How to obtain equivalent occupant protection levels in vehicle independently of vehicle mass and size?

Pascal Delannoy
Safran Engineering, SAFRAN Group
France

Jean Philippe Lepretre
CERAM, UTAC CERAM Group
France

Paper number 13-0007

ABSTRACT

Recent accident studies [3] show and confirm that occupant severity in frontal car to car accident depends on vehicle mass and size.

Despite the introduction of the Frontal Impact regulation ECE R94, the aggressivity rates of heavy vehicles in front to front accidents are mostly unchanged or worse in some countries. A difference between cars which comply with R94 compared to all ages of cars has been observed. This phenomenon has a direct influence on injury rates of light cars compared to heavy ones.

However, this situation is not a 'fait accompli' and can be solved by changing front end force and compartment strength difference amongst cars mainly responsible for this situation.

This paper evaluates and explains why the current frontal impact test using deformable element did not solve this problem and shows its impact on accident data.

It proposes also some different approaches of possible improvements in test protocol and car design for solving this main passive safety issue. Slight modifications will allow light cars to reach the same level of protection as heavy cars in frontal impact accident.

Possible reductions in severe injuries and fatalities are forecast based on the slight modifications to the test protocol. This will allow rates of serious injury and fatalities in light cars to more closely match those in heavy cars.

The influence of vehicle mass on injury severity rate cannot be completely eliminated. However, the effects could be reduced. The same severity rate for vehicles of different mass and size will remain an unreachable goal. However, reducing and harmonizing impact severity rates among vehicles in a regulatory test is one of the first priorities to reduce the number of accident victims.

INTRODUCTION

Frontal impact car to vehicle accidents represent about 30% of all car occupant fatalities, whereas single vehicle frontal impact stands for 15% of these fatalities [3] [4]. According to that, car to car accident is one of the most important issues to reduce and solve in terms of road fatalities and severely injured.

Frontal impact crash protection is legislated for in Europe UNECE Regulation 94.

Under a GRSP informal working group in Geneva a review of the requirements of Regulation 94 has been initiated which should potentially lead to proposals to amend this Regulation. One of the problems found during preliminary work performed was that the accident data available to review the current frontal impact situation in Europe was limited.

TRL was commissioned by the European Commission (EC) to perform a comprehensive European accident study for frontal impact [3] to help prioritize potential future changes to frontal impact legislation for both the short and longer term. In July 2010, TRL published "Technical assistance and economic analysis in the field of legislation pertinent to the issue of automotive safety: provision of information and services on the subject of accident analysis for the development of legislation on frontal impact protection," for the European Commission.

Over the past ten years, with introduction of regulation, rating, insurance test and pedestrian vehicle front end design has changed a lot. Solutions have been optimized to comply with the R94 regulation and self protection, but not to reduce aggressivity in case of car to car frontal impact accident. Both configurations are not considering in

the same time, improving safety against fix obstacles was considered as the priority at that time.

This paper aims at bringing evidence of the impact of UNECE R94 regulation on car designs and the need to amend and correct its side effect to converge towards equivalent severity rates for all vehicles independent of their mass and size. This approach will allow covering on one hand single and one the other hand car to car accident in the same time.

RELEVEVANCE OF VEHICULE AGRESSIVITY

The "aggressivity" metric was used to investigate the relationship between vehicle mass and its partner protection. This was defined by Gabler and Hollowell (1998) as follows:

$$Aggressivity = \frac{Driver\ fatalities\ in\ collision\ partner}{Number\ of\ crashes\ of\ subject\ vehicle}$$

Generally, as vehicle mass or size increases, aggressivity also increases. This relationship is true and observed for all countries, and for all combinations of vehicle age.

The aggressivity of R94 vehicles in impacts with other R94 vehicles is generally less than the aggressivity of R94 vs all vehicles. As the fleet becomes saturated with Regulation 94 compliant vehicles this suggests that casualty rates will reduce and the aggressivity problem will be lessened.

