Scientific Paper / Artículo Científico

UNIVERSIDAD POLITÉCNICA SALESIANA ECUADOR
INGENIUS
Revista de Ciencia y Tecnología
https://doi.org/10.17163/ings.n28.2022.06
pISSN: 1390-650X / eISSN: 1390-860X

Structural Analysis of a Long-distance Double-decker Bus During Crashes

Análisis estructural de un bus de dos pisos de larga distancia durante colisiones

Jimmy Brito Morocho[1], Marco Amaya Pinos[1,*], Luis López López[1], Fabricio Espinoza Molina[1]

Received: 13-05-2021, Received after review: 18-10-2021, Accepted: 26-11-2021, Published: 01-07-2022

Abstract

This study presents an analysis of frontal impact and lateral overturn collisions of a double-decker bus, carried out in accordance with Regulations 66 and 29 of the United Nations Economic Commission of Europe (UN/ECE), and the Ecuadorian Standardization Service Institute (INEN) with its regulation 1323:2009. The INEN is on charge of regulating the buses for transportation of Ecuadorian passengers. The continuous improvement of active and passive safety of buses with respect to accidents, is currently a topic with great social impact. In this context, the present paper applies the finite element method (FEM) to analyze the behavior of a double-decker bus subject to different collision scenarios, such as frontal impact and lateral overturn, with the purpose of studying the effects of an accident of this type of structure, considering that the existing regulations are not specific for this kind of vehicles. The obtained results enable taking into account different considerations when designing these elements.

Keywords: Collisions, rollover, frontal impact, regulation, energy, bus

Resumen

Este estudio presenta un análisis de colisiones de impacto frontal y volcamiento lateral de un autobús de dos pisos, conforme al Reglamento 66 y 29 de la Comisión Económica de las Naciones Unidas para Europa (UN/ECE), y el Servicio Ecuatoriano de Normalización (INEN) con su normativa 1323:2009, encargado de regular los autobuses para el transporte de pasajeros en el Ecuador. En la actualidad la mejora constante de la seguridad activa y pasiva de los autobuses con respecto a los accidentes es un tema de gran impacto social. En este contexto se analiza la colisión de un autobús de dos pisos aplicando el método de elementos finitos (MEF), el cual es sometido a diferentes escenarios de colisión como es de un impacto frontal y un volcamiento lateral, con la finalidad de estudiar los efectos de un accidente de este tipo de estructuras donde la normativa no es específica para esta clase de vehículos. Los resultados obtenidos permiten tener en cuenta consideraciones importantes al momento del diseño de estos elementos.

Palabras clave: colisiones, volcamiento, impacto frontal, reglamentación, energía, autobús

[1,*]Universidad Politécnica Salesiana, Cuenca-Ecuador. Corresponding author ✉: mamaya@ups.edu.ec.

Suggested citation: Brito Morocho, J.; Amaya Pinos, M.; López López, L. and Espinoza Molina, F.“Structural Analysis of a Long-distance Double-decker Bus During Crashes”. *Ingenius, Revista de Ciencia y Tecnología*. N.° 28, (july-december). pp. 63-70. 2022. DOI: https://doi.org/10.17163/ings.n28.2022.06.

1. Introduction

The bus is one of the main transportation means in Ecuador, due to its efficiency, flexibility in service routes and costs for the user; however; in 2018 this transportation mean was responsible for 8 % of the road crashes, significantly contributing to the accident rate and to the number of victims [1]; therefore, there is a great interest in improving both active and passive safety of passengers since the most frequent accidents are frontal impacts and overturns, which are considered the most serious and generate a great social impact due to both human and economic losses.

In 2015, the States Members of the United Nations adopted the 2030 Agenda, which states different sustainable objectives; it is intended to «make cities and human settlements inclusive, safe, resilient and sustainable» [2], and with the goal for 2030 of «providing access to transportation systems that are safe, affordable, accessible and sustainable for all and improving road safety, particularly through the expansion of public transportation, paying special attention to the needs of vulnerable people, women, children, people with disabilities and older people» [2].

International initiatives and regulations developed by government organizations that are sustained on the safety of human beings and which guarantee their integrity, should be considered when generating new public transportation systems and optimizing the existing ones. For example, double-decker buses have a large mass and their center of gravity is located at a point very high with respect to the floor, which significantly reduces its stability and resistance to a collision or to an overturn. If it is taken into account that these passenger transportation units travel long distances, it is relevant to consider all aspects related to the safety in the event of a collision [3].

