Chapter

Passive Safety of Children Carriages on Busses

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Abstract

The safe mobility of young children traveling with carriages in public transportation vehicles is a problem that has not yet been satisfactorily resolved. The lack of national and international standards in this area in the past led to the development of a research developed jointly by the Universitat Politécnica Valencia and the Universidad Politécnica Madrid (Spain). This book chapter shows the results of a research program developed to evaluate the dynamic behavior of occupied children carriages (ChC) during typical driving maneuvering—sudden braking, acceleration and cornering—and in case of low-g accidents reproducing frontal impacts resembling real traffic events (deceleration 2 g, ΔV 20 km/h). In the dynamic trials, three ChC-restraint prototypes and a typical wheelchair (WhCh) back-restraint system combined with two representatives of up-to-date ChC models in misuse and correct use configurations were tested. The results demonstrated the need for preventing children injuries as a consequence of low-g accidents.A Code of Good Practice was proposed jointly with the use of a new ChC-restraint system considering R 107–06 series of amendments. The new design improves the latest revision of regulation R107 regarding the use of back-restraint systems for the transport of WhCh and ChC passengers traveling on busses.

Keywords: transportation safety, children carriages, children injury, restraint system, public transport

1. Introduction

The proper use of public transport systems is currently a vital need that must be pursued by public administrations to maintain quality standards that facilitate the adequate mobility of the majority of the population. These minimum standards should include both accessibility, comfort, and safety when traveling, so that their use can be extended to groups with disabilities or reduced mobility. Among these groups, we must not only include people with physical disabilities but also those who suffer from cognitive or sensory disabilities—auditory or visual. In the same way, accessibility and safety problems were important for passengers traveling in road transport vehicles without leaving their wheelchairs; there are actually passenger groups that experience similar difficulties at the time of using bus transport systems. This is the case of passengers traveling accompanied by children's carriages.

There are not many statistical studies that analyze the accident rate related to the transport of children's carriages (ChC) on busses, but their behavior, from the transport safety perspective, is very close to that suffered by passengers traveling without leaving their wheelchair (WhCh). In this sense, the scientific community has introduced the term *incident* in accident studies, more in line with the interaction of the passenger—with/without reduced mobility—with the transport vehicle environment, considering the source of the accident, not only the vehicle's own impact but also other causes such as the boarding-disembarking action, the use/misuse of restraint systems, or the vehicle's critical or emergency maneuvers.

Most studies related with the concurrence of *incidents* in bus transport have shown that these occurred without impacts and in most cases in urban areas [1, 2]. Some studies have concluded that the injuries produced during these incidents were due to sudden changes in speed (60% in braking and 25% in acceleration) [3] or when the vehicle is stopped, during the boarding/disembarking phases [4], affecting the elderly and the disabled to a greater extent. Most of the damage suffered occurs as a combination of a WhCh overturning and the occupant's fall, followed by incidents without falls and situations in which the occupant falls from the WhCh [5]. In [6] the behavior of WhCh passengers who suffered incidents (with or without vehicle impact), through in-depth analysis of real accident reconstructions, were analyzed. Results showed that the greater severity damages suffered by WhCh users were caused due to the inefficient or nonexistent use of the restraint systems by the WhCh and his occupant, without disregarding the influence of the vehicle's driver when performing emergency maneuvers during normal traffic. The driver's training whose collaboration will be fundamental, both to perform adequate assistance and to ensure boarding-disembarking safe operations, is also important [7].

Taking into account the results obtained in all the aforementioned previous research, it is clear that the transport service operating agencies are aware of the risk that these passengers suffer under normal vehicle conditions. Some data recorded by the EMT Madrid operator during the last 18 months (since April 2018 to date) indicated the occurrence of about 10 incidents with ChC, that is, one every 2 months, in which the baby or child was dropped from the carriage. Most of the incidents were due to sudden braking or closed curve driving, and others due to ChC badly positioned [8]. The EMT Madrid has a fleet composed by approximately 2300 low-floor vehicles.

It should be noted that mobility problems generated by the transport of ChC not only affect the user groups themselves but also the transport service operators, which must face situations of social rejection due to the refusal to accept admission to the transport services of certain types of busses, either due to the absence of specific regulations or due to the ignorance of the possible solutions to the problem generated with this type of users.

The absence of specific standards that regulate the accessibility of ChC to the vehicle constitutes one of the most common difficulties. **Figure 1** shows some examples of typical cases of the troubles that users traveling with ChC in road public transportation vehicles have faced up to. To overcome some difficulties related to access to vehicle interior, some carriage must do so through the front door with the folded carriage (**Figure 1A**). If the carriage cannot be folded, access must be made through the central door to overcome the difference height between the bus stop and the floor of the vehicle (**Figure 1B**). Finally, the maneuverability of the ChC itself inside the transport vehicle constitutes another one of the barriers to mobility that will have to be faced (**Figure 1C**). Another common problem that users' groups and transport operators have had to face consists of the absence of safety systems to hold the ChC during transport (**Figure 2A**), as well as compatibility between market types of ChC and WhCh models, when sharing the space reserved (**Figure 2B**).

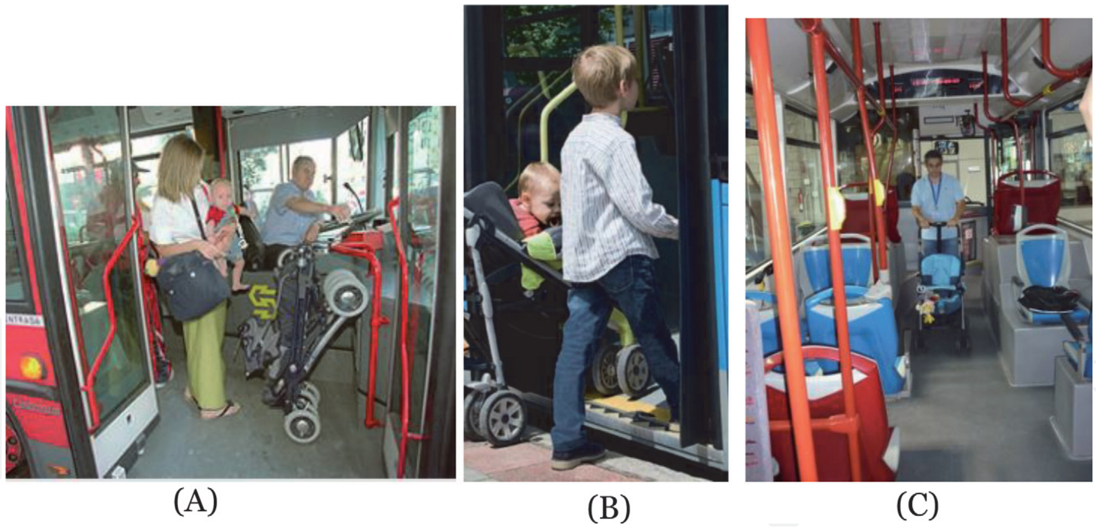


Figure 1.
Examples of the challenges faced by ChC in the access to public transportation vehicles: (A) access with the ChC folded through front door, (B) access with the ChC unfolded thorough central door, (C) difficulties in the maneuverability *inside the vehicle for accessing to the space reserved to ChC (source: EMT Madrid).*

Figure 2.
Examples of the safety conditions in the mobility of ChC in passenger public transportation vehicles: (A) absence of safety systems to hold the ChC unfolded during travel, (B) compatibility of ChC with the WHCHs' space occupied (source: EMT Madrid).