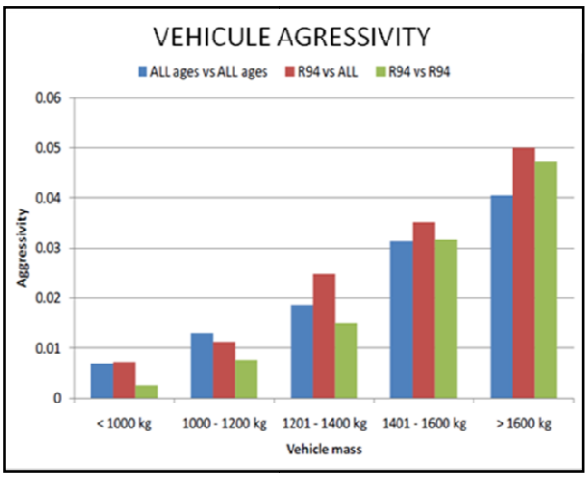
However, the differences in aggressivity between mass categories for R94 vs R94 vehicles is greater than for R94 vs All and indeed the aggressivity for vehicles > 1600 kg is for R94 vs R94 vehicles is equal or greater than for all ages vs all ages. (**Figure 1 and 2**).

This suggests that the introduction of R94 may be making the situation worse in terms of aggressivity (partner protection), although self protection may be improving as aggressivity overall is decreasing..

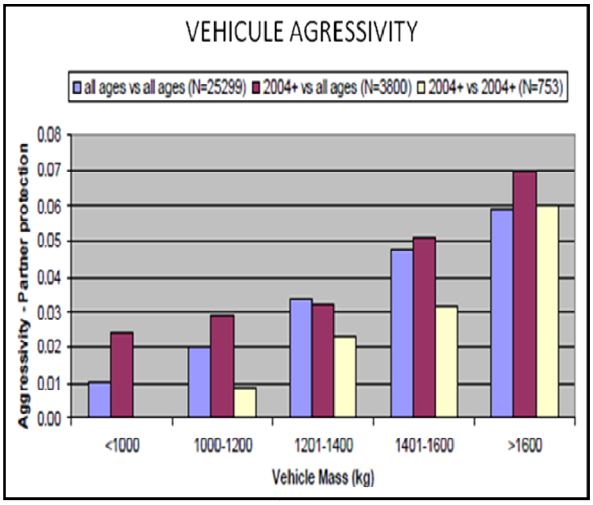
This means that the aggressivity problem in a R94 compliant fleet is worse than before Regulation 94 was introduced for certain categories of vehicles.

Improved occupant protection against fixed and rigid obstacle may have contributed to the increased 'aggressiveness' of vehicle front ends towards other vehicles, especially for heavy vehicles that need to absorb their own kinetic energy.

This important issue is not yet treated.



[3] Figure 1: Vehicle aggressivity from national data in Germany split by vehicle mass



[3] Figure 2: Vehicle aggressivity from national data France split by mass

RELEVANCE OF SEVERITY RATE

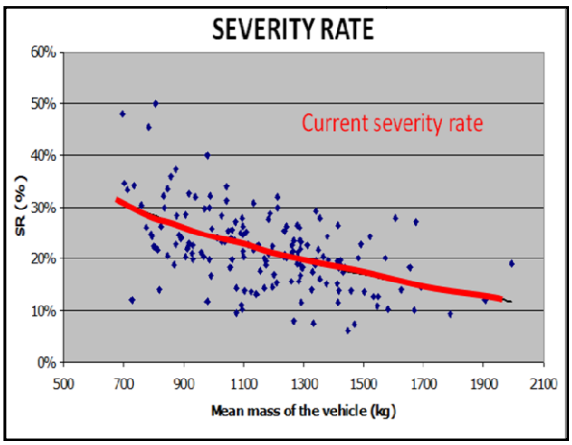
Definition of severity rate

Severity rate (SR) is defined as the proportion of fatal and serious injuries observed in the considered car model (internal injuries)

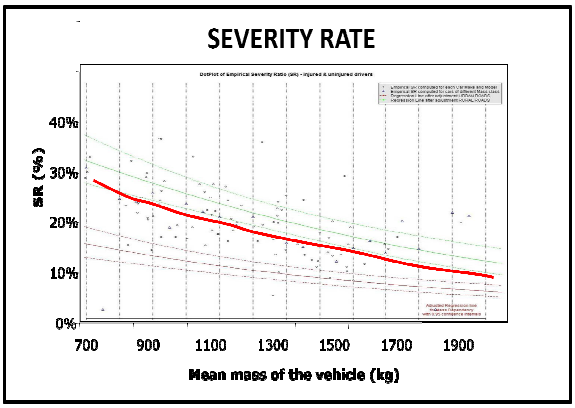
$$Severity\ proportion = \frac{Fatal + Serious\ drivers}{Fatal + Serious + Slight\ drivers}$$

The following figures show it as a function of the vehicle weight for cars that comply with R94 against All.

Distributions in different countries (**Figure 3 and 4**) are similar in terms of level and evolution.



