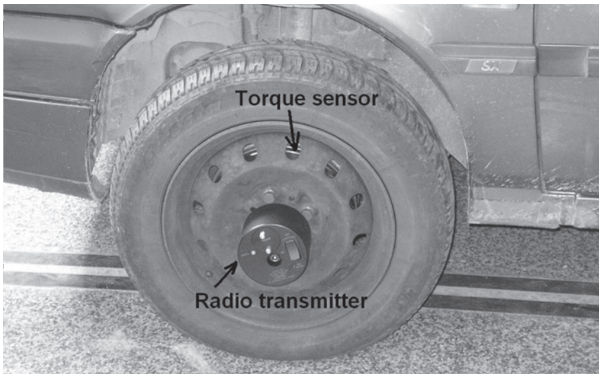

Figure 2. Torque sensor mounted on real vehicle

Slika 2. Mjerač momenta montiran na realno vozilo

The following tests were being made:

- Slow acceleration 0-110 km/h
- Fast acceleration 0-110 km/h
- Road slope ascent with 10 km/h, 20 km/h and 30 km/h
- Standstill (on the clutch) while ascending
- Standstill (on the clutch) while descending
- Road slope descent with 10 km/h, 20 km/h and 30 km/h
- Continuous drive at 40 km/h, 50 km/h, 60 km/h, 70 km/h, 80 km/h, 90 km/h, 100 km/h and 110km/h
- Deceleration from 110 km/h to standstill with gearbox in neutral position

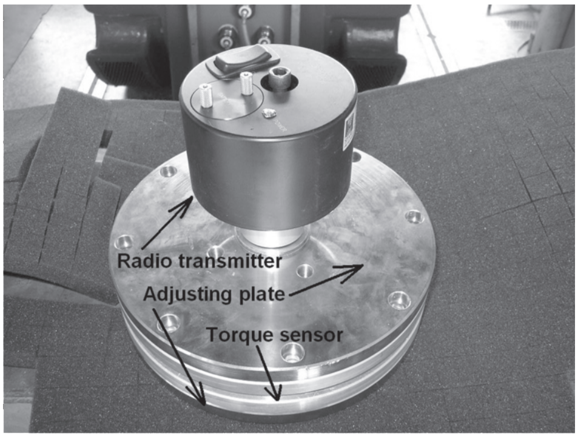

Figure 3. Torque sensor for vehicle torque measurement

Slika 3. Mjerač momenta za vozilo

Figures 4 to 7 shows good relation between simulation on vehicle laboratory model and real vehicle.

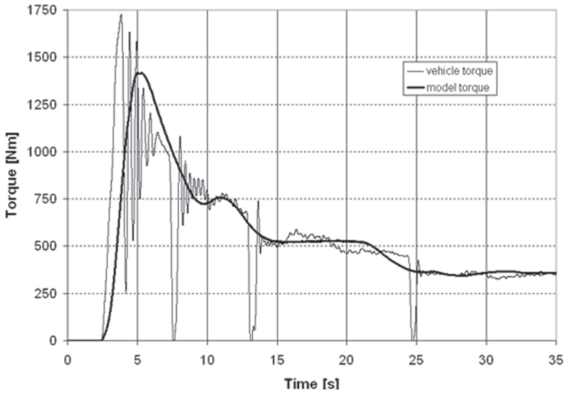

Figure 4. Comparison between vehicle and model torque recorded for vehicle weight of 1720 kg during acceleration to 110 km/h

Slika 4. Usporedba između snimljenog momenta vozila i modela za vozilo mase 1720 kg tijekom ubrzavanja od mirovanja do 110 km/h

