COMILLAS
UNIVERSIDAD PONTIFICIA
ICAI

BACHELOR'S DEGREE IN INDUSTRIAL TECHNOLOGIES ENGINEERING

UNDERGRADUATE DISSERTATION

NUMERICAL SIMULATION OF BUS EVACUATION USING PATHFINDER

Author: Blanca García Martínez-Aedo

Supervisor: Borja Rengel Darnaculleta

Madrid

July 2026

Declaration of originality

I declare under my responsibility that the Project presented with the title **NUMERICAL SIMULATION OF BUS EVACUATION USING PATHFINDER** at the ICAI School of Engineering of the Comillas Pontifical University in the academic year 2025/2026 is of my authorship and has not been presented previously for other purposes. The Project is not plagiarised from any other, either totally or partially, and the information that has been taken from other documents is duly referenced.

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AI has been used to support the initial organisation of ideas and the structuring of the chapters and sections of the document, to discuss the approach of the analysis, such as how to compare the different configurations and scenarios and to conduct preliminary research on specific topics. It has also been used to improve the formal quality of the academic writing in English and to review the consistency of the terminology, as it is not the author's native language.

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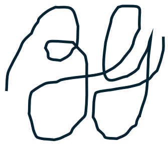

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Date: 09/07/2026

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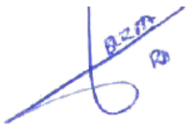

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A mis padres, por apoyarme en todas mis decisiones, alegrarse por mis éxitos y confiar en mí más que yo misma. Gracias por darme la oportunidad de llegar hasta aquí.

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SIMULACIÓN NUMÉRICA DE LA EVACUACIÓN DE AUTOBUSES CON PATHFINDER

Autor: García Martínez-Aedo, Blanca.

Director: Rengel Darnaculleta, Borja.

Entidad Colaboradora: ICAI – Universidad Pontificia Comillas.

RESUMEN DEL PROYECTO

Este Proyecto estudia el proceso de evacuación de emergencia en distintas configuraciones de autobús. Para ello, se lleva a cabo una serie de simulaciones a través del software Pathfinder. El objetivo es identificar qué configuraciones evacúan de forma más rápida y eficiente, analizando factores importantes como el diseño interior del vehículo, el número y distribución de las salidas, la ocupación y el comportamiento de los pasajeros.

Palabras clave: Evacuación, Simulación, Autobuses, Seguridad, Pasajeros.

1. Introducción

En los últimos años se han incorporado cada vez más autobuses eléctricos, de gas y de hidrógeno para reducir las emisiones del transporte. Aunque los incendios en autobuses siempre han existido, estas nuevas tecnologías tienen riesgos de otro tipo [BEAT23]: las baterías pueden sufrir fugas térmicas (thermal runaway) y llegar a explotar, el hidrógeno es altamente inflamable y algunos sistemas pueden liberar gases tóxicos.

Además, los autobuses presentan dificultades como pasillos estrechos y una alta ocupación. En los autobuses viajan pasajeros diversos, incluyendo niños, personas mayores o personas con movilidad reducida (PMR). Todo ello puede generar cuellos de botella y dificultar una evacuación rápida.

A diferencia de la aviación, no existe una normativa que establezca un tiempo máximo de evacuación para autobuses. Además, realizar pruebas reales pondría en peligro a las personas. Por ello, este tipo de análisis se realiza mediante simulación numérica. Pathfinder [THUN24] es un software basado en agentes, lo que permite representar a cada pasajero de forma individual y reproducir de forma realista cómo se mueven e interactúan dentro del vehículo.

El objetivo de este proyecto es analizar cómo influyen el diseño interior de distintos tipos de autobús y las condiciones de una emergencia en el tiempo total de evacuación. A partir de los resultados, se busca identificar qué configuraciones son más seguras y proponer mejoras de diseño.

2. Metodología

Para el estudio se han seleccionado cinco configuraciones de autobús que representan los tipos más habituales: un autobús urbano simple, uno de dos plantas, uno articulado (Clase I), un autobús interurbano (Clase II) y un autocar de larga distancia (Clase III). Cada vehículo se ha modelado en Pathfinder manteniendo su geometría interior real y siguiendo los requisitos de la normativa UNECE R107 [UNEC15]. Esto incluye el ancho y la posición de las puertas, las dimensiones del pasillo y la distribución de los asientos. También se han representado los espacios reservados para PMR y las escaleras.

Los autobuses deben ser accesibles y en ellos puede viajar gente de cualquier perfil. Para representar esto, se han incluido distintos grupos: niños, jóvenes, adultos, personas mayores y personas con movilidad reducida. Como el software permite representarlos como agentes individuales, a cada uno de ellos se le ha asignado una velocidad de marcha, unas dimensiones corporales [IMO_16],[SFPE16] y un tiempo de reacción (pre-movimiento) [CVM213] según su perfil. Además, para fijar este tiempo de pre-movimiento se han distinguido los autobuses de Clases I y II del de Clase III. Esto se debe a que los buses de larga distancia pueden llevar a pasajeros dormidos, lo que hace que estos tarden aún más en reaccionar.

La figura 1 muestra los cinco modelos desarrollados en Pathfinder. En ellos, se puede ver claramente la geometría interior con las distintas distribuciones de asientos, escaleras, zonas reservadas para PMR o personas de pie. Además, se distinguen los distintos perfiles de ocupantes: pasajeros con diferentes alturas, anchuras y orientaciones.

Tras esto, se ha puesto a prueba a cada una de las configuraciones mediante el estudio de cinco escenarios: un caso base con el autobús lleno y todas las puertas operativas, un caso de baja ocupación, un caso con la puerta trasera bloqueada, un caso con el tiempo de pre-movimiento ampliado (que representa el retraso causado por el humo o los gases tóxicos) y un caso crítico que combina la puerta bloqueada con el pre-movimiento ampliado. La combinación de cinco configuraciones y cinco escenarios da lugar a una matriz de 25 casos simulados.

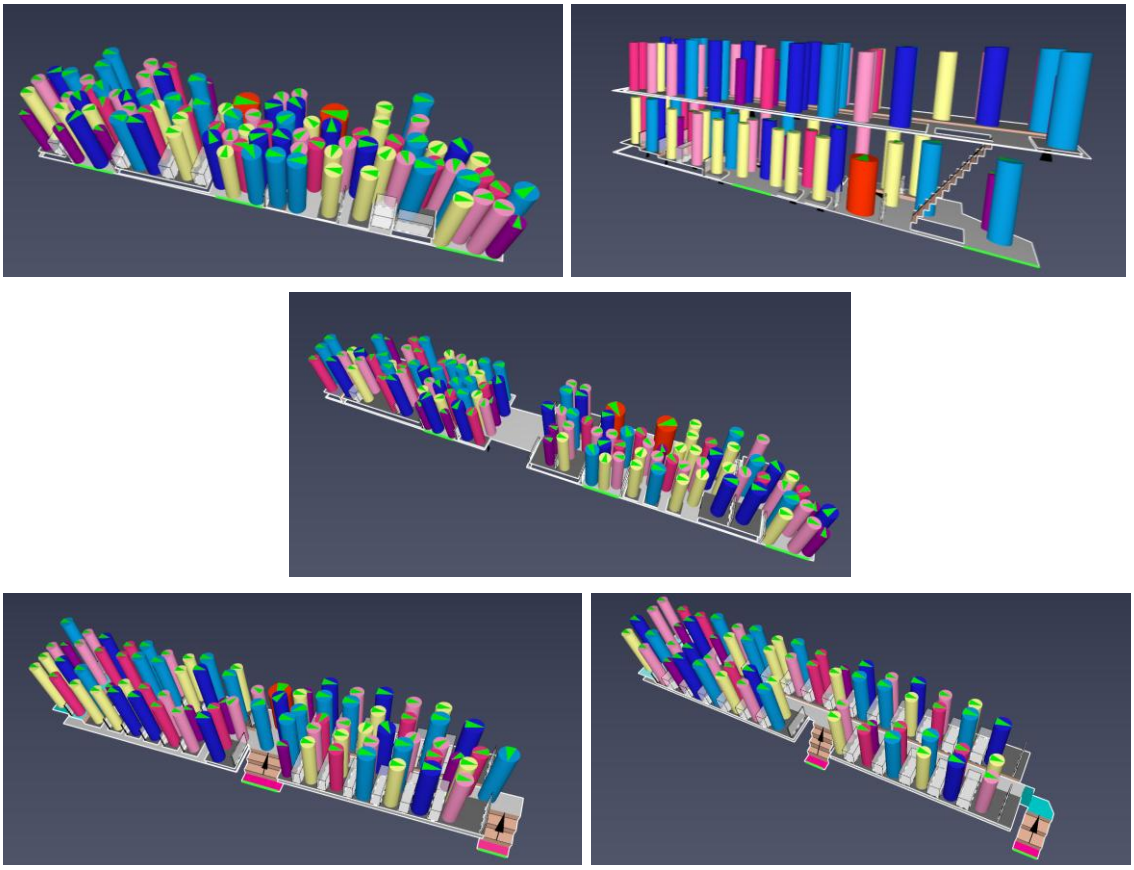

Figura 1: Modelos 3D de las cinco configuraciones desarrolladas en Pathfinder, con los ocupantes distribuidos en su interior.

3. Resultados

Una vez se han simulado los 25 casos, se recogen en la tabla 1 los tiempos totales de evacuación de cada configuración en cada uno de los cinco escenarios. El escenario base se usa como referencia para poder comparar el tiempo de los demás y ver qué configuración evacúa más rápido. Este escenario representa una evacuación del bus al completo sin graves incidencias frente a otras en las que disminuye la ocupación, se bloquea una puerta o se alarga la reacción inicial de los pasajeros.

Modelo del vehículo	Escenario 1: Base	Escenario 2: Baja ocupación	Escenario 3: Bloqueo de Puerta trasera	Escenario 4: Tiempo de pre-movimiento	Escenario 5: Escenario crítico
Bus urbano simple	68.0	65.8	102.0	98.0	122.5
Bus de 2 plantas	151.0	87.0	179.5	159.0	186.8
Bus articulado	70.8	67.3	143.3	97.3	156.8
Bus interurbano	108.8	73.3	187.0	126.8	211.3
Bus de larga distancia	121.0	99.8	144.8	144.0	152.5

Tabla 1: Resumen de los tiempos de evacuación de cada configuración en los cinco escenarios.

El primer análisis que se debe hacer es comparar los escenarios entre sí. En este caso, se observa que los tiempos de evacuación más bajos se obtienen en el escenario 2, que corresponde al de baja ocupación. Esto es completamente esperable, ya que al haber menos pasajeros, el tiempo es menor. En el otro lado está el escenario crítico, que tiene los mayores tiempos de evacuación. Este escenario bloquea una puerta, a la vez que se aumenta el tiempo de pre-movimiento. Ante estas condiciones, el bus interurbano alcanza el mayor tiempo de evacuación de todos los estudiados, 211,3 segundos. Al bloquearse una puerta, el autobús se queda con una única salida, que además es estrecha, para una ocupación muy alta. Esto colapsa el pasillo, que ya contaba con pasajeros de pie.

Si ahora se comparan las configuraciones, se observa que cada tipo de autobús responde de forma muy distinta a los mismos cambios. Un caso llamativo es el autobús de dos plantas: aunque parte del tiempo base más alto (151 s), es al que menos le afecta el hecho de que se aumente el tiempo de pre-movimiento (solo 8 segundos más). Esto se debe a que su escalera actúa como cuello de botella y limita la evacuación independientemente de cuándo empiecen a moverse los pasajeros. Esto se puede ver claramente en el mapa de uso acumulado del autobús de dos plantas (Figura 2), donde la escalera concentra el mayor tránsito de pasajeros durante toda la evacuación.

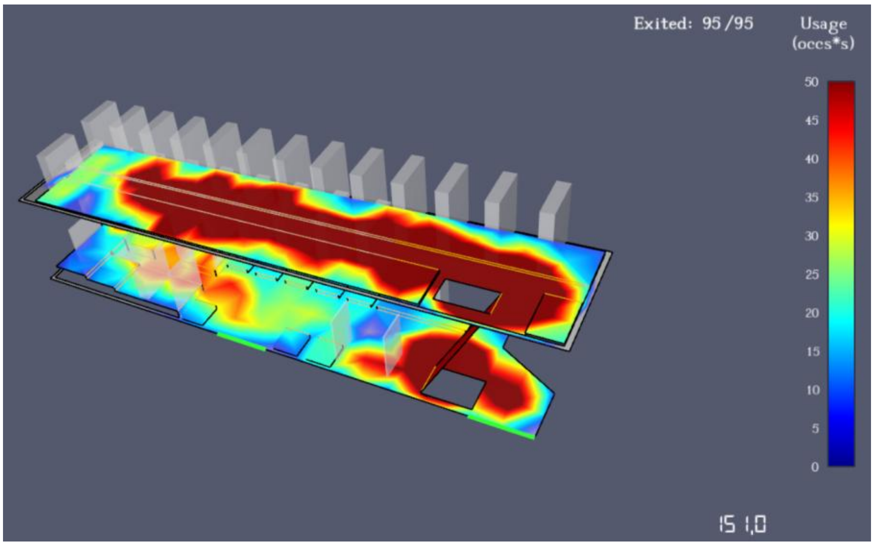

Figura 2: Mapa de uso acumulado del autobús de dos plantas en el escenario base.

En conjunto, los resultados muestran que el factor que más determina el comportamiento de cada autobús es la presencia o ausencia de un cuello de botella dominante. Cuando existe un cuello de botella fuerte, como la escalera del autobús de dos plantas o una única puerta estrecha, este limita la evacuación y el resto de los factores tienen menos influencia. En cambio, cuando no hay un cuello de botella claro, como en el urbano o el articulado, el tiempo de evacuación depende mucho más de la ocupación o del tiempo de reacción de los pasajeros.

4. Conclusiones

Después de analizar los 25 casos, se pueden extraer las siguientes conclusiones sobre la eficiencia en la evacuación de distintas configuraciones de autobús:

- La configuración interior (incluyendo el ancho de los pasillos, las escaleras y el número y ancho de las puertas) es el factor que más domina en el ámbito de la seguridad. Los cuellos de botella geométricos limitan el flujo de pasajeros durante gran parte de la evacuación, independientemente de la carga de pasajeros.
- La eficiencia en una evacuación está condicionada por el nivel de ocupación: en alta ocupación, el tiempo está determinado por la saturación de las salidas (*queueing time*), mientras que en baja ocupación el factor determinante pasa a ser el tiempo de recorrido (*walking time*).
- El hecho de que haya congestión en una configuración hace que otros efectos se amortigüen. En situaciones críticas, los retrasos adicionales (como el tiempo de pre-movimiento) no siempre se traducen en un aumento proporcional del tiempo total, ya que la congestión preexistente absorbe parte de este retardo.

- Los autobuses urbanos y articulados muestran un comportamiento excelente en condiciones normales. Sin embargo, son los más sensibles a cambios drásticos (como el bloqueo de una puerta), a diferencia de vehículos con cuellos de botella fijos, cuyo rendimiento es más estable pero limitado.
- El hecho de que no exista una normativa que establezca tiempos máximos en los que se debe realizar la evacuación hace que sea más difícil estandarizar la seguridad. Por tanto, es necesario que los fabricantes realicen pruebas con escenarios críticos, no solo la operación normal.
- La presencia de pasajeros con movilidad reducida (PMR) introduce un desafío crítico en las configuraciones que tienen un pasillo estrecho. Cada PMR evacúa por la puerta más cercana a su plaza reservada (la central en el urbano y el articulado, y la trasera en el de dos plantas y el interurbano). El problema aparece cuando se bloquea precisamente esa puerta. En ese caso, el PMR se ve obligado a recorrer el pasillo hasta otra salida y necesita que alguien lo asista, ya que la silla de ruedas no cabe por el pasillo. Esto puede interrumpir el flujo de evacuación durante unos segundos, lo que perjudica a la evacuación total.

5. Referencias

[UNEC15] United Nations Economic Commission for Europe (UNECE), "Regulation No. 107: Uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction", Technical Report, Geneva, Switzerland. 2015.

[BEAT23] Bureau d’Enquêtes sur les Accidents de Transport Terrestre (BEA-TT), "Rapport d’enquête technique sur les incendies de deux autobus électriques survenus à Paris les 4 et 29 avril 2022", Technical Report, Puteaux, France. 2023.

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NUMERICAL SIMULATION OF BUS EVACUATION USING PATHFINDER

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Collaborating Entity: ICAI – Universidad Pontificia Comillas.

ABSTRACT

This Project studies the evacuation process during an emergency for different bus configurations. In order to do so, a series of simulations are carried out by using the software Pathfinder. The objective is to identify which configurations evacuate in the safest and fastest way, analysing some important factors such as the interior design of the vehicle, the number and distribution of doors, occupancy levels and the passengers' behaviour.

Keywords: Evacuation, Simulation, Buses, Safety, Passengers.

1. Introduction

In recent years, more and more electric, gas and hydrogen buses have been introduced to reduce transport emissions. Although bus fires have always existed, these new technologies have different types of risk [BEAT23]: batteries can suffer thermal runaway and even explode, hydrogen is highly flammable and some systems can release toxic gases.

In addition, buses present difficulties such as narrow aisles and high occupancy. Very diverse passengers travel on them, including children, elderly people and people with reduced mobility (PRM). All of this can create bottlenecks and make a fast evacuation difficult.

Unlike aviation, there is no regulation that establishes a maximum evacuation time for buses. Moreover, carrying out real tests would put people at risk. For this reason, this type of analysis is done through numerical simulation. Pathfinder [THUN24] is an agent-based software, which makes it possible to represent each passenger individually and to reproduce realistically how they move and interact inside the vehicle.

The objective of this project is to analyse how the interior design of different bus types and the conditions of an emergency influence the total evacuation time. Based on the results, the aim is to identify which configurations are safer and to propose design improvements.

2. Methodology

Five bus configurations were selected for the study, representing the most common types: a simple urban bus, a double-decker bus, an articulated bus (Class I), an intercity bus (Class II) and a long-distance bus (Class III). Each vehicle was modelled in Pathfinder keeping its real interior geometry and following the requirements of the UNECE Regulation No. 107 [UNEC15]. This includes the width and position of the doors, the dimensions of the aisle and the seating layout. The spaces reserved for PRM and the staircases were also represented.

Buses must be accessible and people of any profile can travel on them. To represent this, different groups were included: children, young people, adults, elderly people and people with reduced mobility. Since the software allows them to be represented as individual agents, each one was assigned a walking speed, body dimensions [IMO_16], [SFPE16] and a reaction time (pre-movement) [CVM213] according to their profile. In addition, to set this pre-movement time, a distinction was made between Class I and II buses and the Class III coach. This is because long-distance buses may carry sleeping passengers, who take even longer to react.

Figure 1 shows the five models developed in Pathfinder. The interior geometry can be clearly seen, with the different seating layouts, staircases, and areas reserved for PRM or standing passengers. The different occupant profiles can also be distinguished: passengers with different heights, widths and orientations.

After this, each configuration was tested under five scenarios: a baseline case with the bus at full capacity and all doors operational, a low occupancy case, a case with the rear door blocked, a case with an extended pre-movement time (representing the delay caused by smoke or toxic gases) and a critical case combining the blocked door with the extended pre-movement time. The combination of five configurations and five scenarios results in a matrix of 25 simulated cases.

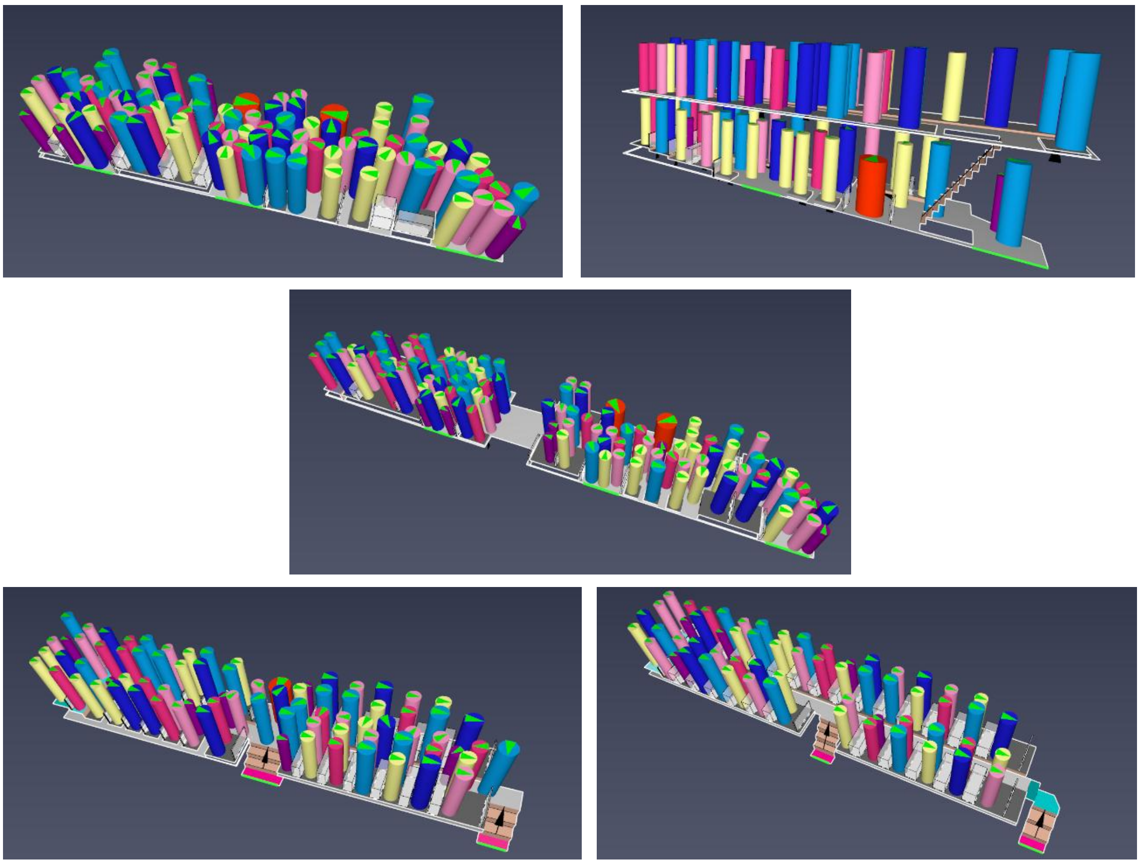

Figure 1: 3D models of the five configurations developed in Pathfinder, with the occupants distributed inside.

3. Results

Once the 25 cases were simulated, Table 1 gathers the total evacuation times of each configuration under each of the five scenarios. The baseline scenario is used as a reference to compare the times of the other scenarios and see which configuration evacuates faster. This scenario represents an evacuation of the full bus without major incidents, as opposed to others in which the occupancy is reduced, a door is blocked or the initial reaction of the passengers takes longer.

Vehicle model	Scenario 1: Baseline	Scenario 2: Low occupancy	Scenario 3: Rear door blockage	Scenario 4: Extended pre-movement	Scenario 5: Critical scenario
Simple urban bus	68.0	65.8	102.0	98.0	122.5
Double-decker bus	151.0	87.0	179.5	159.0	186.8
Articulated bus	70.8	67.3	143.3	97.3	156.8
Intercity bus	108.8	73.3	187.0	126.8	211.3
Long-distance bus	121.0	99.8	144.8	144.0	152.5

Table 1: Summary of the evacuation times of each configuration under the five scenarios.

The first analysis is to compare the scenarios with each other. The lowest evacuation times are obtained in scenario 2, which corresponds to low occupancy. This is completely expected, since with fewer passengers the time is shorter. On the other side is the critical scenario, which has the highest evacuation times. This scenario blocks a door while also increasing the pre-movement time. Under these conditions, the intercity bus reaches the highest evacuation time of the whole study, 211.3 seconds. When a door is blocked, the bus is left with a single exit, which is also narrow, for a very high occupancy. This collapses the aisle, which already contained standing passengers.

If the configurations are now compared, each type of bus responds very differently to the same changes. A remarkable case is the double-decker bus: although it starts from the highest baseline time (151 s), it is the least affected by the increase in pre-movement time (only 8 more seconds). This is because its staircase acts as a bottleneck and limits the evacuation regardless of when the passengers start moving. This can be clearly seen in the accumulated usage map of the double-decker bus (Figure 2), where the staircase concentrates the highest passenger flow during the whole evacuation.

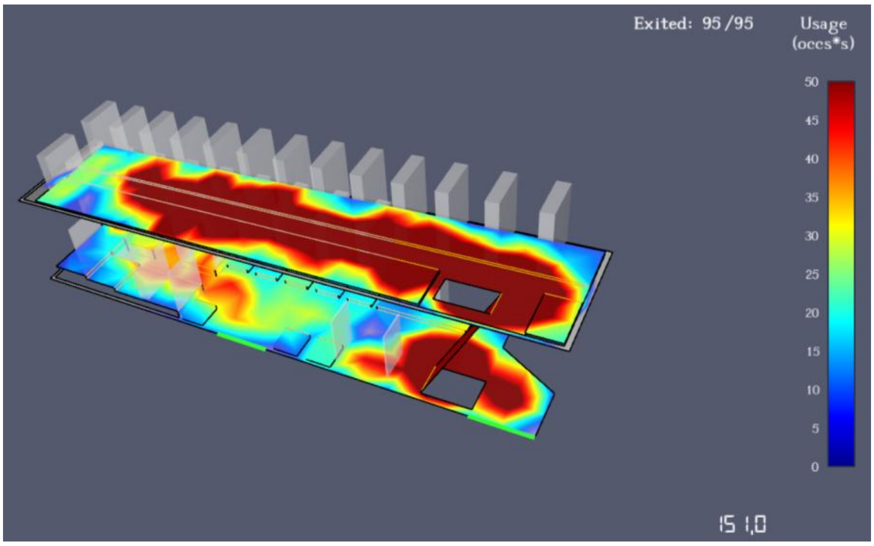

Figure 2: Accumulated usage map of the double-decker bus in the baseline scenario.

