Analysis of Driving Safety Criteria Based on National Regulations for the Suspension Systems of NGVs

Article *in* Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis · March 2015

DOI: 10.11118/actaun201563010253

ACTA UNIVERSITATIS AGRICULTURAE ET SILVICULTURAE MENDELIANAE BRUNENSIS

Volume 63 32 Number 1, 2015

http://dx.doi.org/10.11118/actaun201563010253

ANALYSIS OF DRIVING SAFETY CRITERIA BASED ON NATIONAL REGULATIONS FOR THE SUSPENSION SYSTEMS OF NGVS

Ronald Mauricio Martinod[1], German René Betancur[1], Leonel Francisco Castañeda[1]

[1] Mechanical Engineering Department, Engineering School, Universidad EAFIT, Cra. 49 Nº 7 Sur-50 Medellín, Colombia

Abstract

MARTINOD RONALD MAURICIO, BETANCUR GERMAN RENÉ, CASTAÑEDA LEONEL FRANCISCO. 2015. Analysis of Driving Safety Criteria Based on National Regulations for the Suspension Systems of NGVs. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis,* 63(1): 253–261.

The work analyses the technical evaluation process of the suspension system for vehicles that have been adapted to natural-gas-fuelled engines from power light-duty gasoline, and diesel vehicles; this evaluation is done through a mechanical review established by national regulations. The development of this analysis is focused on establishing the relationship between the natural-gas-fuelled equipment and the dynamic effect caused by the extra-weight, according to two measuring criteria that determine the safety and driving comfort, these are: (i) tire-road adhesion index; and (ii) tire excitation phase angle. The paper also proposes new elements that can be added to the current national regulations and that are currently applied to assess the suspension of natural gas vehicles, recorded using a test standard benchmark for the evaluation of the suspension.

Keywords: adhesion index, EuSAMA, phase angle, natural gas vehicle, suspension system, viscous damping ratio

INTRODUCTION

Natural Gas-fuelled Vehicles (NGVs) with spark-ignited engines can either be 'bi-fuel' indicating the possibility to switch back and forth between gasoline and natural gas, or 'dedicated' which means that the gasoline fuelling hardware is completely removed and the engine can only work with natural gas. There are many motivations to replace gasoline or diesel-fuelled engines with NGVs engines in different countries (see Tab. I), in most of the cases because of the following reasons:

i) potential fuel cost savings,
ii) reduced dependence on imported foreign oil, and
iii) reduced engine emissions e.g. carbon dioxide, nitrogen oxide, etc. (Daziano, 2012); NGVs are actually helpful for the increase of energy conservation and also for the decrease of gas emissions.

The weight and volume of NGVs containers storage are considered significantly greater when compared to gasoline/diesel tanks. Gasoline can be stored on a vehicle at approximately atmospheric pressure in a thin-walled, light-weight tank (~1 lb/gal depending on the construction). The shape of the tank can be adjusted as needed to fit the available space, thus decreasing the impact on cargo space. Regular gasoline has a density around the 6.1 lb/gal. Diesel fuel is stored as easy as the gasoline and has a density of about 7.1 lb/gal. A full 10-gal tank of gasoline/diesel will hence weigh a bit more than 71/81 lb and will employ a slightly greater space than the fuel volume (Keoleian *et al.*, 1998).

On the other hand, Compressed Natural Gas (CNG) is stored on a vehicle in a high pressure cylinder that is able to resist pressures up to 3600 psig. CNG are constructed in different ways, almost 90% of cylinders that are use nowadays, I: *Top ten countries of NGVs globally (NGV Global, 2012b)*

Ranking	Country	NGVs [Units]	Refuelling Stations [Units]	Fraction NGVs in world [%]	Data received
01	Iran	2 859 386	1 820	18.80	Dec-2011
02	Pakistan	2 850 500	3 300	18.80	Dec-2011
03	Argentina	1 900 000	1 902	12.50	Nov-2011
04	Brazil	1 694 278	1 719	11.20	Sep-2011
05	India	1 100 000	724	7.20	Dec-2011
06	China	1 000 000	2 120	6.6	Dec-2011
07	Italy	779 090	858	5.1	Dec-2011
08	Ukraine	390 000	324	2.6	Apr-2011
09	Colombia	348 747	651	2.3	Aug-2011
10	Thailand	300 581	458	2.0	Nov-2011
...	...	...	...	...	...
16	United States	123 000	1 000	0.81	Dec-2011
...	...	...	...	...	...
19	Germany	96 215	903	0.63	Dec-2011
20	Russia	86 000	247	0.57	Dec-2011

II: *Cylinders storage tank classification for 140-L tank –water volume (Whyatt, 2010)*