[2] Figure 3: Current severity rate situation from national France - R94 vs all cars



[2] Figure 4: Current severity rate situation from national Germany- R94 vs all cars

Figures 3 and 4 clearly illustrate that severity rates decrease as mass of the cars increase.

This shows that the chance to be killed or seriously injured in a frontal car to car accident is three time higher in the light car than a heavy one. The protection level in case of a frontal accident is clearly mass dependent. However, this situation is not a 'fait accompli' and can be improved.

Explanation of severity rate curve

In case of car to car accident, homogeneous severity rate is dependent upon a correct distribution of the kinetic energy between the two vehicles involved.

Contrary to certain perceived ideas, the mass plays no significant role in the energy distribution. In fact, the force deflection is the main parameter; the weaker vehicle absorbing the energy even it is the heavy one.

If one vehicle supplies higher force than other, it stopsdeforming, and then all the remaining energy is absorbed by the other vehicle. In the following example (**Figure 5**) by virtue of its greater stiffness (force deformation), the vehicle on the right stops deforming, immediately resulting in a larger deformation of vehicle on the left.

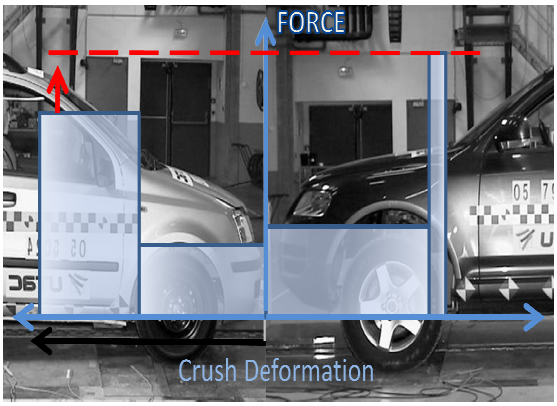


Figure 5: Force mismatch responsible for higher severity rate for light car

Adequate situation to solve this problem

To solve this problem, the two cars involved must supply approximately similar deformation forces to absorb their share of the impact energy. In other words, both cars should provide an acceptable force matching (**Figure 6**).

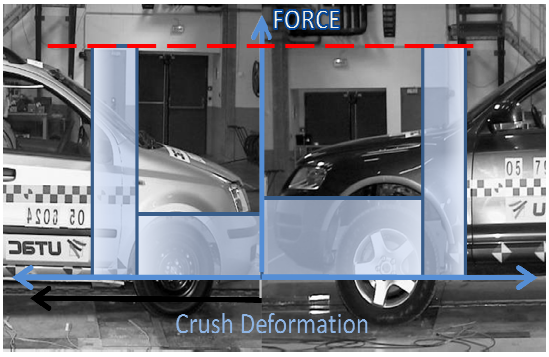


Figure 6: Ideal energy absorption to obtain equivalent severity rate

Unfortunately, this situation is difficult to reach because the most common situation is a difference in force that makes the homogeneous deformation and the adequate energy absorption distribution unreachable.

Unreachable because the heavy car must provide an acceptable level of self protection. In case of single obstacle accident, its structure generates higher force, by design, than a small car to compensate for its greater mass.

But it is not the only one parameter that explains higher force level. The test protocol today using weak deformable element is also partly responsible for this situation.

The approximately constant energy absorbed by the barrier makes the test more severe for heavy cars.

Because of this, heavy cars are penalized two times:

- by their mass,
- by the test protocol.

Even if there are no obvious solutions to compensate for the higher mass problem, it is easy to address the test protocol problem.

RELEVANCE OF ECE R94 ON THIS SITUATION

Vehicles are designed to fulfill ECE R94 using EEVC barrier. However, over time and with the new generation of vehicles which are safer and stiffer, now the barrier fully collapses and vehicles bottom out against rigid wall behind.
Hence, the energy absorbed by the barrier is now more or less constant independent of vehicle size, so the severity of the test depends on the vehicle's mass. This means that the test severity represented by EES (Energy Equivalent Speed) is mass dependent and rises up with the mass (**figure 7**)

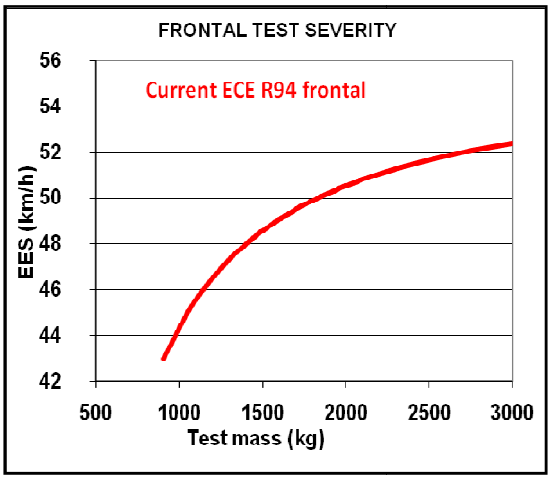


Figure 7: ECE R94Frontal test severity

So in order to reach the same level of self-protection, cars designed to comply with the deformable barrier test which bottom out, results directly in even stiffer heavy cars.