Overall, the results show that the factor that most determines the behaviour of each bus is the presence or absence of a dominant bottleneck. When there is a strong bottleneck, such as the staircase of the double-decker bus or a single narrow door, it limits the evacuation and the rest of the factors have less influence. On the other hand, when there is no clear bottleneck, as in the urban and articulated buses, the evacuation time depends much more on the occupancy or the reaction time of the passengers.

4. Conclusions

After analysing the 25 cases, the following conclusions can be drawn about the evacuation efficiency of the different bus configurations:

- The interior configuration (including the width of the aisles, the staircases and the number and width of the doors) is the most dominant factor in terms of safety. Geometric bottlenecks limit the passenger flow during most of the evacuation, regardless of the passenger load.
- The efficiency of an evacuation is conditioned by the occupancy level: at high occupancy, the time is determined by the saturation of the exits (queueing time), while at low occupancy the determining factor becomes the walking time.
- Congestion in a configuration causes other effects to be dampened. In critical situations, additional delays (such as the pre-movement time) do not always translate into a proportional increase in the total time, since the pre-existing congestion absorbs part of this delay.
- Urban and articulated buses show an excellent behaviour under normal conditions. However, they are the most sensitive to drastic changes (such as the blockage of a door), unlike vehicles with fixed bottlenecks, whose performance is more stable but limited.

- The fact that there is no regulation establishing maximum evacuation times makes it more difficult to standardise safety. Therefore, manufacturers need to test their configurations under critical scenarios, not only under normal operation.
- The presence of passengers with reduced mobility (PRM) introduces a critical challenge in configurations with a narrow aisle. Each PRM evacuates through the door closest to their reserved space (the central one in the urban and articulated buses, and the rear one in the double-decker and intercity buses). The problem appears when precisely that door is blocked. In that case, the PRM is forced to travel along the aisle to another exit and needs assistance, since the wheelchair does not fit through the aisle. This can interrupt the evacuation flow for a few seconds, which penalises the total evacuation.

5. References

[UNEC15] United Nations Economic Commission for Europe (UNECE), "Regulation No. 107: Uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction", Technical Report, Geneva, Switzerland. 2015.

[BEAT23] Bureau d'Enquêtes sur les Accidents de Transport Terrestre (BEA-TT), "Rapport d'enquête technique sur les incendies de deux autobus électriques survenus à Paris les 4 et 29 avril 2022", Technical Report, Puteaux, France. 2023.

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Chapter 1. INTRODUCTION

Public transport and specifically bus systems are of vital importance for the reliable, economical and environmentally sustainable movement of people. In order to encourage citizens to adopt a preference for urban buses and reduce car dependency and the number of private vehicle trips, it is fundamental that these bus systems provide a high level of safety.

In the last decade there have been technical advances in the development of green vehicles such as electric or hydrogen-powered buses. While these cutting-edge technologies are essential for sustainable objectives, they present new safety challenges and uncertainties. Unforeseen fire risks due to thermal runaway from electric buses as well as toxic gas emissions can lead to public scepticism, resulting in a decrease in the use of public transport. Real-world incidents, such as the 2022 Paris Bluebus fires, have already demonstrated how rapidly these situations can escalate. In that case, complete vehicle destruction occurred within seconds, leaving no margin for a safe evacuation.

In addition to these risks related to propulsion, it is necessary to take into account the geometry of modern buses. These are characterized by narrow aisles and are designed to be accessible to a diverse range of passengers, people of all ages and mobility conditions, such as those using strollers or wheelchairs. This requirement creates significant congestion, especially near the entrance and exit doors. These areas become critical bottlenecks that can hinder passenger flow and delay a rapid evacuation during safety emergencies.

With the aim of ensuring passenger safety and reducing the operational risks of these bus systems, it is indispensable that these complexities are addressed by conducting rigorous performance-based analyses of passenger egress dynamics. Unlike aviation, where regulatory bodies impose strict evacuation time limits, no equivalent binding standard exists for buses, which makes simulation-based assessment all the more necessary. Consequently, this project aims to model various evacuation scenarios across different bus configurations using Pathfinder, evaluating their safety performance and proposing design or operational improvements.

1.1 PROJECT MOTIVATION

The transition towards a cleaner planet and a more sustainable mentality has led to an accelerated development of different propulsion systems. However, this rapid shift has moved faster than the safety protocols that should accompany them. The motivation behind this project arises from the need to bridge this gap. It is not enough to have an eco-friendly face towards the public, but people need to trust that they will be safe under any circumstances if they choose buses as their transportation method. If passengers do not trust this transport system because of their fear of electric batteries fires, such as thermal runaway, or potential hydrogen leaks, the green transition will fail, and people will rely on other private, less sustainable means of transport.

Furthermore, this project is motivated by the actual necessity of inclusion while maintaining safety levels at their maximum. Most urban buses are equipped with a dedicated wheelchair space, which makes them accessible for people with reduced mobility. However, modern buses are designed with narrow gangways and spaces, which increase the challenges in case of extreme situations. As illustrated in Figure 1, real operating conditions frequently involve high passenger densities that severely limit movement within the vehicle. Analysing how people with different capacities interact in these confined spaces is a need and an ethical responsibility, as these transport systems need to be accessible for all and be within reach of anyone in the population.

Finally, this project will include valuable information based on different realistic data. By using Pathfinder, it is possible to replicate extreme emergency scenarios, such as total door blockages or the delayed reactions caused by smoke and reduced visibility, without putting real lives at risk in physical drills. This can help local authorities and enterprises with decision-making when acquiring new fleets to offer the safest transport for their citizens or workers. The motivation behind this project is to provide a comparative tool and reach a conclusion on the number of floors or doors that will secure everyone's safety. It offers quantitative answers in relation to evacuation times instead of subjective opinions. In addition to preserving lives, using the collected data can help companies to avoid massive economic losses. An optimized design can reduce legal claims, property damage and harm to the firm's reputation. Ultimately, the core motivation behind this project is simple: ensuring that every passenger, regardless of their physical condition or the bus they are travelling on, has a real opportunity to get out safely.

Figure 1: *High passenger density in a typical urban bus, illustrating the congestion challenges that characterise emergency evacuation scenarios.*

1.2 ALIGNMENT WITH SUSTAINABLE DEVELOPMENT GOALS (SDGS)

This dissertation is committed to the United Nations 2030 Agenda for Sustainable Development, [UN_15] considering that safety in urban and intercity buses is essential to address global challenges such as inequality and climate change. Public transport connects people to employment, education, and healthcare. Ensuring that it operates safely under all conditions, including emergencies, is therefore a matter of both engineering responsibility and social justice. With this in mind, the project aligns with three Sustainable Development Goals that reflect the breadth of its impact. In the following table (Table 1) a summary of the dimension, role and goal of each of the SDGs is presented.

SDG dimension	SDG identified	Role	Goal
Society	**SDG 11:** Sustainable Cities and Communities	Primary	**Target 11.2:** By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all.
	SDG 3: Good Health and Well-being	Primary	**Target 3.6 & 3.9:** Halve global deaths/injuries from road traffic accidents and reduce illnesses from hazardous chemicals.
Economy	**SDG 9:** Develop resilient infrastructure, promote inclusive and sustainable industrialisation, and encourage innovation.	Secondary	**Target 9.4:** Upgrade infrastructure and retrofit industries to make them sustainable, with greater adoption of clean and sound technologies.

Table 1: Summary of dimension, role and goal of SDG.

1.2.1 SDG 3: GOOD HEALTH AND WELL-BEING

The SDG 3 focuses on ensuring healthy lives and promoting well-being for all at all ages. Within the societal dimension, this project addresses two critical targets. First of all, Target 3.6, which aims to halve the global number of deaths and injuries from road traffic accidents; Second of all, Target 3.9, which focuses on reducing the number of deaths and illnesses from hazardous chemicals, air pollution, and contamination. In public transit infrastructure, vehicle collisions cause immediate physical trauma risks. In addition, fires involving modern, alternative propulsion technologies introduce severe thermal and chemical hazards. Thermal runaway in lithium-ion batteries generates high heat release rates and releases highly toxic substances such as hydrogen fluoride (HF) and carbon monoxide (CO). It is vital to minimize human exposure to these elements during the critical early stages of an on-board fire, in order to prevent permanent respiratory illness, acute intoxication or fatalities.

This project contributes to SDG 3 as a primary goal by evaluating passenger safety during an on-board emergency. The evacuation times of different bus configurations are obtained by using Pathfinder. Then, they are compared to determine which designs allow occupants to leave the vehicle more quickly, reducing the time they are exposed to a potentially hazardous environment. This makes it possible to identify optimized vehicle layouts that minimize the time occupants spend inside a hazardous environment. By protecting human health, it supports the mandate of both Target 3.6 and 3.9.

1.2.2 SDG 11: SUSTAINABLE CITIES AND COMMUNITIES

SDG 11 is the most directly connected goal to this dissertation. Target 11.2 aims to provide universal access to safe, affordable, accessible, and sustainable transport systems by 2030, with particular attention to the needs of vulnerable groups. In most cities, buses are the primary means of transport for a large share of the population, and their importance is increasing as urban areas implement strategies to reduce car dependency and lower emissions. However, the transition towards greener fleets introduces new operational safety challenges. If these technological shifts are accompanied by risks such as thermal runaway incidents, it could seriously damage public confidence in shared transport. As a result, citizens could be forced back to private vehicles, causing the green transition to fail.

This project contributes to SDG 11 as a primary goal by ensuring that the shift towards sustainable bus technologies does not come at the expense of passenger safety. By evaluating evacuation performance across different vehicle configurations using Pathfinder, this research identifies which internal geometries and exit distributions are the best to protect all passenger groups during an emergency. This incorporates not only a quantitative way of evaluating bus safety, but also a qualitative approach, including children, elderly travellers, and people with reduced mobility under worst-case emergency conditions.

1.2.3 SDG 9: INDUSTRY, INNOVATION AND INFRASTRUCTURE

Target 9.4 of SDG 9 focuses on upgrading infrastructure and promoting the adoption of cleaner and more efficient technologies across industries. In the transport sector, this means not only deploying greener vehicles, but also developing the tools needed to properly assess their safety performance.

The use of Pathfinder to simulate bus evacuation scenarios is a good example of this kind of innovation. Instead of relying on costly physical drills or overly simplified models, this research shows how agent-based simulation can produce rigorous and reproducible safety assessments that account for real passenger behaviour and realistic emergency conditions. This approach can be adopted by manufacturers, regulators, and transport operators. As a result, this can contribute to a safer and more forward-thinking industry, as well as allowing the evaluation of layout safety performance before making capital-intensive fleet decisions.

Figure 2*: Sustainable Development Goals 11, 3 & 9 Icon [UN__15].*

Chapter 2. STATE OF THE ART

2.1 REGULATORY FRAMEWORK

The safety and technical configuration of passenger-carrying vehicles are governed by an extensive set of international regulations. These standards ensure that vehicle design, manufacturing, and operational protocols meet minimum safety requirements to protect occupants in both normal conditions and emergency situations. In the context of this research, three primary regulatory standards provide the basis for defining simulation parameters and assessing bus geometry, emergency response for alternative propulsion systems, and evacuation time performance: UNECE R107, ISO 17840, and NFPA 502.

2.1.1 UNECE REGULATION NO. 107

The UNECE Regulation No. 107 [UNEC15] provides the comprehensive framework for vehicle geometry, including buses such as the ones that will be tested throughout this dissertation as well as the materials used in the design of them. This regulation encompasses M2 and M3 vehicles with the exception of vehicles designed for the secure transport of people, the carriage of school children, injured or ill people or state security forces and bodies. M2 vehicles are defined as vehicles designed for the transportation of eight or more passengers in addition to the driver which have a maximum mass that does not exceed 5 tonnes. M3 vehicles have the same characteristics with the distinction that their maximum mass does exceed 5 tonnes. These technical definitions are crucial for this study, as urban, intercity buses and coaches, which comprise M3 vehicles can have an enormous number of passengers and therefore, present significant challenges during emergency evacuation scenarios.

In addition to the distinction by maximum mass, the UNECE regulation establishes a classification according to the vehicle internal configuration and passenger capacity. First of all, it is important to distinguish between vehicles that can carry less or more than 22 passengers. If the capacity exceeds 22 occupants as is the case with the buses that this study focuses on, there are three classes of vehicles:

- Class I: vehicles constructed with areas for standing passengers. Urban buses have these characteristics.
- Class II: specially designed to transport seated passengers but allowing standing travellers, with a strictly regulated capacity, ensuring that the allocated zone does not exceed the area typically occupied by two double seats. Intercity buses belong to this classification.
- Class III: vehicles that can exclusively transport seated occupants. Coaches comprise this last class.

This research analyses the three vehicle classes, as the high occupancy density and the presence of standing passengers result in very critical situations. To ensure the most reliable evacuation analysis, it is essential to define the technical requirements and occupant capacities for each vehicle category as established by UNECE Regulation No. 107. The maximum standing capacity is established using a surface area requirement of 0.125 m^2 per passenger (8 people per square meter). This represents a worst-case scenario significantly higher than the standard adopted by other operators such as EMT Madrid (3.75 people per square meter).

The following table (Table 2) shows parameters such as door widths, minimum number of exits and passenger distribution for each vehicle class. These values are based on UNECE Regulation No. 107 and standard 12-meter models (except articulated buses, which are 18 meters), and are included to provide an order-of-magnitude understanding of the occupancy levels. The exact values used in the simulation models are defined in Chapter 5, once the specific floor plans for each vehicle are introduced.

Bus Type (Reference)	Seated Passengers	Standing Passengers	Total Occupancy	Service Doors	Service Door Width	Min. Gangway Width (Aisle)
Class I: Urban Simple (Fig. 2.1)	28	72	100	2	1200 mm (Double)	450 mm
Class I: Double Decker (Fig. 2.2)	65	15	80	2	1200 mm (Double)	450 mm (Lower deck)
Class I: Articulated (Fig. 2.3)	45	105	150	3	1200 mm (Double)	450 mm
Class II: Intercity (Fig. 2.4)	51	14	65	2	1200 mm (Central) 650 mm (Front)	300 mm
Class III: Coach (Fig. 2.5)	55	0	55	1	650 mm (Single)	300 mm

Table 2: Summary of passenger capacities and exit widths for Classes I, II, and III.

In addition, Figures 3 to 7 illustrate real-world examples of each vehicle class. These figures also highlight geometric and operational features that are important when carrying out the evacuation analysis. A clear example is the double-decker bus (Figure 4). Although it appears larger, Table 2.1 shows it has a lower total occupancy than single-deck models. This is due to UNECE R107 safety standards, which prohibit standing passengers on the upper deck to ensure vehicle stability. In addition, the internal staircase reduces the available standing area on the lower deck. Despite this lower total capacity, these vehicles are commonly used because they offer more seating, which is preferable on longer routes where passengers are expected to remain seated. Similarly, Class III buses have narrower doors (Figure 7), which means the evacuation flow will be slower than in configurations equipped with double doors.

Figure 3: Example of a modern Class I urban bus.

Figure 4: Example of a Class I double-decker urban bus.

Figure 5: Example of a Class I articulated urban bus.

Figure 6: Example of a Class II intercity bus.

Figure 7: Example of a Class III long-distance coach.

With regard to the internal configuration of the bus, all the valuable information is contained in Annex 3 of Regulation No. 107. First of all, it is important to distinguish the total surface area available for passengers S_0 and the standing area S_1. The calculation of both areas is of vital importance, as S_0 does not include the driver's compartment nor the non-usable space such as the steps or the area swept by the doors, and S_1 is the zone where more people will assemble and, therefore, the area where congestion is more likely to occur. Standing areas (S_1) are expected to reach critical densities, significantly reducing walking speed and increasing evacuation time. Moreover, the regulation ensures that all types of passengers, including those with reduced mobility, can transit throughout the gangway. In order to accomplish this, the gangway must permit the free passage of a gauging device consisting of two co-axial cylinders and an inverted truncated cone, as it is illustrated in figure 8. This requirement is fundamental for the evacuation model because it guarantees a minimum unobstructed path. Regarding the evacuation points, the regulation includes the requirements for service doors. While urban buses require at least two doors, long-distance coaches only require one, relying on emergency exits in case of a danger situation. To ensure accessibility from the outside, the doors must accommodate the passage of specific test gauges (Test Gauge 1 and 2), as shown in Figure 9. Annex 3 establishes specific widths of 650 mm for single doors and 1,200 mm for double doors. These dimensions are critical parameters for the simulation, as they directly dictate the maximum passenger flow rate for each specific bus typology.

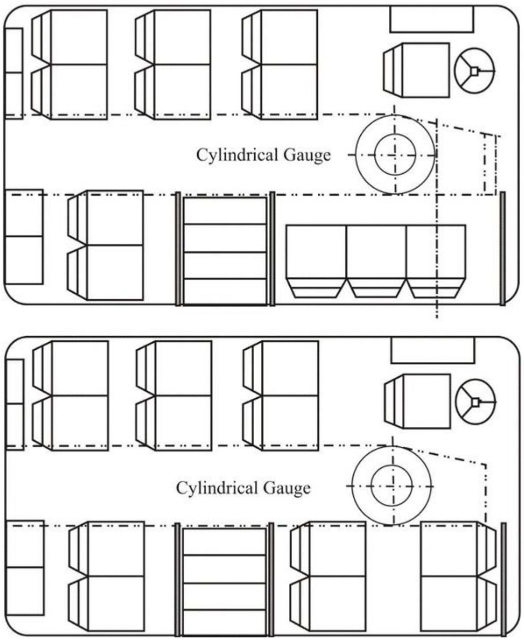

Figure 8: Gauging device for checking the accessibility of the gangway and the driver's compartment according to UNECE R107 [UNEC15].

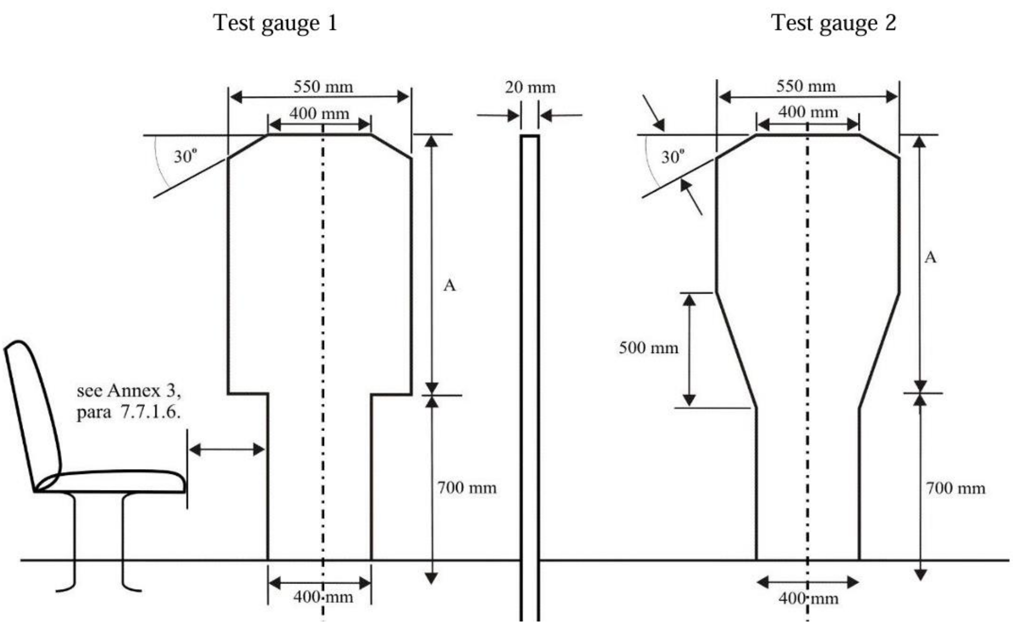

Figure 9: Test gauges for checking the accessibility of service doors according to UNECE R107 [UNEC15].

Regarding accessibility, Annex 8 of Regulation No. 107 establishes the technical framework for people with reduced mobility (PRM). It is essential to take into account that wheelchair users significantly influence the evacuation flow. First of all, the regulation distinguishes between forward-facing wheelchairs and rearward-facing configurations. The first one requires complex restraint systems which must be capable of being easily released by hand in case of an emergency. This means that the time required to initiate movement is different for these occupants. Furthermore, it is necessary that buses are equipped with boarding devices such as ramps or lifts, which require the bus to be at complete standstill. According to paragraph 3.11.4., a ramp must provide a minimum usable width of 800 mm. When considering the 700 mm width of the reference wheelchair (Annex 4, Figure 21) illustrated in figure 10, it can be seen that even through a 1,200 mm double door, there is not enough space for parallel movement. Therefore, the evacuation of a wheelchair user does not allow the flow of other passengers through that exit. This dimensional bottleneck, added to the slower evacuation speeds of PRM agents, increases the overall evacuation time and must be considered when determining the vehicle's safety margins.

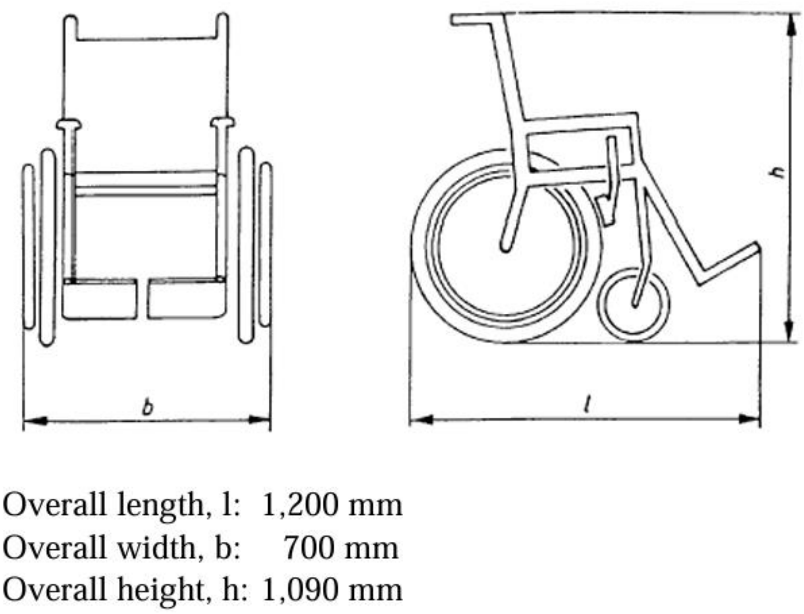

Figure 10: Reference wheelchair dimensions according to UNECE R107, Annex 4, Figure 21 [UNEC15].

Finally, it is essential that vehicles are protected against fire risks. While Annex 5 of Regulation No. 107 is currently reserved, Annex 3 (paragraph 7.5.), establishes the framework for active safety. Vehicles of classes I, II, and III must be equipped with automatic fire detection and suppression systems in the engine compartment and any separate combustion heaters. These systems must warn the driver with acoustic and visual alerts as well as activate the vehicle's hazard lights. In addition, to prevent the fire from spreading, any soundproofing or insulation material in the engine compartment should be covered by an impermeable sheet to avoid accumulation of flammable fluids, and the engine compartment must have a heat-resistant partition to isolate the engine compartment from the passenger area. Furthermore, batteries must be secured in a ventilated compartment separated from the passengers and easily accessible. Additionally, this information is complemented with another regulation that contains the passive safety standards: UNECE Regulation No. 118. This framework ensures that interior materials are fire-resistant. It establishes the maximum horizontal burning rate of 100 mm/min and prohibits the formation of flaming droplets. This ensures that the interior materials do not significantly contribute to fire growth or help the flame to spread within the passenger compartment. As a result, the development of hazardous conditions such as high temperatures and reduced visibility due to smoke is delayed, increasing the available time for evacuation. This is a key factor in the analysis of evacuation performance, as it increases the time available for occupants to reach an exit under emergency conditions.

2.1.2 ISO 17840

UNECE Regulation No. 107 governs the materials and geometry of buses. However, the arrival of other propulsion methods, such as electric, hybrid, or hydrogen-powered buses, causes new risks to appear that traditional regulations did not fully contemplate, especially the phenomenon of 'Thermal Runaway' in lithium batteries. For this reason, the ISO 17840 standard [ISO_19] was developed, which provides key information to emergency services, to guide their actions in emergency situations in case they have to carry out a rapid evacuation.

By standardizing the communication of technical hazards, this framework reduces the time spent by rescuers identifying the vehicle's risks. This is very important when passengers' evacuation flow is slower than expected due to high occupancy densities, the presence of elderly passengers with slower reaction times, or people with reduced mobility (PRM) who cannot evacuate autonomously. Delays in emergency response can worsen already critical conditions and, therefore, minimizing the time required to identify hazards is essential to ensure safe and effective passenger egress.

The ISO 17840 standard [ISO_19] is divided into four parts. Part 1 and part 2 contains the rescue sheets for different types of vehicles. While part 1 focuses on rescue sheets for passenger cars, the second one addresses buses and trucks, providing the standardized templates for rescue sheets that are relevant to the M3 category vehicles analysed in this dissertation.

Moreover, part 3 defines the Emergency Response Guide (ERG), which contains information for first and second responders' rescue. This guide is essential to assure the safety of passengers who are not able to evacuate by their own, as it provides firefighters with specific instructions for stabilisation, disabling hazards and how to intervene in case of different emergency scenarios, such as fire or submersion.