Type	Construction process/materials	Composition
Type-1	Solid metal walls/Chrome molybdenum steel or manganese steel	CrMo steel (34CrMo4)
Type-2	Hoop-wrapped/Glass, aramid or carbon fiber composite along the straight sides of the cylinder	Steel or Al with ~15% glass fiber, or steel or Al with ~35% carbon fiber
Type-3	Full composite wrap over a thin metal liner	Al liner with ~48% carbon fiber
Type-4	Full composite wrap over a plastic liner	Plastic liner with carbon fiber

are Type-1 (Whyatt, 2010; NGV Global, 2012a), see Tab. II. In comparison, a gasoline tank would provide a fuel+tank mass of about lbs/gal capacity with a volume ratio slightly less than 1. Type-1 tanks weight 4 to 5 times more than the same capacity gasoline tank (compared with full tanks), and occupies a roughly three times larger volume inside the vehicle. Using Type-3 tanks, the weight is a haft in comparison with the weight a gasoline tank, but the volume exceeds 4 to 5 times the size of the gasoline tank (Whyatt, 2010).

The modified vehicles' suspension technical condition has physical thresholds (e.g. stiffness, damping, and overload) that cannot be exceeded, for any vehicle, even for the newest design vehicle. The thresholds are defined by the designers, factories or assemblers, of each type of vehicle. Furthermore, there is a great contribution of the ten countries with the highest number of NGVs, they has a meaningful participation, equivalent to 87.1%of NGVs globally (NGV Global, 2012a); most of these countries are non-developed countries that do not have the ability to design, redesign or manufacture some kind of these commercial vehicles (e.g. Pakistan, Argentina, India, China, Colombia, Thailand, etc.). Then in the actual field the workshops that switch vehicles from gasoline/diesel to natural gas; or the ones that make structural changes through refurbishing the power source to get 'bi-fuel' fuelled old vehicles, do not consider the design or the thresholds values. The workshops are restricted only by the state regulations.

The paper discusses the national regulations that are currently applied to evaluate the suspension of NGVs, it also will be focused on the analysis of the technical condition of the suspension system in the case that the vehicle is subject to switch from power light-duty gasoline/diesel vehicles to NGVs. Later, the paper will refer to studies about the relation between the storage tanks and the suspension technical condition. Displaying the following NGVs types are specifically considered in this paper:

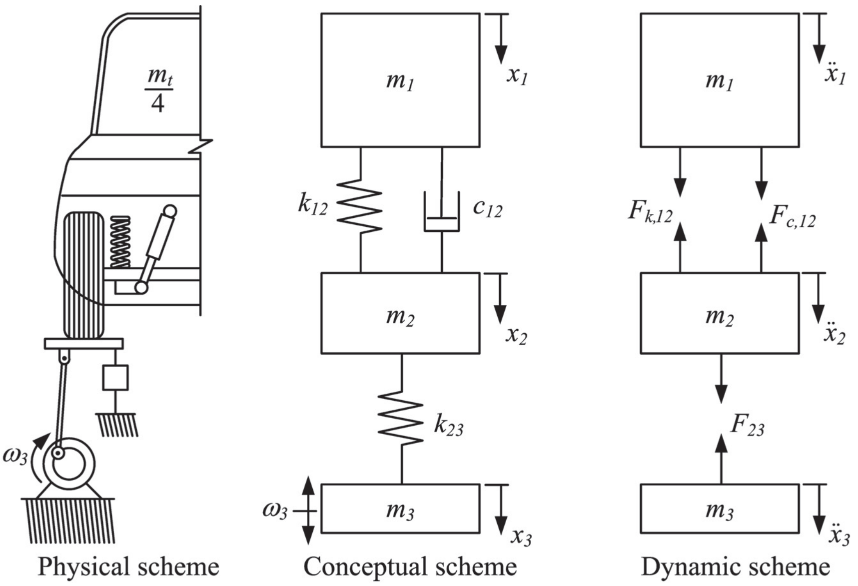
i) gasoline-fuelled, light-duty, vehicles used primarily for private transport; and
ii) gasoline-fuelled (e.g. cars, pickups, small vans, taxis, etc.) or diesel-fuelled (e.g. scholar vans, delivery trucks, station wagons). The necessity of including additional criteria for the safety/comfort evaluation in NGVs has been identified in this paper since the extra-mass, due to the storage tank, affects the tests' results defined by the state regulations.

The state regulations of the European Union country members, United States, Japan, Colombia, among others; establish that there must be a periodic technical review for the different systems that vehicles possess (see Tab. III):

III: *State regulation for vehicle revision*

Country/region	Peridiocity	Regulatory entity	Issue date
European Union	Biennial	Council Policy 96/CE	1996
United States	Biannual/annual*	Office of the Law Revision Counsel	2006
Japan	Biennial	National Agency of Vehicle Inspection	--
Colombia	Biennial	Transit and Transport Ministry	2002

* Varies according to the laws of every state



1: *¼ model of 2-Degrees of Freedom (DoF) vehicle*

i) suspension system,
ii) state of the bodywork,
iii) gas emission level, among others.

