ANALYSIS OF COMPATIBILITY AND OCCUPANT INJURY MECHANISMS IN FRONTAL COLLISIONS INVOLVING BUSES IN SPAIN

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ABSTRACT

The European Regulations introduced over the last years on the enhancement of secondary safety of buses and coaches are proving to be efficient, reducing accident seriousness and their consequences, as real accident data can show. However these measures seem to be insufficient, especially in certain impact configurations such as frontal collisions in which not only the driver and the crew are the most prone to casualty but also the rest of the occupants who often suffer severe or fatal injuries.

The aim of the study presented in this paper is to identify the main characteristics of large passenger vehicles (LPVs) frontal collisions that have occurred in Spain over the last years, and to analyse the compatibility of these vehicles with their collision partners or obstacles in frontal impacts.

The study has two main parts: a statistical analysis based on the Spanish Accident Database that includes bus accidents occurred in Spain between 1993 and 2008 investigated by the Police Forces with at least one injured person as consequence of the accident; and an in-depth study using a LPV accident database including highly detailed information, retrospective investigation, reconstruction, police reports and medical records with injury description and mechanisms. A total of 28 real-world accidents were considered, in depth-analysed by the Accident Research Unit of INSIA and investigated in collaboration with the Police Forces, Paramedics and Hospitals.

It is expected that the results obtained in this research will help to gauge the extent of the problem in the Spanish roads and to understand the influence of compatibility on the injury severity of the occupants of both vehicles and their mechanisms.

The statistical analysis revealed that interurban frontal bus accidents represent around 50% of the total Spanish interurban bus accidents with killed or severe injuries. The in-depth analysis based on the injury mechanisms most commonly found suggests that new structural solutions in the frontal design of the bus should be considered to enhance occupant protection and to improve the compatibility between the vehicles involved.

There are not many research works about LPVs frontal collisions up to day, so the potential enhancement of secondary safety is still high. This study is based on Spanish data and its conclusions reflect the situation in the Spanish roads, however it should be extended and considered as guidelines for future research works.

INTRODUCTION

Large passenger vehicles (LPVs) are rarely involved in road accidents compared in proportion to other vehicles. The casualties registered each year in these accidents are quite few; making buses and coaches one of the safest means of mass transportation. In Europe, bus and coach accidents represent less than 1% of all traffic fatalities [1], whilst in the United States an average of 200 occupants are killed in a year from which 40 are occupants of the bus [2]. The ratio of these fatalities by the number of passengers and travelled kilometres is often compared to the one obtained in trains and planes [3]. Nevertheless, the media impact when a bus or coach accident occurs is stunning. The outcomes in terms of injury severity for occupants of both the bus and its collision partners, when involved, suggest that issues like compatibility and occupant protection, in certain accident configurations, still have a large potential of enhancement.

Substantial efforts have been undertaken as regards the rollover protections for occupants of LPVs. In Europe, real accident data are proving the effectiveness of the Regulations enforced over the last years on the enhancement of secondary safety of buses and coaches. However, there is still a potential to reduce furthermore the casualties, especially on compatibility issues when head-on collisions are considered.

Compatibility is a complex issue, and it has been recognised by many research teams during the last decades. Although the issue of compatibility has been highlighted since the 1960s, little systematic research has been performed until recently.

The International Harmonised Research Activity (IHRA) on compatibility was one of the six Working Groups set up following the Melbourne ESV (May 1996), as it was recognised that international co-ordination of research programmes would be beneficial.

The European Union and the European Enhanced Vehicle-safety Committee (EEVC – WG15) were asked to be the lead for compatibility. The first meeting was held on 1997. Its main objective has been to develop a test procedure for car frontal impact compatibility.

However the major research effort has been focused on car compatibility. LPVs compatibility is an issue that needs to be addressed in order to reduce the number of fatalities and injuries among occupants of both the LPV and its collision partner.