Based on this regulation, the most critical tool for rapid evacuation in M3 vehicles is the Rescue Sheet, defined in the second part of the ISO 17840. Rescue sheets are technical documents which explain the most crucial information of the vehicle in order to give firefighters fundamental data during the initial critical minutes of an emergency. This technical document with a maximum length of 4 pages utilizes universal symbols called iconograms. It is essential that, independently of the rescuer's language, they are able to understand the basic features of the transport system. One of the most important things that are contained in these sheets are the views of the vehicle. It is mandatory that the document addresses a lateral view, as well as a top or "drone" view, as it is illustrated in figure 11. This figure shows the Rescue Sheet for a Volvo electric bus, where the top view is vital for locating the lithium-ion batteries and the connection on the roof. Regarding the symbols that are shown in the sheets, they give information about the type of propulsion system that the vehicle has, the location of low-voltage and high-voltage batteries, fuel tanks, where to find the air conditioning component or the cut zones. This given information is crucial in case of an emergency. If the vehicle is involved in a traffic crash, it can suffer some kind of structural deformation, in which case the doors could not be operative. In this situation, rescuers can know the places where it is safe to cut the coachwork, avoiding the traction voltage power cable, the air conditioning line or the fuel tank. This ensures a safe extraction of the occupants.

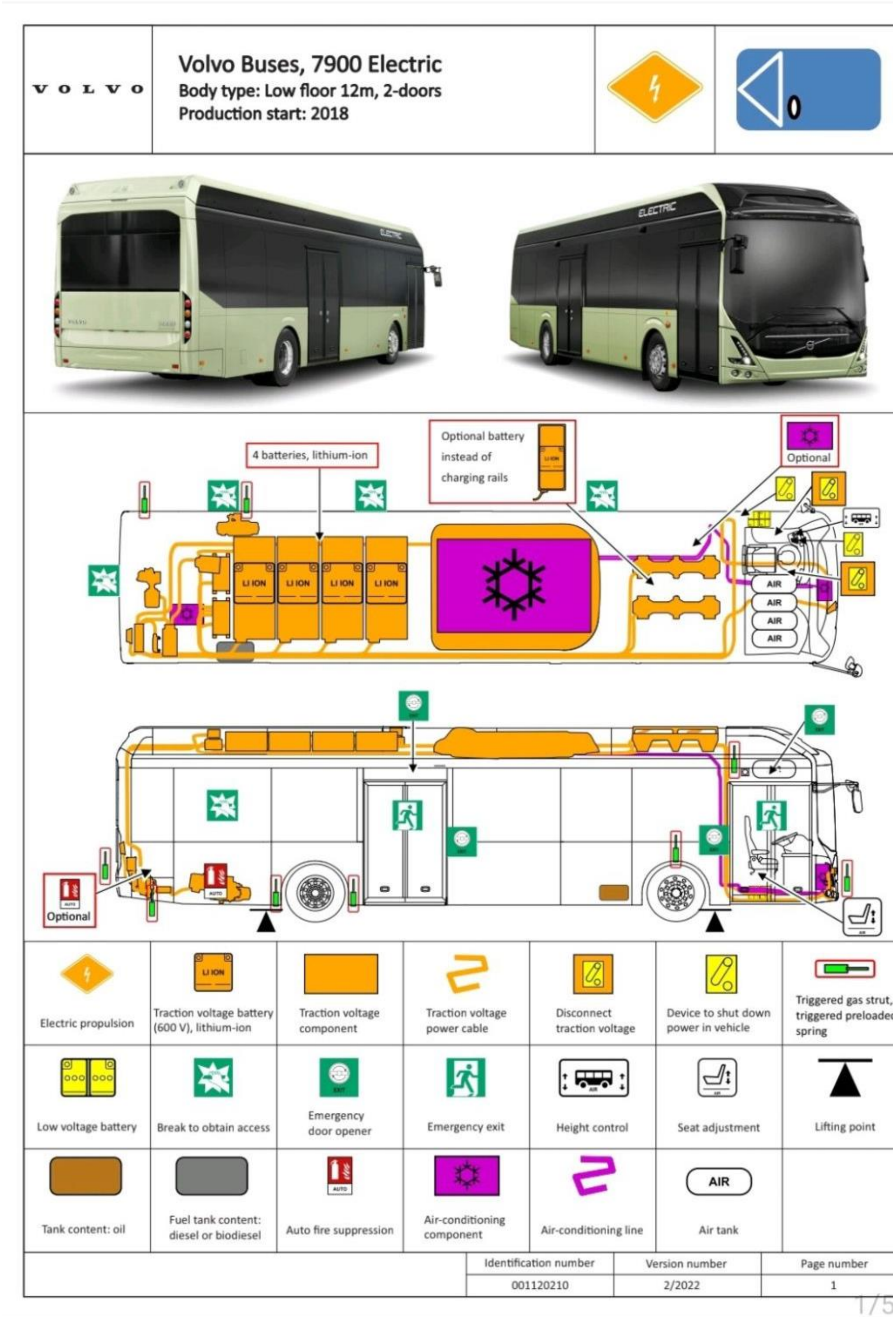

Figure 11: Example of a standardized Rescue Sheet for an electric bus (Category M3) according to ISO 17840-2, featuring top and side views with universal hazard symbols [ESBR16].

Finally, the fourth part of the standard focuses on the visual identification of the propulsion system. In order to allow rescuers to approach the vehicle with the suitable rescuing equipment, it is essential that they rapidly identify the vehicle’s energy source. The regulation establishes six different colours that appear in diamond-shaped symbols and permit rescuers to quickly identify from a safe distance the propulsion system.

However, the system does not rely solely on colour coding, as it also includes specific symbols and text to define the exact technology. For example, within the orange category, different icons distinguish between battery electric vehicles (BEV) and hybrid electric vehicles (HEV), which present different energy storage configurations. Similarly, in gaseous fuel systems, the behaviour of different fuels can vary significantly, affecting risk conditions during an emergency. These details enable emergency services to adapt their intervention strategy to the specific physical and chemical properties of each propulsion system.

While ISO 17840 focuses on improving the identification and management of risks associated with modern propulsion systems, it does not define evacuation performance criteria. It helps emergency services to act in a more efficient way, but it does not determine whether passengers are able to evacuate the vehicle within a safe time frame. Therefore, additional frameworks are required to assess evacuation dynamics and quantify evacuation times under emergency conditions.

2.1.3 NFPA 502

While UNECE R107 focuses on vehicle geometry and construction and ISO 17840 focuses on the identification of the vehicle’s characteristics for rescuers, NFPA 502 [NFPA20] establishes the life safety and fire protection requirements for infrastructures such as tunnels or depressed highways. In order to allow the safest evacuation, it is necessary to evaluate if the environment remains tenable during an emergency situation, including fire. Although this research does not focus on tunnel infrastructure, this standard is used as a reference for environmental tenability, as no equivalent standard exists for the interior of buses.

One of the most critical things that NFPA 502 studies is the Heat Release Rate (HRR), which quantifies the fire's power. In previous versions, such as the 2020 edition, Annex G provided values of HRR for different types of vehicles, which went from 20 MW to 30 MW for standard buses.

However, the latest 2026 edition has done significant changes to consider the alternative propulsion systems.

The 2026 version takes into account that traditional fires do not have the same performance as fires caused by BEV (Battery Electric Vehicles) or HFCV (Hydrogen Fuel Cell Vehicles). One of the things that characterizes lithium-ion batteries is that they cause "thermal runaway". In this situation, batteries emit toxic gases that are different from those of diesel combustion and there is a rapid heat energy release. For this reason, NFPA 502 states that the fire load should be determined based on the type of fuel and energy storage capacity of the vehicle.

Furthermore, Annex B of NFPA 502 provides guidance on the tenability criteria that define when an environment becomes unsafe during an evacuation. These criteria include the following thresholds:

- Visibility: it is essential that passengers can see the emergency exits through the smoke. A minimum threshold of typically 10 meters is considered.
- Temperature: preventing exposure to excessive convective heat. A temperature of approximately 60°C is commonly adopted to ensure occupants can evacuate without respiratory or skin damage.
- Toxicity: it limits the concentration of carbon monoxide (CO) and other fire by-products. This is measured through the Fractional Effective Dose (FED).

These thresholds offer a useful reference for the environmental limits that a safe evacuation need to respect. However, since NFPA 502 is designed for tunnel infrastructure and does not establish a maximum evacuation time for buses, this dissertation does not compare the evacuation times obtained in Pathfinder with these criteria directly. Instead, the analysis focuses on comparing the evacuation performance of the different bus typologies (Class I: simple, double-decker and articulated, Class II and Class III). This highlights the absence of a specific regulatory time limit for this type of vehicle.

By integrating the geometric data from UNECE R107 with the context provided by the 2026 evolution of NFPA 502, this research ensures a comprehensive approach to passenger safety under fire conditions.

2.2 ANALYSIS OF REAL-WORLD ACCIDENTS

In order to show the necessity of this research, it is very important to analyse real-world accidents that involved buses. These cases show that fire behaviour is highly unpredictable, especially in real conditions. Although regulations like UNECE R107 provide a safety baseline, emergency situations, especially with new propulsion technologies and high occupancy, can be much more complex than what is assumed in theoretical models.

Therefore, these real-world events are used to justify the assumptions made in the evacuation models and to highlight critical factors affecting passenger egress, such as smoke propagation, exit availability and passenger response time.

2.2.1 THE PARIS BLUEBUS FIRE

In April 2022, two spontaneous fires occurred in electric Bluebus buses operated by RATP in Paris. Although neither of these vehicles were involved in a collision, both fires started during normal operation and buses ended up completely destroyed. These incidents were a turning point for the study of Battery Electric Vehicles (BEV).

- Fire dynamics: According to the official investigation carried out by BEA-TT [BEAT23], both fires were caused by an internal-short circuit in the high-voltage battery packs. These batteries were LMP (lithium-metal-polymer), with four of them out of the six that the buses had contained in the roof. The report states that the cause of these accidents was a manufacturing defect in the Mylar insulation, which led to the thermal-runaway phenomenon. The investigation shows that only 7 seconds after the first signs of smoke, the batteries completely exploded. This is illustrated in Figure 12. In addition, temperatures inside the bus reached 1420ºC, which caused the stainless-steel roof to melt and collapse inside the cabin. As it can be seen in Figure 12, 17 seconds after the first flames, molten metal was ejected from the bus and reached between 3 and 4 meters in its vicinity.

Figure 12: Chronological sequence of the thermal runaway in a Bluebus [BEAT23].

- <u>Evacuation constraints</u>: in the first accident, the bus was carrying only 14 people. Thanks to this low occupancy and the driver's fast reaction time to stop the bus and open all the exit doors, there were no fatalities. This urban bus can be classified into Class I, meaning that there were multiple double doors, which allowed for a quick evacuation. However, the report [BEAT23] stated that just 15 seconds after the vehicle stopped, the battery pack fell into the cabin. This is illustrated in figure 13. Additionally, the diagnostic systems failed and did not give any prior warning to the driver, meaning the evacuation started when the fire was already visible. If the bus had been as full as in the worst-case scenario (100 passengers), the evacuation time would likely have exceeded the available evacuation time. Furthermore, the melted metal that was projected created a danger zone around the outside of the bus, introducing another hazard during the egress process. In the second accident, the bus was completely empty.

Figure 13: Interior view of the bus after the incident [BEAT23].

- Relevance to research: This accident reflects the importance of using Pathfinder to carry out different simulations and include these new propulsion systems. By using this program, we can represent the effect of this kind of incident, for example by blocking one of the exits. In addition, we can increase the reaction time of passengers to resemble this situation in which the driver was not warned and the evacuation started when the smoke or the flames were already visible. This helps us analyse if a safe evacuation is still possible when passengers react later.

2.2.2 FIRE AT EMT VALENCIA DEPOT

In May 2020, an enormous fire occurred at the San Isidro depot of the Municipal Transport company (EMT) in Valencia. The fire started in a 19-year-old diesel bus that had been parked for two days. Although the depot was equipped with fire protection systems, the fire spread rapidly, destroying and damaging 26 buses. This example shows that depot configurations with vehicles that have various propulsion systems represent a high-risk environment for fire propagation.

- Fire dynamics: according to the internal reports and the fire department's intervention log, the fire was likely caused by an electrical short circuit in the bus's internal systems. Before the fire became visible, the SAE system registered several technical errors, which may indicate an internal electrical problem in the bus systems. Although the fire started in a diesel vehicle, the flames had a rapid propagation due to the compressed natural gas (CNG) buses that were parked close. When the fire reached these vehicles, their safety relief valves opened automatically to release pressure. This resulted in an increase in the release of gas and an increase in fire intensity, as illustrated by the enormous smoke column seen in Figure 14.

Figure 14: Extensive fire involving multiple buses at the EMT Valencia depot [VALE20].

- Evacuation constraints: the fire occurred in a depot, which means that there were no occupants at the moment of the accident. However, there was a delay in the activation of fire suppression systems during the early stages of the incident. Additionally, the fire produced large quantities of smoke, which was enough to reduce visibility in the surrounding area. This led to the temporary closure of transport infrastructures, including a highway and a train station, due to zero visibility conditions.

- Relevance to research: this incident shows how difficult it is to identify a bus's energy system during an emergency. Especially in depot environments, where buses that have different propulsion technologies (diesel, CNG, hybrid or electric) can be parked close to each other. This highlights the importance of ISO 17840 throughout this dissertation, as it establishes a system of colours and symbols depending on the vehicle's propulsion type. In addition, this case also supports the need to consider the vehicle configuration and bus type, as the passenger distribution can significantly affect evacuation behaviour in emergency scenarios. Additionally, this case shows how fast visibility decreases under high-energy fire conditions in mixed fleets. Although no passengers were present, this case is relevant for the simulation environment definition in Pathfinder. This effect is represented in the model through an extended pre-movement time.

2.2.3 FIRE AT STUTTGART BUS DEPOT

In September 2021, a major fire occurred at the Gaisburg bus depot in Stuttgart, which resulted in the destruction of 25 buses. Investigations suggested that the fire may have originated during the charging process of an electric bus, although the exact cause was not confirmed.

- Fire dynamics: reports indicate a possible technical failure in an electric bus (Mercedes eCitaro) connected to the charging system. This case highlights the uncertainty associated with BEV fire initiation, particularly during charging operations in depots. Once the fire started, it rapidly spread due to the proximity of other vehicles inside the depot (Figure 15).
- Evacuation constraints: as it happened in a depot, no passengers were involved in this accident. However, the fire developed quickly enough to limit the relocation of buses. A critical factor was that several vehicles were still connected to charging stations, which made their removal very difficult during the first stages of the incident. This reduced even more the available operational response time. This aspect is relevant for Pathfinder simulations, as it introduces constraints that affect scenario dynamics during a rapid fire development.

Figure 15: Fire at the Gaisburg bus depot in Stuttgart, with multiple buses affected [SUST21].

- Relevance to research: this case shows how electric buses introduce different challenges in depot fire scenarios, especially during charging. Unlike diesel or CNG vehicles, the fire in this case is linked to the electrical charging system. This makes it harder to understand how the fire starts and how it develops during the first seconds. Unlike the Valencia case, where the main issues were smoke and visibility, this scenario is more related to how quickly the fire can develop in the early stages. In addition, having several buses connected to charging points at the same time made it more difficult to move them quickly, which limited the initial response. In the Pathfinder simulations, a situation like this is represented through the scenarios that block a rear exit and extend the passengers' pre-movement time. This reflects how a fire in the charging or propulsion system can disable one of the exits and delay the reaction of the occupants.

2.2.4 OVERALL IMPLICATIONS

Overall, these case studies show that, in order to carry out a safe bus evacuation, it is necessary to analyse the interaction between fire dynamics, system performance and human behaviour. Although many bus incidents are not included in this research, the selected accidents (Paris, Valencia and Stuttgart) represent different types of fire scenarios and failure conditions. The Paris case highlights the impact of very rapid fire development in battery electric vehicles, which significantly reduces the available reaction time. The Valencia incident shows the importance of smoke production and visibility loss. Both factors affect tenability conditions during evacuation. Finally, the Stuttgart case represents a scenario in which the fire develops quickly in the early stages and limits the initial response.

These aspects are then used as inputs for the Pathfinder simulations developed in this dissertation. Pathfinder does not model fire or smoke directly. Therefore, the conditions that are observed in the accidents that were studied are translated into the simulation through the occupants' pre-movement time and the availability of exits.

Case	Fire Type	Key evacuation limitation	Represented in scenario
Paris Bluebus fires (2022)	Battery thermal runaway (BEV)	Extremely short detection time, sudden structural failure	Blocked rear exit and extended pre-movement time (Scenario 5)
Valencia EMT depot fire (2020)	Diesel fire with CNG involvement	High smoke production, rapid visibility loss	Extended pre-movement time due to delayed reaction (Scenario 4)
Stuttgart depot fire (2021)	Electric bus fire during charging (suspected BEV)	Rapid fire development in early stages, limited initial response	Blocked rear exit and extended pre-movement time (Scenario 5)

Table 3: Summary of real-world accident parameters and their implementation as Pathfinder simulation inputs.

Chapter 3. DESCRIPTION OF TECHNOLOGIES

The main objective of this research is to determine how bus evacuations can be made as safe as possible, reducing the risks associated with toxic gas inhalation and burn injuries. Buses are increasingly being adopted as one of the most promising alternatives for reducing carbon emissions from private vehicles. New propulsion technologies, such as lithium battery systems and hydrogen-powered engines are accelerating this transition. However, evaluating the safety of these vehicles through real physical tests would be neither practical nor responsible. Therefore, simulation software has become the most reasonable approach. This way, people are not needlessly exposed to extreme situations that could have serious consequences.

Throughout the simulations studied in this work, a range of realistic conditions will be taken into account: presence of passengers who may be asleep, individuals with reduced mobility, door system failures or the presence of obstacles blocking the evacuation path. These scenarios will be repeated under different circumstances and across the various vehicle configurations studied, which, if conducted with real participants, would mean exposing people to high-risk situations on multiple occasions. Furthermore, from an ethical standpoint, it is simply unacceptable to develop emergency response protocols by putting the lives of test participants at serious risk.

The following chapter focuses on the technological tools that will be used throughout the dissertation. First of all, it is necessary to understand the mathematical and theoretical concepts behind crowd movement, which will explain why certain simulation methods are chosen over others.

3.1 TECHNICAL FOUNDATIONS OF EVACUATION MODELLING

In order to develop safety protocols without human risk, transport engineering relies on computational egress modelling. According to the classification frameworks established by the National Institute of Standards and Technology [NIST10] and the *SFPE Handbook of Fire Protection Engineering* [SFPE16], computational evacuation models can be separated into three methodological approaches:

- **Flow-based or continuous models:** This method looks at the evacuating crowd as a single, continuous flow rather than a group of individuals. The movement is calculated using general rules of density and speed, which means it does not take into account personal choices, individual behaviours or the physical sizes of different passengers. It prioritizes global flow averages over individual characteristics.

- **Agent-Based Models:** Each person in the simulation is modelled as an independent individual with their own characteristics: body size, walking speed, reaction time and behaviour. These individuals interact with each other and with the physical space around them, which makes it possible to observe realistic situations such as bottlenecks, people slowing each other down at narrow exits or differences between a young person and an elderly passenger.

- **Hybrid Models:** These combine both approaches. In areas where it is necessary to consider individual behaviour in a detailed way, such as a narrow aisle or an exit door, each person is tracked individually. However, in large open areas where precision is less critical, the simpler flow-based calculation is used instead. This approach reduces computing time without losing accuracy.

Throughout this whole dissertation, evacuations carried out in different bus configurations will be studied. Therefore, it is necessary to implement a strict agent-based model. Buses are highly confined environments where space is extremely limited and occupancy can be remarkably high, sometimes packing more than 100 people into an area of less than 40 m^2. Furthermore, public transport systems are designed to be inclusive, meaning that passengers with diverse physical capacities and mobility conditions interact simultaneously within these tight dimensions. Traditional flow averages are not able to replicate human interactions or characteristics. This condition makes individual agent tracking essential to get a truly realistic safety assessment.

3.2 REVIEW OF EVACUATION SIMULATION TOOLS

As explained in the regulatory framework, analysing bus safety under real fire conditions is necessary but difficult to do in real life. In the transit sector, standard simulation tools like PTV VISSIM are widely used, but they only focus on transport efficiency and how passengers move around bus stations [PTV_25]. These programs are not designed for safety and cannot simulate individual passenger behaviour or physical crowd interaction inside a narrow bus aisle.

On the other hand, although UNECE Regulation No. 107 defines the legal dimensions for seats, gangways, and doors [UNEC15], it only requires basic physical tests under ideal and risk-free conditions. Dangerous situations like the ones mentioned in NFPA 502, such as battery thermal runaway, toxic gases, or heat cannot be tested with real people for ethical and safety reasons. Therefore, to evaluate how these alternative propulsion hazards affect passenger movement, using an agent-based evacuation simulator like Pathfinder is the only reasonable choice. Traffic simulation tools such as PTV VISSIM [PTV_25] are designed for steady-state passenger flow analysis and are not suited for emergency evacuation scenarios. Pathfinder, by contrast, models the internal geometry of the vehicle at the level of detail required to identify congestion points at exits and narrow aisles. These elements are critical in a bus evacuation context but are not taken into account in macroscopic flow models. For this reason, Pathfinder has been selected as the simulation tool for this study.

3.2.1 PATHFINDER: DESCRIPTION AND NAVIGATION MODES

In order to achieve the requirements of a high-occupancy and tight space environment, it is necessary to use a 3D agent-based evacuation simulator. The chosen software is Pathfinder [THUN24, THUN24b], which allows users to calculate passengers' flow and human movement through confined spaces. This evacuation simulator developed by Thunderhead Engineering [THUN24] is widely used in fire safety engineering and academic research. Spatial navigation can be tested through two different simulation modes that modify the mathematical resolution of agent velocities:

- **SFPE mode:** This mode applies the traditional calculations from the *SFPE Handbook of Fire Protection Engineering* [SFPE16]. It is a density-dependent mode, which means that a passenger's speed depends only on how crowded the room or the corridor is. In this mode, passengers do not have a real physical body or size within the simulation. They do not collide, push, or overtake each other dynamically. Passengers simply flow along pre-calculated paths based on how many people the doors or aisles can hold at the same time.

- **Steering mode:** This is the advanced mode chosen for this dissertation because it calculates movement and behaviours at each time step. Here, every passenger is treated as an independent agent with a realistic physical size, representing their shoulder width. The software constantly calculates a balance between where the passenger wants to go (the closest exit) and the paths they need to take to avoid walls, seats, and other moving passengers.

Using the Steering Mode is absolutely necessary for this project. In a space as narrow as a bus aisle, passengers naturally slow each other down, create physical friction, or try to overtake slower people. The simpler calculations of the SFPE mode would completely miss these realistic human interactions, making the simulation inaccurate for a bus evacuation.

3.3 CHARACTERIZATION FRAMEWORK FOR OCCUPANTS AND GEOMETRY

To perform a rigorous evacuation analysis, passengers cannot be treated as a homogeneous crowd with identical physical capacities and reaction times. Pathfinder allows users to break this limitation by characterising both the environment and the occupants through three main geometric, kinematic, and behavioural pillars.

- **Geometric Representation and Constraints:** The software translates the vehicle's physical boundaries into a continuous two-dimensional surface known as the Navigation Mesh (NavMesh) [THUN24]. Fixed architectural elements, such as rows of seats, act as direct constraints on this mesh, automatically defining narrow pathways like central aisles, which represent the primary bottlenecks of the system.
- **Occupant Profiles and Kinematic Parameters:** Each passenger is defined by a specific profile that dictates their physical movement [THUN24]. As shown in Figure 16, the software allows the customization of individual traits for each agent. The key parameters governing the kinematics of each agent include:
    - Physical Clearance and Height: This defines the real physical space occupied by the agent's body by considering its shoulder width. This parameter is critical because it restricts simultaneous flow through narrow exits and aisles.

- Walking Speed: This determines the maximum velocity of the agent. Instead of using fixed values, the software allows the implementation of statistical distributions to reflect the differences between distinct age groups and physical conditions.
- Reduction Factors: These parameters modify the speed of an agent when their environment is experiencing severe congestion or when they need to reorientate in order to move through tight spaces.

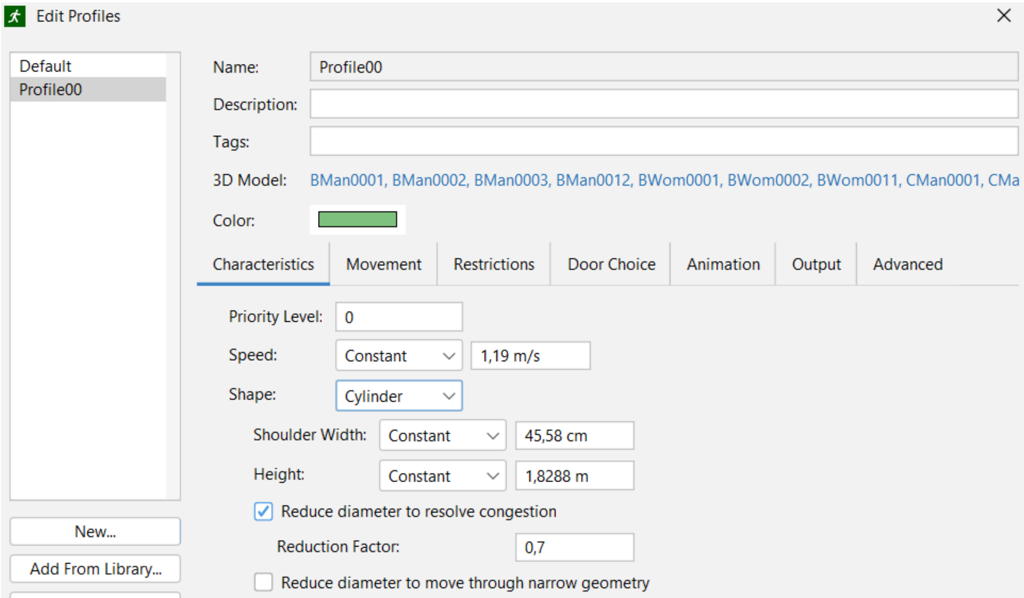

Figure 16: Pathfinder occupant profile configuration interface, showing physical dimensions, walking speed, and diameter reduction parameter [THUN24].