This regulation establishes two types of periodic reviews for the suspension system:

i) visual inspection, examines the state of: fixations and suspension components, presence of fissures, corrosion symptoms, existence of welded repairs, and presence of damages, deformations, and oil leakage (MITC, 2006); and
ii) mechanical review, identifies the suspension condition according to the method denominated EuSAMA (EuSAMA, 1976), which has been a fundamental document about studies about the equipment for the evaluation of vehicles suspension system conditions (SAE, 1996; SAE, 2000); and national standards.

The current evaluation of NGVs suspension system is done following the guidelines of the original method established by EuSAMA regulation (EuSAMA, 1976; Koláček and Dostál, 2013). While there has been a significant increase in the amount of consumers' interest in the driving safety/comfort issues of privately owned vehicles. The role played by this method in the purchasing consumers decisions is poorly understood (Koppel *et al.*, 2008), specially the one relative to NGVs.

EuSAMA regulation uses a criteria in function of the vertical oscillation frequency of the tire ω_3 (see Fig. 1), denoted adhesion index[1] $A(\omega)$, which is critical to basic safety, it is therefore very important that the levels of $A(\omega)$ are measured. In the case that a vehicle has a reduced level of adhesion, then it has a high potential driving accident due to the skid effect (Robinson, 1997; Buczaj *et al.*, 2007; Martinod *et al.*, 2013). NGVs incorporate an extra-mass m_a, to the design mass of the vehicle m_v, and causes an increase in the total mass of the vehicle m_t, where $m_t = m_v + m_a$, and $A(\omega)\mu m_t$. The present study proposes to include the phase angle[2] $\psi(\omega)$ criterion, where $\psi(\omega)\mu m_t^{-1}$, this criterion has been defined by SAE (SAE, 2000).

Besides, another state regulation that is related to NGVs is the equipment size/weight, thus the manufacturers must follow the international

1 Adhesion index $A(\omega)$, ratio of the vertical force exercised by a tire in respect to the load in the contact surface of the road, during a vertical oscillation of an tire (SAE 960735, 1996).
2 Phase angle $\psi(\omega)$, measure of the angular difference between the contact force of the tire and the position of the excitation platform for each instant in time (SAE 960735, 1996).

IV: *Evaluation of vehicle suspension systems (Tsymberov, 1994; SAE, 1996)*

Criterion	Evaluation of vehicle suspension systems			
	Excellent	Good	Fair	Defficient
A_{min}[%]	{60, …, 100}	{40, …, 60}	{20, …,40}	{0, …,20}
ψ_{min}[deg]	{60, …, 180}	N. A.	{30, …,60}	{0, …,30}

V: *Statistical results of tests (Arbeláez and Marín, 2007)*

Statistical variable	Stat. DoF	τ(0.20)	τ(0.05)	Experimental error estimator	Treatments quantity	Power [%]	Reliability [%]
$min(F_{23})$	10	1.372	2.228	4 934.87	10	80	95
A_{min}	10	1.372	2.228	28.91	10	80	95
	20	1.325	2.086	28.91	10	80	95

regulations (NFPA, 1996; ISO/DIS, 2000; ANSI/CSA, 2000), the storage tanks are standardized according the tank size (FMVSS, 2012), which is defined by the volume capacity in terms of the equivalent water volume capacity v_c, then v_c is defined by the range values v_c = {30, …, 150} L (see Tab. VII).

MATERIAL AND METHODS

The proposed procedure to evaluate the suspension performance of NGVs considers two measurement criteria:

i) A_{min}, and

ii) ψ_{min} which can be recorded by a standard commercial suspension tester machine.

The tester machine consists of hardware (sensors + transducers) with processing software, and a mobile oscillating platform in a metal frame on which are mounted casters and handle; the platform is on one side connected to electric motor with an eccentric shaft and the opposite side is stored in the pivot, an oscillating circular cam lifts the platform with an wheel up to a frequency of 25 Hz, under the platform, there is installed a load cell, which is sensing the wheel load on the platform (Buczaj *et al.*, 2007; Koláček and Dostál, 2013).

To the present work is used a suspension tester for cars and vans (series VLT 3673/M) with display accuracy 1% of end value, supplied by Van Leeuwen Test Systems from Holland, applied to a MacPherson non-semiactive suspension installed in a Nissan Sentra vehicle, with a tire type 185/70 R13, which has a load index of 84, equivalent to 450 kg with a pressure of 2.2 bar (Reimpell *et al.*, 2001).

The laboratory tests have been designed from the power sampling to obtain a high significance level in the tests, the estimation of the power sampling is based on the stochastic method proposed by W. Cochran (Cochran, 1977). The control of the parameters associated with the variables of each laboratory test yielded a power value of 80% (see Tab. V), with two sets of test treatment, to each treatment was done ten repetitions as minimum, it allows to achieve a suitable reliability level of study

VI: *Summary of the results of lab. tests (Arbeláez and Marín, 2007)*

Set tests	Preload test [N]	m_a average [kg]	A_{min} average [%]
1	1696.55	0.00	66.00
2	1794.25	9.96	67.00
3	1929.62	23.77	69.00
4	2020.48	33.03	70.00
5	2040.48	35.07	70.50
6	2588.96	91.00	76.29
7	2677.22	100.00	77.44
8	2755.67	108.00	77.65

(Tab. VI), which is considered valid for the scope of the experimental study.

