Fuel Economy and Mobility of Multi-Wheel Drive Vehicles: Modeling and Optimization Technology

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ABSTRACT

A distinctive feature of unmanned and conventional terrain vehicles with four or more driving wheels consists of the fact that energy/fuel efficiency and mobility depend markedly not only on the total power applied to all the driving wheels, but also on the distribution of the total power among the wheels. As shown, under given terrain conditions, the same vehicle with a constant total power at all the driving wheels, but with different power distributions among the driving wheels, will demonstrate different fuel consumption, mobility and traction; the vehicle will accelerate differently and turn at different turn radii.

This paper explains the nature of mechanical wheel power losses which depend on the power distribution among all the driving wheels and provides mathematical models for evaluating vehicle fuel economy and mobility. The paper also describes in detail analytical technology and computational results of the optimization of wheel power distributions among the driving wheels. The presented math models of a multi-body vehicle with any given number of the driving wheels and type of suspension are built on a novel inverse vehicle dynamics approach and include probabilistic terrain characteristics of rolling resistance and friction, micro- and macro-profiles of surfaces of motion. Computational results illustrate up to 15%-increase in energy efficiency of an 8x8 vehicle that is guaranteed by the optimal power distribution among the driving wheels. This technology can be applied for improving energy/fuel efficiency and mobility of tactical and combat military and unmanned robotic vehicles with mechanical and mechatronic driveline systems, vehicles with individually-driven wheels and vehicles with hybrid driveline systems.

INTRODUCTION

Improving mobility and fuel efficiency of high-mobility terrain vehicles are mutually contradictory technical problems – to improve mobility usually requires extra fuel, and the optimization of fuel consumption can negatively impact mobility. Traditional vehicle dynamics, as the theory of vehicles in motion, has never developed analytical approaches to parallel optimization of mobility and energy efficiency. As a result, high-mobility vehicles demonstrate poor fuel economy (MPG) performance. For example, High Mobility Multipurpose Wheeled Vehicle (HMMWV) at 15,400 pounds gross vehicle weight currently gets 4-8 miles per gallon [1].

To improve mobility of terrain vehicles, multi-wheel drive platforms, e.g. platforms with four or more driving wheels have been in use for decades. However, the simple addition of a drive axle can drastically increase fuel consumption and negatively impact the overall vehicle dynamics and performance. The problem here is that the performance of multi-wheel drive vehicles depend markedly not only the number of the drive axles, but also on the distribution of the engine power among the drive axles, and to the left and right wheels of each axle. When the power is differently distributed among the driving wheels, a given vehicle will demonstrate different fuel consumption, different terrain mobility and traction performance; the vehicle will accelerate differently and turn at different radii. Depending on wheel power split, the vehicle can run into either understeer or oversteer and then sometimes become unstable and skid in lateral direction, and finally move into rollover [2-5].

Wheel power distribution is largely determined by a vehicle's driveline systems, which consists of a set of power dividing units (PDUs, see Fig. 1).