- **Behavioural parameters and Pre-Movement Time:** When an emergency alarm sounds, evacuation does not instantly begin, as passengers have different reaction times. It is completely necessary to model human behaviour by introducing two fundamental concepts:
  - Speed-Density Profile: In real life, the more crowded a space is, the slower people walk. The software replicates this by automatically dropping a passenger's speed as the local density (people per square meter) increases. This is essential to show exactly where and how bottlenecks form inside the bus.
  - Initial Delay: There is a time interval, also known as pre-movement time, between the moment in which the alarm starts sounding and the moment in which the passenger decides to act after processing the situation. This delay is influenced to a large extent

by alertness, for example if the passenger is awake or asleep, cultural behaviour and familiarity with emergency protocols. The software models this human response using complex statistical distributions, such as log-normal distributions.

Once the static environment and occupant profiles are defined, dynamic constraints representing fire-induced hazards must be integrated, as detailed in the following section.

3.4 PHYSICAL HAZARDS AND FIRE DYNAMICS FRAMEWORK

Although Pathfinder is an excellent tool for tracking human movement, it has some limitations. It does not calculate fluid dynamics, smoke propagation or visibility reduction. However, these aspects are the most critical ones and it is important that they are tested before launching new fleets. To overcome this limitation and analyse the safety of alternative propulsion systems, these real-world physical threats must be translated into explicit geometric and operational constraints within the model.

Depending on the vehicle technology and manufacturer design, the simulation scenarios will implement the following modifications:

- **Rear Door Blockage:** This represents a fire in the rear of the vehicle. In this part of the bus is where the propulsion system can be found. In addition, in some electric buses, is where the batteries are located. In the simulation, this is modelled by completely disabling the rear service door. This forces all passengers from the back rows to queue in order to reach the next available exit, creating a highly critical bottleneck in the central aisle.

- **Roof Battery and Hydrogen Fires:** For configurations where energy systems are mounted on the roof, a fire will cause toxic gases and heat to accumulate inside the cabin. Since Pathfinder cannot simulate smoke or gas directly, this effect is represented by extending the occupants' pre-movement time. This reflects the additional delay caused by reduced visibility and presence of toxic gases.

- **Pre-Movement Delays:** To simulate the immediate physical impact of toxic gas inhalation, the initial shock of an alarm, or reduced visibility, different statistical curves of *Initial Delay* will be applied to the occupant profiles. This ensures that agents do not start moving instantly, adding a realistic human behaviour factor to the fire scenario.

The simulation can assess the impact on the evacuation time for each configuration under different conditions by converting these hazards into specific constraints like blocked exits or changes in the passengers' behaviours (extended pre-movement time).

3.5 SIMULATION OUTPUTS AND RESULT INTERPRETATION

Once a simulation is completed, Pathfinder generates both quantitative data and visual results that are essential for the analysis. Instead of looking at just numbers, the software organizes the outputs into specific formats:

- Total egress time: The exact time it takes for the last passenger to exit the vehicle safely.
- Individual clearance times: Detailed tracking of each agent, showing exactly when they reached their assigned exit.
- Flow rates and congestion: Continuous data of the use of doors and aisle, which helps identify the exact seconds when bottlenecks occur.
- Visual animations and trajectories: 2D and 3D videos that show the real-time movement of the passengers and where people group together.

All these numerical results are exported as raw data files and then processed using Microsoft Excel or MATLAB to organize the statistics, compare the different bus configurations and plot the final charts.

Chapter 4. PROJECT JUSTIFICATION

4.1 OBJECTIVES

The main objective of this project is to analyse, through numerical simulation, the emergency evacuation process across different bus typologies, assessing their performance under conditions that go beyond the minimum requirements established by current regulations. The aim is to determine whether passengers can evacuate safely within acceptable timeframes when realistic variables such as high occupancy, different passenger behaviours or blocked exits are introduced. To achieve this, the following specific objectives are defined:

- Objective 1: Development of numerical models in Pathfinder.

To develop and validate reliable numerical models that represent the main bus typologies that are currently in circulation. Since the propulsion technology does not substantially change the interior geometry of a bus, each fuel type is not modelled as a separate configuration. The influence of the new propulsion technologies is instead considered through the types of emergency they may cause, which are studied in the different scenarios.

- Objective 2: Simulation of diverse emergency scenarios.

To carry out evacuation simulations under several critical conditions: variations in occupancy, blocked exits and longer passenger reaction times. These conditions represent the types of risk that can occur during a bus emergency, some of which are especially relevant for the new propulsion technologies, such as fires that disable an exit or the release of smoke and toxic gases that delay the passengers' reaction.

- Objective 3: Analysis of interior configuration and occupant behaviour.

To quantify how the internal distribution (aisle width, seating arrangement, and number of doors) affects total evacuation times. This objective also focuses on the behaviour of different passenger profiles, including sleeping passengers, identifying bottlenecks and flow constraints within the vehicle's geometry.

- Objective 4: Design recommendations and operational protocols.

To synthesize the simulation findings into a set of optimization guidelines. The goal is to propose specific interior design improvements or operational emergency protocols tailored to each bus type, ensuring maximum safety and efficiency for passenger evacuation in future transport systems.

4.2 METHODOLOGY

The work carried out in this dissertation combines document analysis, digital modelling and numerical simulation to produce results that are both rigorous and comparable across different vehicle configurations.

The starting point was the regulatory and technical context established in the previous chapters, which provided the basis for defining realistic simulation inputs. In addition to this, real accident reports were examined to understand how real emergency situations develop, identifying the factors that most critically affect the time available for safe evacuation.

From there, the bus typologies that will be studied in the following chapters were selected and modelled in Pathfinder. Each vehicle was built with its specific interior geometry, including door widths and positions, aisle dimensions, seating layout, and any elements that can affect passenger movement such as wheelchair spaces or staircases in double-decker configurations. Occupants were then assigned as individual agents reflecting the diversity of real passengers such as elderly travellers, people with reduced mobility, wheelchair users, and both seated and standing occupants.

With the models in place, evacuation scenarios were run for each configuration. These covered a range of conditions, from straightforward baseline cases to more demanding situations involving exit blockages and longer pre-movement times caused by smoke or reduced visibility. Each variable was adjusted independently so that its specific effect on evacuation time could be measured and compared.

The output of each simulation was analysed and compared across the different configurations and scenarios, identifying which designs evacuate more efficiently and which are more affected by adverse conditions. These findings form the basis for the design and operational recommendations presented in the final chapter, which are intended to be of practical use to manufacturers, transport operators, and regulatory bodies alike.

Chapter 5. SIMULATION FRAMEWORK UNDER DIFFERENT CIRCUMSTANCES

One of the central challenges of this research is translating abstract regulatory frameworks into something that can be tested and measured. To do that, this chapter builds a computational environment where those rules can be tested against realistic emergency conditions rather than focusing just on the ideal ones.

All simulations were developed using Pathfinder, a 3D agent-based simulator made specifically for evacuation analysis. What makes this tool particularly well-suited to the problem is how it handles passengers: instead of treating them as simple flows or averages, each person is modelled as an independent agent with their own speed, decisions, and physical limits. This makes it possible to see things that basic models completely miss, such as the formation of bottlenecks, people competing or helping each other at the doors and the chain-reaction delays that can happen in real evacuations.

Furthermore, the simulations were designed to look beyond perfect conditions. Real evacuations are rarely simple, so testing only the best-case scenarios would not provide useful data. Instead, each vehicle layout was tested under five different scenarios covering realistic emergency conditions such as door blockages and extended passenger reaction times.

Additionally, consistent criteria have been established to compare simulations as fairly as possible, allowing a clear analysis of how each variable affects the final results. The specific passenger settings, geometric properties and characteristics of each vehicle model are detailed in the following sections.

5.1 SIMULATION METHODOLOGY AND WORKFLOW

The same methodology was applied to all five configurations. This way, any differences in the results can be attributed to the vehicle design rather than to inconsistencies in the simulation setup. The process consisted of four sequential phases:

1. Geometric Preparation: First, import and verify the scale of manufacturer floor plans. This is followed by generation of the Navigation Mesh (NavMesh).
2. Environment Definition: Modelling of internal obstacles, exit door assignments and vertical connectivity for multi-level configurations.
3. Occupant Characterisation: Assignment of profiles including walking speed distributions, physical clearance parameters, and pre-movement delays.
4. Scenario Implementation: Application of fire-induced constraints such as door blockages and aisle obstructions across the defined simulation scenarios.

5.2 SELECTION AND GEOMETRIC ANALYSIS OF VEHICLE CONFIGURATIONS

5.2.1 VEHICLE CONFIGURATIONS

This section describes the five distinct vehicle configurations chosen for this research. They have been selected to cover a wide range of operational environments, door layouts and passenger capacities within public road transport:

- Class I:
    - Simple urban bus: a standard city transit vehicle which is characterized by a low-floor design, high standing capacity and wide doors that optimize passenger exchange on routes which have a high frequency. The main limiting factor for crowd egress is door width.

- Double-deck urban bus: a high-capacity city bus featuring a two-level layout connected by internal staircases. This introduces specific vertical evacuation dynamics.
- Articulated bus: an 18-meter high-capacity vehicle with an intermediate articulation joint. This offers a higher passenger capacity and a distributed three-door configuration.

- Class II:
  - Interurban bus: a medium-distance suburban vehicle which combines fixed seating with a dedicated central area for standing passengers and a wheelchair/PRM platform. This class testes the evacuation efficiency of combining high-capacity seated passengers and standing ones.
- Class III:
  - Long-distance coach: a high-comfort vehicle dedicated for travelling long distances, featuring an elevated floor layout, high-density seating, a single narrow central aisle and a restricted number of service doors. This configuration serves as the most demanding safety scenario due to its high seat density and restricted egress points.

5.2.2 GEOMETRIC AND CAPACITY LAYOUT SPECIFICATIONS

To build the simulation geometries, the core operational parameters of each vehicle category were compiled. These include the total passenger capacity, the number of available doors, and their specific clearance widths. Table 5.1 presents these key technical specifications along with the calculation of the total available egress width for each model.

Vehicle Model	Passenger Capacity (N)	TOTAL Passenger Capacity (N)	Number of Doors (D)	Clearance Width per Door (m)	Total Egress Width (m)
Class I: Simple Urban	Standing: 69 Seated: 25 PMR: 2	96	3	Double Doors (1.2 m each)	3 x 1.2 = 3.60
Class I: Double-Deck Urban	Standing:15 Seated:79 PMR: 1	95	2	Double doors (1.2 m each)	*2 x 1.20=2.40*
Class I: Articulated Urban	Standing: 75 Seated: 39 PMR: 2	116	3	Double Doors (1.2 m each)	3 x 1.2 = 3.60
Class II: Intercity	Standing: 15 Seated:65 PMR: 1	81	2	1 Front (0.65m) + 1 Center-Right (1.20m)	0.65 + 1.20= 1.85
Class III: Coach	Standing: 0 Seated:60 PMR:0	60	2	1 Front (0.65m) + 1 Center-Right (0.65m)	2 x 0.65= 1.30

Table 4: Technical specifications and total egress width per vehicle configuration.

In bus design, the dimensions of the internal aisle and seats are also primary factors that influence how quickly an evacuation can be completed. The clearance along the main aisle determines the flow rate of occupants moving toward the exits, preventing or causing bottlenecks in high-density conditions.

Table 5.2 establishes the internal dimensions used to model the vehicle interiors. These measurements follow the design intervals and minimum limits set by the UNECE R107 framework to represent standard, realistic commercial bodyworks.

Vehicle Model	Main Aisle Width (m)	Seat Width (m)	Bus length (m)
Class I: Simple Urban	0.61	0.43	12.20
Class I:Double-Deck Urban	Lower deck: 0.55 Upper deck: 0.5	Lower deck: 0.45 Upper deck: 0.47	12.00
Class I: Articulated Urban	0.61	0.43	18.14
Class II : Intercity	0.48	0.45	14.88
Class III: Coach	0.5	0.47	14.90

Table 5: Internal aisle widths and seating dimensions per vehicle class.

As shown in Tables 4 and 5, the long-distance coach presents the most restrictive egress conditions: the highest seat density combined with a single central aisle and the fewest service doors. The articulated bus, by contrast, benefits from three distributed doors and a wider aisle, which distributes the passenger flow more evenly. These structural differences are expected to produce significant variations in total egress time across configurations, as analysed in Chapter 6.

5.3 IMAGE PRE-PROCESSING AND SCALING METHODOLOGY

The geometric models were built in Pathfinder using top-view floor plans provided by a bus manufacturer as the primary drawing reference. When importing these images into the software, a problem was detected: the proportions of the original drawings are often changed during file copying or exporting. In particular, the scale along the horizontal axis (X) did not always match the scale along the vertical axis (Y).

In evacuation modelling, it is essential that both axes keep the same scale. If an image is calibrated using only Pathfinder's standard two-point scaling tool based on the length of the vehicle, this kind of distortion would change the width of the bus. As a result, some critical internal dimensions would be wrong, such as the width of the main aisle, the space between seats or the door widths. Since these narrow gaps determine the walking speeds and where bottlenecks form, any error in them would make the simulation results unreliable.

To ensure maximum precision, a calibration methodology was implemented for each floor plan before drawing any components.

1. The raw layout image was initially imported into an editing program to verify the real relation between the axes.

2. The overall length of the vehicle was used to set the horizontal scale. Then, the width in the drawing was measured and compared with the manufacturer's official data sheet.

3. In cases where the measured width did not match the manufacturer's data sheet, a correction factor was calculated and applied to the horizontal axis. For the long-distance coach, this factor was 0.879.

4. Once the scale was correct, the floor plans were imported into Pathfinder. This ensured that the aisle and seat widths were accurately represented in the model.

The original scaled floor plans used as the geometrical basis for each of the five configurations are presented below:

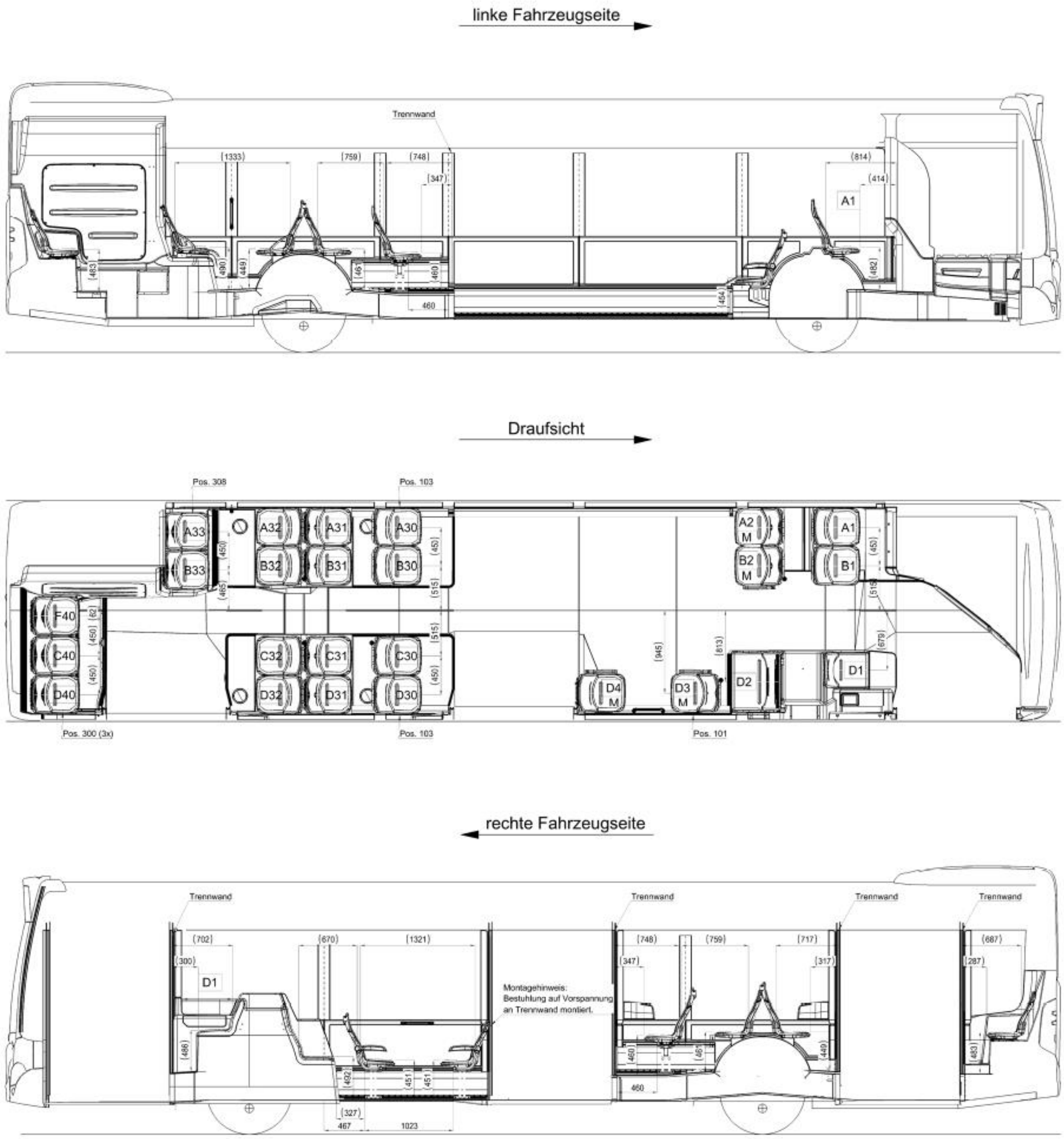

Figure 17: Technical floor plan of Class I Simple Urban Bus.

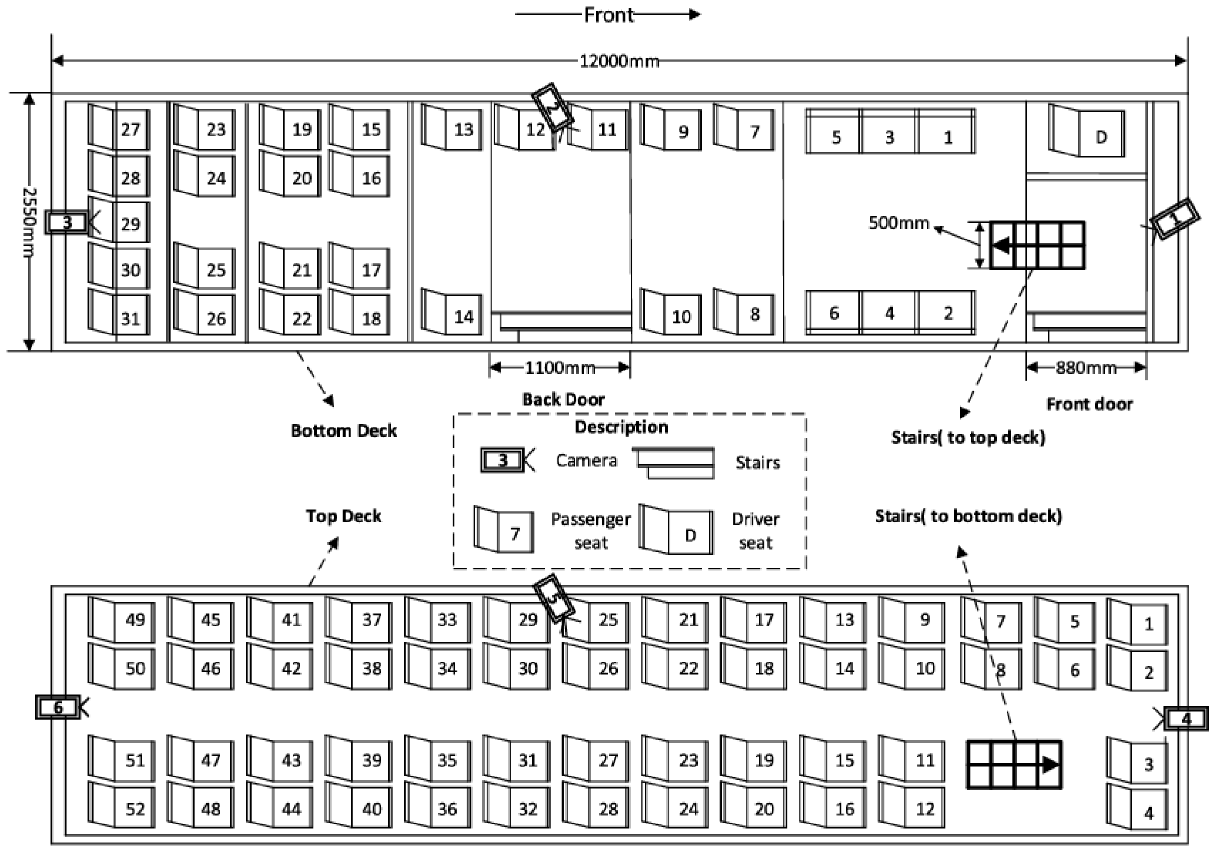

Figure 18: Technical floor plan of Class I Double-Deck Urban Bus [LIXU21].

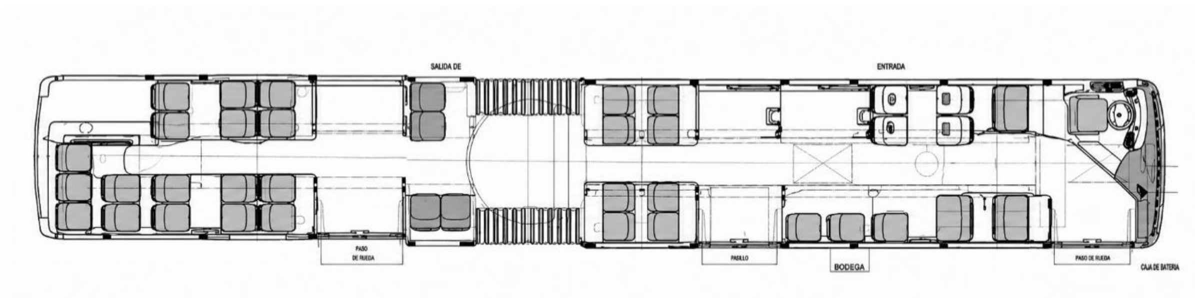

Figure 19: Technical floor plan of Class I Articulated Urban Bus.

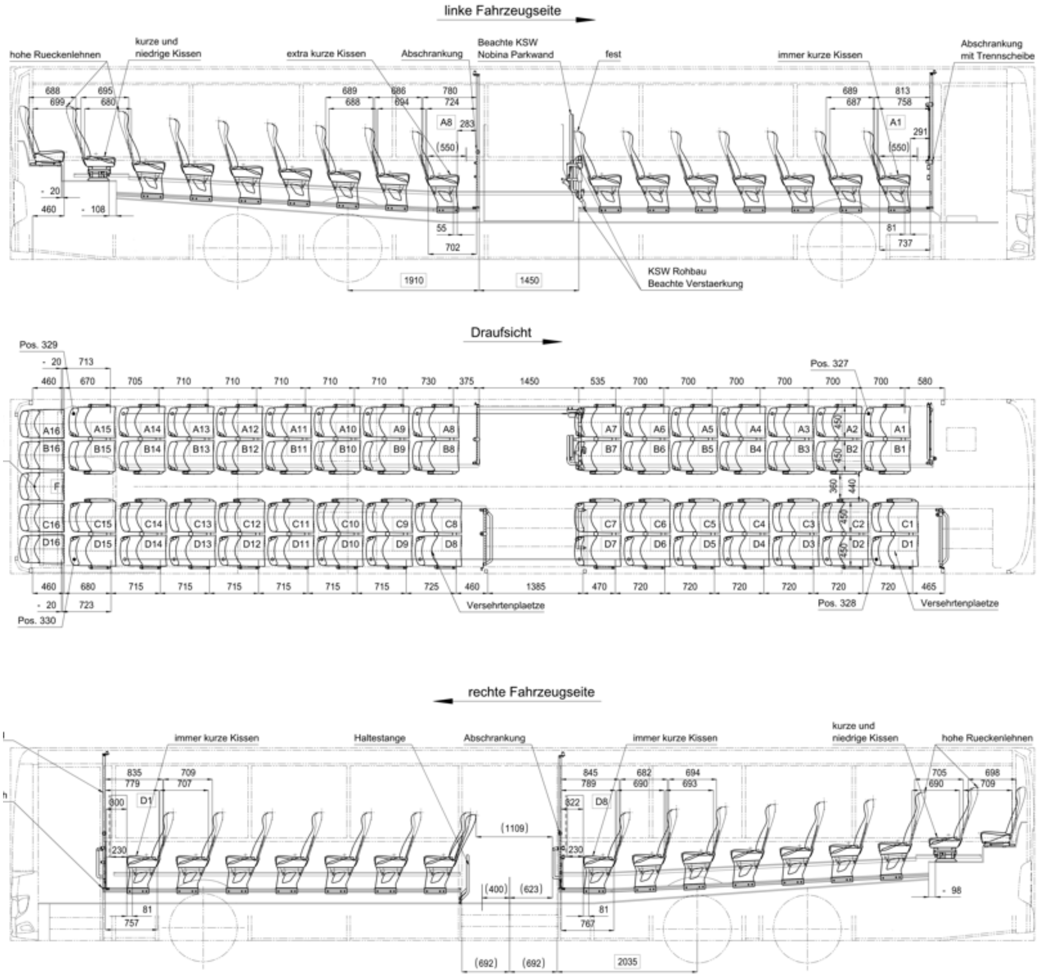

Figure 20: Technical floor plan of Class II Interurban Bus.