There have not been many studies related to the problem of transporting ChC in urban busses. One of the few and most prominent has been the ASUCAR[1] research project. In the first phase of this project were analyzed the accessibility and safety conditions which ChC had to face up to in this type of mobility. The study was based on a survey of companies operating public and private transportation services in Spain, mainly in urban areas, with the collaboration of the Association of Urban and Road Transports (ATUC) [9]. Of the more than 70 surveys launched in 2008, the responses of 44 companies were analyzed. The results obtained showed that companies used to regulate the access of ChC to urban transport vehicles by applying internal, local, or regional regulations in 70% of cases; the rest, 30%, did

[1] The research project, *Determination of accessibility and safety requirements in the use of children's carriages in public transport vehicles (ASUCAR)*, was funded by the Spanish Ministry of Science and Innovation during the period 2008–2010, within the Program PETRI (REF No. PET2008_0328_01 and PET2008_0328_02), coordinated by the Polytechnic University of Valencia (UPV-IDF), and participated by the Polytechnic University of Madrid (UPM-INSIA) and the Municipal Transport Companies of Madrid (EMT Madrid) and Valencia (EMT Valencia).

not apply any rule or left the final decision at the discretion of the driver. Eighteen percent of the companies did not allow access to tandem-type ChC (twin). Only 45% allowed access to unfolded ChC, which should be located in the area reserved for WhCh (34%), of which only 23% established the preference of WhCh over ChC. Only 25% of companies' limited access to one ChC and 34% facilitated the transport of a maximum of two ChC. Only 25% of them forced the ChC to apply their brakes during transport.

At present, there are companies in Spain that operate urban public transport services that have implemented their own accessibility policy and have regulated access to the different vehicle configurations of their fleet to all types of passengers with reduced mobility, including WhCh, electric scooters, ChC, passengers with walkers or suitcases, bicycles, etc. Such is the case, for example, of the Municipal Transport Company of Madrid (EMT Madrid), which developed in 2015 is an internal regulation that facilitates the mobility of different passengers with reduced mobility with different configurations of transport vehicles [10]. In the case of ChC, and depending on the type of vehicle and the existence or not of other PMR users, access of up to four single or double ChC (tandem) is allowed.

1.1 Legal framework for children carriages' travel mobility

Currently, one of the few international regulations that states the mobility of ChC in road transport vehicles is the UNECE Regulation R107 [11], which explicitly establishes the technical requirements that the spaces reserved for the displacement of ChC in M2 and M3 vehicles must comply. In the UNECE Regulation R107, it is established that transport vehicles legalized according to these regulations must allocate at least one space reserved for unfolded ChC, with minimum dimensions of 1300 mm in length and 750 mm in width. The area reserved for the ChC may be the same as that occupied by a WhCh (if a single reserved space is available), or adjacent to it, in which the carriage must travel in a plane parallel to the longitudinal axis of the vehicle, but without specifying, explicitly, if the orientation of the ChC must be forward or rearward facing. UNECE R107 [3] does not explicitly require the use of any safety system to prevent the carriage and its occupant from being damaged due to sudden maneuvers of the transport vehicle (turning, braking, or accelerating), or in worst-case scenarios, when an impact as a result of an accident occurs. The approach established in this transport configuration, therefore, is based on the use of passive safety systems for the transport of ChC based on back-restraint walls, as due for WhCh.

The accessibility conditions of the ChC must be the same as those necessary for a WhCh, that is, there must be at least one door that allows access to this area, and the carriage must be able to maneuver and move through the interior without problems and without any steps, holes, or uprights that make it difficult to access the reserved place. To prevent the ChC from moving inside the passenger compartment, conditions similar to those required for a WhCh are established when traveling with an orientation rearward facing, that is, the reserved area must be contiguous to one side or the wall of the vehicle, while on the other side, a retractable bar—or equivalent rigid device—that limits the lateral displacement of the ChC must be allocated. At the front end of the area reserved for the ChC, a backrest perpendicular to the longitudinal axis of the vehicle shall be placed, which must meet the same structural and resistant requirements required in the case of WhCh transport.

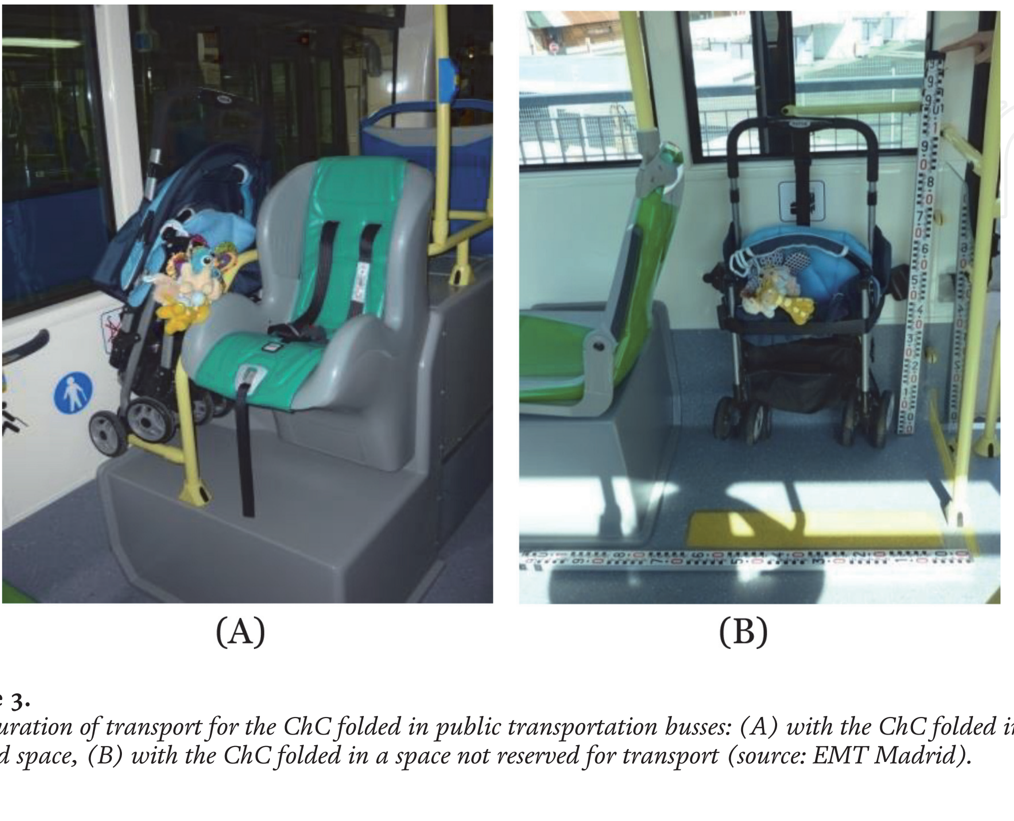
In addition, the companion person must be able to be attached during the trip to a bar or handle, anchored to the side or wall of the vehicle. The reserved area must have a pictogram indicating that the area is reserved, as well as pictograms on the vehicle access doors through which the ChC has to enter and exit. The reserved area will be completed with a warning device (button or similar), which allows the passenger to request the driver of the transport vehicle to stop at the next stop.