Among the different types of accidents in which buses may be directly involved, frontal impacts and lateral overturns are deadliest. A study conducted by Transport Canada shows that frontal impacts represent 70 % of all bus accidents. In addition, it is considered one of the collisions that produce more deaths and serious injuries than any other accident. In general, when two vehicles that approximate at a high speed are involved in these impacts, the front structure of the vehicle is involved [4].

A study presented by Ramírez *et al.* [1] also indicate that traffic accidents that occur in roads involving public passenger transportation systems are mainly frontal collisions. Similarly, they state that the difference between the masses and configurations of the vehicles during the impact, generate critical material damages and serious injuries or even loss of life of the occupants.

The resistance to collisions is the capability of the structure to absorb the kinetic energy of the overturn or frontal impact, which should provide an appropriate protection to the vehicle occupants during the traffic accident. This criterion is especially important in passenger transportation vehicles such as buses [5]. This is the reason why, the purpose of the simulations performed in the bus superstructure is to analyze the amount of energy absorbed during a frontal impact or lateral overturn collision in a double-decker bus. Such structure should be deformed as little as possible and should avoid any element to get into the bus survival space [6], according to regulations 29 [7] and 66 of the UN/ECE [8] and regulation NTE INEN 1323:2009 [9].

2. Materials y methods

The study of interest starts with a 3D modeling considering all the details and dimensions of the structure of the double-decker bus. CAD tools were used with the purpose of obtaining the final model for the simulation stages using the FEM; Solidworks was used for the preprocessing stage, while Ansys – LS DYNA [10] was used for the processing and post-processing stages.

The overturn study of the bus structure using the FEM was based on the NTE INEN 1323:2009 regulation [9] and on regulations 29 and 66 of the UN/ECE [7, 8]. The latter is pioneer in increasing the safety of public transportation year after year, implementing regulations that enable guaranteeing the safety of the occupants when a bus experiences a collision and no invasion of the structure to the passenger survival space occurs during an overturn.

In the application domain, regulation 66 of the UN/ECE states that it only applies to single deck vehicles, rigid or articulated, belonging to categories M2 or M3; according to regulations NTE INEN 1323 [9] and 2656 [11], double-decker buses belong to category M3; for these reasons, the overturn test of a double-decker bus may be carried out according to regulation 66, which supports the application of the regulation indicated in this study [8].

Once the overturn analysis was carried out, it was studied a frontal collision of the structure, which enabled visualizing the effect of this type of collision on structure deformation and how it invades the survival space [12].

2.1. Delimitation of the survival space

The survival space shows the geometrical features stated in regulation 66 of the UN/ECE considering the bus dimensions, and it should be located along its entire length as observed in Figure 1. Passengers and operators are in this space; during a collision, this space must not be invaded by the bodywork structure or any accessory that may affect the physical integrity of the occupants [8].

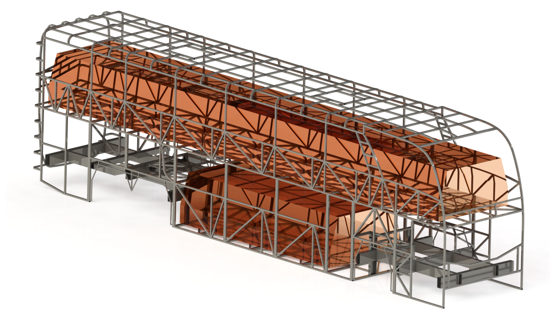

Figure 1. 3D modeling of the survival space within the bus passenger compartment

2.2. Conditions of the bus superstructure

Annex 4 of regulation 66 of the UN/ECE presents the perspectives of the structural description of the bus superstructure; the profiles and structural materials should comply with national and international standards [8].

The structural profiles used in the bus bodywork are shown in Table 1.

Table 1. Bus structural profiles

Profile	Quality	Regulation
R 80 × 40 × 2 mm	ASTM A-500	NTE INEN 1623
R 60 × 40 × 3 mm	ASTM A-500	NTE INEN 1623
R 60 × 40 × 3 mm	ASTM A-500	NTE INEN 1623
R 40 × 20 × 2 mm	ASTM A-500	NTE INEN 1623
C 50 × 50 × 3 mm	ASTM A-500	NTE INEN 1623

Paragraph 1.3 of annex 9 of regulation 66 of the UN/ECE [8] indicates that the data necessary to carry out the test must be met, where the values of mass, center of gravity and moments of inertia of the bus structure must be obtained in advance.