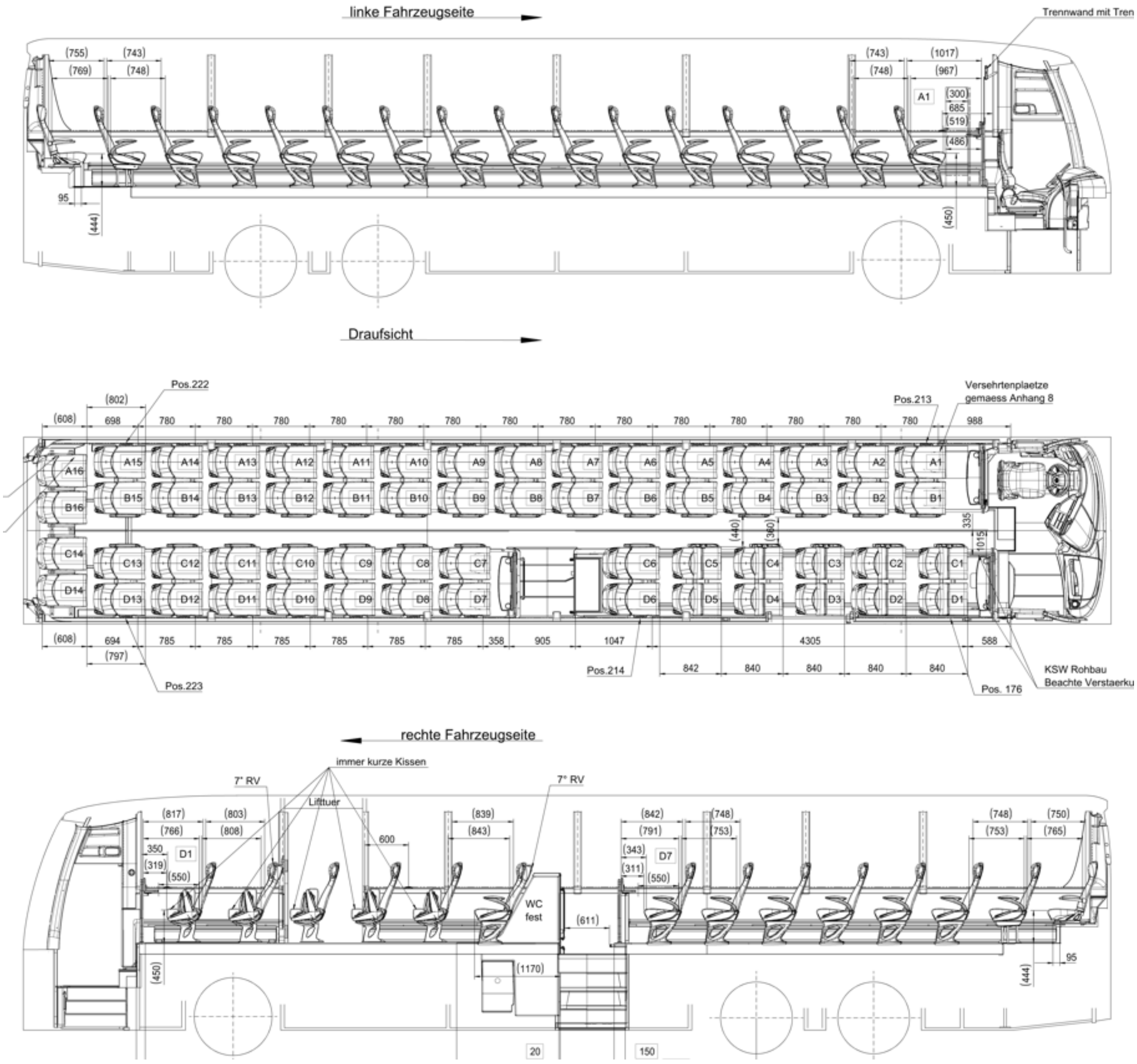

Figure 21: Technical floor plan of Class III Long-Distance Coach.

5.4 IMPLEMENTATION AND 3D MODELLING IN PATHFINDER

Once the background reference images were correctly scaled and verified for axis consistency, they were used to build the navigable environments within Pathfinder. The interior of each vehicle was modelled as a single navigable room following the internal contour of the passenger cabin. Some areas of the bus have different floor levels, such as raised platforms, steps at the doors or intermediate landings. These transitions were modelled as separate rooms, connected by stairs or ramps at the corresponding heights.

Over this floor area, the internal fixed obstructions were traced manually to create exclusion zones that restrict agent movement. The driver's compartment and the toilet modules appear as floor holes, which removes those areas from the navigable surface. Instead of placing obstacles around each individual seat row, they were added between seat groups, so that agents at their seats can only exit through the central aisle. The occupants are placed at their assigned positions but are modelled as standing agents, since Pathfinder does not allow passengers to be seated. To take this into account, the time each passenger needs to stand up is included in the pre-movement time. Finally, the emergency service doors follow the clearances of the floor plan and act as exit regions, connecting the cabin directly to the safe exterior area.

For the high-capacity configurations, the connections between the different parts of the vehicle had to be modelled: the vertical connection between decks in the double-decker bus, and the horizontal connection between sections in the articulated bus.

- In the Class I double-decker bus, the two floors were modelled as separate rooms connected by an internal staircase. The geometric reference was taken from [LIXU21]. However, since that study uses different agent parameters, some dimensional adjustments were necessary to ensure consistency with the rest of the simulation matrix: door widths were updated to meet the minimum clearances set by UNECE Regulation No. 107 [UNEC15] , and the central aisle width on both decks was widened to fit the agent profiles defined in Section 5.5. For the standing passenger capacity on the lower deck, no official data was available from the reference model. As an indicative estimate, the value of 15 standing passengers established in Table 2.1 has been adopted, which was derived from the maximum standing density criterion of UNECE R107. Additionally, since the reference floor plan does not include a dedicated wheelchair space, three seats were removed from the lower deck to accommodate one PRM position, to ensure that the model meets the minimum accessibility requirements set by UNECE R107. The final configuration for this vehicle is therefore 79 seated passengers, 15 standing and 1 PRM.
- In the Class I articulated bus, the 18-meter walkable geometry was split into two main sections connected by an intermediate navigable zone representing the articulation joint.

The final 3D geometric implementations developed inside the Pathfinder environment for each vehicle configuration are illustrated below:

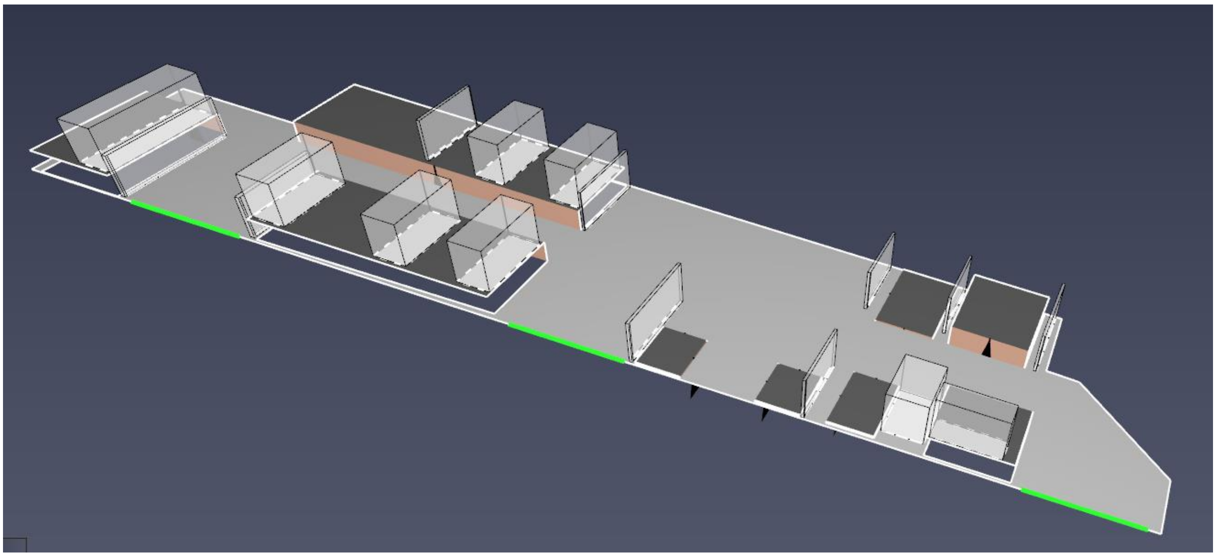

Figure 22: Pathfinder geometric model for Class I Urban Bus.

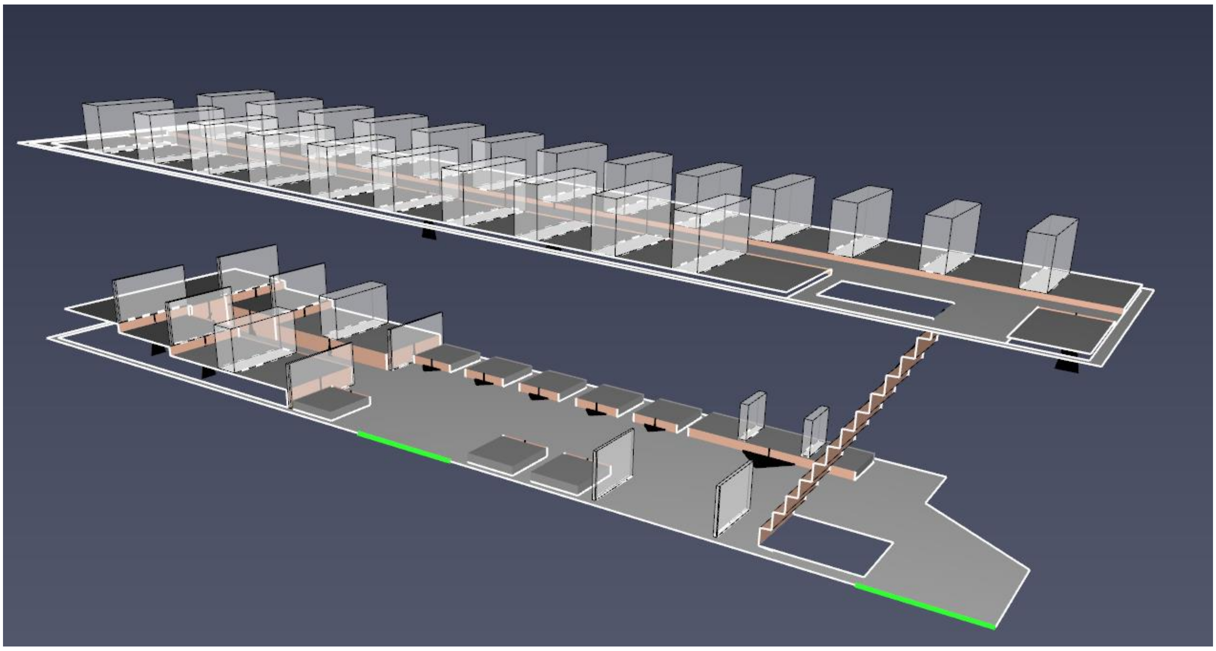

Figure 23: Pathfinder geometric model for Class I Double-Deck Urban Bus.

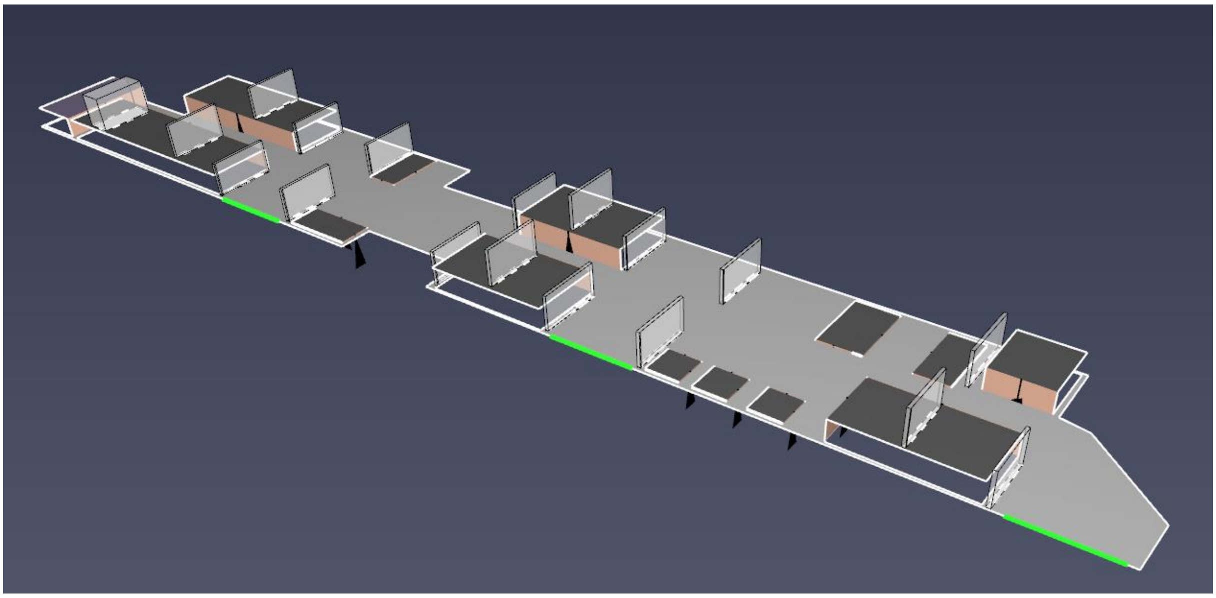

Figure 24: Pathfinder geometric model for Class I Articulated Urban Bus.

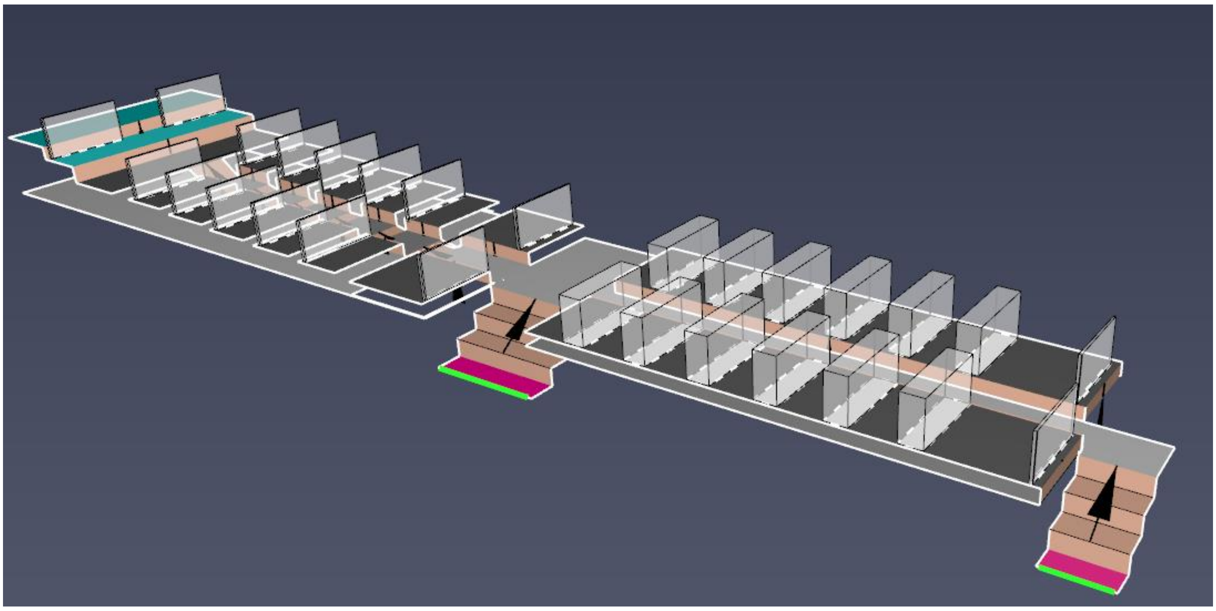

Figure 25: Pathfinder geometric model for Class II Interurban Bus.

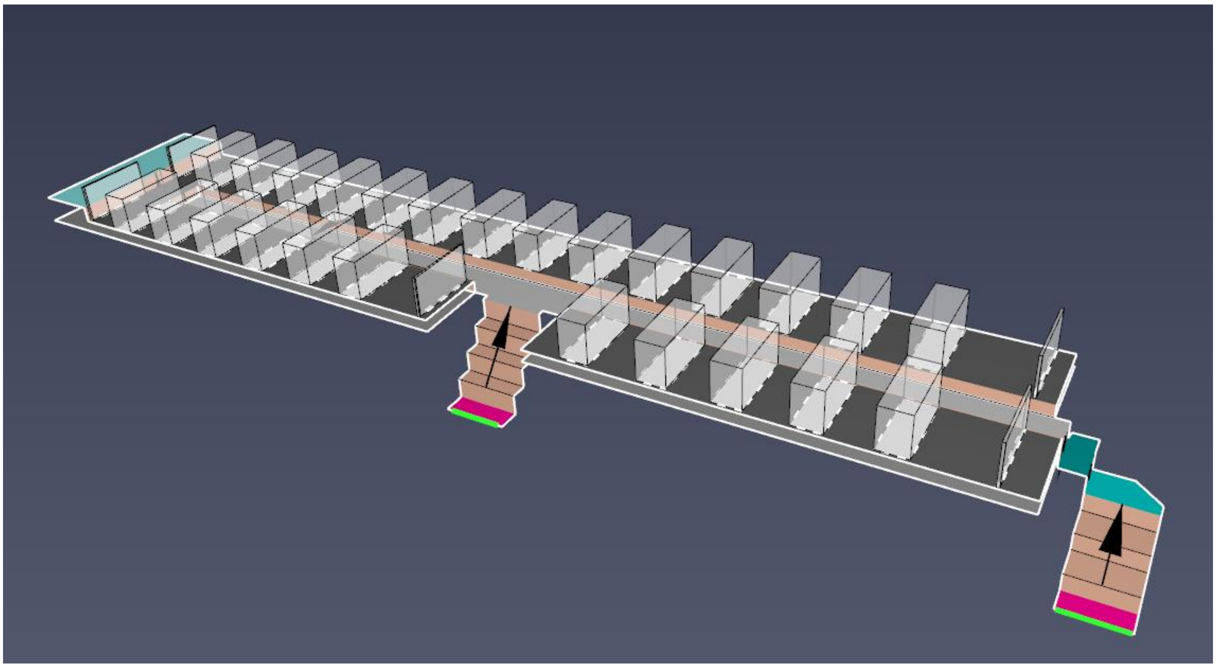

Figure 26: Pathfinder geometric model for Class III Long-Distance Coach.

5.5 CHARACTERIZATION OF OCCUPANTS

In the following section, it is going to be defined the physical, kinematic and behavioural traits of the passengers simulated within the different vehicle layouts. In a tight and confined space like a public bus, the total evacuation time (also known as RSET) changes dramatically depending on who is onboard. In real life, an evacuation flow is very sensitive to human diversity: people have different walking speeds, body sizes and reaction delays. If it was assumed that every passenger was identical, the simulation would be completely unrealistic. In a narrow central aisle, one slower passenger or a vulnerable person can easily create a bottleneck, slowing down the entire row behind them.

To ensure a realistic approach, the occupant profiles have been developed using operational transit statistics and international evacuation benchmarks. Therefore, there are three main factors that have been modified for the simulated agents: walking velocity, physical shoulder width and the initial reaction delay following the alarm. It is very important to test the vehicle configurations with this diverse passenger mix in order to evaluate how the interior geometry performs under realistic emergency conditions.

5.5.1 POPULATION DISTRIBUTION AND PROFILING OBJECTIVES

In order to establish an evacuation environment that is representative of real-world situations, the passenger capacity needs to be distributed across realistic demographic groups rather than assuming an identical crowd. For this purpose, the number of passengers, including both seated and standing ones, is distributed following the demographic guidelines derived from the international maritime safety standard IMO MSC.1/Circ.1533 [IMO_16].

While this standard serves as the baseline framework to classify the crowd, the adult population has been subdivided by different groups depending on age to capture in a better way the differences in physical capacity between younger and older adults. The resulting distribution is the following:

- Males under 30 years: 15%
- Males between 30 and 50 years: 20%
- Females under 30 years: 15%
- Females between 30 and 50 years: 20%
- Elderly passengers (over 50 years): 20%
- Children: 10%

According to the SFPE Handbook of Fire Protection Engineering [SFPE16], evacuation models for public transit need to include a significant proportion of vulnerable passengers to avoid results which are overoptimistic. Therefore, it is necessary to choose a higher percentage of elderly and child passenger. This will to ensure that the simulation is tested under more demanding conditions.

Passengers with Reduced Mobility (PRM) who use wheelchairs are treated separately, as a fixed number rather than a percentage of the crowd. The number of wheelchair spaces included in each vehicle depends on the specific layout and the minimum accessibility requirements established by UNECE Regulation 107 [UNEC15]. This number can range from 0 to 2 dedicated spaces depending on the vehicle class.

The five passenger categories used in the simulation are the following:

- **Males under 30 (15%):** They are the fastest group and have the widest shoulder width. This makes them more likely to cause congestion at narrow exits if they accumulate behind slower passengers.
- **Males between 30 and 50 (20%):** They have lower speeds than the younger group but are still among the highest in the simulation.
- **Females under 30 (15%):** Their walking speeds are intermediate and they have a narrower shoulder width. This gives them more flexibility to move through dense areas.
- **Females between 30 and 50 (20%):** Lower speeds than younger females. This reflects the progressive reduction in physical capacity with age.
- **Elderly passengers over 50 (20%):** It is the most vulnerable group in the simulation. Their walking speed is lower and they have less physical endurance. It is very important to include them in order to test the real performance of each layout under critical conditions.
- **Children (10%):** Values are established to represent young passengers of around 6 years old. This group introduces unpredictable movement patterns and shorter strides, reflecting the realistic dynamics of families travelling together.
- **Wheelchair Users / PRM (fixed number per vehicle class):** These passengers occupy the largest space inside the vehicle and cannot compress their mobility aid. They are restricted to dedicated wheelchair zones and represent a fixed constraint in the model. In real operations, these dedicated zones are frequently occupied by pushchairs and walking frames as well. Although these cases are not explicitly modelled, they would introduce similar geometric constraints and could increase the evacuation time in that area.

5.5.2 AGENT PARAMETRIZATION

Once the passenger groups have been defined, each one needs to be characterised by specific physical and movement values so that Pathfinder can simulate them realistically. Three main parameters have been configured for each agent:

- Walking speed (expressed in m/s).
- Shoulder width.
- Height.

To capture the natural variability between passengers within the same group, walking speeds are defined using a uniform statistical distribution. This means that instead of assigning the same speed to every passenger, Pathfinder assigns each agent a random value within a defined range. The speed ranges used are based on the experimental data provided by IMO MSC.1/Circ.1533 [IMO_16]. On the other hand, shoulder width is assigned as a fixed value for each profile. The chosen value represents the mean of the IMO range.

One of the most important aspects of the simulation is how passenger speed changes depending on how crowded the space is. In a real evacuation, people reduce their speed when the aisle is packed. Pathfinder models this automatically through a Speed-Density relationship, as illustrated in Figure 27. This is what creates realistic bottlenecks in the simulation.

- When local density is below 0.5 pers/m², agents move at their full assigned speed.
- As the aisle fills up, speed drops progressively, reaching around 55.8% of the speed at 2 pers/m².
- It then drops to nearly 8% of the original speed at densities above 3.2 pers/m².

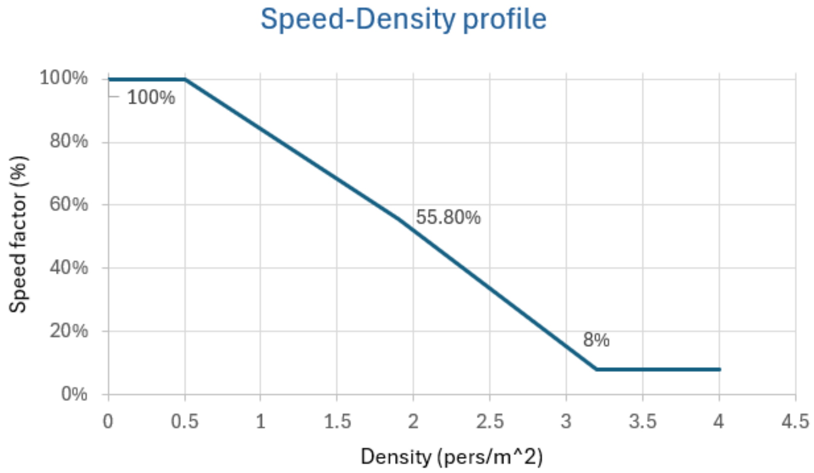

Figure 27: Variation of passenger walking speed according to crowd density, based on the SFPE model [SFPE16].

It is also important to mention that Pathfinder applies two different speed penalties automatically. The first one reduces walking speed based on how crowded the surrounding area is: the more people around, the slower everyone moves. The second one kicks in when a passenger needs to pass through a space that is narrower than their shoulder width, reducing their speed to account for the difficulty of squeezing through tight gaps.

All the physical and kinematic values used for each passenger profile are summarised in the following table:

Profile	Walking speed (m/s)	Shoulder width range (cm)	Shoulder width used (cm)	Height (m)	Congestion factor	Narrow space factor
Males<30	1.11 – 1.85	38-48	43	1.83	0.70	0.9
Males 30-50	0.97-1.62	38-48	43	1.83	0.75	0.9
Females<30	0.93-1.55	32-42	37	1.68	0.70	0.9

Females 30-50	0.71-1.19	32-42	37	1.68	0.75	0.9
Elderly	0.56-0.94	32-42	37	1.68	0.80	0.9
Children	0.80-1.40	28-35	32	1.33	0.65	0.9
Wheelchair/ PRM	0.50-0.80	50-80	65	1.40	Constant	Non-comp

Table 6: Geometrical Characterization of Simulated Passenger Profiles.

5.5.3 PRE-EVACUATION RESPONSE TIMES

In evacuation simulations, the pre-evacuation response time represents the interval between the moment the alarm is triggered and the moment a passenger begins to move. This delay encompasses three steps: alarm perception, situational assessment and the decision to act. It is one of the most influential parameters in the total evacuation time.

For a rigorous justification of this parameter, the values proposed in the normative document C/VM2 Verification Method: Framework for Fire Safety Design (Amendment 4) [CVM2] have been adopted. This document establishes pre-movement time ranges as a function of occupant type and context. The table below summarises the reference values:

Occupant Type	Time in area of origin (s)	Time in remote area (s)
Awake, alert and familiar	30	60
Awake, alert and unfamiliar (passengers)	60	120
Sleeping, familiar	60	300

Table 7: Pre-movement times according to C/VM2 [CVM213].

