Setting up divisions in transport vehicles as a safety measure to reduce cumulated neighbor inertial forces on passengers

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Frequently, humans and animals are densely confined during transportation processes in both small and large spaces (containers, subways, wagons, buses). Clearly when sudden braking or collisions unfortunately occur, passengers may suffer physical damages. Then in order to avoid injuries due to unexpected decelerations during transportation, we propose to build simple extra divisions to decrease cumulative pressures due to the inertial force on standing-up stacked passengers due to neighbor passengers. In order to avoid fractures, we measured maximum compression forces on young adult thoraxes and the corresponding thorax compression limit. For situations of high crowding of these passengers, we estimate the size of the compartments as function of the expected decelerations and speeds. Implementation of the proposed divisions is simple and economical.

Keywords: Interdisciplinary applications of physics; elastic properties; transportation.

Con frecuencia, los seres humanos y los animales están densamente confinados durante procesos de transporte, tanto en espacios pequeños o grandes (contenedores, el metro, vagones, autobuses). Es claro que cuando por desgracia ocurren frenados bruscos o colisiones se producen, los pasajeros pueden sufrir daños físicos. Entonces con el fin de evitar lesiones debido a desaceleraciones inesperadas durante el transporte, se propone la construcción de simples divisiones adicionales para disminuir las presiones acumuladas sobre pasajeros apilados de pie debido a la fuerza inercial de los pasajeros vecinos. Con el fin de evitar fracturas, medimos las fuerzas de compresión máxima sobre el tórax de adultos jóvenes y el límite de compresión del tórax correspondiente. En situaciones de alta aglomeración de pasajeros, estimamos el tamaño de los compartimentos en función de las desaceleraciones y velocidades esperadas. La implementación de las divisiones propuestas es sencilla y económica.

Descriptores: Aplicaciones interdisciplinarias de la física; propiedades elásticas; transporte.

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1. Introduction

A large fraction of the economy of every country deals with merchandise and passenger transportation costs, leading to many different problems such as safe transportation and air pollution, for instance. Furthermore, in a near future, transport costs may increase, due to the increasing technical difficulties to obtain fuel for air and road transportation from exhausting oil sources [1]. Therefore, in order to save fuel, a growing share of passenger transportation will be carried on by collective transportation media, which unfortunately leads to problems associated with human crowds. A general problem-specially in overpopulated cities- is the crowding in both private and public transport vehicles, especially during peak-hours. This situation may get worse due to lack of transport budgets or because the increase of buses implies further saturation of street traffic. In general, there are several ways to increase the safety of passengers travelling in different kind of vehicles. The goal of minimizing the occurrence and consequences of injury-related *accidents* could be achieved by improvements in both vehicle safety and roadway conditions.

People in crowds or travelling in collective transport media are facing potential risk of suffer asphyxia during the events of human agglomeration because passengers or people in crowds may not have enough space to perform their natural breathing movements. For instance, a very large percentage of all mechanical energy injury deaths in the USA were caused by motor vehicles, among other causes such as firearms use, fallings, etc. [2].

Let us now mention some important improvements in vehicle safety regarding crushing stresses that could be induced by *dynamical accelerations* inside containers. The generalized use of seat belt -or safety belt- is a very important advance to protect human lives. The seat belt is a safety harness designed to secure the occupant of a vehicle against harmful movement that may result from a collision or a sudden deceleration. Another more recent contribution to vehicle safety is the airbag device, which consists of a flexible device designed to inflate rapidly in a head-on collision. The first airbags were marketed as the *Air Cushion Restraint System (ACRS)* airbags in the 1970s. Since a very rapid response is crucial in a collision, an airbag must be able to function in a matter of milliseconds from the initial collision impact, and hence, the first component of the airbag system is a sensor that can detect collisions and immediately triggers the ignition of a pellet to generate gas filling a nylon or polyamide bag. However, it has been pointed out that airbags can also injure or kill vehicle occupants; in particular little babies or old passengers. To learn more about the physical and chemical functioning of airbags see, for example, Refs. 3 and 4, respectively.

