

A method to assess the gravity response efficiency of a truck

JOSE A. ROMERO NAVARRETE¹, FRANK OTREMBA²

Tanks for Dangerous Goods and Accident Mechanics
Federal Institute for Materials Research and Testing (BAM)
Unter den Eichen 44-46, 12203 Berlin
GERMANY

¹jose-antonio.romero-navarrete@bam.de <http://www.bam.de>

²frank.otremba@bam.de <http://www.bam.de>

Abstract: - Transport activities contribute with around 14% of the total green-house gases emitted to the atmosphere as a result of human activities. Several efforts have been made to reduce such emissions through better vehicle designs and environmentally friendly operating conditions. One crucial element in this process, consists of objectively assessing the performance of the vehicles in that respect. The passive performance of the vehicle, namely the operation of the vehicle without any power input, represents an important component of such assessment, to measure the rolling, drag and mechanical losses of the vehicle. In this paper, a methodology is proposed to assess the passive performance of the vehicle, which avoids the uncertainties associated to the current standard testing methodologies. Such a method is based upon the loss of potential energy when the vehicle performs a U-turn along a long ramp. Both, comparative and parametric analyzes can be carried out with the testing facility, whether to assess the potential environmental performance benefits of different technologies, or to quantify the effects of several potentially influential parameters. In particular, the cargo condition (liquid or solid) and the container shape (elliptical, cylindrical).

Key-Words: - Road tankers, energy efficiency, environmental assessment, gravity response, transportation energy, rolling resistance, drag resistance

1 Introduction

Whether for goods or for people, the satisfaction of society's transportation needs implies an important part of the total consumption of energy by humans. For example, in Germany the traffic-related consumed energy in 2018 represented 30% of that country's total consumed energy, which was the greatest part of such a total (29.5% in industry, 25.5% in households, and 15% in Business/Commerce)[1], further revealing an increase of 5% in that concept, with respect to the year 2008. In the case of the United states, transporting people and goods represented in 2018 28% of the total consumed energy in that country [2]. In 2000, the transportation sector represented 27% of the total energy consumed in that country [3]. While in these countries the average transport energy is around 30% of the total consumed energy, there are countries in which the amount of energy for transport is relatively greater and it is accelerating at a greater rate. For example, in the case of Mexico, it is reported that in 2017, transport activities represented 44% of the total consumed energy [4], which represented in 2000 only 38.4% of the total consumed energy [5]. In this regard, road transportation is used predominantly in the different countries. For example, in the United

States, the light vehicles consume 55% of the total transport energy, as it is illustrated in Table 1. According to these numbers, it seems that improving the transport sector energy performance could significantly improve the energy performance of this and any other society

TABLE I
ESTIMATED SHARES OF TOTAL U.S. TRANSPORTATION ENERGY USED BY
MODE (WITH DATA FROM [3])

Vehicle	% of total
Light-duty vehicles (cars, small trucks, vans)	55
Commercial and freight trucks	24
Jets, planes, and other aircraft	9
Boats, ships and other watercraft	4
Train and buses	3
Other	5

While the environmental effects concerning the green-house gas emissions (GHG) do not keep the same proportions by sector as the consumption of energy, the transport-related pollution in the form of GHG has still a big contribution, as it is illustrated

in Figure 1, with the agriculture and electricity/heat production being the biggest GHG emitters [6].

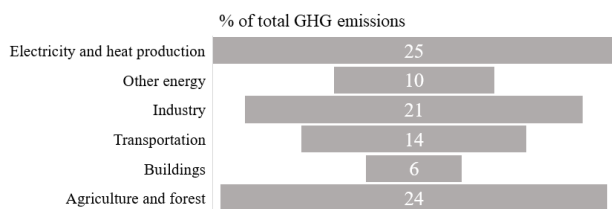


Fig. 1 Percentage contribution of the economic sectors to the total CGH emissions in U.S.A. in 2017. (with data from [6]).

Consequently, while any improving in the environmental friendliness during the electricity or heating production would have a greater effect on the overall human-activities related GHG emissions, still any action aiming at reducing the environmental unfriendliness of the transportation activities, would improve the overall living condition of any society. In this respect, it should be noted that in the case of vehicles using fossil fuels, there is a direct relationship between the fuel consumed and the amount of GHG emissions [7].