Unlike aircraft evacuations, where cabin crew are trained to actively guide passengers towards the exits, bus evacuations take place without dedicated evacuation personnel on board. Although the driver may provide some assistance, there are no emergency instructions given to passengers before the journey. Therefore, passengers must react and navigate towards the nearest available exit almost independently. This makes the 'awake, alert and unfamiliar' category the most representative baseline for the configurations studied.

The applicable range depends on the vehicle type, since the possibility of passengers being asleep varies significantly across the configurations studied.

- Class I urban buses: Passengers are assumed to be awake and alert, as the short duration of urban journeys makes it unlikely that passengers fall asleep. Therefore, we need to apply the values corresponding to awake, alert and unfamiliar occupants. These pre-movement times range from 0 to 60 seconds.
- Class II interurban buses: The same category is applied. Although journeys are longer, the 0 to 60 second range can already resemble the asleep passenger through the upper tail of the distribution.
- Class III long-distance coaches: It is not difficult to assume that a proportion of passengers can be asleep at the time of the emergency. In this case, the range is extended to 0 to 90 seconds to represent the additional delay associated with waking up and processing the situation.

Pre-evacuation response times are modelled using a log-normal statistical distribution applied to the “Initial Delay” parameter in Pathfinder. This distribution was selected because it reflects the asymmetry observed in empirical human response data: most passengers react within a short interval after the alarm, while a smaller proportion takes longer. In a uniform distribution all values within the range are equally probable. However, the log-normal distribution concentrates most responses at the lower end of the range, with a tail extending towards the maximum. This avoids the assumption of a uniform response for all occupants. The specific parameters used in Pathfinder for the log-normal distribution are a mean value of 30 seconds and a standard deviation of 5 seconds for Class I and II vehicles (range 0–60 s), and a mean of 45 seconds with the same standard deviation for Class III (range 0–90 s). These values place the centre of the distribution at the midpoint of each range. This ensures a balanced representation of response times across the simulated population.

An exception applies to wheelchair users / PRM. In real emergency evacuations, according to the FTA [FTA_20], the bus operator assists passengers with mobility impairments from outside the vehicle, helping them down physically without deploying the ramp. Therefore, the pre-movement time of the PRM is determined primarily by the time needed for the driver to react, exit the vehicle and position themselves to assist. Based on this, a fixed pre-movement time of 60 seconds is assigned to PRM passengers in scenarios where the bus is already stationary. This value may be adjusted in scenarios where the bus is in motion, as described in Section 5.6.

Beyond physical parameters, cultural and geographic background can also influence pre-movement times. This can affect factors such as familiarity with emergency procedures and predisposition to follow instructions. Although this variability cannot be quantified precisely, the statistical distribution that is applied already accounts for a range of response times across the simulated population.

5.6 Simulation scenarios

Each vehicle configuration was tested under five scenarios. These do not only reflect ideal conditions, but they cover the type of situations that can realistically occur during a bus emergency.

- Scenario 1- Baseline: All doors are operational and the bus is at 100% capacity. Passengers are distributed in a uniform way and pre-movement times follow the log-normal distribution defined in Section 5.5.3. This scenario will be used for all comparisons.
- Scenario 2 - Low occupancy: Same conditions as the baseline but with the bus at 50% capacity. This allows the effect of occupancy level on evacuation time to be studied and separated from other variables.
- Scenario 3 - Rear door blockage: The bus is at 100% capacity, but the rear service door is disabled. This represents a fire in the rear area of the vehicle, where the propulsion system and, in some configurations, the energy storage are located. This type of risk is especially

relevant for the new propulsion technologies. Therefore, all passengers need to evacuate through the remaining exits.

Scenarios 4 and 5 apply an extended pre-movement distribution to simulate the presence of smoke and reduced visibility that can happen during an accidental fire. Under these conditions, passengers will take more time to react and start moving, as they need to perceive the alarm, assess the situation and locate the nearest available exit. To simulate this, the log-normal distribution is established.

- For Class I and II vehicles, the range is 0-90 seconds with a mean value of 45 seconds.
- For Class III, the range is 0-120 seconds with a mean value of 60 seconds.

The pre-movement time of PRM passengers is also extended to 90 seconds, as reduced visibility and the presence of smoke can also delay the driver´s ability to help them.

- Scenario 4 - Extended pre-movement: All doors are operational and the bus is at 100% capacity, but the initial delay range is extended as described above. This represents situations with reduced visibility or the presence of toxic gases.
- Scenario 5 - Critical scenario: The rear door is blocked and the extended pre-movement distribution is applied at the same time. This is the most demanding scenario: a fire at the rear can generate smoke that slow down passenger reaction while also reduces the options of the available exits.

The five scenarios applied to the five vehicle configurations define a simulation matrix of 25 cases, the results of which are presented in Chapter 6.

Chapter 6. RESULT ANALYSIS

Once the five different scenarios that will be studied throughout this dissertation have been defined and the evacuation simulations for the five bus configurations have been completed, this chapter analyses the obtained results. The combination of the five scenarios with the five configurations results in a 5X5 matrix with a total of 25 simulation cases.

For each scenario, a summary table will first be presented with the evacuation times obtained from the 5 bus configurations, which will allow for a global comparison of the models for a specific situation. This will be followed by an individual analysis of each of the configurations based on the accumulated usage map inside the vehicle and on the evolution of the number of occupants remaining inside the vehicle over time. These will help us identify bottlenecks as well as congestion areas.

6.1 SCENARIO 1- BASELINE

6.1.1 GLOBAL RESULTS

Vehicle model	Number of passengers	Available exits	Evacuation time (s)
Simple urban bus	96	3 exits of 120 cm	68.0
Double-decker bus	95	2 exits of 120 cm	151.0
Articulated bus	116	3 exits of 120 cm	70.8
Intercity bus	81	1 exit of 120 cm & 1 exit of 65 cm	108.8
Long-distance bus	60	2 exits of 65 cm	121.0

Table 8: Evacuation times obtained for the five vehicle configurations in Scenario 1 (Baseline).

The obtained results show that there are noticeable differences between each configuration. The urban bus and the articulated bus have the smallest evacuation times (68.0 s and 70.8 s) as they have three available exits of 120 cm, despite the articulated bus being the one with the highest occupancy.

On the other hand, the double-decker bus shows the highest evacuation time (151.0 s). Although this bus has a similar occupancy to that of the urban bus, its evacuation time is considerably higher. This can be due to the availability of only 2 exits and the need to evacuate the upper deck using the narrow stairs.

The intercity bus and the long-distance bus also present high evacuation times (108.8 s and 121.0 s), despite having a lower occupancy than the urban and articulated ones. In both cases, the narrow width of one/both of their exits (65 cm) limits the flow of passengers, slowing down the evacuation . The long-distance bus takes longer than the intercity bus despite having fewer passengers (60 compared to 81). This can be explained by its longer pre-movement time, as there can be different delays during their evacuation due to the fact that class III passengers may be sleeping or resting at the time of the emergency. This shows that pre-movement time, occupancy and exit width can have a big impact in the final evacuation time.

6.1.2 INDIVIDUAL ANALYSIS

6.1.2.1 Simple urban bus

The simple urban bus model has been simulated with a total occupancy of 96 passengers and three available exits of 120 cm: one at the front, one at the middle and one at the rear of the vehicle. The evacuation time obtained for this configuration in the baseline scenario was 68.0 seconds.

The accumulated usage map (figure 28) shows high usage throughout the aisle, specially towards the second half of the bus, where the colour is more intense. This indicates sustained occupancy during the evacuation. All three exits show high usage, but the front one is the least used. The darkest area, shown in dark red, corresponds to the PRM seating zone. This makes sense, since these passengers remain in the bus until the surrounding area is clear enough for the bus driver to help them evacuate.

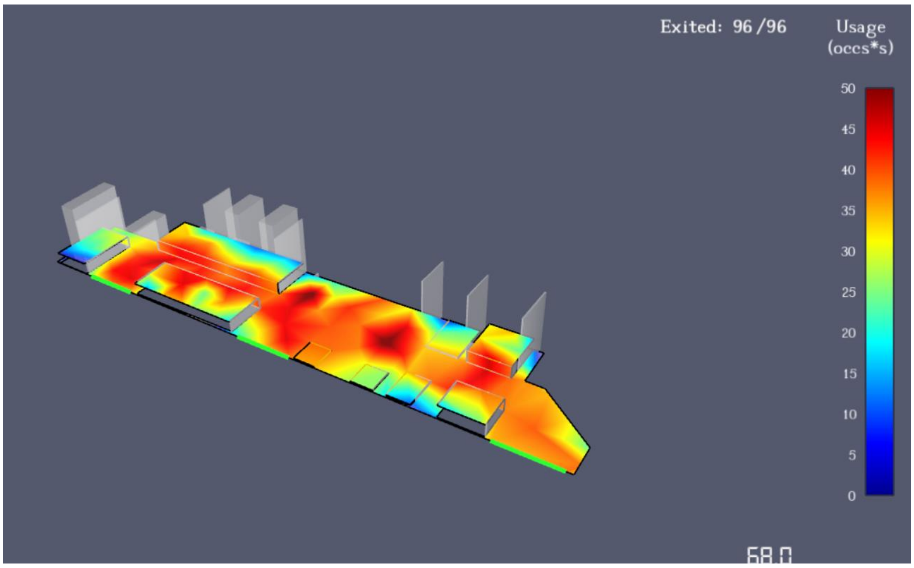

Figure 28: Accumulated usage map of the simple urban bus (Baseline).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 24 occupants evacuated with a flow rate of 0.35 p/s/m.
- Middle door: 42 occupants evacuated with a flow rate of 0.55 p/s/m.
- Rear door: 30 occupants evacuated with a flow rate of 0.43 p/s/m.

This shows that the front door was the least used, as we had already seen on the usage map. The middle door was the one that handled the biggest part of the evacuation. This is consistent with the space utilisation map, where the middle and rear areas of the aisle show the highest usage values. This suggests that passengers who were seated in those zones had more direct access to their respective exits. Regarding flow rates, the middle door shows the highest value (0.55 p/s/m), which is consistent with the larger number of passengers that used it. The front and rear doors show similar values (0.35 and 0.43 p/s/m), reflecting a lower evacuation load.

The graph (Figure 29) shows the evolution of remaining occupants over time. The number of passengers inside the bus decreases at a steady rate from the start of the evacuation until the end. This indicates that there is no passenger that significantly delays the end of the evacuation, and the process concludes at 68.0 seconds.

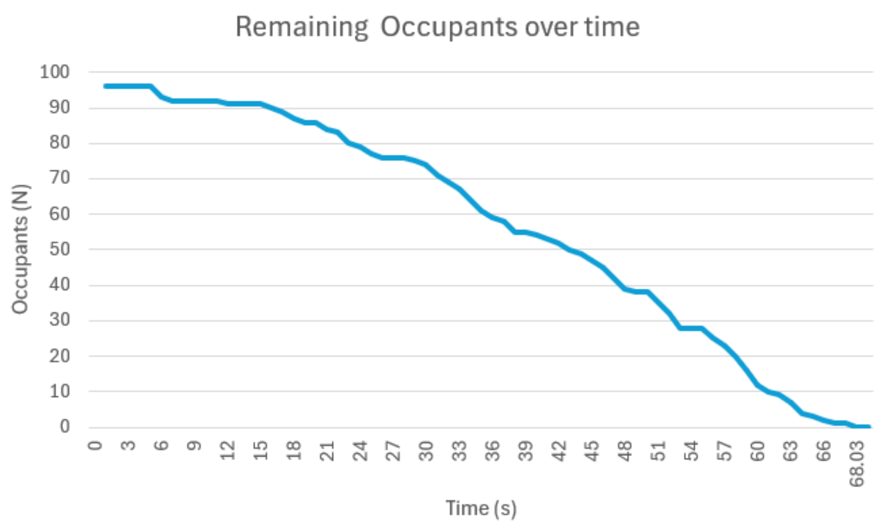

Figure 29: Number of occupants remaining inside the simple urban bus during the simulation (Baseline).

6.1.2.2 Double-decker bus

The double-decker urban bus model has been simulated with a total occupancy of 95 passengers and two available exits of 120 cm. The evacuation time obtained for this configuration in the baseline scenario was 151.0 seconds.

The accumulated usage map (Figure 30) shows that the upper deck presents very high usage along almost the entire floor, indicating that passengers on the upper deck spent a long time moving towards the stairs. On the lower deck, the highest usage is concentrated near the stairwell area, which creates a bottleneck affecting the front exit. The rear aisle also shows an orange colour, indicating a high usage. The PRM seating area shows a red colour, as this passenger remains inside the bus for an extended period due to their high pre-movement time.

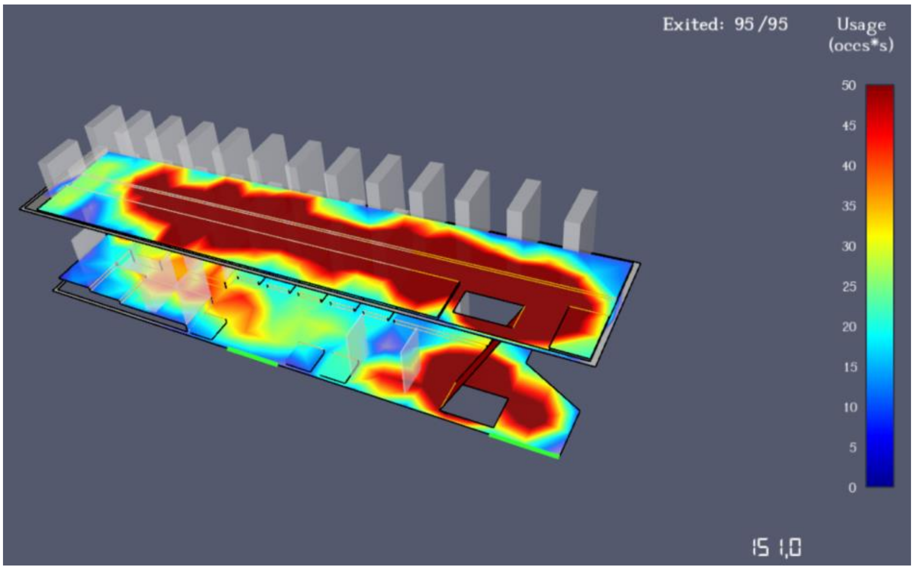

Figure 30: Accumulated usage map of the double-decker bus (Baseline).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 58 occupants evacuated with a flow rate of 0.36 p/s/m.
- Rear door: 37 occupants evacuated with a flow rate of 0.49 p/s/m.

This shows that the front door handled the majority of the evacuation, with 58 occupants compared to 37 through the rear door. This is consistent with the space utilisation map, as the majority of passengers descending from the upper deck chose the front exit. This kept the stairwell and front aisle in use until the end of the simulation. Regarding flow rates, although the rear door was used by fewer passengers it shows a higher value, as it was active for a shorter period.

The graph (Figure 31) shows the evolution of remaining occupants over time. The curve presents two different phases: during the first 64 seconds, the descent is steeper and less uniform, as passengers from both decks are evacuating simultaneously. After second 64, the rate becomes steadier and more linear, reflecting that the remaining occupants are almost entirely from the upper deck, who exit in a continuous queue down the stairs and towards the exits.

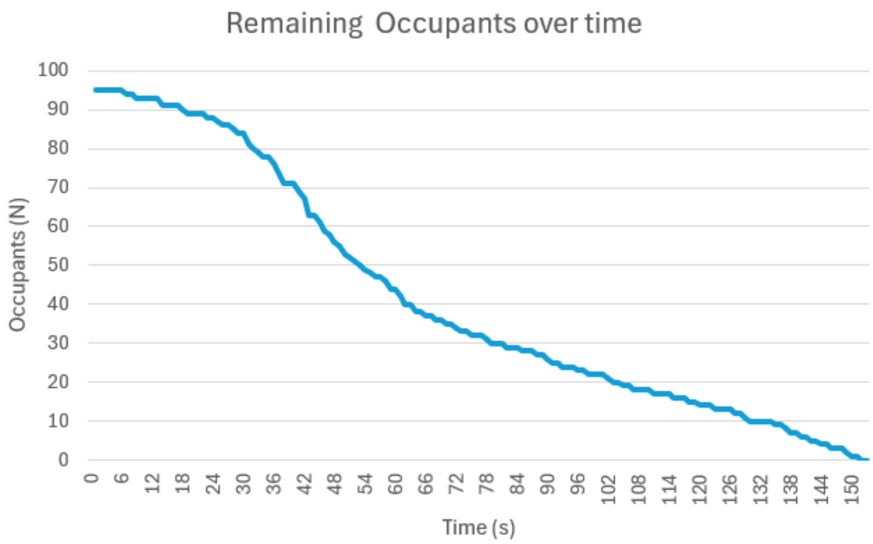

Figure 31: Number of occupants remaining inside the double-decker bus during the simulation (Baseline).

6.1.2.3 Articulated bus

The articulated bus model has been simulated with a total occupancy of 116 passengers and three available exits of 120 cm: one at the front, one in the middle and one at the rear of the vehicle. The evacuation time obtained for this configuration in the baseline scenario was 70.8 seconds.

The accumulated usage map (Figure 32) shows that the front door and the front aisle present yellow-orange tones, reflecting that this exit stopped being used earlier and handled fewer passengers. The middle door and its surrounding area show red tones, indicating sustained high usage. The articulated section appears in light blue, as passengers pass through it to reach the other sections but do not remain there. The rear aisle and rear door show the highest usage values appearing in a darker red.

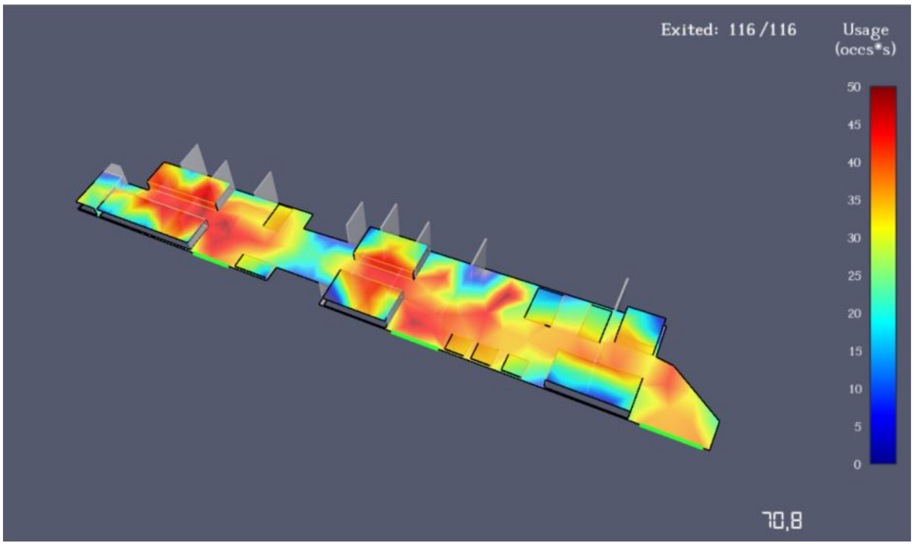

Figure 32: Accumulated usage map of the articulated bus (Baseline).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 24 occupants evacuated with a flow rate of 0.34 p/s/m.
- Middle door: 48 occupants evacuated with a flow rate of 0.63 p/s/m.
- Rear door: 44 occupants evacuated with a flow rate of 0.56 p/s/m.

This shows that the front door was the least used, while the middle and rear doors were used by almost the same number of occupants. The flow rates reflect this distribution, with the middle door showing the highest value (0.63 p/s/m) due to its higher evacuation load. The front door shows the lowest (0.34 p/s/m), consistent with the fewer passengers that used it.

The graph (Figure 33) shows a similar behaviour to the graph of the urban bus. The number of passengers decreases steadily until the end of the evacuation, with no delays due to the PRM. The evacuation is complete at 70.8 seconds.

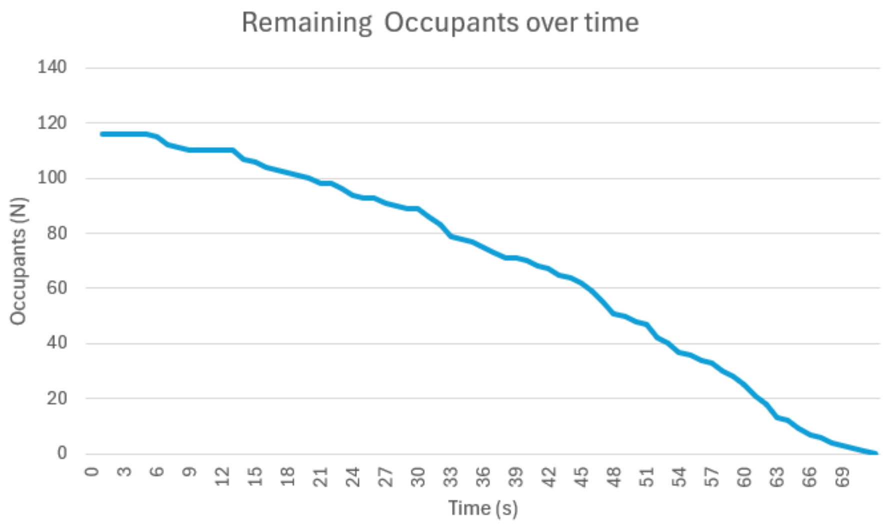

Figure 33: Number of occupants remaining inside the articulated bus during the simulation (Baseline).

6.1.2.4 Intercity bus

The intercity bus model has been simulated with a total occupancy of 81 passengers and two available exits: one of 120 cm located in the middle of the vehicle and one of 65 cm located at the front. The evacuation time obtained for this configuration in the baseline scenario was 108.8 seconds.

The accumulated usage map (Figure 34) shows that the rear aisle and the middle door area present the highest usage values, appearing in dark red. The front aisle shows yellow tones near the seats, turning to dark red as it narrows towards the centre. The front door appears in an orange-red tone, showing high usage. The PRM seating zone is also among the dark areas of the map. This means that passengers who are on the rear part of the bus take longer to abandon the bus than the ones seating on the front part.

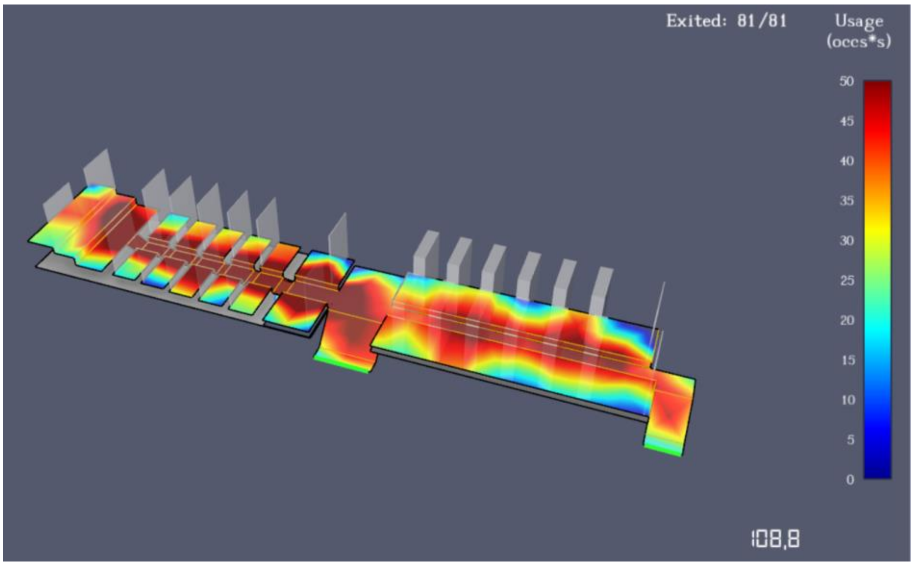

Figure 34: Accumulated usage map of the intercity bus (Baseline).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 26 occupants evacuated with a flow rate of 0.54 p/s/m.
- Rear door: 55 occupants evacuated with a flow rate of 0.44 p/s/m.

This shows that the rear door was used by more than twice as many passengers as the narrower front door. With regard to flow rates, despite being used by more occupants, the rear door shows a lower value (0.44 p/s/m) due to its wider width and longer active period. The front door achieves a higher flow rate (0.54 p/s/m) because of its narrower width and shorter active period.

The graph (Figure 35) shows two phases. During the first 72 seconds, the descent is slightly less steep, as passengers from both sections of the bus are using both exits simultaneously. After this moment, the rate becomes more pronounced. This can be seen in the simulation as passengers separated towards their nearest exit: those in the front section used the front door and those in the rear section used the rear door. This allowed for a more efficient flow towards the exits.

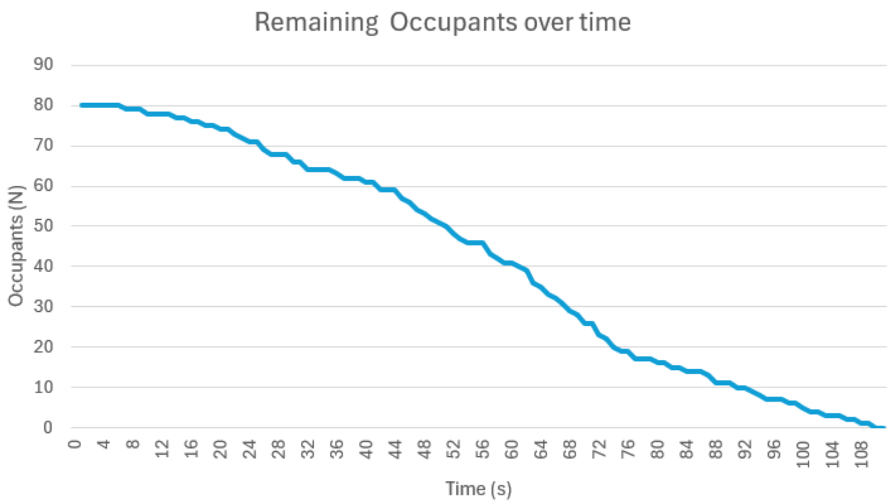

Figure 35: Number of occupants remaining inside the intercity bus during the simulation (Baseline).