The test severity for a 2000 kgs mass car is 16% more severe than for a 1000 kgs ones.

Current ODB barrier is not yet adapted to the new generation of cars. It was raised by EEVC WG 15 in its final report [3] .This test severity which is dependent on the vehicle mass is partly responsible for the aggressity level and severity rate observed.

Therefore, it is urgent to harmonize the test severity for vehicle range mass to reach a homogeneous fleet that lead to better balance in terms of severity rates.

INFLUENCE ON CURRENT DESIGN

The current situation observed by studies ***(figure 1 and 2)*** directly comes from this test severity inhomogeneity.

Force deformation determines the distribution of energy between the two vehicles. If one of these vehicles stops deforming, because it is stiffer, then all the remaining energy is absorbed by the other vehicle

Due to the specific nature of self-protection tests (more stringent for large vehicles), these improvements have driven manufacturers to increase the stiffness not only of their small vehicles, but that of larger ones also. Large vehicles which due to their design are stiffer already...

In effect, the quest for similar intrusion performance, whether for a small or a large vehicle, leads naturally to greater stiffness in the front unit and passenger compartment.
Figures 9 and 10 explain how the increase of deformation loads has allowed the degree of passenger-compartment intrusion to be significantly reduced. Note that large vehicles - even if they are for the most part longer - require higher deformation loads.
In recent years, all car manufacturers have made significant progresses in structures and restraint systems.

Kinetic energy and Energy absorbed

By laws of physics, heavy cars must absorb more energy than small ones.

Figure 8: Amount of energy to be absorbed by light and heavy car in current frontal offset test

Part of the amount of additional energy is absorbed by the front but also by the compartment. However, the front end is not long enough to absorb the full additional energy (**figure 10 and 9**).

Figure 9: Force level and Energy absorbed for light car

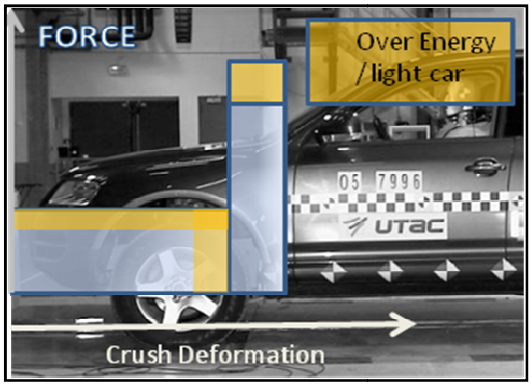


Figure 10. Current front end design of heavy car to absorb over energy compare to light car

Reducing the intrusion level for single accident involves increasing front force deformation of the front end but also of passenger compartment.

This increase in force deformation is likely to be greater for heavy vehicles.

The difference in force levels has been measured in offset tests (**Figure 11**). The maximum force generated by a 2000 kg car can be twice the force generated by a 1000 kg one.

In this condition with lack of force matching, adequate energy distribution between vehicles is unreachable and severity rate cannot be harmonized.

These force deformations increases have already been proven dangerous for older-generation vehicles, but now are also proving to be detrimental for vehicles of the same generation.

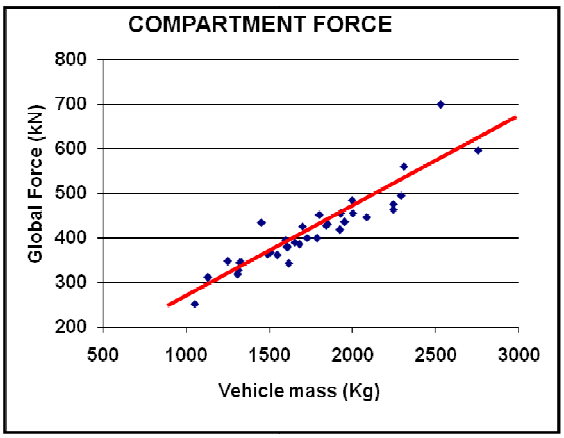


Figure 11. Global force generated by compartment (measured on offset test)

Heavy cars cannot be developed today with force deformations that match with small ones.