2. Accessibility analysis of children carriages in urban busses

The compatibility between the different market typologies of ChC with the different urban busses designs requires the analysis of some habitability parameters, such as ChC dimensions (maximum and minimum gauges of the folded and unfolded ChC) and constructive characteristics of urban busses (dimensions in the passenger compartment, number and location of accessible doors).

Based on results obtained in the development of the ASUCAR project, these constructive parameters were defined with some clarity in previous research [12]. In the aforementioned work, two transport configurations of the ChC inside the vehicle were determined: those configurations in which the ChC is folded and those in which it is used unfolded. When the ChC is used folded inside the vehicle, the child will travel in the arms of a companion or in a special seat for the children's transportation, if there is one installed on the bus (**Figure 3A**); in that case, the ChC is transported as a luggage. To do this, a special area inside the cabin must be enabled so that folded ChC can be deposited as if they were luggage; thus preventing unwanted maneuvering of the vehicle could cause discomfort or damage to other passengers. There is, however, the possibility of transporting the folded ChC in an inappropriate place inside the vehicle (**Figure 3B**), where, in case of sudden movements due to unusual maneuvers of the vehicle, the carriage instability can cause inconvenience to other passengers.

In the case of ChC being transported unfolded in the vehicle, it is usual for the child to travel inside, and in that situation the ChC is used as a motor vehicle seat. **Figure 4A** shows an example of good transport configuration, in which the carriage is located occupying the space reserved for the WhCh, oriented in a rearward-facing direction with the backrest attached to the back restraint. However, it is also common to find incorrect situations in which the carriage occupies the space



(A) (B)

Figure 3.
Configuration of transport for the ChC folded in public transportation busses: (A) with the ChC folded in a reserved space, (B) with the ChC folded in a space not reserved for transport (source: EMT Madrid).

(A) (B)

Figure 4.
Configuration of transport for the ChCs unfolded in public transportation busses: (A) example with the ChC unfolded in the space reserved for the WHCH, (B) example with the ChC unfolded with the space reserved for the WHCH occupied by a companion (source: EMT Madrid).

reserved for the WhCh facing rearward, with a companion touching the back restraint instead of the ChC (**Figure 4B**). This problem occurs as a result of ignorance or misinformation from the users and operators, which do not have internal standards or codes of good practice that regulate the conditions in which this type of mobility must occur.

Finally, in the study conducted by [9, 13, 14], the maximum and minimum dimensional gauges corresponding to more than 150 types of ChC were determined, both in the folded and unfolded configurations. The values obtained allowed to define the most extreme gauges from the dimensions measured on the up-to-date market ChC. These gauges were classified according to the type of carriage to be used, as stroller, twin chair, or tandem. For defining these gauges, two facts in the use of these products were also being considered:

- Firstly, carrycot type is only used during the first months of the child's life or until he reaches 10 kg of weight or 76 cm in height.

- Secondly, the use of car seats is limited to their permanent installation in private vehicles, although in some public transport busses they could be installed as an alternative (**Figure 3A**) when the ChC is folded.

During the development of the ASUCAR project, up to 77 models of continuous low-floor busses interiors were analyzed, representing the majority of large capacity urban accessible vehicles to transport ChC [13]. The objective of this analysis was based on determining which configurations of accessible vehicles to WhCh minimum and maximum dimensions of the front and rear bus aisles, the number of access doors and the length of space reserved for WhCh of the vehicle, and the number of referenced WhCh which fit in it were established—1200 mm length, 700 mm width, and 1350 mm height [11, 15].

To determine if the ChC is dimensionally compatible with the different low-floor busses designs, a comparative analysis was carried out between the maximum gauges obtained for the deployed carts. **Figure 5** shows the maximum and minimum gauges obtained for unfolded (A) and folded (B) carriages, respectively. This study was intended to verify if an occupied ChC could circulate deployed from

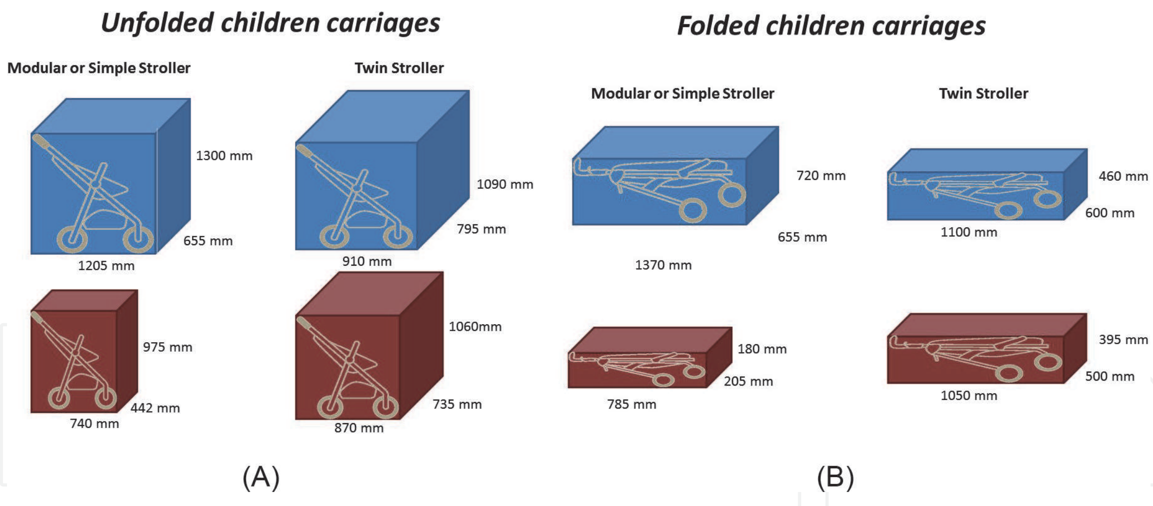


Figure 5.
Maximum and minimum gauges of the (A) unfolded and (B) folded ChCs [12–14].