6.1.2.5 Long-distance bus

The long-distance bus model has been simulated with a total occupancy of 60 passengers and two available exits of 65 cm: one at the front and one in the middle of the vehicle. The evacuation time obtained for this configuration in the baseline scenario was 121.0 seconds.

The accumulated usage map (Figure 36) shows that the front aisle of the bus appears in blue, green and yellow tones, with the front door also in blue, indicating low usage. Throughout the front area there are some random dark spots, showing that some passengers were asleep and took a longer time to react and start moving. On the other hand, the rear aisle shows mostly orange, red and dark red areas, with the rear door showing very high usage. This reflects that most passengers concentrated around that exit throughout the evacuation.

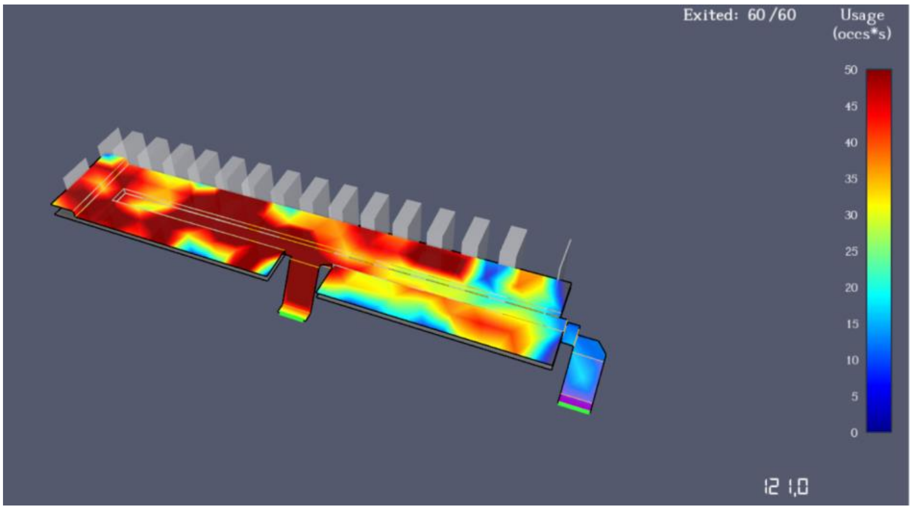

Figure 36: Accumulated usage map of the long-distance bus(Baseline).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 14 occupants evacuated with a flow rate of 0.28 p/s/m.
- Middle door: 46 occupants evacuated with a flow rate of 0.62 p/s/m.

This shows that the middle door was used by most of the passengers during the evacuation. Since both doors have the same width, the difference in flow rates is explained by the higher number of passengers using the middle door despite its longer active period. The front door stopped being used at around second 91, 30 seconds before the evacuation was completed.

The graph (Figure 37) shows that passengers begin evacuating at around second 10, reflecting a higher pre-movement time. It can also be seen that the descent is irregular and stepped throughout the entire evacuation, reflecting the wide range of pre-movement times. While some passengers started moving within the first few seconds, others did not react until around second 70. This produces periods where the number of occupants remains constant for several seconds before dropping again. From second 70 until the end, the graph shows a more linear descent, as by that time most passengers have already start moving and are waiting in a queue to exit. The evacuation is complete at 121.0 seconds.

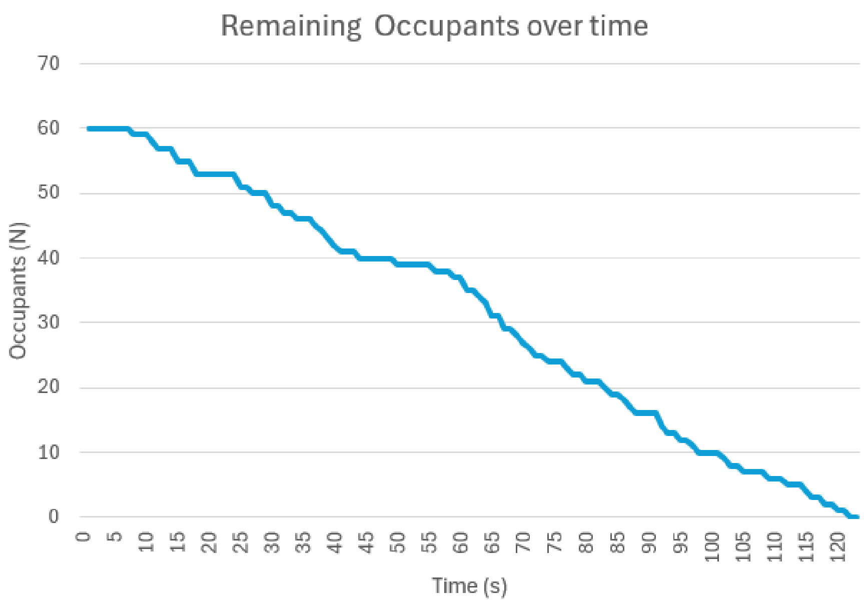

Figure 37: Number of occupants remaining inside the long-distance bus during the simulation (Baseline).

6.2 SCENARIO 2- LOW OCCUPANCY

6.2.1 GLOBAL RESULTS

Vehicle model	Number of passengers	Available exits	Evacuation time (s)
Simple urban bus	48	3 exits of 120 cm	65.8
Double-decker bus	48	2 exits of 120 cm	87.0
Articulated bus	58	3 exits of 120 cm	67.3
Intercity bus	41	1 exit of 120 cm & 1 exit of 65 cm	73.3
Long-distance bus	30	2 exits of 65 cm	99.8

Table 9: Evacuation times obtained for the five vehicle configurations in Scenario 2 (Low occupancy).

The obtained results show that in this second scenario the evacuation times are considerably lower than in the baseline scenario for most configurations, which is consistent with the reduced number of passengers.

It is important to analyse this behaviour to understand the effect of occupancy on evacuation time. In high-density situations, like the baseline scenario, bottlenecks are created at the exits and aisles, as passengers need to queue before being able to reach the exit. However, when density is reduced, the total evacuation time is mostly determined by walking time and pre-movement times.

The urban bus and the articulated bus have evacuation times of 65.8 s and 67.3 s, which are very similar to their baseline values (68.0 s and 70.8 s). This small difference suggests that when the bus is at full occupancy these configurations were already close to their maximum efficiency. Therefore, reducing the number of passengers does not result in a significant improvement.

The double-decker bus also shows a high reduction in evacuation time, from 151.0 s to 87.0 s, as the lower occupancy reduces the queue forming on the upper deck and the stairwell bottleneck.

The intercity bus also benefits from the reduced occupancy, reaching an evacuation time of 73.3 s. However, the long-distance bus has an improvement from 121.0 seconds to 99.8 seconds. Although the evacuation time has been reduced by more than 20 seconds, this configuration has the biggest evacuation time for this scenario. This is due to the pre-movement time of some passengers. With only 30 occupants, queues do not form, so the evacuation rate is totally influenced by the reaction times. This value has a big range in class III buses.

6.2.2 INDIVIDUAL ANALYSIS

6.2.2.1 Simple urban bus

The simple urban bus model has been simulated with a total occupancy of 48 passengers and three available exits of 120 cm. The evacuation time obtained for this configuration in the low occupancy scenario was 65.8 seconds.

The accumulated usage map (Figure 38) shows a significant reduction in usage throughout the entire bus compared to the baseline scenario. The aisle and exit areas, that appeared in red and orange tones, now show blue and green values. This reflects the lower number of passengers. The only area that maintains higher usage values is the PRM seating zone, which appears in yellow-orange as these passengers remain in the bus for a high amount of time. Their pre-movement time depends on the driver, their reaction capacity and ability to clear the bus, so they are the last to evacuate in this situation.

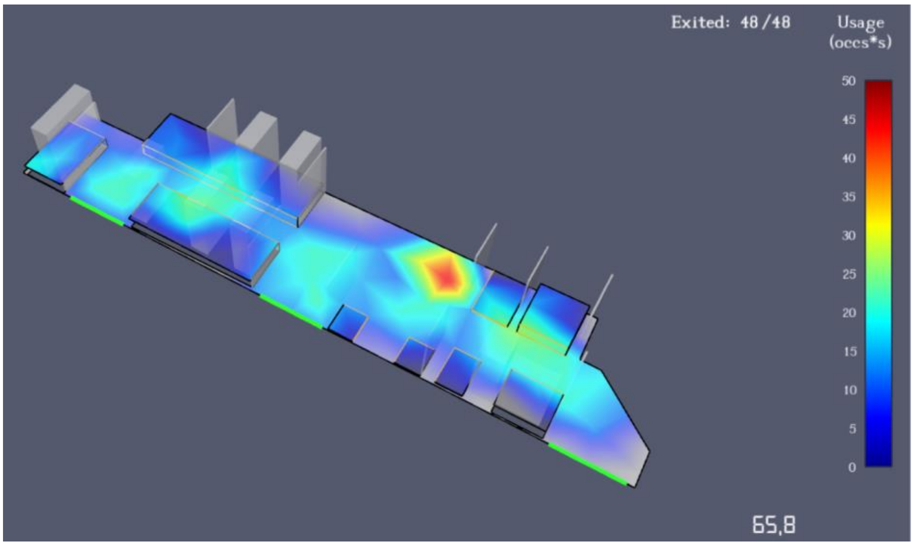

Figure 38: Accumulated usage map of the simple urban bus (Low occupancy).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 12 occupants evacuated with a flow rate of 0.38 p/s/m.
- Middle door: 14 occupants evacuated with a flow rate of 0.21 p/s/m.
- Rear door: 22 occupants evacuated with a flow rate of 0.67 p/s/m.

This shows that, as in the baseline scenario, the front door was the least used. However, in this case, the middle door was not the one that handled the biggest part of the evacuation, as this was the rear door. Regarding flow rates, the middle door shows a lower value (0.21 p/s/m) compared to the other exits. This is due to the PRM passenger exiting through it, which extends the active period of that door and reduces the calculated flow rate.

The graph (Figure 39) shows that the number of passengers decreases steadily until around second 40, when it stabilises at 1 occupant until the end of the simulation at 65.78 seconds. This corresponds to the PRM passenger.

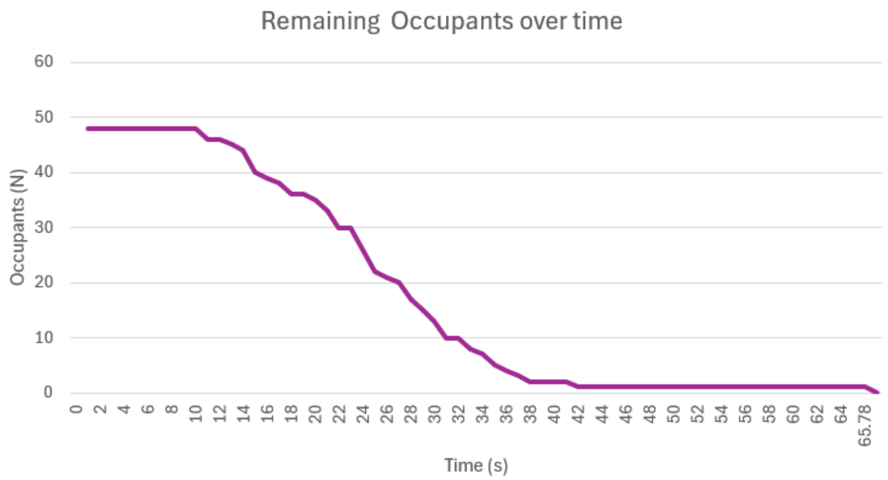

Figure 39: Number of occupants remaining inside the simple urban bus during the simulation (Low occupancy).

6.2.2.2 Double-decker bus

The double-decker urban bus model has been simulated with a total occupancy of 48 passengers and two available exits of 120 cm. The evacuation time was 87.0 seconds.

The accumulated usage map (Figure 40), compared to the baseline scenario, shows a notable reduction in usage on the upper deck, which now presents orange and yellow tones instead of the intense red seen previously. On the lower deck, the highest usage remains concentrated near the stairwell area and the PRM seating zone, which still appears in red.

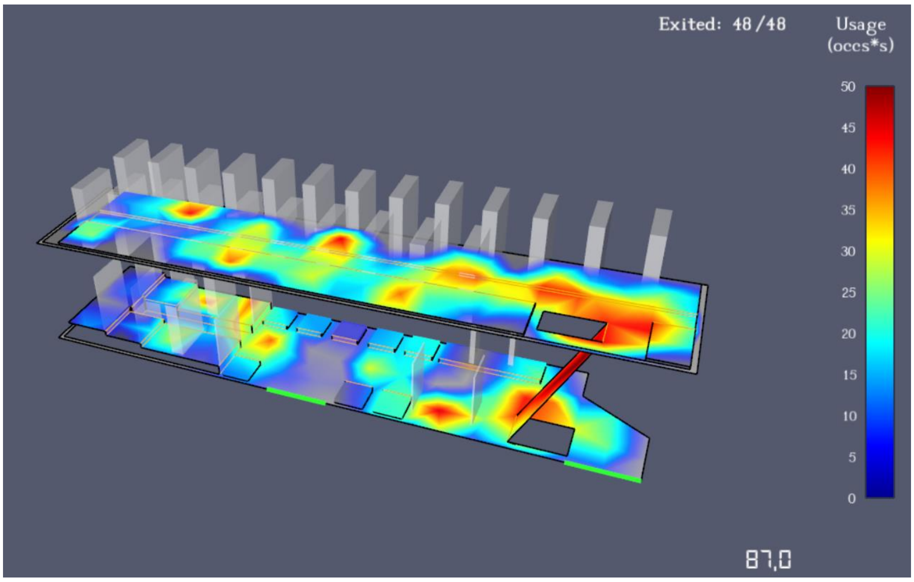

Figure 40: Accumulated usage map of the double-decker bus (Low occupancy).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 29 occupants evacuated with a flow rate of 0.34 p/s/m.
- Rear door: 19 occupants evacuated with a flow rate of 0.29 p/s/m.

This shows that, as in the baseline scenario, the front door handled more passengers than the rear door. Both flow rates are lower than in the previous scenario, which is consistent with the reduced number of occupants. Their values are not very different, which means that both doors were used at a similar intensity despite the difference in the number of occupants.

The graph (Figure 41) shows a continuous descent throughout the evacuation. It has a different behaviour from the one of the baseline scenario. As the occupancy is reduced, the upper deck empties more quickly, and the two phases that were seen previously are no longer distinguishable. The evacuation is complete at 87.0 seconds.

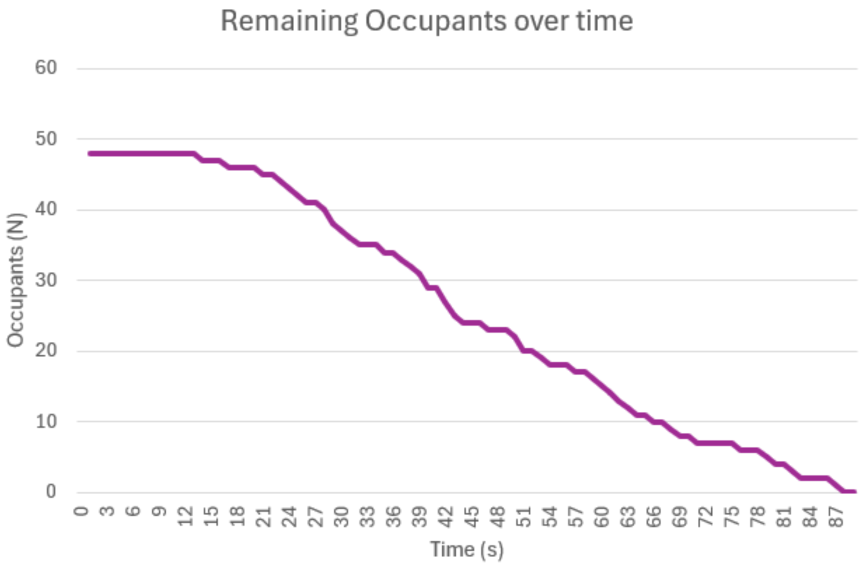

Figure 41: Number of occupants remaining inside the double-decker bus during the simulation (Low occupancy).

6.2.2.3 Articulated bus

The articulated bus model has been simulated with a total occupancy of 58 passengers and three available exits of 120 cm. The evacuation time was 67.3 seconds.

The accumulated usage map (Figure 42) shows a general reduction in usage throughout the bus. The articulated section appears completely grey, indicating that no passenger remained in that area during the evacuation. This suggests that, with lower occupancy, passengers from the rear section exit directly through the rear door, while those in the front section use the front and middle doors. The front and rear sections show random red and orange spots near the exits and seating areas, which reflect the localised concentration of passengers as they moved towards the doors.

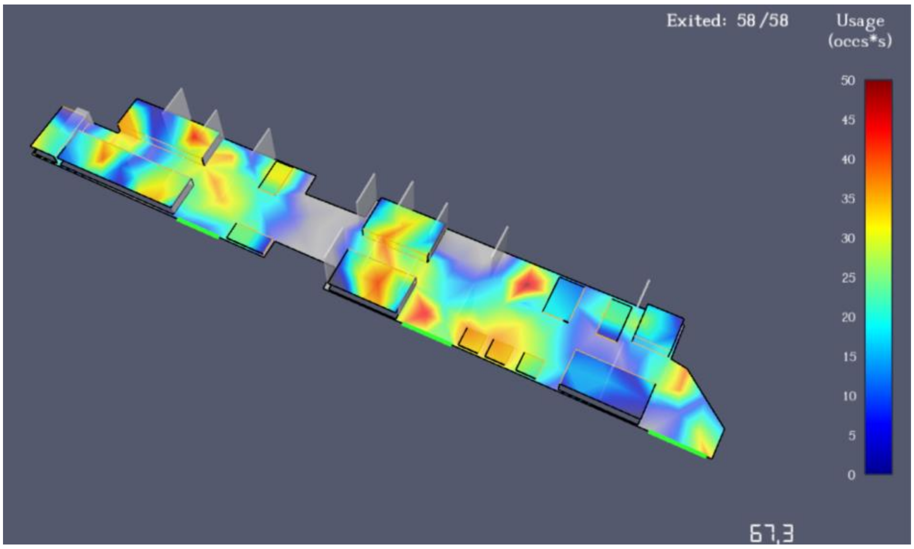

Figure 42: Accumulated usage map of the articulated bus (Low occupancy).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 7 occupants evacuated with a flow rate of 0.13 p/s/m.
- Middle door: 22 occupants evacuated with a flow rate of 0.29 p/s/m.
- Rear door: 29 occupants evacuated with a flow rate of 0.41 p/s/m.

This shows that the rear door was the most used by passengers, unlike the baseline scenario, where the middle door was the most used. All flow rates are lower than in the baseline scenario, consistent with the reduced occupancy.

The graph (Figure 43) shows a continuous descent until around second 64, when it stabilises for a few seconds at 1 occupant corresponding to the PRM passenger, who remains inside until the end of the simulation at 67.3 seconds.

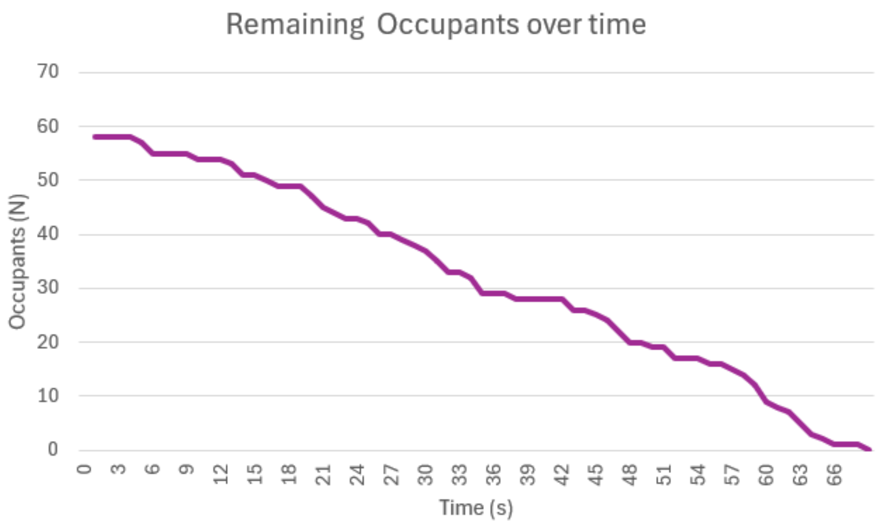

Figure 43: *Number of occupants remaining inside the articulated bus during the simulation (Low occupancy).*

6.2.2.4 Intercity bus

The intercity bus model has been simulated with a total occupancy of 41 passengers and two available exits. The evacuation time obtained was 73.3 seconds.

The accumulated usage map (Figure 44) shows a significant reduction in usage throughout the bus. Most of the vehicle appears in blue and green tones. The area around the middle door shows yellow and orange tones, which reflects the concentration of passengers moving towards that exit. The seats immediately behind the middle door appear in red, as some passengers stopped there to let faster occupants pass. Lastly, the PRM zone shows an orange colour, as it is one of the last passengers to evacuate.

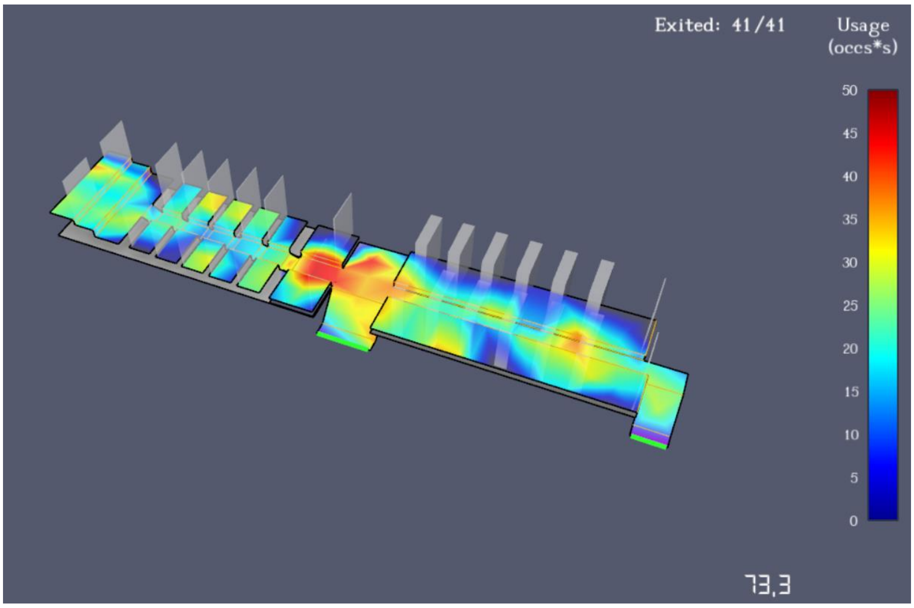

Figure 44: Accumulated usage map of the intercity bus (Low occupancy).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 9 occupants evacuated with a flow rate of 0.40 p/s/m.
- Rear door: 32 occupants evacuated with a flow rate of 0.40 p/s/m.

This shows that, as in the baseline scenario, the rear door handled the majority of the evacuation. Both doors have the same flow rate, although their width is different and the rear door is used by most of the passengers.

The graph shows a continuous descent throughout most of the evacuation. Around second 61, the descent stops for approximately 3 seconds, coinciding with the moment the PRM passenger exits the vehicle. This small interruption suggests that the PRM disrupted the flow of the remaining occupants for a few seconds as they passed through the same exit. The evacuation is complete at 73.3 seconds

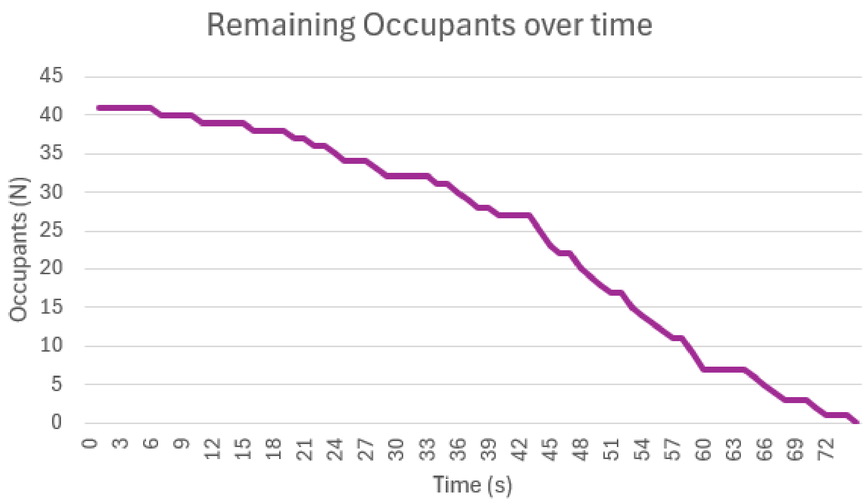

Figure 45: *Number of occupants remaining inside the intercity bus during the simulation* (*Low occupancy).*

6.2.2.5 Long-distance bus

The long-distance bus model has been simulated with a total occupancy of 30 passengers and two available exits of 65 cm. The evacuation time was 99.8 seconds.

The accumulated usage map (Figure 46) shows a very different distribution than in any other configuration. Most of the central aisle shows blue and green colours, which indicate a low usage. The front door shows the lowest usage and the rear door shows intermediate usage, as most of the passengers used the rear door but they did not need to queue to evacuate the bus. There can be seen several random spots with the darkest values, showing that some passengers took a great time to react. This reflects what was explained in chapter 5, as in long-distance buses, passengers may be asleep and have enormous reaction times.