A_{min} is defined as the ratio between the minimum vertical force, $min(F_{23})$, see Fig. 1, in the contact surface of an tire (unsprang mass m_2), and the static wheel load on the platform P, exercised by the corresponding m_2 (SAE, 1996), this is

$$A_{min}[\%] = 100\,\frac{min(F_{23})}{P}. \quad (1)$$

ψ_{min} is defined as the minimum angular difference between the vertical position of the excitation platform x_3, and the vertical position of m_2 in relation to the platform x_{23} (SAE, 1996); x_3 is expressed as a sinusoidal function based on the movement equation

$$x_3(t) = a \times \sin(\omega_3 \times t + \phi_3), \quad (2)$$

where

t .... instant in time domain of the test,

a .... amplitude of the platform displacement,

ω_3 ..... platform excitation frequency at instant t, and

ϕ_3 ...... phase.

x_{23} is indirectly found using the magnitude of the tire-platform contact force $F_{23}(t)$, expressed as a sinusoidal function

$$F_{23}(t) = F_0(t) \times \sin(\omega_{23} \times t), \quad (3)$$

where

VII: *CNG storage cylinder Type-1 tank based on European-Indian factory*

Cylinder diam. ϕ [mm]	Cylinder length [mm]	Water vol. v_c [L]	Gasoline equiv. [L]	Empty weight w_s [kg]
244	838	30	10	39
	1270	50	17	60
	1529	60	20	70
279	895	40	14	58
	1016	50	17	60
	1270	60	20	70
	1633	80	27	99
324	970	64	22	71
	1016	70	24	75
	1191	80	28	88
	1450	100	34	106
356	841	64	22	90
	899	70	24	99
	1021	80	28	111
	1461	120	41	154
	1755	140	48	160
406	1229	125	43	146
	1440	150	51	167

$F_0(t)$ .. amplitude of the force, and
ω_{23} .... response frequency of the unsprung mass.

Expressing the platform displacement angle as $\psi_3(t) = \omega_3 \times t$, and the displacement angle of m_2, as $\psi_{23}(t) = \omega_{23} \times t$; and joining the equations (2) and (3),

$$\psi_3(t) = \sin^{-1}\left(\frac{x_3(t)}{a}\right),$$

$$\psi_{23}(t) = \sin^{-1}\left(\frac{F_{23}(t)}{F_0(t)}\right), \tag{4}$$

therefore, the phase angle for the unsprang mass m_2, can be expressed as $\psi(t)[\text{deg}] = \psi_3(t) - \psi_{23}(t)$. Then the evaluation is performed independently to each unsprung mass (to each tire of NGVs) with a suspension tester machine where (SAE, 1996):

i) the machine registers the wheel load on the platform, P;
ii) the platform has an initial oscillation frequency $\omega_{3.0} = 0$ Hz increasing the frequency to $\omega_3 = 25$ Hz, with a constant amplitude of 6 mm; and
iii) the equipment registers $F_{23}(\omega)$, and the position of the platform $x_3(\omega)$.

Previous studies (Tsymberov, 1994; SAE, 1996; Buczaj *et al.*, 2007) have established four (4) acceptance states that clearly qualify the evaluation of vehicle suspension systems, according to the values obtained for A_{min} and ψ_{min} (see Tab. IV).

RESULTS AND DISCUSSION

The weight of NGVs fuel storage tank w_s, is given in function of v_c, where $w_s \propto v_c$. There are some vehicles with refurbished storage that have twins tanks installed in order to achieve long-range travels (Bhattacharjee *et al.*, 2010). This type of modifications is classified as changes in the physical environment, while the modifications and changes in the availability of products are considered structural modifications (Lund and Aarø, 2004). Therefore, it is possible to establish the following range relation $w_s = \{40, \ldots, 320\}$ kg. w_s is relatively close to m_a, $w_s \cong m_a$, therefore, the mathematical model considers that the elements and accessories of the natural-gas-fueled engines has a despicable mass, i.e. w_s and m_a are equivalent, $w_s = m_a$. In the case that m_a value exceeds the maximum design load C_{max} of a standard vehicle, it means $m_a > C_{max}$, NGVs requires a modification in the suspension system to conserve the design safety standards.

The model represents the dynamic behaviour equivalent to ¼-car (Gáspár *et al.*, 2007), through 2-DoF and considering a system of 3-masses (Haroon and Adams, 2008; Pourqorban *et al.*, 2010):

i) m_3 – platform mass;
ii) m_2 – tire or unsprung mass; and
iii) m_1 – sprung mass.