The values of mass, moments of inertia and center of gravity of the bus structure are shown in Table 2, and were obtained during the modeling process.

Table 2. Data sheet of the bus structure

Parameter	Value
Mass	3632,73 kg
Longitudinal position of the COG	6,78 m
Transverse position of the COG	1,30 m
Transverse height of the COG	1,48 m
Ixx	$7,30179 \times 10^7$ mm^4
Ixy	$-7221,14$ mm^4
Ixz	$48267,2$ mm^4
Iyy	$7,09992 \times 10^7$ mm^4
Iyz	$-1,68985 \times 10^6$ mm^4
Izz	$7,86809 \times 10^6$ mm^4
I_{11}	$7,3018 \times 10^7$ mm^4
I_{22}	$7,10443 \times 10^7$ mm^4
I_{33}	$7,82286 \times 10^6$ mm^4

The location of the center of gravity of the bus structure must be clearly defined, as shown in Figure 2.

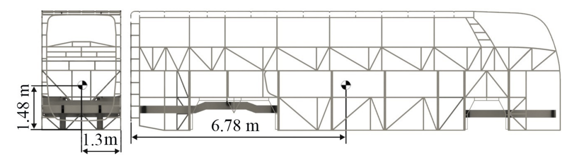

Figure 2. Location of the center of gravity of the bus structure

2.3. Analysis using finite elements

The accuracy of finite elements models depends on the number of nodes and elements, as observed in Figure 3, which depends on the size and the types of components of the mesh; hence, the smaller the size and the larger the number of elements in a mesh, more precise will be the results of the analysis [13].

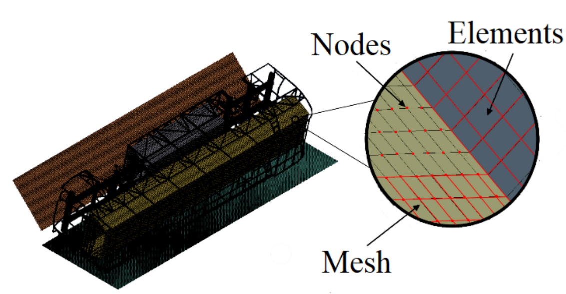

Figure 3. Nodes and elements of a mesh

Important aspects, such as the quality and type, should be taken into account to generate the mesh of the bus structure; these aspects are related with the density and type of the mesh used, which for this case study is a 20 mm hexahedral mesh [14, 15].

2.4. Computer simulation of the overturn test of a vehicle as equivalent homologation method

The bus overturn test is a quite fast and dynamic process with well differentiated stages; this should be considered when planning the test. The bus will tilt without balancing and without dynamic effects until it reaches an unstable equilibrium and starts to overturn, as specified in Figure 4 [8].

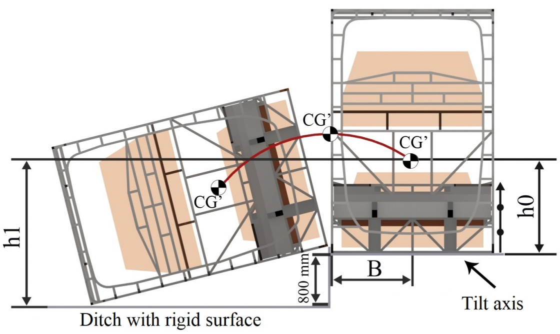

Figure 4. Specification of the overturn test of a vehicle at initial position in the platform

Annex 9 of regulation 66 of the UN/ECE, is applied through the finite element method for computer simulation of the overturn test of a double-decker bus structure. The mathematical values entered in the software to simulate the overturn correspond to the bus turning speed with respect to an axis located in the tilting platform and the gravity, in order to simulate the movement of the structure with respect to the platform.

Equation (1) gives the value of angular speed to be applied.

$$\omega = \sqrt{\frac{2 \cdot m \cdot g \cdot \Delta h}{I}} = 3,3953 \; rad/s^2 \qquad (1)$$

Where:

m = mass (kg)
g = gravitational constant (m/s^2)
Δh = height variation (m)
I = rotational inertia (kg·m^2)

The contacts between the master surface and a set of slave nodes are defined for the simulation. The master surface is defined through the rigid elements used to establish the surface on which the structure of the bus impacts, as seen in Figure 5.