The severity rate curves cannot be improved without changing this trend.

POSSIBLE IMPROVEMENTS

The main issue is to switch towards adapted designs that reduce force mismatch and indirectly severity rate differences.

There are two possibilities for improving the situation. The first one is to adapt the car design to the current regulation, the second is to change the test protocol towards a better comprehensive one that solve the side effect introduced by the current deformable barrier.

Keep the current R94 test protocol and change the vehicle design

To obtain acceptable force matching independent of vehicle mass, two possibilities have been proposed for limiting the compartment force:

- increase intrusion level in compartment space,
- increase front end overhang.

<u>Intrusion level</u>

Limiting compartment force for better compartment force balance is one of possibilities to solve the problem.

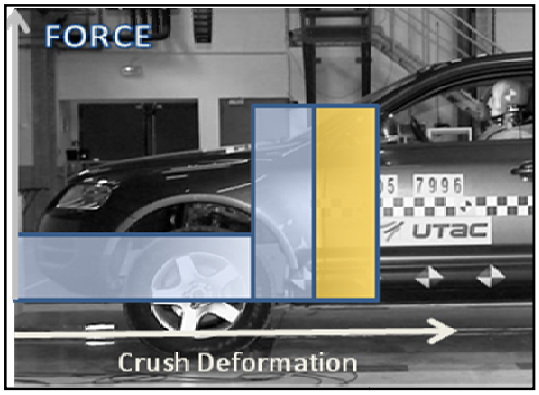


Figure 12: increase compartment intrusion

However, the self protection level would be seriously compromised with higher intrusion in the compartment space.
Even if this solution is a good answer to better force mismatch, it is not acceptable for self protection.
The risk associated with compartment intrusion is too important to accept this design.

Increase overhang

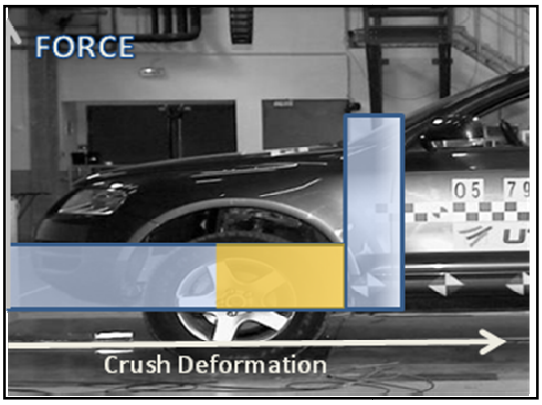


Figure 13: increase overhang to absorb over energy

This solution allows absorption of the additional energy from the mass and the test protocol in the front end and limits the compartment force. Unfortunately, this front end design is not realistic.

The trend is to reduce size of this part of the car instead of increasing it, in order to give more space in the compartment for occupants. Furthermore, it is counter productive for reducing mass and CO2 emissions.

Change the current R94 test protocol and adapt vehicle design

To obtain homogenous test severity independent of vehicle mass, three possibilities have been proposed:

- adapt the deformable element to new vehicles generation,
- remove deformable element
- introduce test speed dependent on the vehicle mass

The goal of the different improvements proposed in this chapter is to change the test severity EES towards a stable and constant one independent of mass.
The **figure 14** illustrates this approach to switch the curve from the red that represent the current situation to the blue one that represents the target for the future.
The blue severity is more appropriate for having a chance to reduce the severity rate.

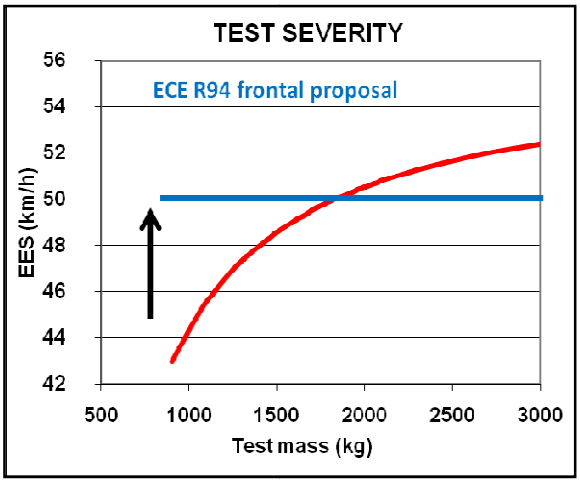


Figure 14: possible test severity harmonization among vehicle masses

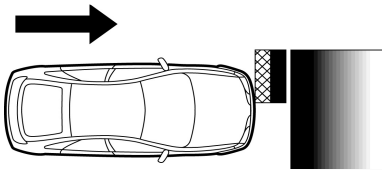
Introduce test speed depending on vehicle mass

According to the behavior of the barrier which bottoms out and absorbs a constant amount of energy independently of the car mass, one possibility is to introduce a test speed depending on the kerb weight of the tested vehicle.