the front door to the area reserved for WhCh, or if it should do so from the central door. Also, the maximum number of ChC that could be located in the area reserved for the ChC was determined. The results of the comparative study are shown in [13] and can be summarized as follows:

- In the case of the transportation vehicle which has only a space reserved for WhCh:
    - If the space reserved for WhCh is not occupied, a deployed ChC can be placed in the longitudinal direction, or two ChC in the transverse direction.
    - If the space reserved for WhCh is occupied, there is only one possible configuration in which a WhCh can travel simultaneously with a ChC in the longitudinal direction.
- When the transport vehicle has two spaces reserved for WhCh:
    - If the reserved space for WhCh was unoccupied, one or two ChCs deployed in the longitudinal direction, or up to four ChCs in the transverse direction, can be placed.
    - If the reserved space is occupied by only one WhCh, a WhCh and a ChC can be traveled simultaneously in the longitudinal direction, or the WhCh and two ChCs in the transverse direction.
    - If the reserved space is occupied by two WhChs, no ChC deployed inside the vehicle can be moved.

3. Children carriages' kinematics during driving vehicle maneuvers

During the development of the ASUCAR project, a series of experimental tests were carried out whose objective was to reproduce the dynamic behavior of a ChC inside a public transport vehicle, under typical traffic maneuvers, such as sudden accelerations, critical braking, and extreme turns at maximum speed. The tests tried to reproduce urban and suburban traffic conditions and were implemented both in closed and open circuits [14]. The closed-track tests were carried out at the facilities of the Institute for Automobile Safety Research (INSIA), from the Polytechnic University of Madrid, and at the facilities of the municipal transport operators of Valencia and Madrid. The open circuit tests took place in the streets of the cities of Valencia and Madrid (Spain). These open circuit tests were carried out with congested traffic, representing routes where frequent stops, traffic lights, roundabouts, tunnels, and slopes could be found on the bus tracks.

Transport vehicles of category M3 were selected. The vehicle model was a SCANIA N230 E4 with a CARSA City body. The maximum authorized weight was 19,000 kg, with a length of 11.99, 2.5 wide and 2.845 m high. During the trials three representative ChCs were used among the most up-to-date market models, based on their accessibility and safety features; thus, the most bulky, the heaviest, and the most unstable carriage models were defined as Model A, B, and C, respectively. **Table 1** shows the technical characteristics of the ChC used in the experimental trials. The ChCs were oriented during the tests in a direction parallel to the longitudinal axis of the vehicle, both in forward- and rearward-facing directions, and also perpendicular to the longitudinal axis of the vehicle. **Figure 6** shows a couple of examples of the configurations used in the field trials [9, 14].

In the trials three types of dummies were used to reproduce different ages of children: a newborn model to rehearse the ChC with horizontal carrycot, a 9-month mannequin to rehearse strollers and car seats, and a dummy of 3 years to test strollers. The newborn and 9-month mannequins represented, inertially, an equivalent mass of 3.4 and 9 kg, respectively. These two dummies did not use any type of instrumentation to measure accelerations as established by UNECE Regulation R44 [16]. In contrast, the 3-year-old dummy consisted of a TNO P3 model dummy, weighing 15 kg, which contained triaxial accelerometers on the head and chest, as required by the R44. The instrumentation used for data acquisition during the tests consisted of different sensors and signal conditioning systems. Specifically, a triaxial AHRS400CC gyroscope with a range of *2 g* was used, located in the center of gravity of the bus. With the gyroscope, the angles, angular velocities, and accelerations of the three axes could be measured. In each of the centers of gravity of the ChC, a Kistler K-Beam 8390A10 triaxial accelerometer with a range of *10g* was installed. For the data acquisition, an HBM MGCplus AB22 system connected to a portable PC for the configuration, control, and storage of the recorded information was used. All data was acquired at a frequency of 12 Hz, and several 12 V batteries were used to ensure system power.

All trials were recorded by several digital video cameras, anchored to the structure of the vehicle, for further analysis of the images. In some of them, several tests were reproduced simultaneously with different ChC and configurations, to save costs and time. The developed test battery tried to reproduce different behaviors of the ChC when traveling inside the vehicle. In that sense, three possible situations were identified for each of the ChC tested:

- The ChC with the wheels spinning freely.
- The ChC with the brakes applied on the wheels.
- The ChC held with the hands of an adult.

The first closed-track test consisted of a slalom test, consisting of passing the bus between five cones separated with a distance of 15 m from each other. The speed of the bus was around 25 km/h. The second closed-track test was to make the vehicle follow a circular path, similar to the passage through a roundabout. The turning

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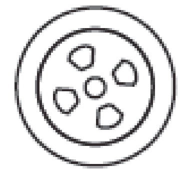
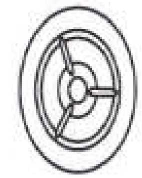
Children carriages' technical data	**Model A**	**Model B**	**Model C**
Frame type	 Three-wheel stroller	 Rectangle frame	 Telescopic port
Wheel type	 Multi-radial	 Solid	 Radial
Track width	Different track	Same track	Different track
Handle type	 Complete	 Simple	 Complete
Modes	 Flatbed/car seat/stroller	 Stroller	 Flatbed/car seat/stroller
Folding type	 Book	 Umbrella	 Book

Children carriages' technical data		Model A	Model B	Model C
Length (mm)		1050	890	1130
Width (mm)		655	442	560
Height (mm)		1105	1035	1140
Weight (kg)*		15.28	6.48	13.76
Front track (mm)		292	345	385
Rear track (mm)		594	345	510
Wheelbase (mm)		650	545	625
Folded	Length (mm)	1105	1040	1370
	Width (mm)	655	310	560
	Height (mm)	540	270	720

**Note: maximum weight between possible configurations—flatbed, car seat, or stroller.*

Table 1.
Technical characteristics of ChC used in dynamic tests (source: [14]).