Figure 5. Bus in position of first contact with the rigid impact surface

2.5. Computer simulation of the frontal collision

Recent statistics of traffic accidents demonstrate that almost two thirds of the collisions are frontal, and half of them show a coverage between 30 and 50 % of the front surface [16]. Computer simulation tests are conducted according to regulation 29 of the UN/ECE [8], to assess the effects of this type of collision.

Computer simulation tests of frontal impacts against stationary objects, enable observing the behavior of the vehicle during a collision; it is also an inexpensive method, compared to a real Crash Test [10], [17,18].

The frontal impact is analyzed at 64 km/h, considering that the bus has a frontal impact against a centered stationary barrier (Figure 6). This impact intends to simulate the most frequent type of collisions in roads that result in serious or deadly injuries, since most frontal crashes in double-decker buses directly involve the operators' cabin [19].

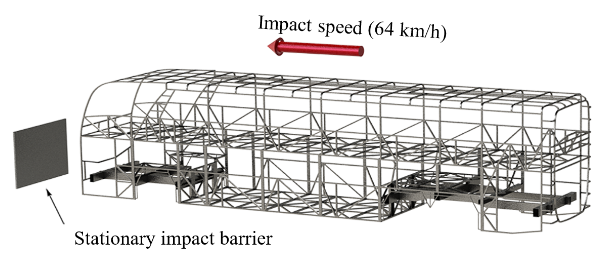

Figure 6. Specifications for simulating the bus frontal impact

It is important to indicate that the speed limit for this type of vehicles in straight roads is 90 km/h, according to the Ecuadorian National Transportation Agency, situation which is considered in other research works that analyze the frontal impact of a single-deck bus [20].

3. Results and discussion

3.1. Bus overturn

The application of the overturn test of the double-decker bus structure using the finite element method, works well until the structure reaches its maximum deformation at time instant $t = 0.621s$ after impacting the rigid surface.

3.1.1. Energies

The values of height obtained for the centers of gravity during the overturn, shown in Table 3, are used to find the difference between the heights (Δh) of the center of gravity, equation 3, which is a variable required in equation 2 that gives the total energy (E_T) that will be absorbed by the bus superstructure in the overturn test.

Table 3. Centers of gravity

Parameter	Value
Point of instability (H)	2284,8 mm
Point of contact (HC)	632 mm

$$E_T = 0,75 \cdot m \cdot g \cdot \Delta h \quad (2)$$

$$\Delta h = H - HC \quad (3)$$

$$E_T = 4,42 \times 10^7 \ J$$

According to the equations of regulation 66, the total energy absorbed by the bus is $4,42 \times 10^7$ J, and the maximum value of total energy absorbed obtained in the simulation (Figure 7) is $4,56 \times 10^7$ J. When comparing the total energy calculated and the one obtained in the simulation there is a difference of 3.32 %, which is due to the fact that the center of gravity is not exact because not all mechanical and finishing components, such as glasses, seats, etc., are considered in the modeling process. Although this difference exists between the values obtained in the calculation and in the simulation, it may be considered that they are coherent and acceptable.

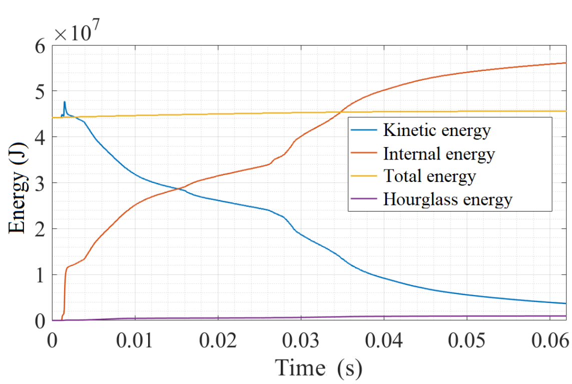

Figure 7. Energies obtained from the simulation of the bus overturn test

The maximum value of Hourglass energy during the overturn test is $0,0966 \times 10^7$ J, which represents 2 % of the total energy. According to annex 9 of regulation 66, this value should not exceed 5 % for the simulation to be accepted; therefore, this requirement is fulfilled.

3.1.2. Survival spaces

Considering that regulation 66 states that the structure should never invade the survival space or vice versa during the overturn, when the bus structure reaches maximum deformation, it does not fulfill such regulation.