This solution can be adopted without any change in the test protocol. The heavy car would be tested at lower speed than light car to switch towards a constant test severity.

Rule makers could decide the test severity (52 kph for example) and by easy calculation, the test speed curve could be defined.

However, another issue regarding aggressivity (structural interaction) highlighted by expert communities as a priority will not be solved by this solution.



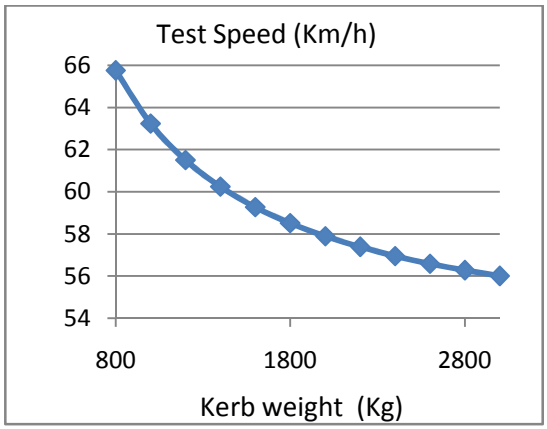


Figure 16: test speed corresponding to a test severity of 52 kph

This approach for limiting test severity for heavy car was adopted in part by Euro NCAP **[1]**. Aware of that situation and the risk of increasing aggressivity of heavy cars,the Euro NCAP test protocol fixes the test speed to 56 km/h for vehicles above 2500 kg and 8 seats and more.

Adapt deformable element to new car generation

Change the deformable element to a new one able to absorb more energy that makes the bottoming out phenomenon rare and allows heavy cars to put more energy into the barrier than light ones.

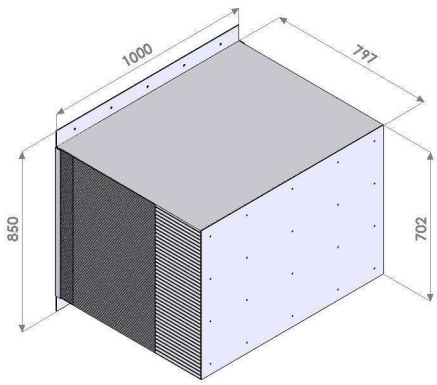


Figure 15: Progressive Deformable Barrier [10]

The PDB barrier showed good capability for absorbing different amounts of energy. Thus it seems possible to normalize test severity with the use of the deformable element, which will allow for controlling other parameters, such as partner protection and structural interaction [10]. The PDB barrier also showed its capability to answer the problem of heavy cars. NHTSA considers after numerous evaluations that PDB performed as designed for heavy vehicle [5].

Remove the current deformable element

This solution is the easiest and the cheapest approach to solve the problem.

The current ODB barrier is obsolete and its stiffness is too low for modern vehicle **[7]**. Removing it should be possible without any change in test results. This operation must be accompanied by fixing lower speed equal to the desired test severity.

Without deformable element, the EES is equal to the testing speed, test severity is constant and not dependent on the vehicle mass.

However, even if it solves test severity and creates a better force mismatch, structural interaction will not be improved. For the structural interaction issue, the potential of this solution is limited.

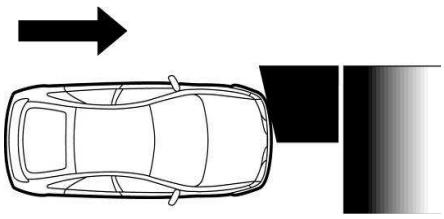


Figure 17: Test severity against rigid wall is equivalent to test speed

IMPACT OF THE CHANGING TEST PROTOCOL

Harmonized test severity gives the opportunity to have better force matching and to solve part of severity rate difference.

Impact on compartment force (figure 18)

The heavy car could be designed according to its mass without higher forces due to increased test severity introduced by the test protocol.

Naturally the light car will become “stiffer” (higher force) and the heavy vehicle will become “weaker” (lower force).

The global force curve generated by the structure will be more “horizontal” which makes the force matching easier to achieve.

However, the perfect horizontal cannot be reached. To compensate for its mass, a heavy vehicle will always have to stay stiffer than a light cone.