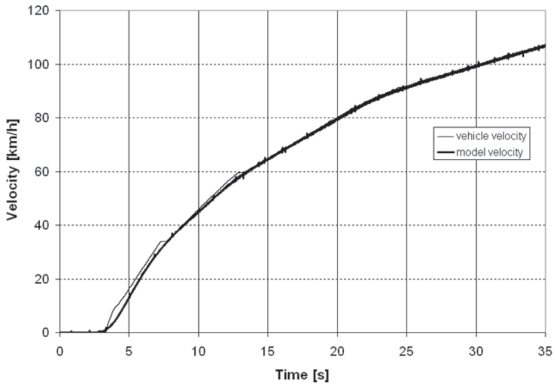

Figure 5. Comparison between vehicle and model velocity recorded for vehicle weight of 1720 kg during acceleration to 110 km/h

Slika 5. Usporedba između snimljene brzine vozila i modela za vozilo mase 1720 kg tijekom ubrzavanja od mirovanja do 110 km/h

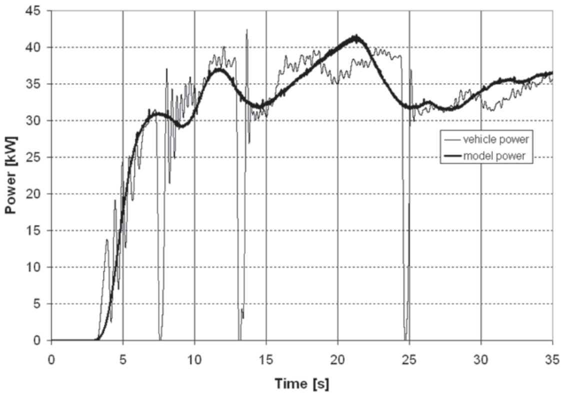

Figure 6. Comparison between vehicle and model power recorded for vehicle weight of 1720 kg during acceleration to 110 km/h

Slika 6. Usporedba između snimljene snage vozila i modela za vozilo mase 1720 kg tijekom ubrzavanja od mirovanja do 110 km/h

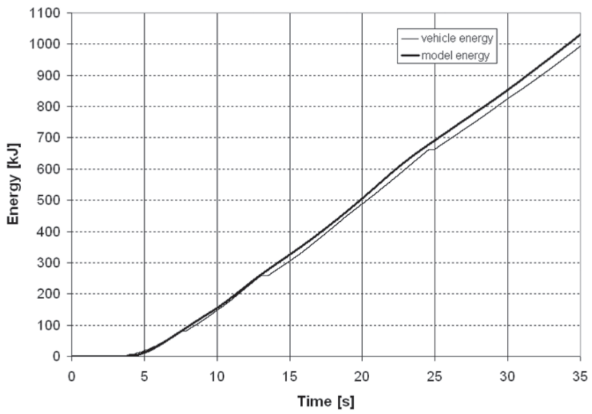

Figure 7. Comparison between vehicle and model energy recorded for vehicle weight of 1720 kg during acceleration to 110 km/h

Slika 7. Usporedba između snimljene energije vozila i modela za vozilo mase 1720 kg tijekom ubrzavanja od mirovanja do 110 km/h

5. Conclusion

This laboratory model can simulate real vehicle in motion traction system loads according to equations from chapter 3. The simulation factor ***k*** describes real vehicle and model equations.

The model measurement system accuracy can be assessed to 1%. If one wants to simulate traction system loads of a big vehicle (trucks or bus from Table I), then the value of simulation factor ***k*** is very big (from 60 up to 350). With the assessed accuracy of model measurement system and largeness of simulation factor ***k***, one could see that the error, due to model measurement system accuracy, would be big for considerable simulation factor ***k***.

Therefore, one should limit the application of laboratory simulation model to the simulation of vehicle traction system load to vehicles with smaller simulation factor ***k*,** i.e. for $k<30$.

Expectations considering simulation demands were completely fulfilled. Namely, after the simulation of Fiat Tempra vehicle traction system loads was conducted, similar tests were carried out on the same vehicle (Fiat Tempra). A comparison of real and simulated loads showed an excellent match.

The research of model possibilities enables the extension of its application by introduction of the following parameters and ideas: "base vehicle", "base mass" and "simulation factor".

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