The relation of the masses is

$$m_t \cong \sum_{r=1}^{4} m_r ,$$

where $r = \{1, \ldots, 4\}$ symbolizes a standard vehicle with four wheels. Assuming the storage tank is installed on the rear-end vehicle, then m_a is distributed in the rear tires. Then, the study is focused on the performance of the rear tires, because the sprung mass is added the half of the weight of the fuel storage tank

$$\left(m_1 + \frac{w_s}{2}\right),$$

where

$$\frac{w_s}{2} = \{20,\ldots,160\}\,\text{kg}.$$

The numeric model has been subject of a validation process remaining previous experimental study (Arbeláez and Marín, 2007). The experimental study consisted in a set of laboratory tests, in a tests' bed (see Appendix B, Fig. 4), for the analysis of adhesion to suspension evaluations of light vehicles based on the EuSAMA principles. The model with mechanical properties of a commercial vehicle is denoted by a reference model, the general parameters of ¼-NGVs model are the following: m_1 = 173 kg; m_2 = 35 kg; k_2 = 18.71 kN/m; k_{23} = 127.20 kN/m; c_{12} = 1.30 kNs/m; x_3 = 6E-3m; ω_3 = {0, …, 25} Hz; and the model has been structured in two stages:

i) Modelling of NGVs with a range of storage tank capacity v_c = {30, …, 250} L, keeping the features of the commercial standard vehicle suspension system; and
ii) Modelling of NGVs with a range of storage tank capacity v_c={30, …, 250} L, and with a modification of the suspension system properties:
   a) the loss of properties (ageing of the elements); and
   b) the improvement of the damping properties.

The results of the two modelling stages are shown above:

NGVs with Sandard Vehicle Suspension

The parametric space of the extra-mass is equivalent to incorporating different storage tanks cylinders, v_c = {30, …, 250} L. Fig. 2 exposes the dependence of criteria A_{min} and ψ_{min} to the variation of m_a. A_{min} has a directly proportional tendency, obtaining a 2-order polynomial regressive model with a correlation coefficient of $\sqrt{R^2} > 0.99$,

$$A_{min}[\%] = -0.0003\, m_a^2 + 0.1394\, m_a + 65.598. \quad (5)$$

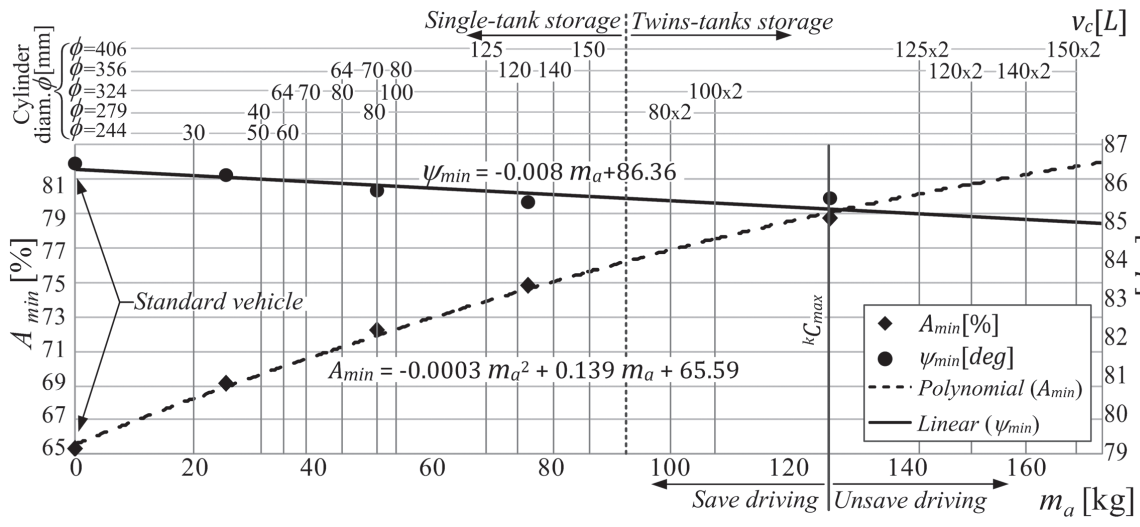
The regressive model is considered valid knowing that the $\sqrt{R^2}$ value represents the association measure of the statistic model with the obtained data, which has an acceptable level for the scope of this study.

The maximum design load equivalent to ¼-car is $C_{max} \cong {}^{500}/_{4}$kg; this represents the limit value to which the vehicle can be loaded with extra-weight without requiring modification in the suspension system. However, Fig. 2 shows if the extra-mass is in the range m_a = {C_{max}, …, 170} kg then $A_{min} \geq 79\%$, such relation expresses that: the evaluation criterion for the evaluation of the suspension state A_{min} qualifies the behavior of the standard suspension of NGVs as *excellent*, even in cases in which the maximum design load C_{max} is exceeded. Furthermore, the criterion A_{min} indicates that the suspension state for NGVs improves indefinitely with the increase of extra-mass m_a. Therefore, it is possible to assure that the criterion A_{min} is not enough for evaluating the suspension state of NGVs.