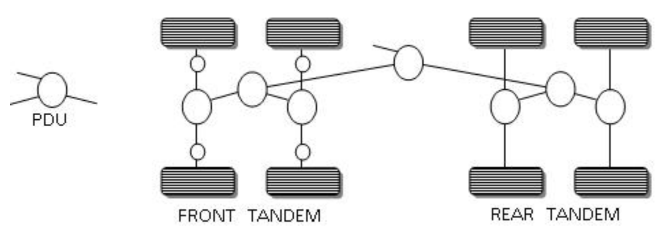

Figure 1. A driveline system layout of an 8x8 vehicle

There is no consensus among experts concerning the effect of driveline system parameters on the road and terrain of vehicle's fuel consumption. Many are of the opinion that, for example, the use of two drive axles instead of one unalterably increases the vehicle's fuel consumption, irrespective of the parameters of power dividing units, and of driving conditions. Their main argument usually consists of the higher power consumption for providing motion to the drive components of the additional driving axle. Others researchers claim that a permanently engaged drive with an open interaxle differential improves the fuel economy of a sedan as compared with a single-axle drive by up to 2 mpg on highways. There are some interesting examples of the effect of the driveline system on the fuel economy. A timber truck with a total mass of 25.5 tons achieved its highest fuel economy when the vehicle used an open interaxle asymmetrical differential. When moving with one drive axle, the truck's fuel consumption increases by 5.5-8% whereas locking of the interaxle differential increased the fuel consumption by 8.5-12% [6]. Audi also proved experimentally that its all-wheel drive Quattro has a better fuel efficiency than a front-wheel drive car with an identical power rating [7].

However, not much systematic research was done in the area of wheel power management with the purpose to simultaneously enhance terrain vehicle mobility and energy efficiency. In 1940-60s, researchers mostly concentrated on tire-terrain interaction and did not fully recognize the wheel power management problem [8, 9]. In 1971 - 2001, some research was done for terrain vehicles with four driving wheels with positively engaged drive axles [10-13]. Today, some leading automotive driveline suppliers and OEMs work on "torque vectoring" and "torque management" systems for passenger cars and SUVs [14-24]. However, these modern technologies do not control distribution of power among the driving wheels to both save fuel and improve mobility of vehicles.

The fundamental aspects of the influence of different PDUs on power distribution, vehicle mobility, and fuel consumption, require a better appreciation. This confirms by the fact that today's designs and controls of PDUs are so far from providing optimal vehicle dynamics, mobility and fuel efficiency.

This paper provides an analytical insight into the mechanism of the effect of the driveline system on the vehicle's fuel consumption and terrain mobility and discusses an optimization methodology.

FUEL ECONOMY

The fuel economy of a vehicle is represented by the fuel consumption referred to the distance traveled by the vehicle:

$$Q_s = \frac{Q_h}{V_x} = \frac{g_e P_e}{V_x}, \quad gram/km \tag{1}$$

where Q_h is fuel consumption, $gram/h$, V_x is the vehicle velocity, km/h; g_e is the specific fuel consumption, $gram/(kW-hour)$ and P_e is the effective power of the engine which can be represented using Fig. 2 as follows:

$$P_e = P_{trm} + P_{drl} + P_{ts} + P^{out} \tag{2}$$

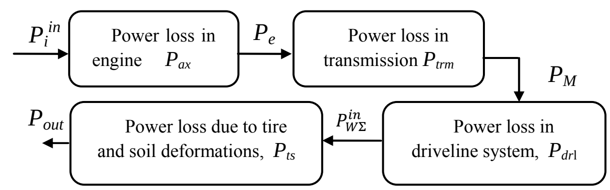

Figure 2. Block-diagram of vehicle power losses

The power loss in tire-soil interaction, P_{ts}, is presented by the two components in the following equation:

$$P_e = P_{trm} + P_{drl} + P_{\delta\Sigma} + P_{f\Sigma} + P^{out} \tag{3}$$

here, $P_{f\Sigma}$ is the power loss for the normal deflection of the tire and soil (rolling resistance power) and $P_{\delta\Sigma}$ is power lost due to the tire-soil longitudinal deflection (slippage power). The two components of the power-balance equation (3) present the influence of the driveline system on the power loss and hence vehicle energy efficiency and its fuel consumption – they are P_{drl} and $P_{\delta\Sigma}$.

With reference to Fig. 2 expressions for the loss P_{drl} of mechanical power in the driveline system and the slip power loss $P_{\delta\Sigma}$ can compiled as follows:

$$P_{drl} = P_{w\Sigma}^{in}(1-\eta_M)/\eta_M \tag{4}$$

$$P_{\delta\Sigma} = P_{w\Sigma}^{in}\left(1-\eta_\delta\right) \tag{5}$$

here, η_M and η_δ are the total mechanical efficiency of the driveline system and tire slip efficiency. These efficiencies, η_M and η_δ, characterize the effect of the distribution of power among the driving wheels on the mechanical power losses in the driveline system and on the power lost in tire slipping.