The present research study, based on real-world accident data of accidents involving at least one LPV in a frontal collisions with an obstacle or other vehicles, aims to identify specific characteristics of this scenario, which could serve to find new efficient protections measures. This work should lead to improve the LPV frontal compatibility for both the opposite vehicle and self protection.

SOURCES AND METHODS

Statistics from the National Accident Database

A sample of accidents involving LPVs in head-on collisions was extracted from the Spanish Accident Database. This database is compiled by the Road Traffic Directorate (DGT) and includes all road accidents occurred in the Spanish public roads, with at least one injury person as consequence and one motor vehicle involved, all reported by the Police Forces. It contains an average of 93000 accidents per year.

The available information about LPVs does not allow splitting into categories M2 and M3 according to European Directive [4]. So, “LPVs” includes indistinctively both “buses” and “coaches”.

A descriptive statistical analysis of the derived dataset has been performed. Records related to compatibility issues were extracted for this purpose. First the crashworthiness of the collision partner was studied; smaller vehicles with less mass like cars and vans were considered and their behaviour was compared. Then the impact on the LPV was analysed separately, considering for this a wide range of collision partners from cars to heavy goods vehicles (HGVs). Finally the crashworthiness of bus and coaches was contrasted with other large vehicles that have a different frontal geometry and structural behaviour, such as lorries, comparing the consequences for occupants.

Only the consequences for the occupants of the first row were considered for this analysis, for both the LPV and its collision partner.

In-depth analysis of real LPV accidents

The second part of this study uses fully detailed information of real-world LPV accidents to identify the main characteristics of frontal collision involving buses and coaches. Only M3 category vehicles have been analysed during this phase.

The aim was to depict the injury mechanisms and to study the frontal damage of the LPV and the collision partner in head-on impacts.

Representative cases were selected from an in-depth survey of real-world bus and coach accidents (SIRABUS database), which are gathered in a dataset of 28 accidents. These are serious accidents with killed or severely injured occupants as consequence, collected between 1996 and 2009. Detailed information from scene, vehicle and human records is available in the dataset.

The SIRABUS database was commissioned to INSIA by the DGT and includes retrospective investigations, accident reconstructions through computer simulations, police reports and medical records with injury descriptions and mechanisms.

Kinematic parameters were estimated from the in-depth analysis and derived from the simulations, all presented in the next section.

Representative cases that stand out due to their particular characteristics and consequences are summarized in this paper, and their most interesting aspects are contrasted with the patterns found from the statistical analysis.

RESULTS

Statistical research

First part of the research is a statistical analysis of accidents with LPVs involved occurred in Spanish roads. They make a 2% average share of annual road accidents across Spain.

The aim is the analysis of compatibility between LPVs and their collision partners in frontal collisions, and comparatively with the equivalent cases with HGV involved.

The period of analysis covers from 1993 to 2008. Two samples were selected from the Spanish Accidents Database in which the cases that fit the following criteria were included:

- First sample collects accidents with at least one LPV involved, and second sample includes accidents with at least one HGV involved. The rest of the criteria are the same for both samples.
- Only frontal collisions have been selected, and with two vehicles involved in the accident. In case of obstacle crashes, it was not possible to identify the bus impact area.
- Accidents must have occurred in interurban areas.
- The injury severity analysis has been performed only for drivers and front seat occupants (they have been called "front row occupants").

The selection of these two samples is justified by several reasons. First, it has been considered interesting the comparison of compatibility features of two types of heavy vehicles: LPVs and HGVs. Secondly, only interurban accidents have been included, to assess the accidents features at high speed. Thirdly, the injury severity analysis has been performed only for the occupants of the front row of the vehicles due to the accident configuration and its relation with compatibility.

When considering two-vehicle accidents it is possible to identify the opposite vehicle. Three different categories have been considered to evaluate their compatibility when crashed with a heavy vehicle: a) passenger cars; b) light goods vehicles (LGVs), with a gross vehicle weight under 3.5 tones, e.g. vans; c) large vehicles like HGVs or other LPVs.

First, the evolution of the number of accidents of each category in the samples selected is presented (in Figure 1).