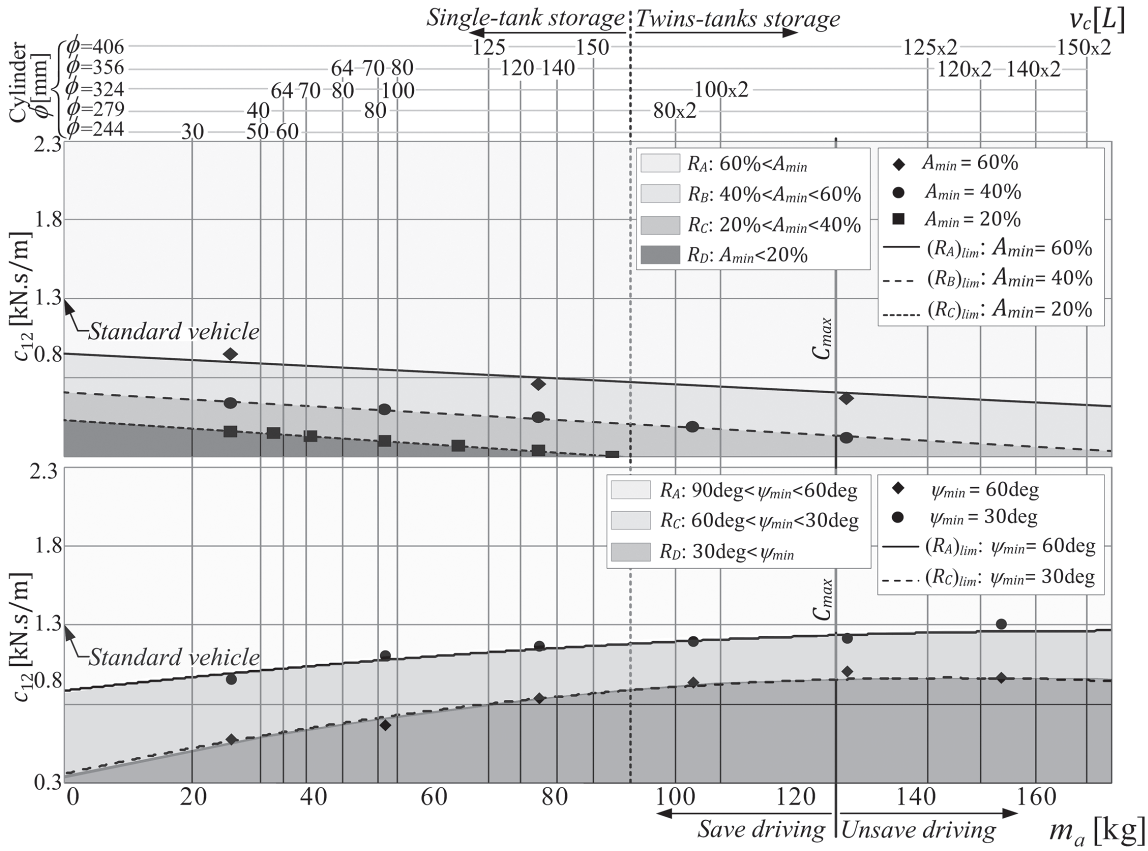
ψ_{min} presents an inversely proportional behaviour, obtaining a linear regressive model

$$\psi_{min} = -8.2E-3\, m_a + 86.363, \quad (6)$$

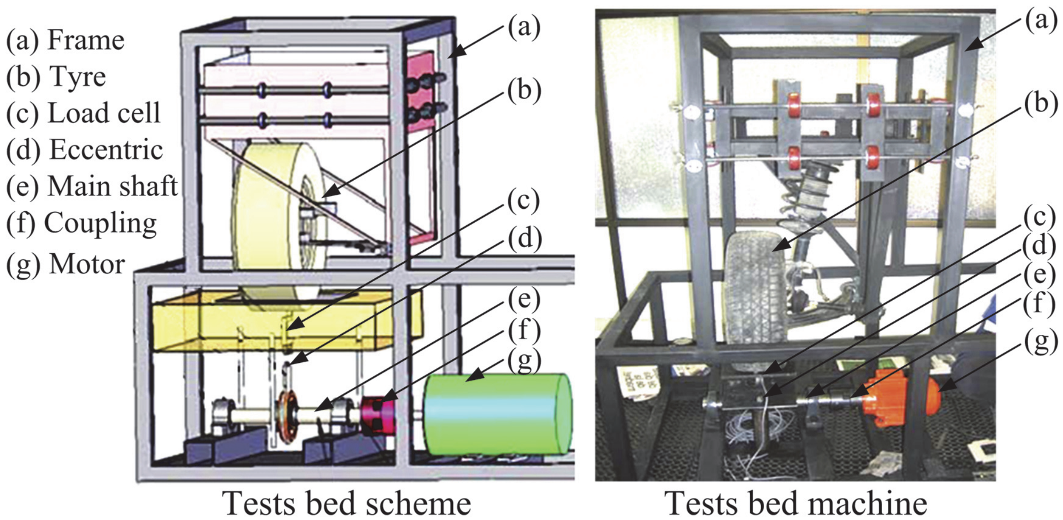
with correlation coefficient of $\sqrt{R^2} > 0.97$, which is considered valid for the scope of this study. The evaluation criterion for the suspension behaviour ψ_{min} presents a coherent relation to the suspension state of NGVs, where it is possible to propose it as limit evaluation value of suspension state for NGVs $(\psi_{min})_{lim}$ = 85 deg, this limit value is highly sensitive to the maximum design load, for that reason it is enough for NGVs evaluation of suspension state.