Reducing GHG emissions has been thus a primordial target of vehicle’s manufacturers and environmental institutions, including efforts to reduce vehicles’ weight and to downsize their engines [8]. To dimension the potential environmental benefits of the different technologies, several testing methods are in use. However, such environmental testing methods are centered on emissions, whether evaporative or running [9, 10]. While the overall efficiency displayed by a certain vehicle greatly depends on the primer motor/engine to convert the fuel/electricity into usable motion power, the overall efficiency is influenced by the passive energy losses derived from the motion of the different vehicle components, including the resistance to roll of the rotating components of the vehicle, as well as the resistance of the vehicle to move in the air. That is, the resistance of a vehicle to move defines the passive component of the overall vehicle efficiency to operate under driving or idling conditions. In general, such passive resistance efficiency has been characterized when measuring vehicle’s aerodynamic drag and rolling resistance. The Society of Automotive Engineers Standard J1263 describes a testing procedure that involves the loss of kinetic energy due to vehicle’s resistance to move [11]. Such resistance involves the aerodynamic drag, the rolling resistance of the wheels as a function of tires and pavement deformation, as well as the mechanical resistances, which are associated to the friction in the mechanical components involved in the rotation of

the vehicle’s axles [12]. Figure 2 illustrates a schematic representation of the coast-down test, where the performance assessment characteristic involves the deceleration rate and the distance that the vehicle travels before stopping due to rolling and aerodynamic drag forces.

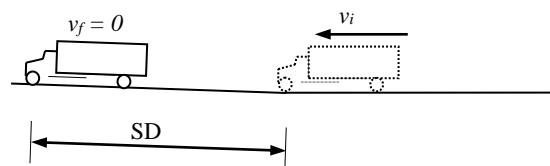


Fig. 2 Schematic representation of a coastdown testing to measure rolling and drag resistance of vehicles.

However, such coast-down technique has been reported as highly dependent on random uncertainties due to the measurement of the variables involved, in particular, the speed and the acceleration [13]. On the other hand, there are other passive performance characteristics of the vehicle which are not considered in this coastdown tests but that could be significant for the environmental performance of a vehicle in a passive way. One of such vehicle characteristics is related with the longitudinal components of the lateral friction forces that come up when the vehicle is negotiating a turn, which imply energy losses and greater vehicle operating costs [14]. In this respect, Figure 3 illustrates the longitudinal components of the rolling resistance forces on each of the tires of a 4-wheel vehicle. The magnitude of such forces will depend on the lateral/longitudinal load transfer of the vehicle and on its yaw stiffness, as a function the vehicle’s center of gravity position and of the individual yaw stiffness of the suspension and tires. The overall effect of such phenomena could thus affect the overall energy efficiency of the vehicle.

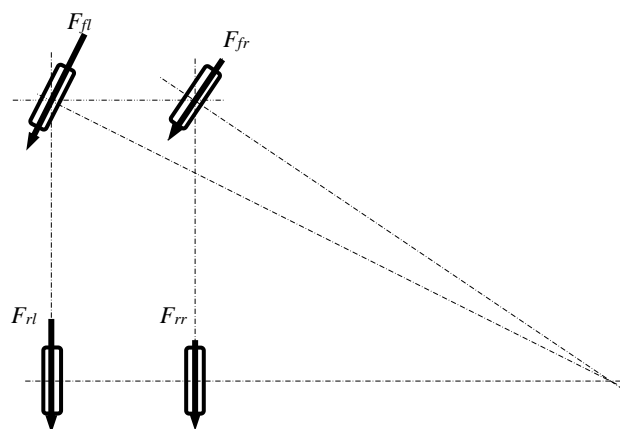


Fig. 3 Schematic representation of the rolling resistance forces on each tire during turning, considering the lateral load transfer.

It should be noted that assessing the passive performance of the vehicle, i.e. when no driving torques act on the wheels, could be applied to conventional and to alternative drive vehicles, such as electric and hybrids. In this respect, such an assessment could represent a potentially significant measure of how a vehicle is using the primer power.

In this paper a methodology is proposed to integrally assess the passive performance of a vehicle. The principles of operation concerning the conceptual design of the testing methodology, are described and discussed. Such a methodology aims at avoiding the uncertainties associated to the current coast-down field measurements, while incorporates the passive steering performance of the vehicle.

2 Gravity Response Efficiency (GRE)

GRE in this paper, is defined as the ability of a vehicle to recover the initial potential energy associated to a position in a ramp. The vehicle is released on this ramp, and its ability to recover such initial potential energy U_i is measured when it travels along an infrastructure providing the possibility to achieving the same initial potential energy U . *GRE* is defined as follows:

$$GRE = \left(\frac{U_i - U_f}{U_i} \right) 100 \quad (1)$$

where subscripts i and f denote the initial and final circumstances, respectively. In terms of the heights over a reference level of the position of the vehicle (bottom of the track), the respective initial and final potential energies can be expressed as follows:

$$U_i = mgh_i; \quad U_f = mgh_f \quad (2)$$

Therefore, *GRE* can be reduced to proportional difference in heights, as follows:

$$GRE = \left(\frac{\Delta h}{h_i} \right) (100) \quad (3)$$

2.1 Factors influencing GRE

The response of the vehicle to the gravity acceleration will depend on many factors that represent different levels of resistance of the vehicle to move. While such factors would also involve the physical properties of the infrastructure or rolling surface, in this paper attention is paid to the vehicle factors, while the infrastructure is taken as a parametric condition.