The power supplied to the driving wheels is

$$P_{w\Sigma}^{in} = \sum_{i=1}^{n} T_{wi}^{'(")} \omega_{wi}^{'(")} = \sum_{i=1}^{n} F_{xi}^{'(")} V_{ti}^{'(")} \tag{6}$$

here T_w is the wheel torque; ω_w is the rotational wheel speed; F_x is the circumferential force of the tire, and V_t is the theoretical tire velocity (with no slip); $'$ and $"$ relate to the left and right wheels; n is the number of the drive axles.

Substituting formulae (4)-(6) into expression (3), one obtains:

$$\begin{aligned} P_e = P_{trm} + P_{w\Sigma}^{in}(1-\eta_M)/\eta_M + P_{w\Sigma}^{in}\left(1-\eta_\delta\right) \\ + P_{f\Sigma} + P^{out} \end{aligned} \tag{7}$$

and, accordingly, the fuel consumption Q_s from formula (1) is:

$$Q_s = \frac{g_e}{V_x} \left[\begin{aligned} P_{trm} + \sum_{i=1}^{n} T_{wi}^{'(")} \omega_{wi}^{'(")} (1-\eta_M)/\eta_M \\ + \sum_{i=1}^{n} T_{wi}^{'(")} \omega_{i}^{'(")} \left(1-\eta_\delta\right) + P_{f\Sigma} + P^{out} \end{aligned} \right] \tag{8}$$

The second and third terms in the square brackets of formula (8) define the direct effect of the vehicle's driveline system on the fuel consumption Q_s. In fact, different driveline systems, e.g. different combinations of PDUs, bring about different distributions of power to the driving wheels which, in its turn, affects the total mechanical efficiency η_M and the power loss in slipping, η_δ. Consider and analyze these efficiencies.

Total Mechanical Efficiency of Driveline System

The expression for the total efficiency η_M in formula (1) comes as (see Fig. 2 and [6]):

$$\begin{aligned} \eta_M = \frac{P_M - P_{drl}}{P_M} = \frac{P_{w\Sigma}^{in}}{P_M} = \frac{\sum_{i=1}^{n} P_{wi}^{in}}{P_M} \\ = \frac{1}{\sum_{i=1}^{p_1} \frac{q_i}{\eta_{Mi}^{pos}} + \sum_{i=1}^{p_2} q_i \eta_{Mi}^{neg}} \end{aligned} \tag{9}$$

Consider components in (9). The coefficient of distribution of power to the *i*th axle is as:

$$q_i = \frac{P_{wi}^{in}}{P_{w\Sigma}^{in}} = \frac{P_{wi}^{in}}{\sum_{i=1}^{n} P_{wi}^{in}} \tag{10}$$

where P_{wi}^{in} is the power supplied to the *i*th axle. It is obvious that

$$\sum_{i=1}^{n} q_i = \sum_{i=1}^{p_1+p_2} q_i = 1 \tag{11}$$

In formula (11), p_1 be the number of drive axles with positive power flow and p_2 – the number of drive axles with negative power flow. It is obvious that

$$p_1 + p_2 = n \tag{12}$$

Power P_M in formula (9) is defined as:

$$P_M = \sum_{i=1}^{p_1} P_{Mi}^{pos} + \sum_{i=1}^{p_2} P_{Mi}^{neg} \tag{13}$$

where P_{Mi}^{pos} and P_{Mi}^{neg} are the components of power P_M; power P_{Mi}^{pos} is fed from the transfer case to the *i*th axle, whereas power P_{Mi}^{neg} is fed from the *i*th axle to the transfer case. These components are defined using formulae (6), (10) and (12):

$$\begin{aligned} P_{Mi}^{pos} = \frac{P_{wi}^{in}}{\eta_{Mi}^{pos}} = \frac{q_i \sum_{i=1}^{n} P_{wi}^{in}}{\eta_{Mi}^{pos}} \\ P_{Mi}^{neg} = P_{wi}^{in} \eta_{Mi}^{neg} = \left(q_i \sum_{i=1}^{n} P_{wi}^{in} \right) \eta_{Mi}^{neg} \end{aligned} \tag{14}$$

where η_{Mi}^{pos} and η_{Mi}^{neg} are the efficiencies of the branches of the driveline system with positive and negative power flows.