2: *Regressive models A_{min} and ψ_{min}, in function of m_a*



3: *Development of regressive models A_{min} and ψ_{min}, in function of m_a and c_{12}*



4: *Laboratory tests' bed (Arbeláez and Marín, 2007)*

NGVs with Variation of Suspension Properties

The parameter m_a is defined by v_c. The parameter c_{12} has parametric space c_{12} = {0.3, …, 2.3} kNs/m considering the extremes damping values: defective and excessively rigid (see Fig. 3). Four areas that classify the suspension state are observed, RE = {R_A, R_B, R_C, R_D,} according to the Tab. VI, where R_A: *excellent*, R_B: *good*, R_C: *fair*, and R_D: *deficient*.

The analysis result of criterion A_{min} shows that each RE = {R_A, R_B, R_C, R_D} area has a boundary parametric function, which possess an inverse relation $c_{12} \propto m_a^{-1}$:

- for $(R_A)_{lim} \rightarrow c_{12} = -1.90m_a + 955.46$, with $\sqrt{R^2} = 0.97$;

- for $(R_B)_{lim} \rightarrow c_{12} = -2.19m_a + 708.91$, with $\sqrt{R^2} = 0.99$; and
- for $(R_D)_{\lim} \rightarrow c_{12} = -2.57m_a + 533.70$, with $\sqrt{R^2} = 0.99$.

Considering the parametric space ({0, …, 170}, {0.3, …, 2.3}), each *RE* area possesses the following proportion: R_A: 77%, R_B: 13%, R_C: 7%, R_D: 3%. This criterion A_{min} is permissive in relation to parametric variables. Additionally, A_{min} qualifies the behavior of NGVs standard suspension as *excellent* (even allowing a reduction of suspension of the dynamic properties), still in cases in which the maximum design load C_{max}, is exceeded. Note that criterion A_{min} qualifies the behavior of NGVs suspension as *excellent,* with a damping ration c_{12} that has values lower than the 60% of the studied nominal property. This decrease of the damping ratio value is equivalent to 60% of damping wear. Thus, once again it is possible to affirm that A_{min} is not enough for evaluating the suspension state of NGVs.

The analysis result of criterion ψ_{min} shows that each area has a 2dn-order boundary parametric function:

- for $(R_A)_{lim} \rightarrow c_{12} = -0.013m_a^2 + 4.37m_a + 885.97$, with $\sqrt{R^2} = 0.94$; and
- for $(R_C)_{lim} \rightarrow c_{12} = -0.029m_a^2 + 8.47m_a + 359.35$, with $\sqrt{R^2} = 0.96$.

Considering the entire possible parametric field, each area has the following proportion: R_A: 65%, R_C: 19%, R_D: 16%. However, criterion ψ_{min} is sensitive to the extra-mass m_a.

CONCLUSION

The current evaluation of the technical conditions of the suspension system to NGVs based on EuSAMA principles, that have been adopted by state regulations, although this does not guarantee an accurate diagnostic of safety/comfort driving.

The main goal of the present work is establish a suitable procedure to the suspension system assessment for NGVs, which considers the evaluation via two criteria: A_{min} and ψ_{min}, providing an accurate diagnostic of the state of NGVs suspension systems focused on the safety/comfort driving issues.

The established procedure can be integrated with the procedures used in periodic vehicle revisions in countries that include a technical inspection into the state regulation (European Union, United States, Japan, Colombia, among others). The proposed method can be implemented maintaining the same installed technical capacity to perform mechanized technical inspection, and without requiring adding new infrastructure neither requiring additional technical elements.

As another remaining conclusion, the paper shows that the structural modification through refurbishing storage to get a long-range travel via twin tanks is not an appropriate solution, due the study found that $m_a \geq C_{max}$, then, NGVs require a modification in the suspension system to conserve the design safety/comfort standards.

The present study can be a reference point for different cases of vehicle suspension analysis, when extra-load has been added to the nominal standard design. Therefore, this methodology can be applied for other studies on suspension systems, where the mass of the vehicle has been modified.

Acknowledgement

The research has been supported by the project "Criterios de Evaluación del desempeño de vehículos automotores (Criteria for performance evaluation of motor vehicles)" financed by Universidad EAFIT.

REFERENCES

ANSI/CSA NGV 2. 2000. *Basic requirements for compressed natural gas vehicle (NGV) fuel containers*. Washington, DC: CSA America, American Gas Association.