2.1.1 Rolling resistance (F_{rr})

The factors influencing the resistance of the wheels of the car to rotate, involve the characteristics and

configuration of the tires, as well as the vehicle speed and the normal wheel force, as follows [15]:

$$F_{rr} = C_r (c_2 V_{kph} + c_3) (W) (0.001) \quad (4)$$

where constants C_r , c_1 and c_2 are rolling resistance constants that depend on the type and condition of the pavement (C_r) and on the type of tires (c_1 and c_2). According to this equation, the mass of the vehicle affects the rolling resistance in a linear proportion. For a vehicle moving on a given pavement profile, the weight W would be the instantaneous force of the vehicle on the pavement, resulting from the vibration of the vehicle due to the pavement input. Such vehicle's vibration would also be influenced by the dynamic interaction of the cargo with the vehicle, as it can be the case of a liquid-sloshing cargo.

2.1.2 Aerodynamic drag (F_d)

The aerodynamic drag of a vehicle depends on the characteristic of the atmosphere, on the operating vehicle speed and on the physical properties of the vehicle, as follows [16]:

$$F_d = C_D A_p \frac{\rho}{2} V^2 \quad (5)$$

where C_D is a drag coefficient, which depends on the shape of the car's body; A_p is the projected area; ρ is the air density; and V is the vehicle speed. In the case of road tankers, different tank shapes would thus generate different drag resistances, as the different shapes would generate respective drag coefficients and projected areas. Figure 4 describes the difference in projected area due to two tank shapes: cylindrical and elliptical. According to this figure, the cylindrical tank shape would have a larger projected area, as it projects some area above the truck cabin.

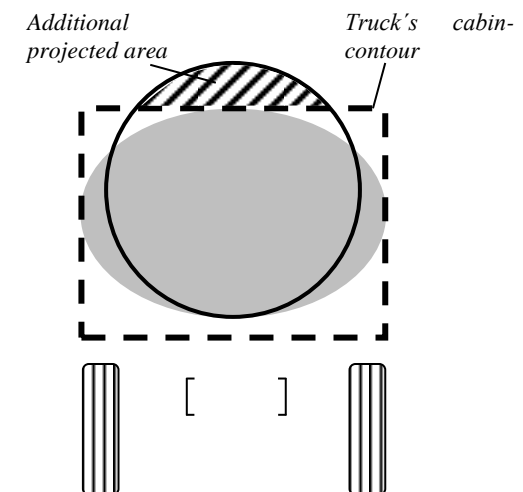


Fig. 4 Projected area differences due to elliptical and cylindrical tank shapes.

2.1.3 Magnitude of vehicle's mass and center of gravity position of the cargo

The amount of mass in the vehicle is another parameter to be evaluated as a specific influential factor regarding the efficiency of the vehicle with respect to its response to gravity accelerations in a ramp, going in conjunction with its center of gravity position. Such vehicle's dimensional and inertial characteristics will influence not only the tires' rolling resistance as expressed in Eq. (1), but also will define the magnitudes of load transfers during turning maneuvers. In the case of a road tanker negotiating a turn, Figure 5 describes the shifting of the liquid cargo due to the lateral acceleration derived from a turning maneuver, causing the increase of the normal force on the external side of the vehicle, while decreasing the magnitude of these forces on the its internal side. The magnitude of the cargo mass shifting will depend on the resulting roll stiffness of the spring suspension. The overall effect, however, should consider any nonlinearities in these relationships, which should be dimensioned through testing.

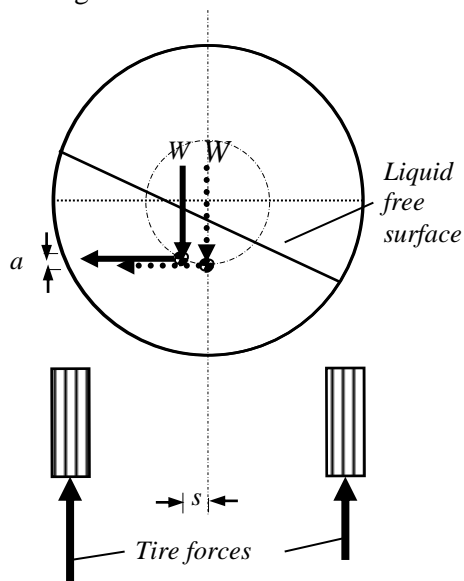


Fig. 5 Lateral transfer due to liquid cargo shifting.