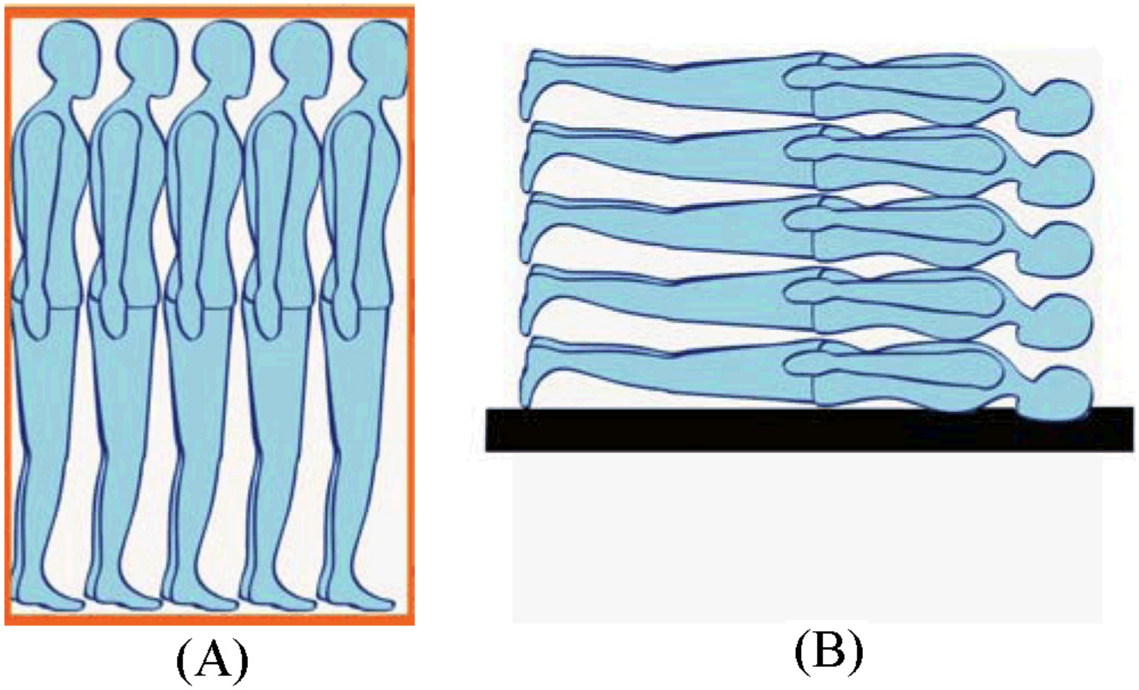

FIGURE 1. Panel (A): Schematic diagram of a crowded container with five people standing-up. Panel (B): Same people but stacked horizontally in a gravitational field. If the container in (A) experiences braking or decelerations in the right direction, then forces on people inside in the container are analogous to vertical gravitational forces suffered by stacked people.

The effects of shock and vibration on humans are widely studied [5], but surprisingly, there is a lack of studies of practical recommendations to improve the passenger safety in wagons in very crowded situations. Therefore, in this article we present a simple preventive measure to reduce injuries during transportation. The basic idea is to reduce the forces on passengers caused by decelerations by setting up divisions in the transportation containers, since on each passenger decelerations cause cumulative pressures due to the dynamical inertial force of neighbor passengers. Here we deal in detail with the case when passengers are confined by walls in relatively reduced spaces and the density of people or beings is very high.

2. Cumulated force on packed passengers due to the inertial force of neighbors

When transportation systems work at their the maximum capacity, passengers can potentially suffer different types of damage. If he force is more or less homogeneously distributed in the thorax and changes slowly, passengers can suffer asphyxia when the chest cannot realise its natural movements to breathe. Also fractures can occur when forces are localized in a small area, like a pointed elbow on a rib causing a high local pressure.

Of course when the pressure is very high, then thorax and other parts of the body can undergo a fracture when transport vehicles brake abruptly while travelling at high speeds.

In this section we restrict our experimental study to *very slow* changes of pressure applied on the human thorax That is, our work focuses on the moderate range of accelerations that produce very dangerous forces and pressures on alive beings, but not on the high acceleration range where very violent collisions in transport vehicles occur, such as those treated, for example, in Refs. 6 to 7.

In order to estimate the cumulated forces in highly packed people, let us now analyze the case when vehicle transports experience sudden or abrupt decelerations due to braking or collisions with smaller vehicles or obstacles in general. The most susceptible person to suffer an injury when the container decelerates, is the one who travels in the frontal part of the container, since this person not only receives the impact force due to his/her horizontal component of his/her weight, but also receives the *cumulated* horizontal force due to people who are behind him/her (see Fig. 1). If the container in Fig. 1A) experiences braking or decelerations along the horizontal direction, then the forces acting on people in the container are equivalent to vertical gravitational forces suffered by stacked people in the horizontal position (Fig. 1B). If for simplicity, we assume identical passengers, then the cumulated force F on the person in the most frontal part of the first passenger, including his/her own inertial mass, is simply

$$F = Nma \tag{1}$$

where N is the total number of people (with $N-1$ persons behind the frontal passenger), m is the mass of each person people and a is the deceleration of the container. Therefore, it is