There is a greater number of accidents with HGV than with LPVs involved. Also the accidents with cars as collision partners are the most frequent for both HGV and LPVs.

The injury severity distributions shown below are based in the ratio of KSI among the front row occupants by the total number of front row occupants, for each kind of vehicle involved and its collision partner.

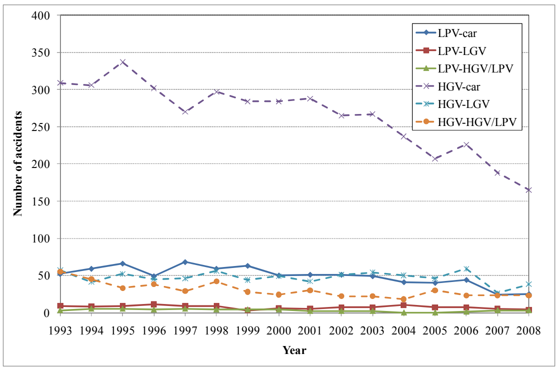

Figure 1. Number of accidents per year.

The following graph (Figure 2) shows the evolution of the ratios for the accidents of the samples selected and in which the collision partner for the LPV or HGV is a car or a LGV.

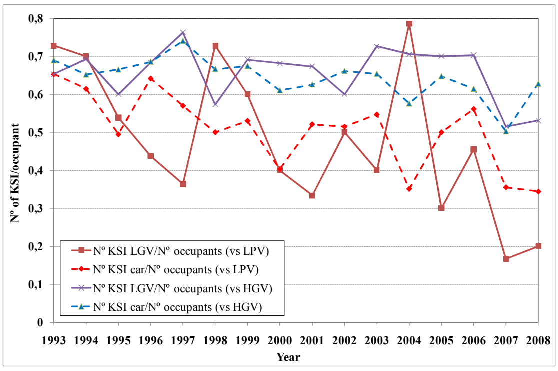

Figure 2. Evolution of the KSI/occupant ratio for cars and LGVs, in frontal collisions with LPVs and HGVs.

Among the front row occupants of cars and LGV in accidents with LPVSs and HGV as collision partners the trends are decreasing along the period of analysis. However the decreasing rate is higher when the opposite vehicle is a LPV whilst when it is a HGV the rate is much lower. The reasons for these facts may be multiple. In the last 10 years, and due to the introduction of the EuroNCAP tests, the car manufacturers have improved greatly the structural behaviour of those vehicles, making them safer in case of frontal collision, and this can explain the downward trends of ratios for passenger cars front row occupants.

Regarding the fact that HGVs are more aggressive than LPVs for the front row occupants of the opposite vehicles, it can be explained by the structural design of the frontal of both kinds of large vehicles. Whilst the frontal underrun protection in HGV has not been compulsory in Spain until 2003 (and only in new vehicles registered from this year), the low floor design in LPVs has been very common since long time; this design presents resistant structures at a low level of the front of the LPV which prevents from underrun, improving the compatibility of these vehicles.

When comparing the ratios of injury distributions among the front row occupants of cars and LGV (for each category of opposite vehicle, bus and HGV), great differences cannot be found. Though the weight of LGV is greater, passenger cars (as stated previously) have experienced an improvement of their structural design in the last years, increasing their crashworthiness.

Among the front row occupants of LPVs and HGVs (Figure 3), the injury severity ratios are greater when the collision partner is a LGV than when it is a car (LGV are heavier and geometrically different than cars).

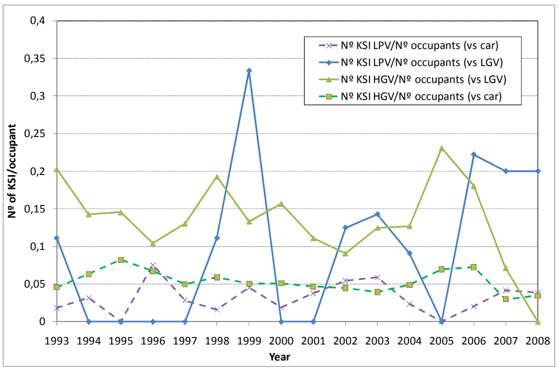

Figure 3. Evolution of the KSI/occupant ratio for LPVs and HGVs, in frontal collisions with cars and other LPVs.