It is seen from formula (9) that the mechanical efficiency of the driveline system decreases with increasing number of negative power flows (the second component in the denominator).

If all the power flows are positive, then formula (9) becomes:

$$\eta_M = \frac{1}{\sum_{i=1}^{n} \frac{q_i}{\eta_{Mi}}} \tag{15}$$

Formula (15) yields an important result. The distribution of power between drive axles and, accordingly, the driveline system, affect the overall efficiency η_M only when the mechanical efficiencies η_{Mi} ,($i = 1$ *to* n) of the driveline system branches are different. If, however, the mechanical efficiencies η_{Mi} of all the *n* branches of the driveline system are identical, then in accordance with formula (11), formula (15) becomes:

$$\eta_M = \frac{\eta_{Mi}}{\sum_{i=1}^{n} q_i} = \eta_{Mi} \tag{16}$$

i.e., the total efficiency is equal to the efficiency of a single branch. In this case the distribution of power between the driving axles has no effect on η_M , since $\sum_{i=1}^{n} q_i$ is always equal to 1.

The above makes it necessary to determine η_{Mi} , ($i = 1$ *to n*) in formulae (9) and (15). Numerous investigations show that the value of η_{Mi} , over the range of potential velocities and force loads are not constant, but depend on the transmitted power. For this reason the parameters q_i , η_{Mi}^{pos} and η_{Mi}^{neg} in formula (9) are interdependent (which also applies to q_i and η_{Mi} in formula (15)). This complicates the application of formulae (9) and (15) in practice. A large number of investigators assume in practical calculations that η_{Mi} are constant, i.e., are independent of the power being transmitted.

Slip Power Efficiency

The efficiency that reflects the power lost in slipping is written as:

$$\eta_\delta = \frac{P_{w\Sigma}^{in} - P_{\delta\Sigma}}{P_{w\Sigma}^{in}} = 1 - \frac{\sum_{i=1}^{n}\left(P_{\delta i}^{'} + P_{\delta i}^{"}\right)}{\sum_{i=1}^{n}\left(P_{wi}^{in'} + P_{wi}^{in"}\right)}, \tag{17}$$

where $P_{wi}^{in'(")} = F_{xi}^{'(")} V_{ti}^{'(")}$ is the power supplied to one of the wheels of the *i*th axle; $P_\delta^{'(")} = F_{xi}^{'(")} V_{ti}^{'(")} s_{\delta i}^{'(")}$ is the slipping power of one of the wheels of the *i*th axle.

Expressing the theoretical velocity of the wheel in terms of its slip ratio and of the actual velocity V_x of the vehicle,

$$V_{ti} = \frac{V_x}{1 - s_{\delta i}}$$

one can transform Eq. (17) to

$$\eta_\delta = 1 - \frac{\sum_{i=1}^{n}\left(\frac{F_{xi}^{'} s_{\delta i}^{'}}{1 - s_{\delta i}^{'}} + \frac{F_{xi}^{"} s_{\delta i}^{"}}{1 - s_{\delta i}^{"}}\right)}{\sum_{i=1}^{n}\left(\frac{F_{xi}^{'}}{1 - s_{\delta i}^{'}} + \frac{F_{xi}^{"}}{1 - s_{\delta i}^{"}}\right)} \tag{18}$$

Equation (18) clearly proves that the vehicle's slipping efficiency changes when the circumferential forces and the wheel slips are not the same for the wheels due to different power distributions.

In summing up the above, an algorithm shall be presented below for assessing the effect of the driveline system on the vehicle's fuel consumption. At the first stage it is required to calculate the circumferential forces, torques, angular velocities, and slip of the wheels, which depend on the driveline PDUs characteristics. Then the efficiencies η_M and η_δ are calculated using the above-presented formulae. Then formula (8) can be used for determining the driveline system influence on the fuel consumption.