(A) (B)

Figure 6.
Provision of ChC deployed during experimental open circuit trials: (A) unfolded rearwards facing Model A carriage and forwards facing Model C carriage; (B) unfolded rearwards facing Model B carriage and forwards facing Model C carriage (source: [14])

radius drawn by the vehicle ranged between 15 and 20 m, and the circulation speed reached between 20 and 25 km/h. This test was consistent with other similar trials such as those developed according to SAE J266 [17] or SAE J2181 [18] standards, both aimed at measuring the dynamic stability of trucks and busses. The third closed-track tests consisted of a braking test, representative of an emergency braking. The vehicle had to be driven in a straight line until reaching a speed of 50 km/h and then proceed to braking in the shortest possible time and the shortest distance, without the driver losing control of the vehicle.

The combination of the different configurations tested, both in open and closed tracks, allowed us to obtain a battery of 61 tests (17 combinations for each of the slalom, circular, and braking path tests and 10 combinations for open circuit tests), using different models of ChC, with different testing dummies, carriage orientations, and brake application status. For all tests, a sign criterion was used for the signals obtained, both for the vehicle and for the ChC, based on the reference system of ISO 4130 [19]. **Figure 7** shows three examples of the behavior of ChC during experimental testing in closed circuit. As can be seen, the dynamics of the vehicle movement during the tests performance can cause carriage, when it is not held by any restraint system, and the wheels are braked, to tip over, and its occupant could hit the ground and the interior parts of the transport vehicle. The overturn, in addition, could occur also when the ChC moves in a rearward-facing orientation, which is the transport configuration recommended by current legislation, UNECE Regulation R107 [11], for this type of products.

From the analysis of the results obtained, and the video recordings made, some conclusions could be drawn about the dynamic behavior of the ChC when subjected to typical maneuvers of urban transport vehicles. From each of the trials, it was concluded that:

A. Slalom test:

- *ChC restrained*: the maximum acceleration corresponds to the Model C carriage (most unstable). The average acceleration is *0.41 g* in X and Y. On Z axis, considering acceleration of gravity, the highest value reaches *1.26 g*.

- *ChC unrestrained*: the acceleration values are higher and correspond to Model A (more voluminous); in many tests, the ChC falls or hits an object, reaching values of *1.72 g* on the X axis and *1.98 g* on the Z axis.

B. Circular test:

- *ChC restrained*: highest accelerations correspond to Model A (more voluminous). On Z axis, considering acceleration of gravity, the highest value reaches *1.49 g*.

- *ChC unrestrained*: wheel brakes applied, the acceleration values are much higher, since in many tests the ChC falls or hits an object, corresponding to Model A (more voluminous), and reaching values of up to *5 g* in the Y direction.

C. Braking test:

- *ChC restrained*: the highest acceleration values correspond to Model A (more voluminous) and reach *1 g* on the X axis. Y values are much smaller, since we are in a braking test where the most important acceleration is longitudinal. In the vertical direction, Z axis, the maximum acceleration reaches *1.9 g*.

- *ChC unrestrained*: with ChC moving freely, the acceleration values are very high since the carriage is violently struck against the interiors of the vehicle, accelerations of up to *6.5 g* are being obtained in the X direction; the most unstable model is Model B (heavier). Even with the Model C (more unstable) of ChC, longitudinal accelerations are achieved: *3.7 g* in X axis and *3.03 g* in Z axis.

D. Open road test:

- *ChC restrained*: in the open circuit the maximum accelerations correspond to the longitudinal direction X, where values of up to *0.43 g* for the Model C (more unstable) are reached; in the vertical direction Z, considering the acceleration of gravity, it reaches *1.56 g*.

- *ChC unrestrained*: the maximum accelerations for the longitudinal axis X are for the most unstable ChC, the Model C, where *1.82 g* is reached; for Model C, *1 g* is reached on the Y axis, and *1.85 g* in the vertical direction Z. The maximum vertical acceleration on the Z axis when the ChC is moving freely is reached with Model A (more voluminous), where it reaches *2.05 g*.

In general terms, it could be concluded that when the ChC is unrestrained and moving freely without the wheel brakes applied, it moves inside the bus, hitting the different parts of the passenger compartment (**Figure 7C**). In these tests it was found that if the ChC is not restrained by an adult or any other system, in the event of normal or emergency movement maneuvers of the vehicle, it tends to slip and hit the bus interiors, regardless of its orientation, even if the wheel brakes are applied (**Figure 7A** and **7B**). When wheel brakes are not applied, the ChC moves but has less tendency to overturn, and the resulting acceleration is somewhat lower.

Many of the ChCs in the current market have a tendency toward lateral overturning that can be easily achieved for vehicle maneuvers with accelerations of less than 5 m/s^2 (*0.5 g*) [12]. When the ChC hits the vehicle's interior without a direct impact of the child, the acceleration of the dummy's head and chest can be up to 10–20% of the ChC deceleration. In case of lateral overturn, in some models of

(A)

(B)

(C)

Figure 7.
Examples of the dynamic behavior of the ChC unfolded during the closed-track tests developed in the ASUCAR project (source: [20]). (A) Circular test: wheel brakes applied. (B) Slalom test: wheel brakes applied. (C) Braking test: wheels spinning freely.

ChC, the child could suffer an impact onto the head when hitting against other parts of the body. In these cases, the deceleration could generate a high risk of damage to the child head.

It was possible to verify that with ChC unrestrained, the safer position for traveling is to place it longitudinally in a rearward-facing direction, resting on the backrest installed in the area reserved for a wheelchair user, as recommended by the UNECE Regulation R107 [11]. However, this position could also be dangerous when the ChC is not restrained in any way to the backrest (as it is a passive safety

(A) (B)

Figure 8.
Most adequate position of unfolded ChC for traveling in M3 vehicles: (A) with space occupied by ChC; (B) with space unoccupied by ChC (source: [14]).

system), so it can rotate and be launched toward the corridor with a relatively high deceleration (*2.5 g*) and jump to the front of the vehicle (*6.5 g*) during an emergency braking. In these cases, the ChC should be held by a restraint system such as the one shown in **Figure 8**, with a safety lap belt. The only drawback of this traveling position is that in case of an emergency braking or a frontal impact, the passengers of the bus, or other ChCs located in front of it, could be thrown against the carriage, causing physical damage to the child or baby. Finally, it should be noted that, for all tests, the transversal position of the carriage to the direction of travel is inadvisable.

3.1 Configurations of children's carriages traveling inside the bus

Taking into account the dynamic analysis of the transport configurations using different ChC models and considering the interior designs of passenger compartment of large capacity passenger vehicles (M3), the areas where the ChC would be traveling and the most appropriate restraint system for each one of them were identified and characterized. In that sense, three possible zones can be identified inside the passenger compartment of the transport vehicle, as shown in **Figure 9**. These areas have the following characteristics:

- **Zone 1**: The area near the backrest of the space reserved for the wheelchair user. If the space reserved for the wheelchair is unoccupied, the ChC must be placed against the backrest, in a rearward-facing direction, with the wheel brakes applied. The use of a seat belt is recommended to secure the carriage.