Next (in Figure 4) it is shown the evolution of the ratio selected for front row occupants of LPVs and HGV when having an accident with a LPV or a HGV as collision partner.

The severity levels are lower for LPV front occupants than for HGV front occupants, when having a collision with large vehicles (LPVs or HGVs). It can be explained partly due to the low number of cases of frontal accidents between buses and HGV/buses. But as the figure shows, despite it is thought that the driver position in LPVs is particularly exposed when having a frontal collision (due to the low distance from the driver position to both the front edge of the vehicle and to the floor), in the case of HGV this problem is not still solved.

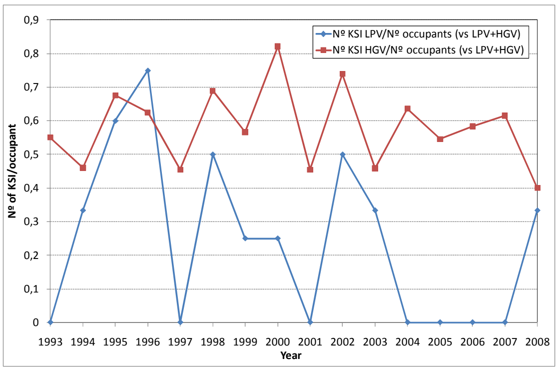

Figure 4. Evolution of the KSI/occupant ratio for LPVs and HGVs, in collisions with HGVs and LPVs.

Overview of frontal collisions included in the in-depth analysis

The revision of all cases included in the SIRABUS database revealed that in 14 out of 28 LPV accidents, one of the most important events of the accident was a frontal impact; this means another vehicle or an obstacle is hit by the frontal of the LPV. The distribution of all the 28 accidents on the Spanish territory is presented in (Figure 5). Frontal accidents are marked distinctively.

As shown on the map, the collected sample covers a wide spread area of the Spanish territory. However, the representativeness of this sample is limited due to the reduced number of cases.

Figure 5. Spread of frontal accidents from SIRABUS.

The vehicle type and the collision partner or struck obstacles for the 14 frontal accidents selected from SIRABUS are listed in (Table 1).

There is only one bus (vehicle designed for urban transport) included in the list, the rest were different sort of coaches (vehicles designed for interurban transport). This is due to the high seriousness of the selected accidents, according to the sampling criteria of SIRABUS, which come about more often out of urban areas, where the driving speed is higher and more suitable for coaches rather than buses.

Table 1. Vehicle type and collision partner or stroke object

Accident ID	Type of LPV	Collision partner/obstacle	Event order
IN1001	Coach	Car	1^{st}
IN1002	Double Decker coach	Mountain wall	2^{nd}
IN1004	Scholar coach	Lorry	1^{st}
IN1007	Coach	Lorry	1^{St}
IN1008	Coach	Lorry	1^{st}
IN1010	Coach	Articulated lorry	1^{st}
IN1013	Coach	Lorry	1^{st}
IN1014	Scholar Coach	Car	1^{st}
IN1016	Coach	Bridge pillar	2^{nd}
IN1017	Coach	Car	1^{st}
IN1018	Coach	Articulated lorry	1^{st}
IN1019	Coach	Sewer siphon	2^{nd}
IN1024	Coach	Articulated lorry	1^{st}
IN1027	Suburban Bus	Mobile crane	1^{st}

All these cases can be classified in three typical scenarios: S1) Head-on collision with a passenger car; S2) Collision with a HGV (which has a considerable mass and a flat surface); S3) LPV crashes into a rigid obstacle.

For all scenarios, the accident took place in conventional roads or highways. The overlap varies from 5 to 100% of the frontal surface.