Formulation of Optimization Problems

As seen from equations (8), (9) and (18), the efficiencies η_M and η_δ should be the objects of attention in assessing the effect of driveline systems on the fuel economy of vehicles.

To provide minimal fuel consumption the driveline system should ensure such distribution of power among the wheels $\left(T_{wi}^{'(")} \omega_{wi}^{'(")}, i = 1, n\right)$, that provide for maximum values of η_M and η_δ under the given travel conditions.

If the driveline system have the identical efficiencies in all its branches, $\eta_{Mi} = \eta_M$, another formulation of the fuel economy optimization comes as follows. To obtain the minimum fuel consumption, the vehicle's set of PDUs should distribute the power among the drive wheels to lead to the maximum in the slip efficiency

$$\eta_\delta \to \max \tag{19}$$

This, together with the above recommended identical mechanical efficiencies η_M of all the n branches of the driveline system, will provide the minimum fuel consumption as it follows from equation (8). This is a constraint optimization problem. The constraints come from the vehicle motion limitations. The total power applied to all the drive wheels should be enough to overcome the external resistance to motion. Consider a free-body diagram of an 2mx2n vehicle with an individual suspension system presented in Fig. 3 (here, m is the total number of axles including the drive and driven ones).

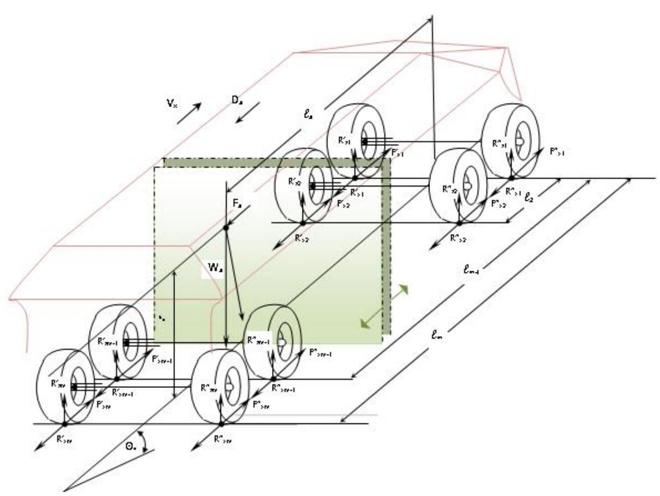

Figure 3. 2mx2n vehicle free-body diagram

With reference to Fig. 3, the equation of motion with the longitudinal acceleration a_x of the vehicle that is needed for determining the total circumferential force $F_{x\Sigma}$ is:

$$F_{x\Sigma} = \sum_{i=1}^{n} F_{x\,i}^{\,\mathrm{I}\,(\mathrm{II})*} = W_a a_x \delta_r / g \pm W_a \sin\theta_n + \sum_{i=1}^{m} R_{x\,i}^{\,\mathrm{I}\,(\mathrm{II})} + D_a \tag{20}$$

where δ_r is the mass factor that makes allowance for the rotating masses of the vehicle. This factor, the wheel resistance forces $R_{x\,i}^{\,\mathrm{I}\,(\mathrm{II})}$ and the air drag D_a can be computed on the basis of well-known recommendations from the engineering literature on vehicle dynamics. The physical meaning of the remaining components of equation (20) is clarified by Fig. 3.