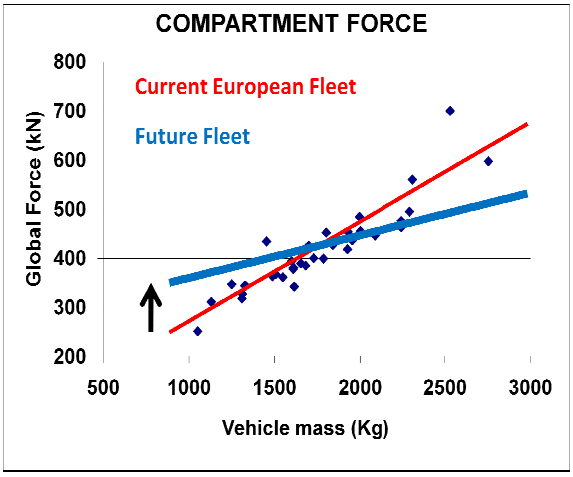


Figure 18: Influence of harmonized test severity on vehicle compartment force

The global force limitation will not be counter productive for self protection against a single obstacle. Due to high stiffness of load, the current efficiency of structure involved in terms of energy absorption in real life accident is limited. Load paths collapse without absorbing the kinetic energy due to lack of stability.

That's why, introducing weaker load paths will improve energy absorption efficiency, and furthermore, load paths will be able to work in many more situations. That it is not the case today.

Impact on severity rate

The lower force differences between light and heavy cars will strongly influence the severity rate distribution (**figure 19**).

Homogeneity of fleets will lead to better force matching in case of car to car accidents. Heavy cars will become less aggressive because of better energy distribution between vehicles involved.

After renewing the fleet, the severity rate curve should decrease, especially for light cars.

Furthermore, the current high difference in terms of Severity Rate will be reduced. However, similar Severity Rate independent of the mass is not reachable. The heavy cars will stay safer than the small car in case of car to car accident.

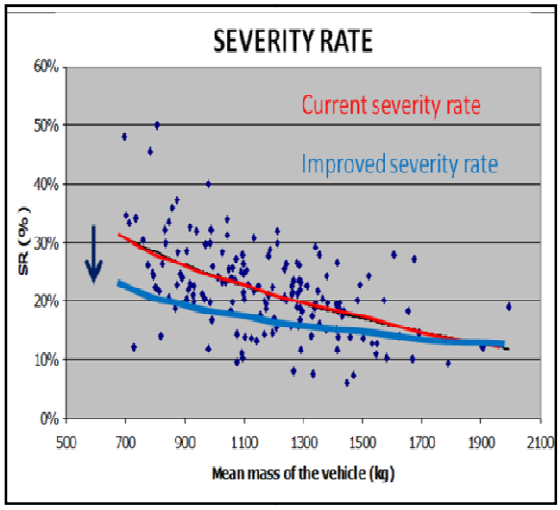


Figure 19: influence of test harmonisation on severity rate

The mass of the car and associated self protection requirements make a horizontal curve unreachable. The Severity Rate curve slope is inversely proportional to the force one.

Impact on safety benefit [4]

An accident analysis carried out in 2010 on population of cars that complied with R94 showed that such evolution of severity rate harmonization, associated to better force mismatch and structural interaction, would lead to avoid 40% of fatalities or severe injuries in head on collision. It represented 7% of victims involved in all impact road accident.

	Head on collisions	All impacts
	Victims reduction (front occupant, belted, head on collision between two cars of conception > 1999 or model year > 2003)	Victims reduction extrapolated to the whole set of car occupants
fatalities and severe injuries	40.3%	7.0%