Whilst in the third scenario the LPV is the only vehicle involved, in the other two scenarios the number of vehicles involved in the accident varies from 2 (most frequently) to 5.

Vehicle damage and impact kinematics

__Scenario 1__ The damage suffered by both the LPV and the car is clearly illustrated (in Figure 6). Some parameters of the collision like velocity change (ΔV), overlap and maximum depth of the deformation are also specified for the LPV.

In one accident (IN1001) the coach caught fire after the collision, resulting most of the vehicle burnt; however damages from the direct impact were clearly differentiated.

By regarding the damages of all vehicles it can be noticed that the coach structure resulted almost unharmed compared to the car. Nevertheless, important deformations were produced at the lower frontal.

The frontal of the passenger car was completely crushed, absorbing most of the plastic deformation energy of the impact.

ID	LPV	Car
IN1001	 ΔV = 31 km/h Contact overlap: 48% Max. depth: 1 m	
IN1014	 ΔV = 11.8 km/h Contact overlap: 10% Max. depth: 1 m	
IN1017	 ΔV = 3.27 km/h Contact overlap: 10% Max. depth: 0.1 m	

Figure 6. Vehicle damage. Scenario 1.

Within this scenario, neither ΔV nor overlap seems to affect directly on the deformation of the LPV and its extent. It is rather an issue of mass, geometric and stiffness compatibility, as shown in previous studies [2].

__Scenario 2__ Eight out of the 28 accidents are included in this scenario. In these frontal collisions against HGVs it was observed that, when directly impacted, the frontal of both vehicles is seriously harmed, and the windscreen is blasted.

Two rear-ends were included in this scenario due to the characteristics of the impact, which from the LPV's point of view were similar to other frontal collisions. In these cases the frontal of the LPV hits the back of a HGV which is a flat and rigid surface and the velocity change is comparable to the rest of head-on collisions of this scenario.

There were intrusions at different heights at the driver and crew positions, affecting especially the leg room. The maximum depth of the deformations depends not only on the velocity change, but on the contact overlap, as shown (in Figure 7), where 4 representative collisions are presented showing the vehicle damage.

It is noticeable that the deformation energy is divided between both vehicles, but the absorption capacity is clearly limited due to the stiffness of the frontal structures.

ID	LPV	HGV
IN1007	 ΔV = 32 km/h Contact overlap: 15% Max. depth: 9 m	
IN1008	 ΔV = 31 km/h Contact overlap: 65% Max. depth: 0.9 m	
IN1027	 ΔV = 32 km/h Contact overlap: 80% Max. depth: 0.8 m	
IN1024	 ΔV = 45 km/h Contact overlap: 100% Max. depth: 1 m	

Figure 7. Vehicle damage. Scenario 2

Comparing the first three out of the four collisions included (in Figure 7), the influence of overlapping on the deformation of the vehicle can be clearly assessed. Thus for similar ΔVs, the deformation of the LPV can vary from almost the entire vehicle length to 0.8m. In the first case (IN1007), the longitudinal frame member absorbs very few impact energy due to the offset with the collision partner at the impact point. In the second (IN1008) one longitudinal frame member is clearly more collapsed than the other, and the maximum longitudinal deformation is 0.9m. In the third case (IN1027), both longitudinals collapse together and the deformation depth is reduced to 0.8m.

The influence of ΔV on the vehicle damage can be observed by comparing the last two cases (IN1027 and IN1024). It can be noticed that in similar conditions and the same overlap, a difference of 13 km/h of the delta velocity can be translated in 20 cm or so of deformation of the entire frontal.

Due to the limited space available, the deformation depth is almost equal to the intrusion, especially for the driver and crew positions.

<u>Scenario 3</u> The influence of both overlapping and ΔV on the vehicle deformation is also manifested in this scenario. Images from the scene are presented together with the vehicle damage (see Figure 8).

In the first collision (IN1002) a double-decker coach crashes into a mountain wall. The deformation affects the entire frontal, causing intrusions into the driver and crew positions, and into the first seat row of the upper deck. Despite the high collision speed, the deformation energy is absorbed by the entire frontal structure limiting the maximum deformation depth. However the deformations are comparable to the intrusions, due to the lack of space available for deformation.