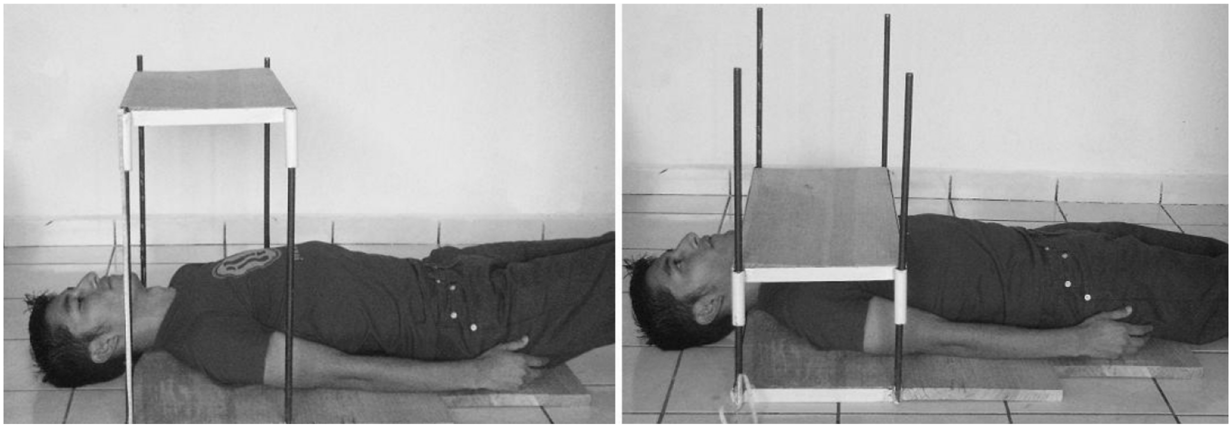

FIGURE 2. Device used to measure the compression of the thorax under vertical stress. Different weights were positioned on the horizontal platform.

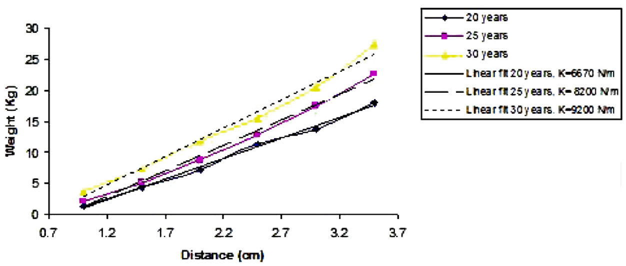

FIGURE 3. Applied force on human thorax vs.compression distance for 20, 25, and 30 years old men. Values of the elastic constants of the law of Hooke's law are also shown.

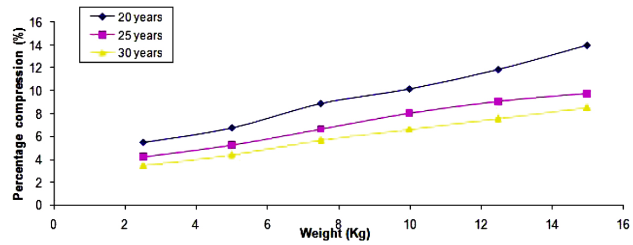

FIGURE 4. Percentage compression from Fig. 3.

important to know the maximum compression forces supported by people on their thorax before impairing breathing capability and producing possible bone fracture.

3. Compression forces on adult thorax: breathing capability and fracture

We now proceed to present experimental results of compressing of male adult thoraces. To establish a limit for the maximum experimental chest compression, we use the fact that the compression that supports the chest before suffering an injury (fracture) is around 38% of the distance from chest to back [8]. That is, we must not surpass this limit in our experiments. With this restriction in mind, we conducted several experiments consisting in adding masses of different weights upon the chest of young adult human beings (see Fig. 2). The total weight did not surpass 20 kg to avoid accidents, and several safety measures were taken in order to preserve the physical integrity of the human subjects, such as not surpassing long periods without breathing. People who collaborated in this experiment were young men; 20, 25 and 30 years old.

Our experimental data for elastic deformation response of human adult chests under the action of distributed forces and the corresponding percentage compression are shown in Figs. 3 and 4, respectively. The experimental data shows a linear elastic behavior, that is, the decrease on the chest height (or chest-to back compression) is directly proportional to the applied force following the law of Hooke;

$$F = kx \tag{2}$$

In the inset of Fig. 3 the corresponding values of k for different ages are shown. These are important results, not only due to the expected linear behavior, but because they allow us to predict values that could not be reached experimentally without causing health risks, like ribs fracture. Since in the plot of the force versus compression the shown slopes increase when age increases, then chests have a more rigid behaviour for older people.