- **Zone 2**: The area near the central entrance door of the bus, and located next to the first row of rear seats, where the ChC and an accompanying adult can travel next to the crossbar located there. In the event that the space reserved for wheelchair is occupied, the ChC could be placed in this area, facing forward or rearward, with the wheel brakes applied and using a flexible restraint system, such as a seat belt.

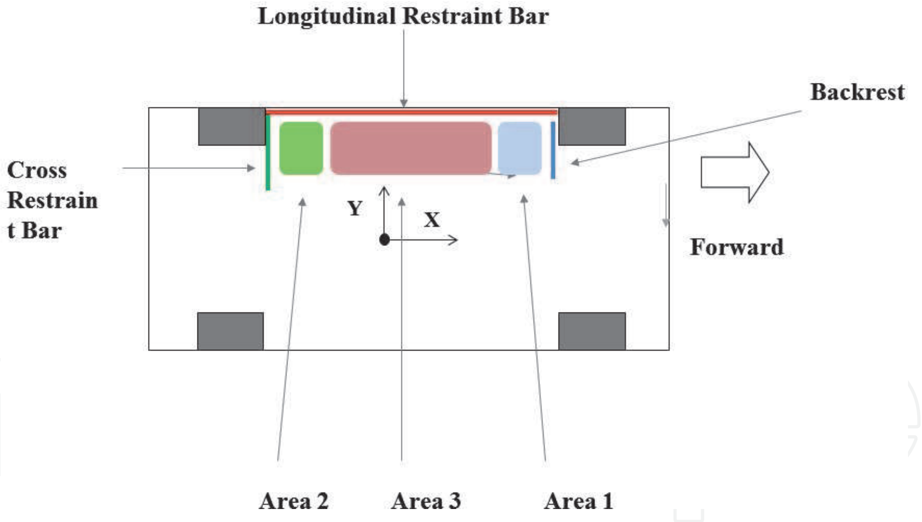


Figure 9.
Characterization of the zones for the location of the ChC unfolded during transport in M3 vehicles (source: [14]).

- **Zone 3**: The central area of the bus between the two zones 1 and 2, in which the ChC and the accompanying adult could travel along the bus sidewall. In that case, it is necessary to use a specific restraint system to hold the ChC in their place following the instructions provided by the transport operator. The child must have the harness attached. The ChC should apply the wheel brakes and should be traveling facing rearward.

As a result of the experimental tests, it was concluded that, among the three zone alternatives, the safest for traveling with ChC is Zone 1, provided that it is not occupied by a wheelchair user, and where the ChC is directly supported on the backrest facing rearward, with the wheel brakes applied and secured by means of a safety belt, that some busses already have incorporated. **Figure 8** shows an example of this configuration.

3.2 Strength analysis for children's carriage restraint systems

Finally, considering the value of the maximum accelerations obtained in the experimental field trials, it was possible to establish the order of magnitude of the forces that the restraint system should withstand to retain the ChC and its occupant. For this calculation, the accelerations generated when the ChC suffered a fall against the floor or the interior parts of the vehicle were not taken into account. The results were obtained considering the total mass of the ChC and its occupant, the maximum deceleration suffered by them during the braking test (which is the most unfavorable). Thus, the maximum force that the restraint system would have to withstand occurs in those cases in which the heaviest ChC is used, reaching the value of 782.46 N. If a safety factor of 2 is applied to the ChC-user set [9], it can be stated that the maximum load that the restraint system would have to bear to withstand the maximum deceleration generated during a braking force would reach the value of approximately 1565 N (1.56 kN).

Analyzing these experimental results, and taking into account that for Zone 3 (located between the backrest of the area reserved for wheelchairs passengers and the first row of rear seats), it was verified that it does not exist currently in the market safety systems designed to facilitate the retention of ChC when traveling in high capacity transport vehicles (M3). So, a new restraint system designed to hold the ChC unfolded during transportation in road vehicles was developed.

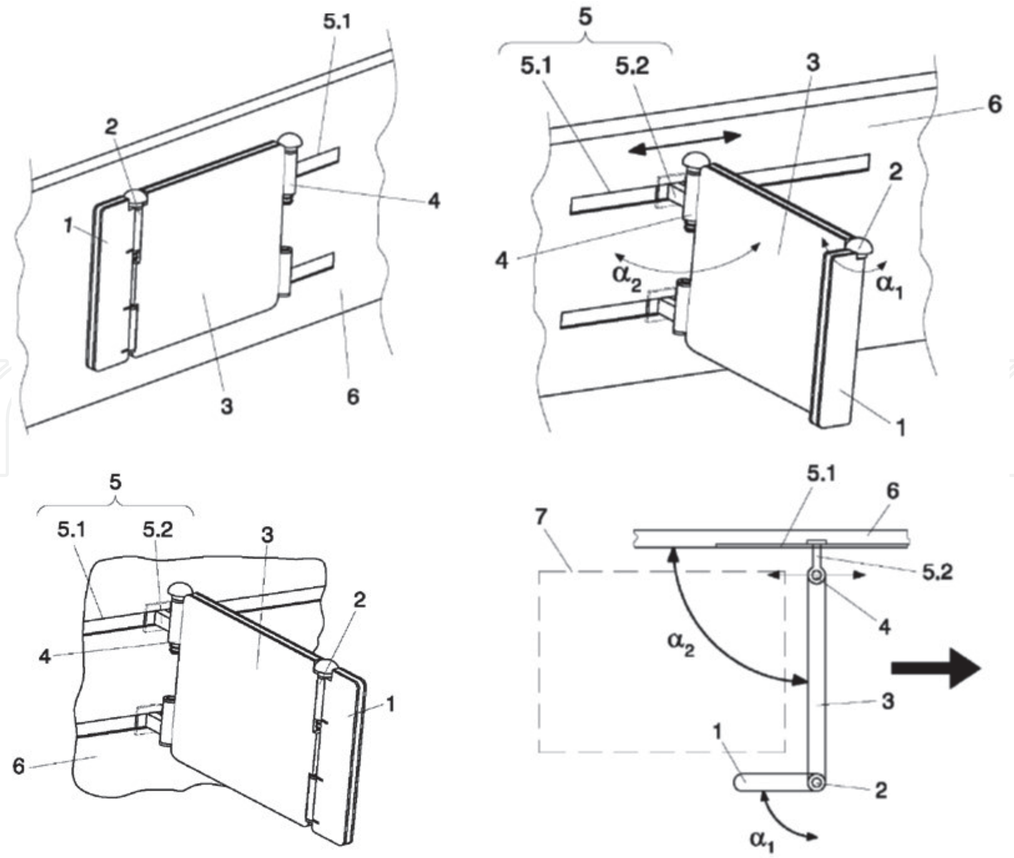


Figure 10.
Scheme of patent ES2403161 defining the operation of a folded-unfolded passive restraint system for the transport of ChC in M3 vehicles (source: [21]).