ARBELÁEZ, J., MARÍN, J. 2007. Modeling, design and construction of a tests bed for the analysis of adhesion to suspensions evaluation of light vehicles based on European Standard Shock Absorber Manufacturers Association (EuSAMA) [in spanish]. Cusco, 23–25 October, 1141–1150: *8th Iberoamerican Congress of Mechanical Engineering*.

BHATTACHARJEE, G. et al. 2010. CNG cylinder burst in a bus during gas filling – lesson learned. *Safety Science*, 48: 1516–1519.

BUCZAJ, M., WALUSIAK, S., PIETRZYK, W. 2007. Diagnostic assessment of technical condition of the shock absorbers in automotive vehicles in a selected diagnostic station. *TEKA Kom. Mot. Energ. Roln.*, 7: 59–66.

COCHRAN, W. 1997. *Sampling Techniques*. 3rd ed. London: John Wiley & Sons.

DAZIANO, R. 2012. Taking account of the role of safety on vehicle choice using a new generation of discrete choice models. *Safety Science*, 50: 103–112.

EUSAMA TS-02-76. 1976. Recommendation for performance test specification of car vehicle suspension testing system. *European Shock Absorber Manufacturers Association*.

FMVSS 304. 2012. Compressed natural gas (CNG) fuel container integrity. US Department of

Transportation, *US Federal Motor Vehicle Safety Standards*, pp. 50.
GÁSPÁR, P., SZABÓ, Z., BOKOR, J. 2007. Parameter identification of suspension system and road disturbance estimation. *Int. J. Vehicle Systems Modelling and Testing*, 2(2): 128–137.
HAROON, M., ADAMS, D. E. 2008. Component restoring force identification for damage identification in vehicle suspension systems. *Int. J. Vehicle Systems Modelling and Testing*, 3(2): 25–46.
ISO/DIS 11439-2. 2000. Gas cylinders – high pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles. *Int. Org. for Standardization*.
KEOLEIAN, G.A., SPATARI, S., BEAL, R. 1998. Life cycle design of a fuel tank system, National Pollution Prevention Center, A report presented at the *University of Michigan, Report Nr. EPA 600/R-97-118*.
KOLÁČEK, S., DOSTÁL, P. 2013. Evaluation of dampers using a resonance adhesion tester. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, LXI(6): 1749–1753.
KOPPEL, S., CHARLTON, J., FILDES, B., FITZHARRIS, M. 2008. How important is vehicle safety in the new vehicle purchase process? *Accident Analysis and Prevention*, 40: 994–1004.
LUND, J., AARØ, L. E. 2004. Accident prevention – presentation of a model placing emphasis on human, structural and cultural factors. *Safety Science*, 42: 271–324.
MARTINOD, R. M., BETANCUR, G. R., MESA, J. F., BENAVIDES, O. M., CASTAÑEDA, L. F. 2013. Analysis of the procedure for suspension evaluation of civil armoured vehicles: Reliability and safety driving criteria. *International Journal of Vehicle Safety*, 6(3): 254–264.
NFPA 52. 1996. Standard for compressed natural gas (CNG) vehicular fuel systems, Washington, DC: *US National Fire Protection Association*.
NGV GLOBAL. 2012a. Vehicle fuel storage. In: *13th NGV global biennial conference and exhibition 2012: natural gas vehicle knowledge base.* Mexico DC.
NGV GLOBAL. 2012b. 2011 natural gas vehicle statistics published. Mexico, DC: *13th NGV global biennial conference and exhibition:* natural gas vehicle knowledge base.
MITC PROCEEDING. 2006. *Manual inspection procedure stations ITV*. Madrid: Spanish Department of Industry, Tourism and Commerce.
POURQORBAN, N., HASSANZADEH, I., HASHEMZADEH, F., ALIZADEH, G. 2010. Optimal active suspension control based on a quarter-car model: an analytical solution. *Int. J. Vehicle Safety*, 5(1): 1–20.
REIMPELL, J., STOLL, H., BETZLER, J. W. 2001. *Automotive Chassis: Engineering Principles*. 2rd ed. London: Butterworth Heinemann.
ROBINSON, B. 1997. *Commercial vehicle tyre adhesion.* Report Nr. 237. Transport research laboratory, Vehicle Standards & Engineering Division, DETR.
SAE 960735. 1996. An improved non-intrusive automotive suspension testing apparatus with means to determine the condition of the dampers, *Society of Automotive Engineers International*.
SAE 1329-2000-01. 2000. Experimental evaluation of a non-intrusive automotive suspension testing apparatus. *Society of Automotive Engineers International*.
TSYMBEROV, A. 1994. *Suspension tester and method US5369974*. United States Patent.
WHYATT, G. A. 2010. Issues affecting adoption of natural gas fuel in light -and heavy-duty vehicles. *Pacific Northwest National Laboratory, Report Nr. PNNL-19745*. Washington, DC: US Department of Energy.

Contact information

Ronald Mauricio Martinod: rmartino@eafit.edu.co
German René Betancur: gbetanc4@eafit.edu.co
Leonel Francisco Castañeda: lcasta@eafit.edu.co