Figure 8 shows the displacement of the structure with respect to the survival space. The lower deck of the bus is not affected by the structure deformation since it is rigid enough to withstand an overturn collision; however, the survival space of the upper deck is invaded by the structure in 48 mm when reaching the maximum deformation during the overturn; thus, it does not fulfill the requirement of regulation 66 of the UN/ECE.

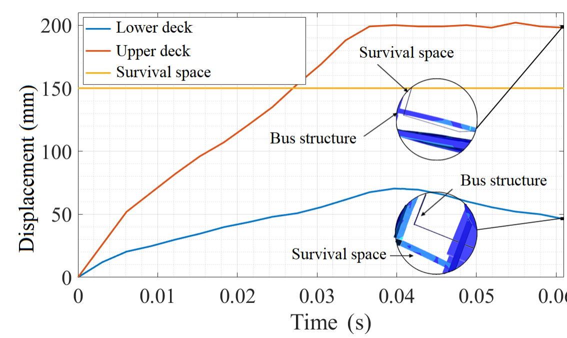

Figure 8. Displacement of the double-decker bus structure with respect to the structure

3.1.3. Speed

The bus speed is high until it impacts on the rigid surface, and after this instant the speed decreases progressively (Figure 9); however, the most important time interval is when the bus impacts on the surface, since our interest is the contact between the two surfaces during the overturn test; the speed value does not decrease to zero, because the overturn simulation is carried out until the maximum deformation of the bus structure according to the regulation.

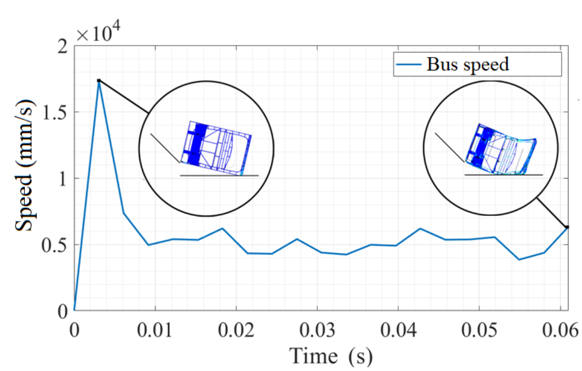

Figure 9. Behavior of the speed during the bus overturn test

3.2. Frontal impact

The bus speed prior to the collision is given by the speed change (ΔV) that the vehicle experiences and by the deceleration, which is a function of the mass and the rigidity of the objects that collide.

The impact zone of the bus with the barrier covers the entire vehicle width; therefore, the bus frame absorbs most of the kinetic energy during the collision, and moreover, the mathematical model was adjusted to obtain the same conditions of a real physical test.

3.2.1. Energies

The maximum total energy generated in the simulation of the bus frontal impact is $4,56 \times 10^8$ J, which remains constant, i.e., is the same before and after the collision; this indicates that the energy produced in the collision is dissipated through the deformation, better known as internal energy (Figure 10).

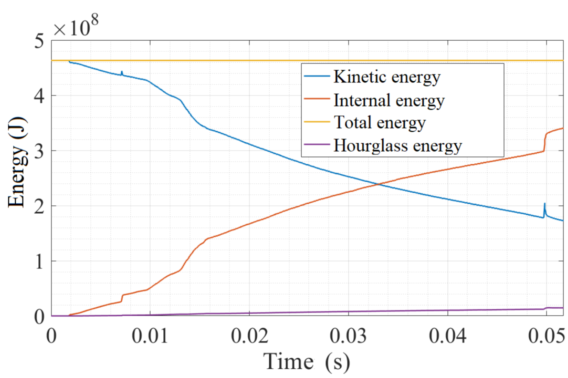

Figure 10. Energies obtained from the simulation of the bus frontal impact

During the bus impact, the maximum value reached by the Hourglass energy is $0,106 \times 10^8$ J (Figure 11), which represents 2.3 % of the total energy; thus, it fulfills the regulation which indicates that this value should not exceed 5 % of the total energy.

3.2.2. Deformation

The cabin of the driver reaches a deformation of 250 mm, as can be observed in Figure 11, due to the impact with the wall. The structure profiles with greater deformation are those that impact directly with the surface; moreover, the chassis wings behave as an underrun bar, which prevents the cabin of the driver from experiencing an excessive deformation, but this does not prevent that structure debris may damage the integrity of the controllers of the transportation unit.