In the second case (IN1016), a high ΔV combined with small overlap results into a tremendous intrusion on the right half of the coach. The deformation is totally unsymmetrical; the left half was almost unaffected. This particular profile of damage suggests that the structural design of the frontal should be improved in order to enhance the force distribution across the entire frontal and thus the absorption capacity, as has been previously proved in smaller vehicles [5], with beneficial results.

By comparing the collision described above with the last collision (IN1019), the influence of ΔV when impacting a rigid object can be assessed. The overlapping is similar in both cases, but in the last case, the coach impacts the sewer siphon at a much lower speed. The vehicle had a previous rollover, sliding along the ditch on its right side, and loosing momentum.

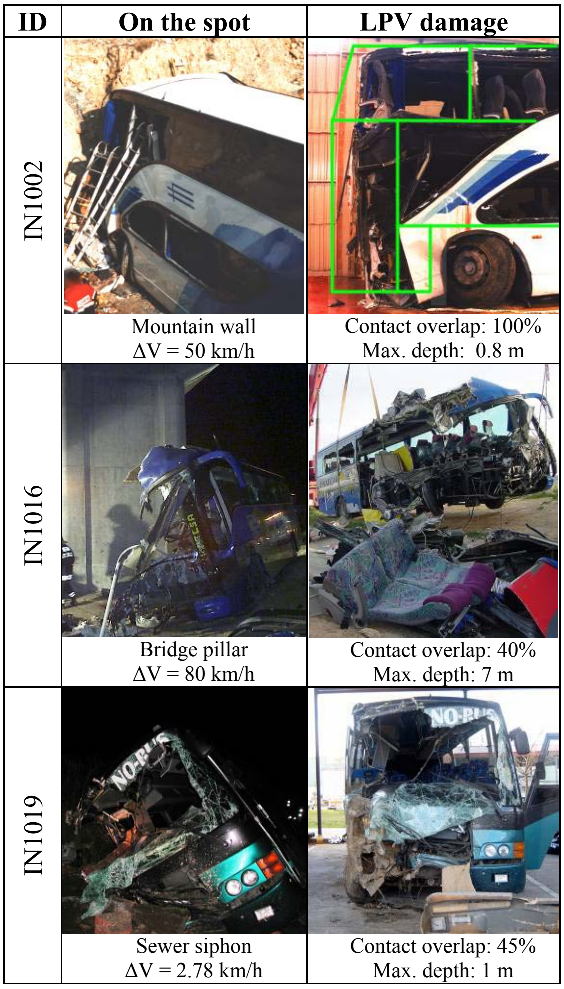

Figure 8. Vehicle damage. Scenario 3

Although the high collision velocity, when the entire frontal structure absorbs the deformation energy (IN1002), the depth results similar to the one obtained at a lower speed and smaller overlap (IN1019).

Injury mechanisms

A brief revision of the injury severity is summarised in Table 2. This shows the occupancy of the LPV at the moment of the accident, the resulted injury severity and, separately, the injury severity of the driver.

The distributions show that 20% of the occupants were killed in the accident, 26% were severely injured, 46% were slightly injured and only 8% of the occupants were unharmed. Within the drivers, the resulted distribution is: 28% were killed, 50% were severely injured, 14% slightly injured and only 7% unharmed.

Table 2. Injury outputs

Accident ID	Nr. of Occupants	Fatalities	Severely injured	Slight injured	Driver Severity
IN1001	58	31	5	15	Fatal
IN1002	48	11	31	4	Severe
IN1004	46	7	14	25	Severe
IN1007	38	27	5	6	Fatal
IN1008	30	0	1	27	Severe
IN1010	18	1	5	8	Severe
IN1013	23	1	5	15	Severe
IN1014	15	0	0	7	Slight
IN1016	43	6	18	17	Severe
IN1017	46	1	15	30	Slight
IN1018	32	0	4	24	Severe
IN1019	12	2	5	4	Uninjured
IN1024	5	1	2	2	Fatal
IN1027	28	3	3	22	Fatal
Total	442	91	115	206	

The drivers suffered the most severe injuries followed by the second row occupants.