Since the behavior of the chest is linear and suffers a fracture at 38% compression [8], we can extrapolate results of Fig. 3 to find this criticalforce, which is approximately 1200 (kg m)/s^2 = 1200 N. For example, a person with a weight of 70 Kg would experience a fracture under an deceleration of around 17 m/s^2.

4. Divisions in transport vehicles to reduce inertial forces on passengers

We analyze inertial cumulative forces on passengers when very crowded vehicles experience sudden or abrupt deceler-

TABLE I. Relevant parameters of various transportation systems in Mexico City.

Transport	Wagon length (m)	Maximum speed (Km/h)	Normal maximum deceleration (m/s^2)	Approximate stopping distance in station (m)
Metro	17.1	80	1.0	100
Metro bus	9	60	1.0	40
Tren Liger	10.3	60	1.8	60
Tren Suburban	25.6	130	0.8	200

TABLE II. Maximum number N of aligned people in a row who can travel without suffering a fracture for initial speed V and braking distance d. Each person has a weight of 70 Kg.

V (Km/h)	N for d= 25m	N for d= 50m	N for d= 100m	N for d= 150m
60	3	6	12	18
80	1	3	6	10
130	0	1	2	3

ations due to braking or collisions with smaller vehicles or any kind of obstacles. We chose three typical normal speeds; 60, 80, and 130 Km/h, which more or less corresponds to the speeds of various public transportation systems in metropolitan Mexico City; Metrobús [9], metropolitan subway Metro [10], Tren Ligero [11] and Tren Suburbano [12]. We consider that these systems are good general examples of other means of transportation all over the world. In Table I, we list some relevant quantities associated to the carriers or vehicles of these transportation. As it will be clear below, the length of the wagons is important in each case in order to find the optimum division of wagons to avoid possible injuries when braking.

In the case when decelerations are constant, then the braking deceleration can be simply deduced from the work-energy theorem $W = \Delta$K, which relates the mechanical work $W = Fd = mad$ made by an external force F upon a rigid object, to change its kinetic energy K from mV^2/2 to zero in a distance d, to yield

$$a = V^2/(2d) \tag{3}$$

where a is the deceleration and V is the initial speed at the start of braking.

As mentioned in Sec. 2, the most vulnerable person is the one that travels in the frontal part of the wagon or container when there is deceleration. To find the total force experienced by each passenger we have to calculate the total mass behind him/her plus his/her own mass. If we consider, for simplicity, that all their masses are equal, then the total force is given by

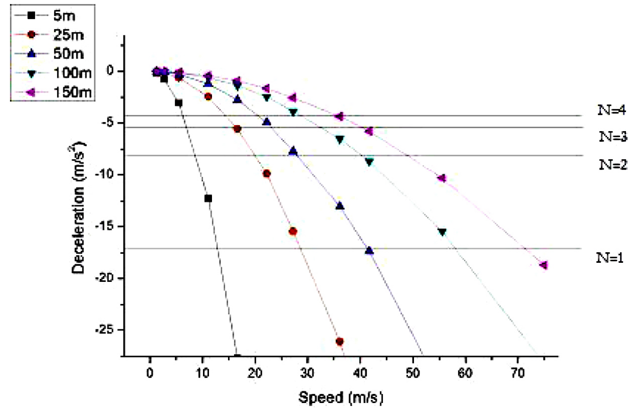

FIGURE 5. Decelerations for various initial speeds and braking distances.

Eq. (1). Figure 5 shows the deceleration for different initial speeds and braking distances and the horizontal lines which correspond to critical decelerations from N =1 up to 4 persons, all with weights of 70 Kg. Obviously, larger speeds or shorter braking lengths imply larger decelerations. Since the horizontal lines cross the deceleration curves at critical injury points, then the number of stacked non-injured people increase with shorter braking distance.

To avoid that such inertial force may reach the fracturing or injuring value, we propose to build up divisions to decrease inertial cumulative forces during decelerations, as shown in Fig. 6.

In Table II we show examples of the maximum number of aligned people that can all travel without suffering a fracture at different speeds and braking distances in the very crowded configuration. From Eq. (1), in our calculations we assumed that each person has a weight of 70 Kg, and considered that the maximum force that supports the chest is of 1200 N.