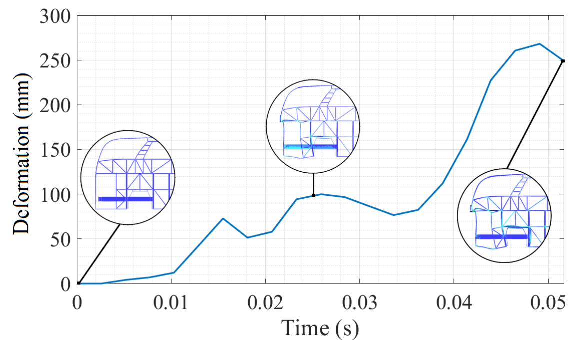

Figure 11. Bus deformation during the frontal impact on the stationary surface

3.2.3. Speed

The bus starts with a speed of 17 800 mm/s (64 km/h), which then decreases continuously due to the impact on the stationary barrier; thus, the cabin of the driver is deformed in a short time interval until reaching a standstill, and the most affected parts are the ones that impact directly on the surface (Figure 12).

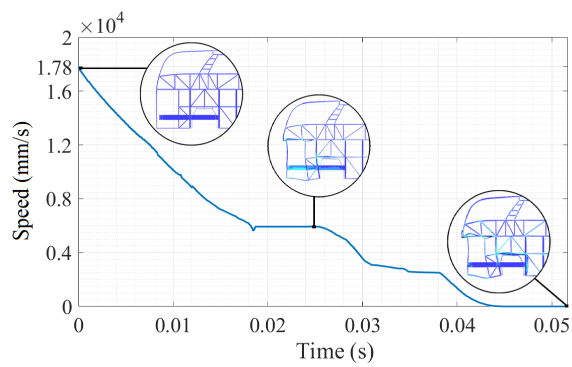

Figure 12. Behavior of the speed during the simulation of the bus frontal impact

4. Conclusions

This study set up two computer simulation processes, namely lateral overturn and frontal impact, of a double-decker bus, according to regulations R66 and R29 of the UN/ECE [8] and regulation NTE INEN 1323:2009 [9]. This enabled to estimate the resistance of the vehicle superstructure during a collision, and also to observe the behavior of the structure with respect to the survival space and the deformation modes of the vehicle.

The collision analysis enables to evaluate the elastoplastic behavior of the steel that makes up the structure of the double-decker buses used in interprovincial transportation, through the computer simulation based on explicit dynamics.

The upper part of the structure was affected during the overturn, since there was a deformation that generated an invasion of 48 mm of the survival space; this can be observed in Figure 8.

Since the center of gravity is not exact, there is a percentage error of 3.32 % between the value of total energy obtained in the overturn simulation and the one calculated using the formulas suggested by regulation 66 of the UN/ECE [8]. It is important to indicate that this numerical error is considered small, and therefore the results obtained for the bus overturn are valid.

The forces generated by the frontal impact of the bus structure on a stationary surface produce high deformation, especially in the cabin of the driver where it reaches values of 250 mm in a very short period of time. This is because the most critical parts are the profiles that receive the impact directly. The bus superstructure is one of the main passive safety components in these vehicles, and therefore design optimization is essential for minimizing the damages that may be caused to passengers and operators of the transportation unit.

In general, the frontal part of the bus structures does not have any protection system to safeguard the life of the cabin occupants during a frontal impact. These elements of the bodywork structure are not capable of totally dissipating the kinetic energy, which should be considered in the design of these elements.

References

[1] B. del Valle Arenas Ramírez, F. E. Molina, A. Arenas, E. Donnet, and F. A. Izquierdo, “Metodología de estudio de accidentes de transporte colectivo de personas en países con carencia de información de calidad = methodology for the study of traffic accident with buses and coaches in countries with lack of quality information,” in *XIV Congreso Iberoamericano de Ingeniería Mecánica (XIV CIBIM)*, 2019, pp. 1–10. [Online]. Available: https://bit.ly/3CUEqDo

[2] United Nations. (2021) Objective 11: Make cities more inclusive, safe, resilient and sustainable. United Nations. Sustainable Development Objectives. [Online]. Available: https://bit.ly/3nPicP8

[3] N. Çolak, U. Şahin, A. Candaş, and C. Ímrak, “Desing and analysis of the protective structure of an intercity bus during a rollover accident,” *Trans Motauto World*, vol. 3, pp. 62–65, 2018. [Online]. Available: https://bit.ly/3re5dIK