Figure 20 [4]: reduction in fatalities and serious injuries

Summary

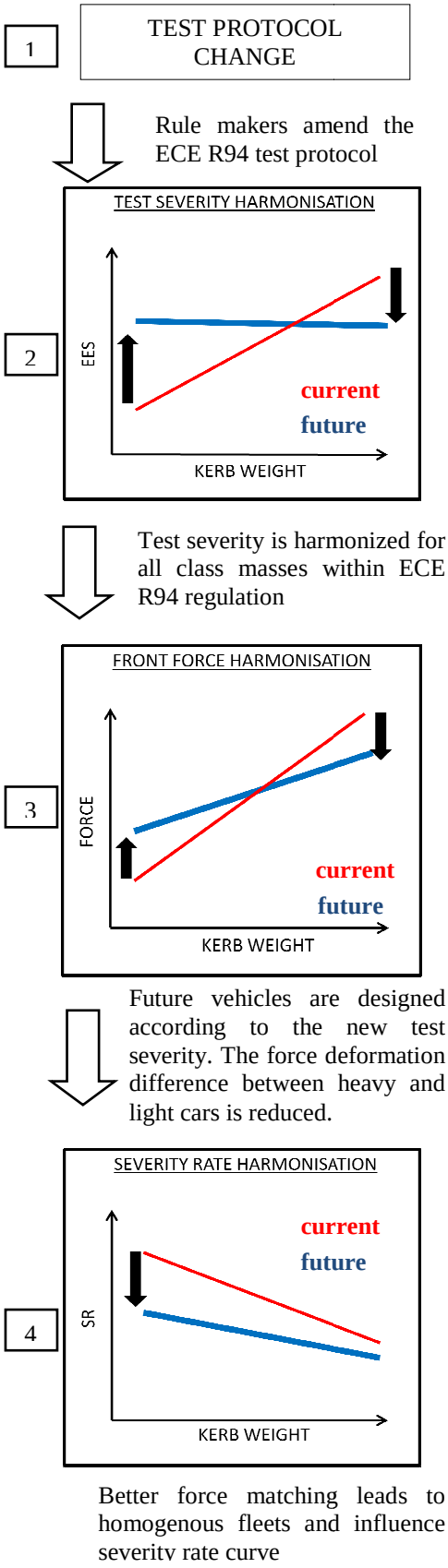


Figure 21: Impact of test protocol change on severity rate

Figure 21 summarizes the global approach and the change in regulation that influence the test severity that influence the vehicle design, that influence the fleet and severity rate and at the end reduce number of fatalities and injured.

CONCLUSIONS

Recent accident studies confirm and show that severity rate harmonization is one of the most effective ways to reduce the number of road accident victims.

Part of the problem comes from the ODB test itself being more severe for heavy vehicle than light one. Hence, the test is considered as mass dependent.

According to different examples shown, adapting the vehicle front end to compensate for the current side effect of the ODB test is not adequate and doable for economic, design and safety reasons.

In contrast, making the test more realistic and adapting it, should be introduced as a first priority to harmonize the test severity for all mass classes. This introduction will allow switching towards a homogeneous fleet that seriously reduces aggressivity and severity rate issues.

Three approaches were proposed with different added value. These are, from the lowest to the highest potential for a desired homogeneous test severity:

- remove the deformable element and fix the test speed to the desired test severity,
- adapt the test speed to the kerb weight of the vehicle taking into account the energy absorbed by the current barrier,
- change the deformable element and fix the test speed according to the desired severity.

These three propositions answer the problem of force matching and global aggressivity, however, only the last one is able to fix the structural interaction, problem, also raised as a priority.

REFERENCES

[1] Heavy vehicle and Assessment Protocol , Euro NCAP 2012.

[2] NHTSA: Evaluation of the Enhancing Vehicle-to-Vehicle Crash Compatibility Agreement: Effectiveness of the Primary and Secondary Energy-Absorbing Structures on Pickup Trucks and SUVs – may 2012

[3] Technical assistance and economic analysis in the field of legislation pertinent to the issue of automotive safety: provision of information and services on the subject of accident analysis for the development of legislation on frontal impact protection –TRL, 2010- D Richards, M Edwards and R Cookson-

[4] Self Protection and partner protection for new vehicles (UNECE R94 amendment) - Cyril Chauvel-ESV Washington 2010 - Paper number 11.0209

[5] Results of NHTSA's Comparison of the Offset Deformable Barrier and the Progressive Deformable Barrier Test Procedures ESV 2009, J. Saunders paper 09-0549

[6] Informal document No. GRSP-41-25, 41st GRSP, 7-11 May 2007, ECE/TRANS/WP.29/GRSP/2007/17 –

[7] EEVC WG 15 Final Report to EEVC Steering Committee, May 2007,

[8] PDB Barrier face evaluation by DSCR and NHTSA'S joint research program, Pascal Delannoy, 20th ESV Conference 2007, Paper No. 07-0303

[9] Australian Research To Support The Ihra Vehicle Compatibility Working Group, K A Seyer, C A Newland and M B Terrell, ESV 2003 Paper No: 274

[10] Compatibility assessment proposal close to real life accidents P.Delannoy, ESV Nagoya 2003, paper number 94

[11] Design Considerations for a Compatibility Test Procedure, Stephen Summers, William T. Hollowell, Aloke Prasad, Society of Automotive Engineers Paper No. 2002-02B-169. March 2002,