The new safety system was registered by the Polytechnic University of Valencia and the Polytechnic University of Madrid, through the Spanish Patent ES2403161 [21]. The originality of this invention is that, unlike other restraint systems applied to assure the mobility of wheelchair users in public transportation vehicles, the passive restraint system developed prevents involuntary displacements of ChC, not only longitudinally but also laterally. **Figure 10** shows a simplified scheme of the assembly, which presents the device when it is in the rest position (folded) and when it is used with the ChC in transport position (unfolded). The passive restraint system can be used simultaneously with wheelchair users according to current regulations (UNECE Regulation R107). The safety system has been manufactured in lightweight materials and is able to withstand forces in impacts of up to *2 g*.

4. Safety requirements of children carriages traveling on busses

To date there have not been many experimental works aimed at obtaining the dynamic behavior of ChC when traveling in road transport vehicles subjected to low speed impact. One of the few references of this type of research was carried out in the development of the ASUCAR project. This project was the first scientific study that has been carried out in Spain in the field of transportation safety of ChC on busses, with no precedents for research projects similar in the rest of Europe [22]. The ASUCAR project continued in a second phase called ASUCAR-2[2], whose main

[2] The ASUCAR-2 research project, *Validation of the usability of a retention system for the safety of children's carriages in public transport vehicles*, was funded by the Polytechnic University of Valencia in the INNOVA 2012 Program (Contract No. 20120579).

objective was the strength and usability validation of the safety system developed to facilitate the restraint of ChC in transport vehicles [23, 24]. The design and manufacture of the new safety system was experimentally validated by performing a battery of representative tests of low speed impact (≈ 20 km/h), with an equivalent deceleration level of *2 g*.

As the Annex 8 of UNECE/UN R107 does not explicitly define any dynamic test to verify the behavior of the ChC under situations of impact, this research was considered an experimental work that could be used for defining the technical requirements for testing the structural behavior of this type of safety systems. In that sense, during the ASUCAR-2 project, a battery of six impact tests were developed on a sled-test platform, whose characteristics were defined based on the results obtained in the first phase of the project. During these tests different prototypes of safety systems were used for the ChC. First, a backrest panel was selected, representative of those used in urban busses, which complied with the technical requirements of UN/ECE Regulation R107. The backrest was provided by the Municipal Transport Company of Madrid. In total, three different prototypes of the safety system developed were used, inspired on the design shown in **Figure 10** [21]. The characteristics of each prototype tested were based on the following aspects:

- *Prototype #1*: folding screen 500 mm high and metal structure covered with wooden panels

- *Prototype #2*: folding screen 400 mm high and metal structure covered with wooden panels

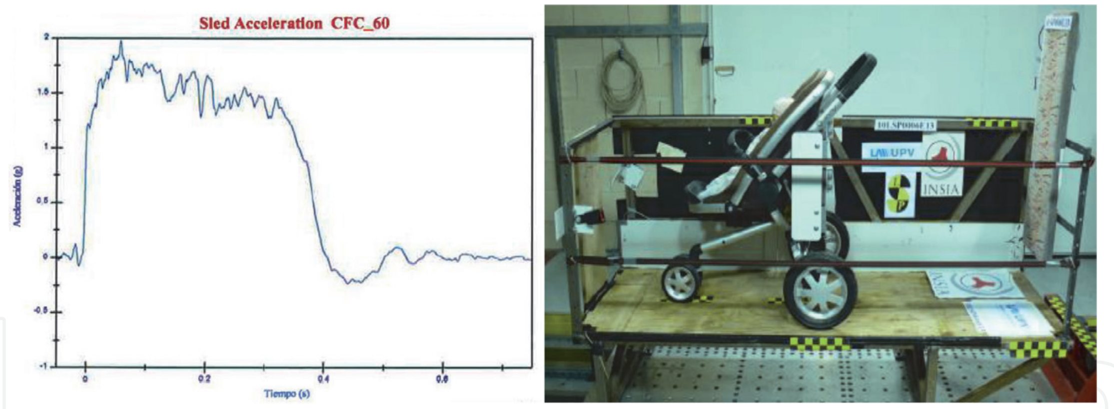
- *Prototype #3*: folding screen 400 mm high and metal structure covered with foam-padded wooden panels

The ChC tested were selected among the most representative models of the market (**Figure 11**), according to the results obtained in previous phases of the ASUCAR project [9, 12], and were characterized by:

- **SX model**: trolley with an adjustable height carrycot. It has four independent wheels, with front steering wheels, and rear wheels with brakes; front and rear tracks are different.

- **QB model**: trolley with adjustable seat angle and used in its highest position. It has four wheels, in which the front ones are twin, and the rear equipped with brakes; front and rear tracks are different.

The sled tests were designed to reproduce an acceleration up to a defined speed (V ≈ 20 km/h) and programmed to stop in a controlled manner with a deceleration of *2 g*, reproducing the deceleration pulse shown in **Figure 11**. Testing took place between July and September 2013 at the facilities of the University Institute of Automobile Research (INSIA), belonging to the Polytechnic University of Madrid (Spain). The ChC restraint system and the WhCh back-restraint were installed on a representative module of the space reserved for a WhCh user, dimensionally and geometrically, similar to that of a standard urban transport M3 vehicle (**Figure 11**). All the tests were carried out with the carriage facing rearward. An accelerometer was installed on the platform module to measure the longitudinal deceleration, according to SAE J211 [25]. All trials were recorded with two high-speed cameras (1000 fps) and a third conventional camera at 30 fps. In



(A) (B)

Figure 11.
(A) Deceleration pulse applied during sled tests. (B) Configuration for sled-test platform (source: [24]).

the trials two types of dummies were used to represent the occupants of the carriage:

- *A TNO P3 dummy* representative of a 3-year-old child equipped with two triaxial accelerometers: one for the head (filter CFC_1000) and one for the chest (filter CFC_180).

- *A Q1 dummy* representative of a 1-year-old child. This dummy was equipped with sensors to measure triaxial acceleration in the head (CFC_1000), chest (CFC_180), pelvis (CFC_1000), and a load cell at the top of the neck to measure forces (CFC_1000) and torques (CFC_600) as well as chest deformation (CFC_600).