2.1.4 Cornering

The magnitude of the torques developed at the wheel-pavement interface as a result of the change of direction of the vehicle will influence the magnitude of the longitudinal vehicle's rolling resistance forces, as a function of the yaw stiffness of the vehicle and of the normal wheel-pavement forces. Such forces will thus depend on different design characteristics of the vehicle, involving the stiffness properties of all of the flexible components

between the chassis and the pavement, that is, it includes the yaw stiffness of the tires and that of the suspension and the chassis. Other dimensional characteristics include the wheelbase of the vehicle and its inertial yaw properties.

3 Gravity response testing facility conceptual design

A testing facility and corresponding procedure are proposed to evaluate the performance of any vehicle when subjected to gravity, aiming at quantifying the amount of energy that is lost due to the rolling as well as the mechanical and drag resistances. The basic concept derives from the SAE standard coast-down procedure described in reference [11].

As it was described in the introductory part of this paper, the limitations of such a testing procedure have to do with the uncertainties associated to measuring the initial speed and its variation along the tests. Additionally, because of the vehicle's straight path associated to such a procedure, the yaw-roll behavior of the vehicle is not assessed, in spite that the dynamic response of the vehicles to directional maneuvers would define the magnitude of the rolling forces and thus influence the environmental friendliness operation of the vehicle. The testing procedure proposed in this paper thus involves a ramp and the consequential gravitational effects as [11], but under a different setting-up to avoid speed measurement uncertainties while including the directional response of the vehicle. For that purpose, the vehicle is set free on a ramp, at a certain potential energy level, while its ability to recover the same initial potential energy is measured by setting a U-path along the ramp. That is, the vehicle should perform the U-turn to further climbing up to expose the remaining potential energy. Figure 6 illustrates the overall configuration of the testing facility, involving a U-turn maneuver performed on a ramp.

While there would be no way to change the slope of the ramp as a testing condition, several other performance measures could be modified as needed, in order to reach reliable results, i.e., to avoid the uncertainties of the existing testing procedures. For example, the path along the inclined surface could be changed as needed to assess the potential influence of the turning radius. On the other hand, different maximum speeds could be considered by setting different initial positions of the vehicle on the ramp, in order for the vehicle to reach higher speeds when negotiating the turn.

By having both the initial and the final speeds equal to zero, the uncertainty of the experiment is

reduced, as the performance is limited to the measurement of longitudes instead of speeds.

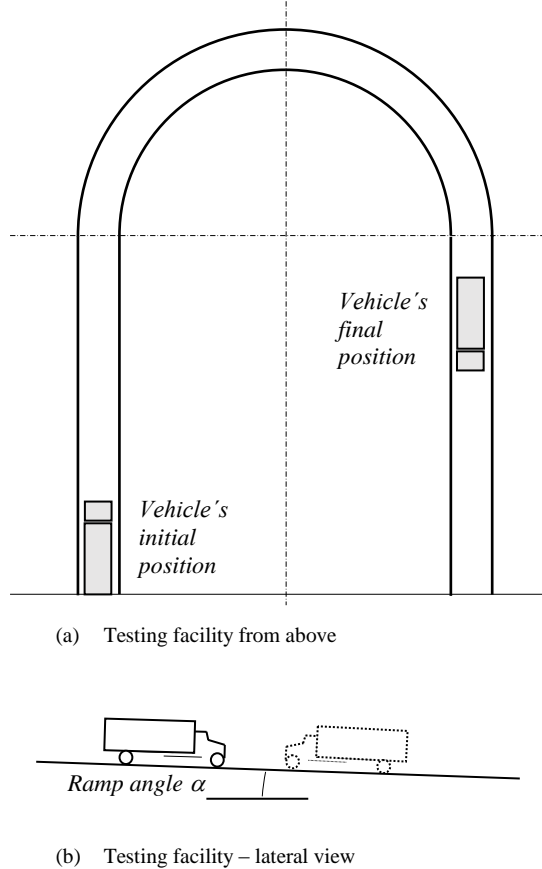


Fig. 6 Schematic representations of the testing facility.

The outputs from the testing procedure will allow to establish a ranking of the environmental quality of the different vehicle designs, and to carry out parametric analyzes. Concerning the turning maneuver, the speed at which it is negotiated should not involve any rollover risk for the vehicle.