The analysis of Table II, shows that braking distance of less or around 25 meters are very dangerous for physical safety of passengers for speeds higher than 80 Km/h. These decelerations are not common during human transportation. In Table III we show parameters of the proposed divisions for different transportation systems considering the

TABLE III. Parameters corresponding to proposed lateral lengths of compartments for different transportation systems to avoid fractures for constant decelerations with braking distance d= 50 m.

Transportation system	Number of people N in each compartment	Length of the compartments (m)	Number of divisions
Metro	6	2.4	7
Metrobus	12	4.8	1
Tren Ligero	12	4.8	2
Tren Suburbano	2	0.8	32

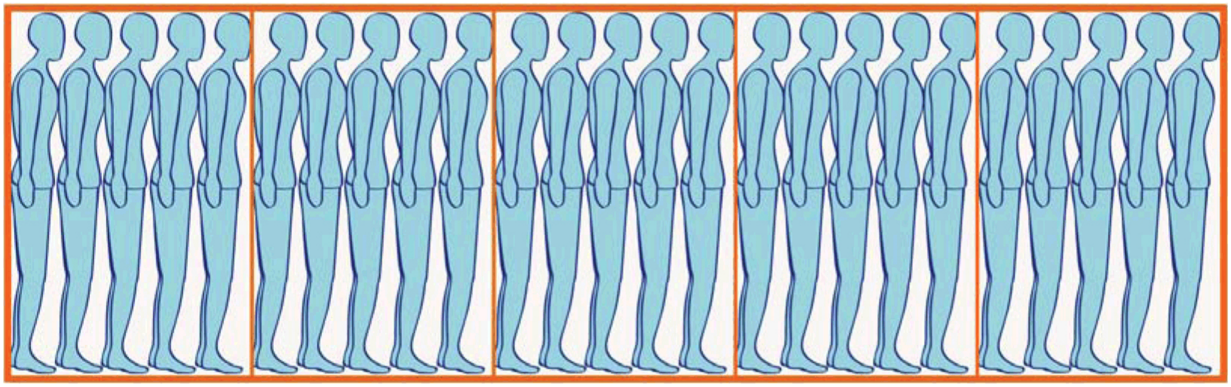

FIGURE 6. Schematic diagram of a crowded divided container. The three divisions separating sets of five people are built in order to decrease cumulative inertial forces.

very crowded configuration shown in Fig. 5 and small braking distance 50 m, taking into account widths of the chest – chest to back distance- of around 40 cm. The lengths of the wagons are taken from Table I.

In these calculations, the length of each compartment or division to avoid injuries in the most extreme case of the fastest Tren Suburbano is only 0.80 cm, which seems to be impractical because its small size. This is a consequence of its corresponding high speed 130 Km/h, extremely small braking distance d= 50 m, and the assumed very crowded packing conditions of the passengers

5. Concluding remarks

The cumulative inertial forces on standing-up passengers due to decelerations when they are stacked in extreme packing conditions (as shown sschematically in Fig. 1.) has been analyzed. Since in more realistic situations, densities are not so high and most passengers can grab handlebars or other type of handlers, the packed configuration of standing-up passengers studied here corresponds to the most extreme and dangerous case.

First, in order to propose modifications to avoid fractures while traveling, we measured maximum compression forces on young adult thoraxes and the corresponding compression limit. We pointed out that the most susceptible persons to suffer an injury are those in the frontal part of the wagon or container when it decelerates, since the force of the impact is not only due to his/her weight, but also to the *cumulated* force due to people placed behind him/her.

To avoid reaching the critical fracturing force while decelerating, we proposed to build up divisions inside the passenger transport vehicles to reduce cumulated inertial forces due to neighbors.

To estimate the lengths of proposed compartments as function of decelerations and speeds we employed a range of parameters corresponding to four public transportation systems in metropolitan Mexico City; Metro bus, metropolitan subway Metro, Tren Ligero and Tren Suburbano, The proposed divisions are unexpensive since their construction do not imply major modifications in the usual design of passenger transport vehicles, while greatly improving passengers safety. The proposed divisions could be made, of transparent plastic material or grids, to avoid decreasing short-range visibility inside the wagons.

In other words our method is based on measuring critical forces and then reducing cumulated inertial forces in wagons or containers by building simple internal divisions. The mathematical and physical tools employed in our estimations are very simple.

Here, for simplicity, we applied this procedure to estimate the lengths of these divisions as function of decelerations and speeds in the particular case of young men as passengers, but our methodology to avoid fractures in accelerated wagons or containers under extreme packing conditions can be employed for both inanimate objects or other living things. We hope that this work may stimulate and promote further safety measures and policies for people in accelerated systems. We acknowledge partial financial support from DGAPA-UNAM, México, through Grants No IN114208 and IN113008.

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