[4] W. T. Gardner, *Evaluation of occupant protection in buses.* RONA Kinetics and Associates Ltd., 2002. [Online]. Available: https://bit.ly/30XY3xo

[5] ENNOMOTIVE. (2019) Choque de vehículos: ¿Cómo se absorbe la energía mecánica? [Online]. Available: https://bit.ly/3CMviko

[6] B. D. Palacios, “Análisis mediante el mef de la protección de los conductores en autobuses,” 2016. [Online]. Available: https://bit.ly/3HVFFWU

[7] UN/ECE, *Regulation No 29 of the Economic Commission for Europe of the United Nations (UN/ECE) – Uniform provisions concerning the approval of vehicles with regard to the protection of the occupants of the cabin of a commercial vehicle.* Economic Commission for Europe of the United Nations (UN/ECE). [Online]. Available: https://bit.ly/3FOFJ96

[8] ——, *Regulation No 66 of the Economic Commission for Europe of the United Nations (UN/ECE) – Uniform technical prescriptions concerning the approval of large passenger vehicles with regard to the strength of their superstructure.* Economic Commission for Europe of the United Nations (UN/ECE), 2011. [Online]. Available: https://bit.ly/3r7Y391

[9] INEN, *NTE INEN 1323. Vehículos Automotores, Carrocerías de Buses, Requisitos.* Servicio Ecuatoriano de Normalización, 2009. [Online]. Available: https://bit.ly/3oU82Mo

[10] E. A. Fazio, F. A. Izquierdo, R. G. Pastoril, and Á. L. M. López, “Aplicación de técnicas de ensayo virtual a ensayos de vuelco de superestructuras de autobuses y autocares.” in *Actas del IX Congreso de Ingeniería del Transporte, CIT 2010.* Madrid, España: Universidad Politécnica de Madrid, 2010. [Online]. Available: https://bit.ly/314TIsy

[11] INEN, *NTE INEN 2656: Clasificación Vehicular.* Servicio Ecuiatoriano de Normalización, 2016. [Online]. Available: https://bit.ly/3lbTpDd

[12] A. Garcia, M. Sanchez, E. Alcala, and A. Carretero, “Diseño estructural de autobuses y autocares,” *DYNA-Automoción y Transporte*, vol. 73, no. 3, 1998.

[13] O. C. Zienkiewicz, *El método de los elementos finitos.* Editorial Reverté, 1981. [Online]. Available: https://bit.ly/3DWiVUf

[14] C. H. A. Arroba, M. A. C. Suárez, C. G. S. Espín, and G. E. C. O. na, “Simulación de vuelco con ANSYS y LS-DYNA de una superestructura de un autobús y su incidencia en el área de supervivencia,” *Ciencia Digital*, vol. 6, no. 4.2, pp. 86–99, 2019. [Online]. Available: https://doi.org/10.33262/cienciadigital.v3i4.2.1011

[15] G. Núñez Milán, "Simulación de un ensayo de vuelco de un autobús mediante ls-dyna," B.S. thesis, 2016. [Online]. Available: https://bit.ly/3CUzK0A

[16] D. D. Illescas Pérez, "Simulación de un choque frontal de un vehículo automóvil contra diferentes tipos de barrera," 2009. [Online]. Available: https://bit.ly/3HZn77U

[17] E. Acar, B. Yilmaz, M. A. Güler, and M. Altin, "Multi-fidelity crashworthiness optimization of a bus bumper system under frontal impact," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 42, no. 9, p. 493, Aug 2020. [Online]. Available: https://doi.org/10.1007/s40430-020-02572-3

[18] M. A. Güler, M. E. Cerit, S. K. Mert, and E. Acar, "Experimental and numerical study on the crashworthiness evaluation of an intercity coach under frontal impact conditions," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 234, no. 13, pp. 3026–3041. [Online]. Available: https://doi.org/10.1177/0954407020927644

[19] Latin NCAP. (2021) Impacto frontal. Latin NCAO. Para autos mas seguros. [Online]. Available: https://bit.ly/2ZpTDPc

[20] D. Cárdenas, J. Escudero, S. Quizhpi, and M. Amaya Pinos, "Propuesta de diseño estructural para buses de carrocería interprovincial," *Ingenius. Revista de Ciencia y Tecnología*, no. 11, pp. 42–52, 2014. [Online]. Available: https://bit.ly/3xtnjYr