These dummies were approved to comply with UNECE Regulations R129 Rev.00 (2014) and R44 Rev.04 [16] for the approval of child safety systems. At the time the study was conducted, there was no international regulation defining the criteria for damage to be applied to Q1 dummies. Therefore, the damage criterion used for this dummy was defined based on the information in UNECE Regulation R94 Rev.01 [26], applying the parameters defined in the work of Mertz, Irwin, and Prasad [27].

The different test configurations were designed to validate the structural behavior of the safety systems developed and analyze the usability of different configurations of the space reserved for wheelchair users and ChC, under low impact conditions. The terms *correct use* and *misuse* as per defining the ideal mobility conditions of ChC during transport were established. All testing was representing worst-case situations regarding ChC model and travel orientation, direction of impact, brakes applied to ChC, and distance from ChC to backrest panel. The configurations of the dynamic impact tests performed are shown in **Table 2**.

The damage criteria for children to define the validity of the results were established by scaling the factors described in [27]. These scale factors had previously been used as reference values in UNECE Regulation R94 Rev.01 [26] for adults of average size as well as in the Federal Motor Vehicle Safety Standards (FMVSS) regulations. The "limit values" established in these regulations, and defined in the analysis of the results of this research, correspond to the probability of generating damage to the different parts of the body. An analysis of the results obtained in the dynamic impact tests allowed us to reach a series of conclusions about the *correct use* and *misuse* configurations in the road transport of ChC. These

Test No.	Test description						Distance from ChC to backrest (mm)	Config.
	Impact direction	ChC orient	Restraint system prototype	Dummy	ChC model	ChC brakes applied		
E01-urban bus module	Frontal	RF	Prototype #1	TNO P3	SX	NO	89 mm	*Misuse*
E02-wheelchair backrest	Frontal	RF	Wheelchair backrest system	Q1	SX	NO	150 mm	*Misuse*
E03-prototype #2	Frontal	RF	Prototype #2	Q1	SX	NO	150 mm	*Misuse*
E04-prototipe #3	Frontal	RF	Prototype #3	Q1	QB	SI	0 mm	*Correct use*
E05-prototype #3	Frontal	RF	Prototype #3	Q1	QB	NO	150 mm	*Misuse*
E06-wheelchair backrest	Frontal	RF	Wheelchair backrest system	Q1	QB	SI	0 mm	*Correct use*

RF: rearward facing.

Table 2.
Configuration for sled testing of ChC (source: [24]).

conclusions were drawn from the battery of tests carried out in the ASUCAR and ASUCAR-2 projects and can be summarized as follows:

a. The safest transport configurations for the mobility of ChC in large capacity road passenger vehicle (M3) are those in which the carriage travels facing rearward, with its back in contact with the backrest panel or bulkhead and with the wheel brakes applied. This configuration is considered as *correct use* to minimize the effects of accelerations on the occupant during the occurrence of a low severity impact.

b. In the case of ChC traveling in an area different from the space reserved for the wheelchair user due to this being occupied, the new restraint system developed (ASUCAR) is capable of supporting the dynamic loads generated during a low speed impact ($2\,g$, ΔV = 20 km/h), representative of the most unfavorable design conditions (more unstable (SX), wider (QB)), when transporting a child up to 15 kg in a large capacity road passenger vehicle (M3).

c. In configuration of *misuse*, with no wheel brakes applied and a gap of at least 150 mm between the ChC and backrest panel, the dynamic parameter values could be increased by two to five times in comparison with *correct use* and may exceed critical values or damage tolerance for ChC occupants, mainly in neck vertical movements.

d. The strength behavior of the restraint system for ChC based on folding rear panels (ASUCAR) has been proven as effective against low severity impacts as the system based on backrest panels established by UNECE/UN Regulation R107, for the transport of users in wheelchairs in large capacity road passenger vehicles (M3). So, it can be considered a useful restraint device compatible with the rigid backrest panel established in actual regulation [11].

5. Conclusions

The recommendations developed in this section have been inspired and grouped based on the *Code of Good Practice* developed as a result of the ASUCAR and ASUCAR-2 projects [13, 20, 22], so that it can be used by the different agents involved in public transportation services: operators and public transport companies, manufacturers, user and consumer associations, as well as public administrations. The *Code of Good Practice* has been structured in three categories:

5.1 Good practices for transportation services operators

Recommendations when ChC travel folded:

A. If there is a space reserved for folded ChC, it must have minimum dimensions necessary to house the majority of existing ChC in the market.

B. If there is a space reserved for folded ChC, it is recommended that for the transport of children, seated seats and/or special seats (groups 0 and 1) be installed facing rearward.

Recommendations when ChC travel unfolded:

A. If there is an unoccupied space reserved for wheelchair users, the ChC must travel in that space facing rearward in contact with the backrest, with the brake wheels applied. The child must have the harness attached.

B. If the space reserved for wheelchair users is occupied, the ChC must travel in the area located next to the panel of the first row of rear seats, facing forwards and using a flexible restraint system (seat belt).

C. If the space reserved for wheelchair users is occupied, and the area closest to the first row of rear seats has insufficient space, there must be a specific restraint system for ChC in the vehicle, which would be used following the operator's instructions. The child must have the harness attached.

5.2 Good practices for ChC manufacturers

A. The ChC manufacturer must inform its customers about the technical requirements of ChC to be used in public transportation vehicles, considering the stability and the protection of the child in the event of a fall or low speed impact.

B. The ChC manufacturer shall design the carriage structurally resistant to support the use of specific restraint systems for transport on busses. The strength of the restraint system must be at least 1600 N.

5.3 Good practices for ChC users

A. Whenever ChC is going to be used for traveling in public transportation vehicles, it must incorporate a harness to hold the child, wheel brakes, and structures as stable as possible.

B. When the vehicle is accessed, it should be preferably travelling in the space reserved for the wheelchair, rearward facing with the wheel brakes and the carriage in contact with the backrest. The companion person must travel in the aisle next to the carriage.

C. If the space reserved for the wheelchair is occupied, it should be travelling in the area near the first row of rear seats, facing forward. In this case, it is recommended to use a flexible restraint system (belt) to hold the ChC structure.

D. When the vehicle is accessed, if the space reserved for the wheelchair is occupied, and there is a special restraint system for ChC, it is recommended to use it with the ChC oriented facing rearward, with wheel brakes applied and the carriage in contact with the folding panel.

E. When the vehicle is accessed, if you cannot travel with the cart unfolded, and there is a reserved space for folded ChC inside the vehicle (provided that the ChC can be folded), it is recommended to locate the carriage in the reserved area and use the special seat (group 0 and 1) for the child, if available.

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