The numerical values of acceleration a_x should be specified from the required velocities V_x that the vehicle should have while accelerating. This is a new approach to synthesizing the properties of driveline systems based on inverse vehicle dynamics: on the basis of required kinematic parameters to determine the total circumferential force that should be developed by the vehicle's driving wheels. Equation (20) is a constraint that should be kept when optimizing variables $F_{x\,i}^{\,\mathrm{I}\,(\mathrm{II})}$ within the summation of $F_{x\Sigma}$ and determining the optimal values $F_{x\,i}^{\,\mathrm{I}\,(\mathrm{II})*}$, which correspond to the maximum in the slip efficiency (see expressions (18) and (19)). Another constraint comes from a functional relation between the circumferential forces $F_{x\,i}^{\,\mathrm{I}\,(\mathrm{II})}$ of tire slippage $s_{\delta\,i}^{\,\mathrm{I}\,(\mathrm{II})}$:

$$F_{x\,i}^{\,\mathrm{I}\,(\mathrm{II})} = f\,(s_{\delta\,i}^{\,\mathrm{I}\,(\mathrm{II})}) \tag{21}$$

with

$$0 < F_{x\,i}^{\,\mathrm{I}\,(\mathrm{II})*} \le \mu_{pxi}^{\,\mathrm{I}\,(\mathrm{II})} \, R_{zi}^{\,\mathrm{I}\,(\mathrm{II})} \;,\; i=1,n \tag{22}$$

here, $\mu_{pxi}^{\,\mathrm{I}\,(\mathrm{II})}$ is the friction coefficient.

Solving the optimization problem (19)-(22) showed a real influence of the driveline system on energy/fuel efficiency. Fig. 4 presents computational results of an 8x8 vehicle's running gear efficiency, η_x^{tr}, which includes the slip efficiency, η_δ, as a component [5].

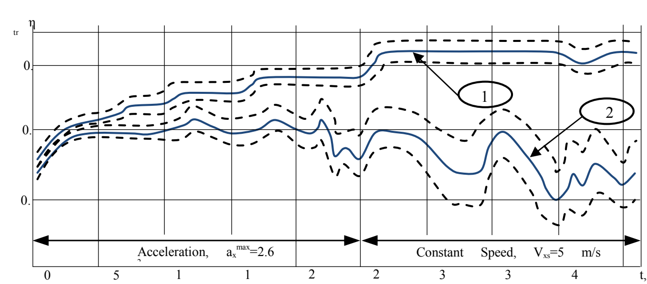

Figure 4. 8x8 vehicle: the running gear efficiency on a concrete highway on level terrain
1 – under optimum wheel power distribution; 2 – with the standard-production driveline system

As seen, an increase in the energy efficiency raises up to 15 percent and more.

However, it is not necessarily true to obtain both efficiencies, η_M and η_δ, maximal under the same wheel power distribution. The contribution of each of these efficiencies on the fuel consumption is different as seen from equation (8). At positive power flows from the transfer case to the driving wheels the effect of η_M and η_δ on Q_s when moving on solid surfaces is commonly commensurable or sometimes the power losses P_{drl} may exceed $P_{\delta\Sigma}$ in all-wheel drive vehicles. To illustrate this, reference can be made to the previously mentioned article concerning the 4x4 Audi Quattro [7]: while having a 1.5 to 3 percent bigger power loss in its driveline system (as compared with the 4x2 version), this car demonstrated a better fuel efficiency due to less power loss in tire deflections. On a deformable surface the effect of $P_{\delta\Sigma}$ may be more perceptible and depends on the type of the driveline system.

In circumstances when the mechanical efficiencies η_{Mi} can't be provided equal due to some design constraints, the fuel economy optimization problem is to be formulated differently:

$$\left\{\sum_{i=1}^{n} T_{wi}^{'(")}\omega_{wi}^{'(")}(1-\eta_M)/\eta_M + \sum_{i=1}^{n} T_{wi}^{'(")}\omega_{i}^{'(")}\left(1-\eta_\delta\right)\right\} \to \min \quad (23)$$

where the wheel power distributions under optimization are presented by the components $T_{wi}^{'(")}\omega_{wi}^{'(")}$, which, being summed up, give the total power at all the driving wheels (see formula (6)). This optimization requires keeping up the constraints represented by (20)-(22).