3.1 Testing protocol

To carry out the testing the different influential factors should be taken into account, so as to set the same operational conditions for the different tested vehicles and to perform fair comparative assessments of the gravity-performance of the different vehicles' design. On the other hand, the parametric testing analysis would involve the characterization of the effect of certain vehicle properties on its environmental performance, in order to assess the performance sensitivity of the different vehicle designs to changes in the operational level and properties of its components. Table II lists the parameters that would influence the environmental performance of a vehicle for the proposed gravity-directional testing. The testing protocol should thus include the registering of all of

the influential parameters and conditions listed in Table II.

TABLE II
 PROPERTIES AND OPERATING CONDITIONS INFLUENCING THE GRAVITY-DIRECTIONAL PERFORMANCE OF THE VEHICLE

Vehicle design characteristics	Environmental and operating conditions
Tires lateral stiffness, as a function of the tire type and make	Initial position of the vehicle on the ramp (defining vehicle's maximum speed)
Tires' inflation pressure	Environmental temperature
Suspension stiffness	
Suspension type	Wind's speed and direction
Wheelbase dimension	
Cargo type	Road roughness
Fill level (road tankers)	
Payload mass	

The instrumentation for rating the performance measure as described by equation (3) above, will simply involve longitudinal measurements, as well as a nomogram describing the relationship between the different distances and the heights over a reference level. The position of the vehicle when reaching the maximum position along the ramp on the return displacement, could be performed by simple inspection, as it would not involve any motion of the vehicle.

3.2 Testing scenarios

Different studies could be performed under the scope of the proposed methodology, including the analysis of some non-linearities regarding the effect of the mass of the vehicle on the rolling resistance. For example, two vehicles aimed to provide the same quality of service, i.e. the same level of comfort in the case of passenger vehicles, could be tested from this environmental perspective.

As it was mentioned above, the purpose of the testing procedure is two-folds, as it is described below.

3.2.1 Comparative analysis

The purpose in this case is to comparatively analyze different vehicles intended for a particular/specific service. In this case, for example, the potential effects of the tank shape could be considered (elliptical, cylindrical). Also, the effects of some specific types of vehicle components, including the type of tires or the operational principles of the vehicle's suspension (air, mechanical). However, through an expansion of the testing potentials of the test, the passive performance of different principles to power the vehicle, could be considered. In this

case, two vehicles intended to provide the same service to the final user, but with different prime movers, could be considered. That is the case of electric cars versus internal combustion cars, which would yield different passive performance due to differences in design characteristics, including the mass and some components' properties.

3.2.2 Parametric analyzes

Under the perspective of these analyses, the sensitivity of a particular vehicle configuration to a given operational parameter would be addressed. Consequently, the list of conditions listed in the right column of Table II, become factors for which levels could be defined. For instance, the speed could be controlled by positioning the vehicle at different initial positions on the ramp. The testing could be performed at different temperatures in order to quantify the effect of such environmental condition on the vehicle performance. That is also the case for the wind speed and direction. In the case of road tankers, the fill level would be another parameter to take into account, which could signify a relevant situation, as the sloshing phenomena and the consequential lateral/longitudinal shifting of the center of gravity of the cargo would involve lateral and longitudinal load transfers potentially affecting the environmental performance of the vehicle.

3.3 Discussion

It has been proposed in this paper a vehicle testing methodology and facility that could be used to assess, on the one hand, the potential environmental benefits of using different technologies in the vehicle and, on the other hand, to characterize the effect of any vehicle or external potentially influential factor, on the environmental performance of the vehicle. This testing methodology is based upon simple physical principles that could consequently provide objective measures of the performance of the vehicles as far as their rolling, drag and mechanical resistances are concerned. The use of such outputs could be used to rank the tested vehicles in a sort of environmental pricing list.

4 Conclusions

In spite that transport activities do not represent the biggest contributor of pollutants emissions, their reduction has been a priority as some other externalities are associated to such emissions and to the transport itself. A crucial element to characterize the behavior of the vehicles against the environment are the losses that such vehicles exhibit in a passive way, that is, without any involvement of power conditions. The energy loses due to the rolling, the drag and to the friction in mechanical components, have been assessed so far in terms of the stopping

acceleration when the vehicle idles on a ramp. However, such a testing procedure produces some uncertainties due to the dynamic conditions that are considered. To avoid such critical limitations, in this paper a testing procedure and facility are proposed, which are based on static conditions of the vehicle at the initiation and at the ending of the test, which are assumed to provide a better reliability to the testing. Some preliminary theoretical analysis should be made in order to validate the operational principles proposed herein for such testing facility.

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