A classification of the occupants by the injury mechanism cause of the most severe injuries has been done (see Table 3); the rate from the total number of occupants of the vehicle is included in round brackets. Projection was the most common for all occupants; intrusion for the first and second row; some partial and complete ejections were also registered, but these were caused by a previous or subsequent rollover, when the case. Some occupants were also entrapped between seats and some few died by asphyxia.

In projected passengers impacted against the backrest of the front seat or bulkhead and the most common injuries were contusions and fractures affecting the face, head, chest, abdomen and both upper and lower limbs. Intrusions provoke lacerations and fractures.

Table 3. Injury mechanisms

Accident ID	Intrusion	Projection	Ejection	Driver Mechanism
IN1001	Unknown	Unknown	Unknown	Unknown
IN1002	4 (8.3%)	30 (62.5%)	0	Intrusion
IN1004	10 (21.7%)	16 (34.7%)	Unknown	Intrusion
IN1007	14 (36.8%)	18 (47.6%)	6 (15.7%)	Intrusion
IN1008	1 (3.3%)	27 (90.0%)	0	Intrusion
IN1010	2 (11.1%)	11 (61.1%)	1 (5.5%)	Intrusion
IN1013	1 (43.4%)	19 (82.6%)	1 (43.4%)	Intrusion
IN1014	0	7 (46.6%)	0	Projection
IN1016	20 (46.5%)	21 (48.8%)	0	Projection
IN1017	Unknown	Unknown	Unknown	Unknown
IN1018	1 (3.1%)	28 (8.7%)	0	Intrusion
IN1019	0	11 (91.6%)	0	–
IN1024	1 (20.0%)	4 (80.0%)	0	Intrusion
IN1027	1 (3.5%)	20 (71.4%)	0	Intrusion

DISCUSSION

The representativeness of the data included in this study and thus the results and conclusions are limited due the available information for the statistical analysis, and the number of cases for the in-depth analysis respectively. However, the complementary results of both methodologies may represent the situation on the Spanish roads, but can not be directly extrapolated.

Although serious accidents involving LPVs occur rarely, making this a safe means of transportation, this study shows that compatibility is still an issue that must be further improved. The connectivity across the frontal should be enhanced so both longitudinal frame member will deform in the event of a frontal collision despite the offset of longitudinal axis of both vehicles.

It was concluded that the space available for the vehicle deformation is almost inexistent; this may generate intrusions in the vehicle making their occupants prone to injury, especially in the front seats.

New solutions should be adopted to improve the frontal of buses and coaches, considering the shortcomings on the structural behaviour presented in this paper. In this sense, the solution described by Steinmetz [6] should be highlighted. Other solutions – [7] and [8] – regarding the absorption capacity of large vehicles should be also considered.

CONCLUSIONS

Accidents involving LPVS do not happen very often in the Spanish roads in comparison to other vehicles. However, the media impact generated around them motivates the interest of having a clear picture of the issue.

The statistical analysis performed in this study reveals that in Spain, interurban accidents are the most serious, and among this group, frontal collisions represent a half of the cases. Nevertheless it was found that the rates of killed and severely injured per occupant within this accidents are not especially high compared to other large vehicles. The crashworthiness of the LPV depends on the collision partner, and especially on its size and mass.

The in-depth analysis revealed that on head-on collisions with passenger cars, the absorption capacity of the LPV is very low, so the car absorbs most of the deformation energy.

In collisions in which the LPV frontal hits a rigid obstacle or another large vehicle, the deformations and the intrusions suffered by the vehicle depend directly on both overlapping and velocity change.

The findings suggest that the frontal design of buses and coaches could be improved to enhance the connectivity across the frontal and thus the occupant protection.

ACKNOWLEDEGEMENTS

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