VEHICLE MOBILITY

The mobility of vehicles is their ability to move under road-less terrain conditions, while still performing their functions. Off-road travel of vehicles involves a significant reduction in their speed and output. For this reason mobility is usually assessed using indicators such as the transport efficiency [13], the average velocity V_{avg}, and even the average fuel consumption Q_{avg}. However, in extreme conditions of motion when it is vitally important to keep the movement by all the means, the energy efficiency related indices can't be in use.

The ability, in principle, of a vehicle to move is determined by the condition

$$F_{x\Sigma}^{\max} = \sum_{i=1}^{n}\left(F_{xi}^{'} + F_{xi}^{"}\right)_{\max} \geq F_\psi \quad (24)$$

where F_ψ is the total force of resistance to motion; $F_{x\Sigma}^{\max} = \sum_{i=1}^{n}\left(F_{xi}^{'} + F_{xi}^{"}\right)_{\max}$ is the sum of the maximum possible circumferential forces of the driving wheels that the engine, transmission, driveline system and the wheels can supply under the conditions of motion, that are represented by the force F_ψ.

Condition (24) is more general than equation (20), in which the sum of circumferential forces of the driving wheels was termed the total circumferential force of a vehicle $F_{x\Sigma}$. Condition (24) clearly illustrates the effect of the driveline system on the vehicle's mobility. If the characteristics of the driveline system provide for such a value of the total circumferential force $F_{x\Sigma}^{\max}$ that inequality (24) is satisfied then the mobility of the vehicle is ensured in principle. In the opposite case, the vehicle loses its mobility and new characteristics for its driveline system must be found in order to satisfy condition (24).

In addition to inequality (24) various additional indicators are used. An assessment of mobility in critical terrain circumstances can be obtained using the dimensionless ratios

$$p_x = 1 - \frac{F_\psi}{F_{x\Sigma}^{\max}} \qquad p_\mu = 1 - \frac{F_\psi}{F_{x\Sigma}^{\mu}} \quad (25)$$

where $F_{x\Sigma}^{\mu}$ is the total circumferential force of the vehicle determined from the conditions of gripping between the tires and the terrain, i.e.,

$$F_{x\Sigma}^{\mu} = \sum_{i=1}^{n}\left(\mu_{pxi}^{'}R_{zi}^{'} + \mu_{pxi}^{"}R_{zi}^{"}\right) \quad (26)$$

The index p_x represents the mobility of the vehicle from the point of view of its traction capacity. The greater $F_{x\Sigma}^{\max}$ is, the higher the vehicle's mobility. In the case of $F_{x\Sigma}^{\max} = F_\psi$, then $P_x = 0$ and the vehicle's mobility is at its minimum, i.e., the vehicle moves within the limits of its capability. A further small deterioration in the conditions of motion will cause complete loss of mobility. The index p_μ

in formulae (25) represents the mobility capacity based on conditions of gripping between the tires and the surface of motion.

The future work will be concentrated on the mathematical modeling of the above indices (24)-(26) as functions of the power distribution among the driving wheels. Based on such modeling, there will be a formulated and solved optimization problem on obtaining combinations of wheel power splits, which provide the best mobility of a multi-wheel drive vehicle. Further, these combinations of wheel power splits will be compared with those which were determined in solving the fuel economy optimization problem. This will facilitate a discussion on the compatibility of both optimal combinations of wheel power distributions for advanced, mechatronics-based driveline system designs.

CONCLUSION ON INNOVATIVE RESEARCH WORK

This paper analytically considered technical problems of improving mobility and fuel economy of terrain, multi-wheel drive vehicles as mutually contradictory technical problems.

Two pioneering analytical approaches to resolving these problems and appropriate mathematical models were presented based on a detailed discussion on the wheel power distribution influence on vehicle energy/fuel efficiency and terrain mobility. The first approach formulates the fuel efficiency optimization problem as a search for optimal wheel power splits to minimize the summation of the two components in the fuel consumption equation (see (8) and (23)). The second considers to the mobility optimization problem based on a search of combinations of wheel power distributions to provide vehicle mobility in critical situations of motion. Future work has also been formulated.

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