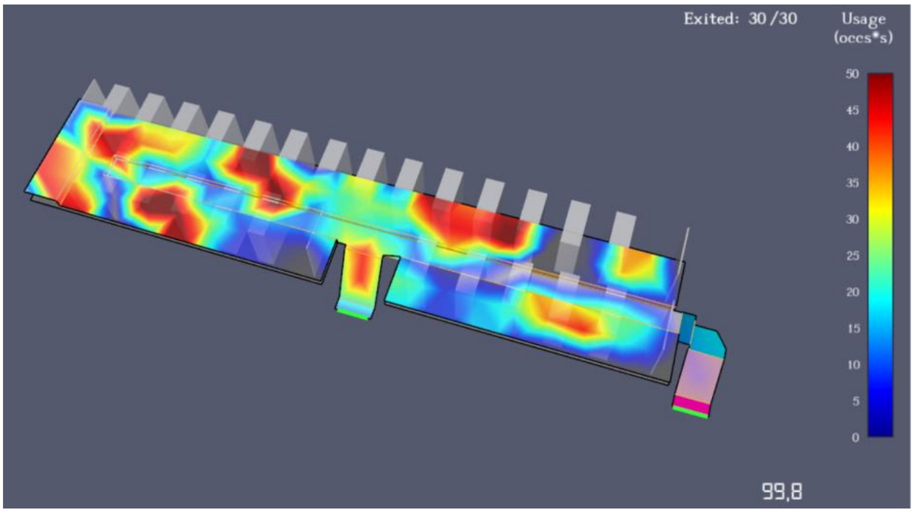

Figure 46: Accumulated usage map of the long-distance bus (Low occupancy).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 5 occupants evacuated with a flow rate of 0.14 p/s/m.
- Middle door: 25 occupants evacuated with a flow rate of 0.42 p/s/m.

This shows that the middle door was used by most of the passengers during the evacuation. The front door was used by very few passengers during a very long period, resulting in a very low flow rate. The difference in flow rates between both doors reflects the higher number of passengers using the middle door, although it was used during a longer period.

The graph (Figure 47) shows a very irregular descent throughout the entire evacuation. It can be seen a lot of pauses during the evacuation with two pronounced periods of approximately 20 seconds each where no passenger exited the vehicle. This behaviour is caused by the wide range of pre-movement times. With only 30 passengers, there are no queues at the exits, so the evacuation rate depends entirely on when each individual passenger decides to start moving. The evacuation is complete at 99.8 seconds.

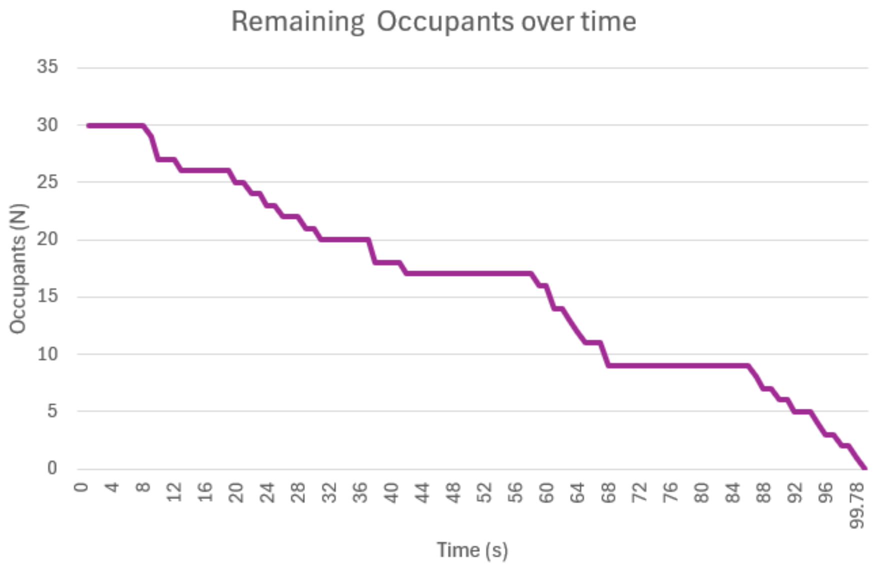

Figure 47: Number of occupants remaining inside the long-distance bus during the simulation (Low occupancy).

6.3 SCENARIO 3- REAR DOOR BLOCKAGE

6.3.1 GLOBAL RESULTS

Vehicle model	Number of passengers	Available exits	Evacuation time (s)
Simple urban bus	96	2 exits of 120 cm	102.0
Double-decker bus	95	1 exit of 120 cm	179.5
Articulated bus	116	2 exits of 120 cm	143.3
Intercity bus	81	1 exit of 65 cm	187.0
Long-distance bus	60	1 exit of 65 cm	144.8

Table 10: Evacuation times obtained for the five vehicle configurations in Scenario 3 (Rear door blockage).

The obtained results show that blocking the rear door has an important impact on evacuation times of all configurations. However, the magnitude of this impact is different depending on the vehicle layout.

First of all, some configurations do not suffer as much as others. For example, the simple urban bus evacuation time increases from 68.0 to 102.0 seconds. This increase of 34 seconds is explained due to the availability of two remaining exits, both of 120 cm. The double-decker urban bus shows the smallest absolute increase of 28.5 seconds (from 151.0 s to 179.5 s). This is due to the necessity of the stairwell, which always creates an enormous bottleneck that limits the evacuation regardless of the number of available doors. The long-distance bus increases from 121.0 s to 144.8 s, an increase of 23.8 seconds. Although it only has one narrow exit available, its lower occupancy and the absence of standing passengers limit the impact of the door blockage.

The bus configurations that have the biggest impact are the articulated and the intercity ones. The first one suffers an increase of 72.5 seconds, rising from 70.8 s to 143.3 s. Although this configuration has 2 remaining doors, its enormous capacity (116 passengers) and the long distance that occupants in the rear section need to travel across the articulated zone to reach the middle door create a severe bottleneck. Then, the second one, with the largest absolute increase, from 108.8 s to 187.0 s, suffers an increase of nearly 80 seconds. This is due to the large number of passengers and the presence of standing passengers that collapse the aisle since the first moment combined with the fact that there is only one narrow exit of 65 cm.

6.3.2 INDIVIDUAL ANALYSIS

6.3.2.1 Simple urban bus

The simple urban bus model has been simulated with a total occupancy of 96 passengers and two available exits of 120 cm: one at the front and one in the middle of the vehicle. The rear door has been blocked to simulate the thermal runaway of an electric battery that is placed at the back of the bus. The evacuation time obtained for this configuration in the rear door blockage scenario was 102.0 seconds.

The accumulated usage map (Figure 48) shows that the entire rear aisle, including the rear door area, and the middle door area appear in very dark red, indicating the highest usage values of the simulation. This reflects the enormous bottleneck that was formed as passengers from the rear section of the bus had to wait and queue before being able to reach the middle door. The front aisle and the area around the front door show orange and red tones, with some spots showing darker colours. Both PRM seats also show high usage values, because they have a higher delay and take longer to evacuate. By the time they exit, the surrounding area remains more occupied than in the baseline scenario, as the reduced number of available exits slows down the overall evacuation flow.

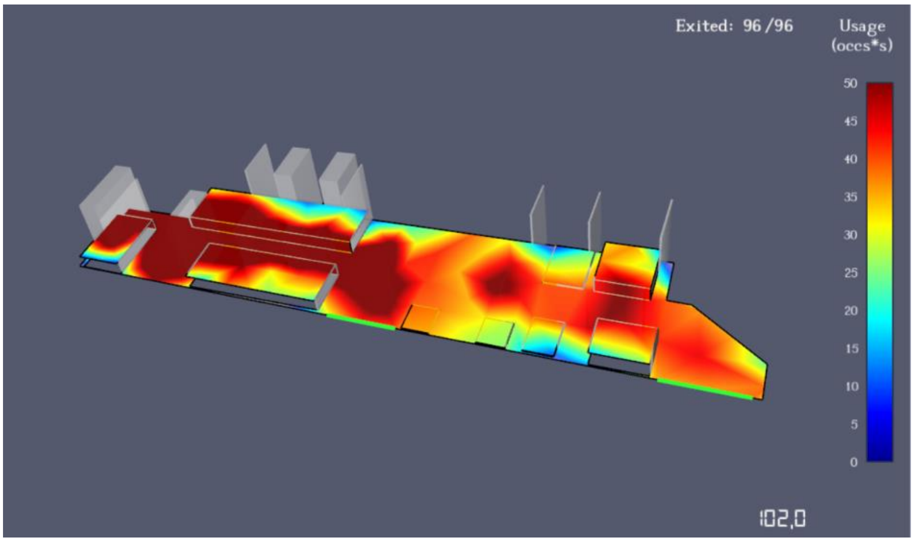

Figure 48: Accumulated usage map of the simple urban bus (Rear door blockage).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 28 occupants evacuated with a flow rate of 0.35 p/s/m.
- Middle door: 68 occupants evacuated with a flow rate of 0.58 p/s/m.

The middle door was used by most of the passengers. This was expected, because passengers that in the baseline scenario used the rear door are now forced to use the next available and nearest door. The flow rate of the middle door (0.58 p/s/m) is considerably higher than that of the front door (0.35 p/s/m), although it is used during a longer period, as the front door is only used until second 71. This reflects it is used by a lot more passengers than the front door.

The graph (Figure 49) shows three different phases. The first one, which lasts until second 56, shows an irregular and gradual descent, as passengers start evacuating using both doors in a very crowded environment. Then, a second period where the descent is more linear and with a bigger slope. Finally, at around second 72, the middle zone has already emptied and passengers from the rear zone evacuate in a queue, showing a lower slope.

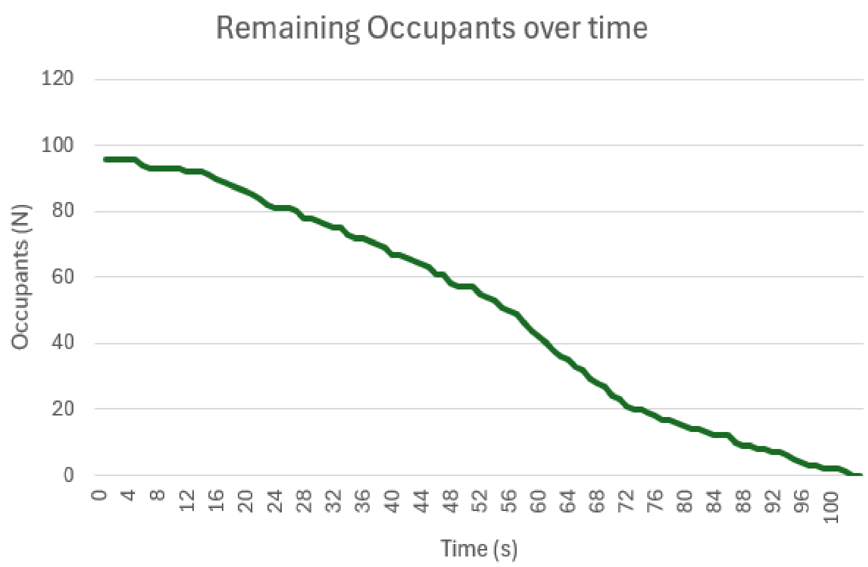

Figure 49: Number of occupants remaining inside the simple urban bus during the simulation (Rear door blockage).

6.3.2.2 Double-decker bus

The double-decker urban bus model has been simulated with a total occupancy of 95 passengers and one available exit of 120 cm at the front of the vehicle. As the only remaining exit is the front door, the PRM passenger cannot pass through the narrow aisle without leaving the wheelchair. To model this, an Assisted Evacuation Team was defined in Pathfinder, with the driver assigned as the assistant and the PRM as the client. In a real evacuation, the PRM would leave the wheelchair behind and be carried by the driver through the narrow aisle. To replicate this, a custom vehicle shape with reduced dimensions was created to allow the assistant to carry the PRM through the narrow aisle. The evacuation time obtained for this configuration in the rear door blockage scenario was 179.5 seconds.

The accumulated usage map (Figure 50) is similar to the baseline scenario on the upper deck, which appears entirely in dark red due to the stairwell bottleneck. On the lower deck, the area around the stairwell and the front door also shows very high usage. However, now the middle and rear sections of the lower deck also show elevated usage values, starting in yellow-orange at the rear and progressively getting darker towards the centre. This reflects the accumulation of passengers who were not able use the rear exit and had to redirect towards the front.

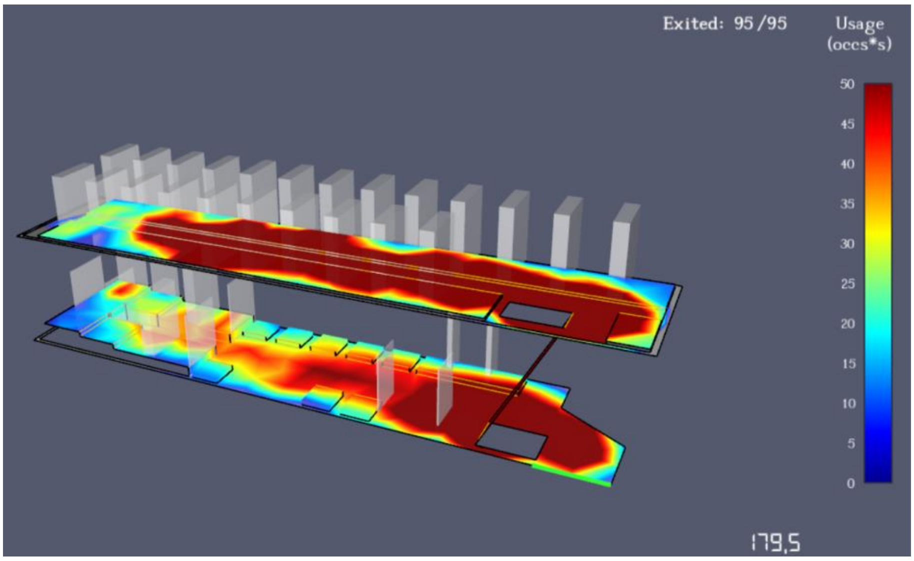

Figure 50: Accumulated usage map of the double-decker bus (Rear door blockage).

As there is only one available exit, all passengers are forced to evacuate through it. This door has a flow rate of 0.47 p/s/m.

The graph (Figure 51) shows two phases. One that lasts the first 105 seconds, where the descent is steady as passengers from both decks evacuate at the same time. When passengers from the upper deck descended the stairs, they interacted with passengers from the lower deck that tried to reach the front door. After second 105, the lower deck has emptied and the evacuation rate depends entirely on the queue descending from the upper deck. This produces a more linear descent until the evacuation is complete at 179.5 seconds.

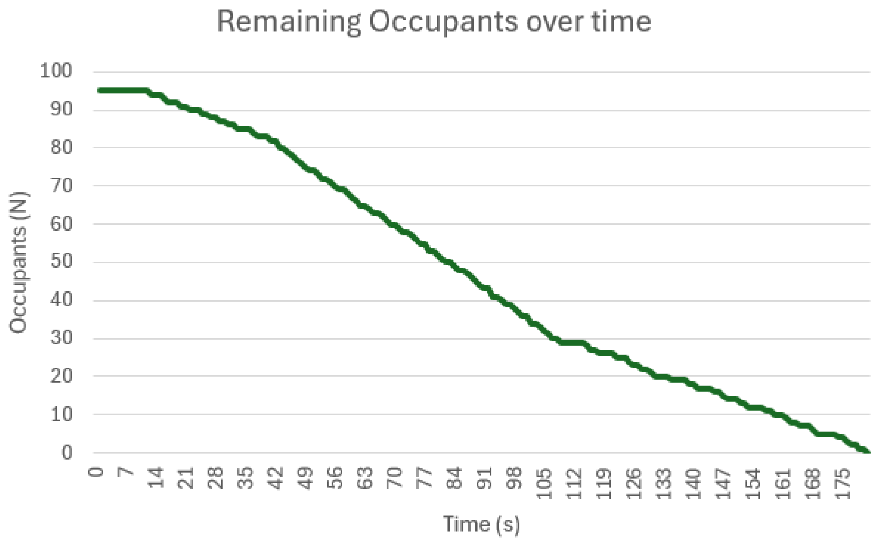

Figure 51: Number of occupants remaining inside the double-decker bus during the simulation (Rear door blockage).

6.3.2.3 Articulated bus

The articulated urban bus model has been simulated with a total occupancy of 116 passengers and two available exits of 120 cm: one at the front and one at the middle, as the rear door has been blocked. The evacuation time obtained for this configuration in the rear door blockage scenario was 143.3 seconds.

The accumulated usage map (Figure 52) shows very dark red colours in all the rear and middle zones (including the articulated area). The seats in this area also show high usage values, as passengers remained seated until the aisle was free enough to move. This reflects the enormous congestion that is formed, as passengers from the rear zone that would evacuate using that door needed to wait a long time before being able to reach the aisle, cross through the articulated zone and reach the middle door. From the middle door towards the front, the map shows yellow and orange tones, reflecting a lower usage. The seat areas in this front section appear in blue and green, as those passengers were able to move into the aisle earlier.

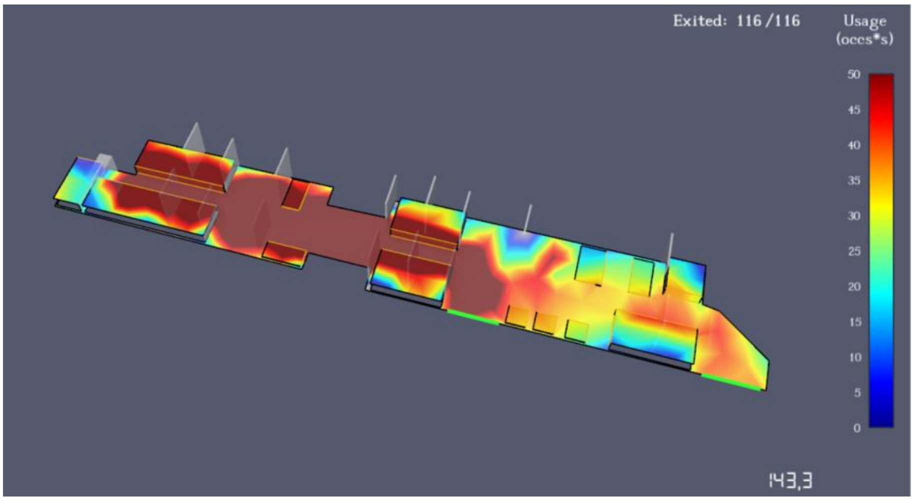

Figure 52: Accumulated usage map of the articulated bus (Rear door blockage).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 25 occupants evacuated with a flow rate of 0.34 p/s/m.
- Middle door: 91 occupants evacuated with a flow rate of 0.55 p/s/m.

This shows that the middle door was used by most of the passengers, as occupants from both rear and middle section chose this door to evacuate. The flow rate of the middle door (0.55 p/s/m) is considerably higher than the flow rate of the front door (0.34 p/s/m), reflecting the much larger number of passengers that used it, despite being used by more than double of time compared to the front door.

The graph (Figure 53) shows two phases. The first one, that lasts until second 70, the descent is steeper as both exits are being used by passengers. After this moment, as the front door was no longer used and both PRM passengers had already exited through the middle door, the evacuation did not have more interruptions. This produces a steadier descent with a lower slope until the evacuation is complete at 143.3 seconds.

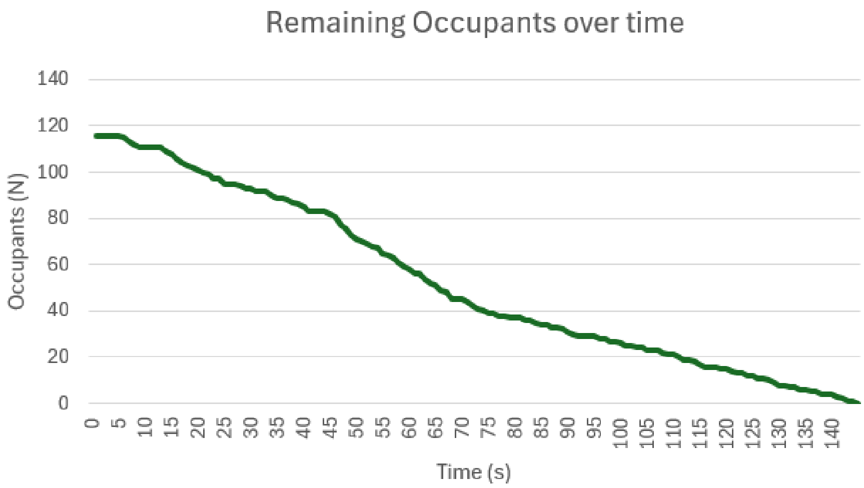

Figure 53: Number of occupants remaining inside the articulated bus during the simulation (Rear door blockage).

6.3.2.4 Intercity bus

The intercity bus model has been simulated with a total occupancy of 81 passengers and one available exit of 65 cm at the front of the vehicle. Passengers can only evacuate using that front door, which means that they necessarily need to use the aisle. However, the PRM passenger cannot pass through the aisle, as the wheelchair is wider than the aisle and will need help. To model this, an Assisted Evacuation Team was defined in Pathfinder, with the driver assigned as the assistant and the PRM as the client. In a real evacuation, the PRM would leave the wheelchair behind and be carried by the driver through the narrow aisle. To replicate this, a custom vehicle shape with reduced dimensions was created to allow the assistant to carry the PRM through the narrow aisle. The evacuation time obtained for this configuration in the rear door blockage scenario was 187.0 seconds.

The accumulated usage map (Figure 54) shows the entire vehicle in very dark red, including the aisle, the seat areas and the door zone. Only some of the front seats show a green and yellow colour, showing these first rows were the first one to leave their seats and move to the aisle. This reflects the extreme congestion that is formed when 81 occupants, some of them standing passengers blocking the aisle, need to evacuate a 14-meter-long bus by using just one narrow door which is located at the front of the vehicle.

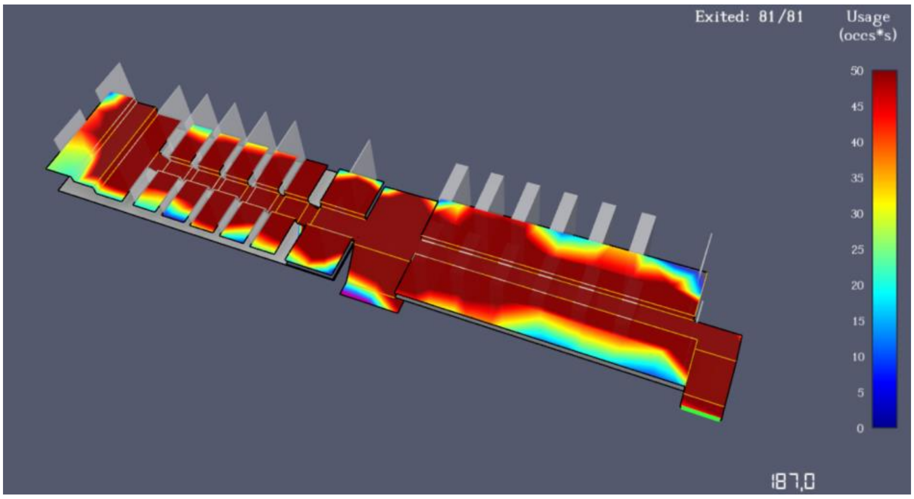

Figure 54: Accumulated usage map of the intercity bus (Rear door blockage).

As there is only one available exit, all passengers are forced to evacuate through it. Its flow rate is 0.69 p/s/m.

The graph (Figure 55) shows two phases. During the first 50 seconds of the evacuation, there are different steps of a few seconds in which one or two passengers evacuate the bus. This reflects the initial congestion and how, during a long period of time, passengers that react faster and want to evacuate need to dodge people that are already occupying the central aisle in order to reach the front door. After that moment, the flow becomes more continuous and the curve descends at a steady and consistent rate until the evacuation is complete at 187.0 seconds.

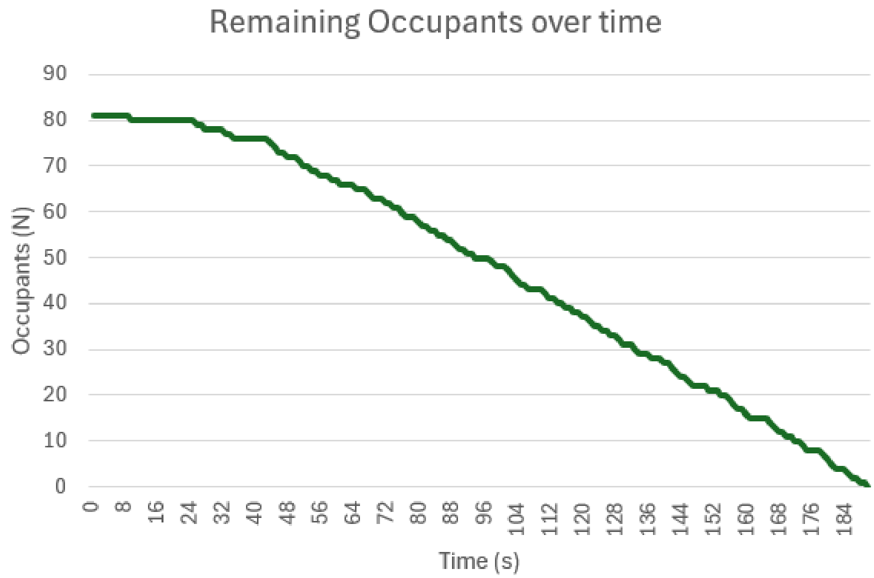

Figure 55: Number of occupants remaining inside the intercity bus during the simulation (Rear door blockage).

6.3.2.5 Long-distance bus

The long-distance bus model has been simulated with a total occupancy of 60 passengers and one available exit of 65 cm at the front of the vehicle, as the rear door has been blocked. Unlike the intercity bus, this configuration has no PRM passengers. The evacuation time obtained for this configuration in the rear door blockage scenario was 144.8 seconds.

The accumulated usage map (Figure 56) shows almost the entire vehicle in dark red. However, there are some random spots located on the seating zones that appear in blue, green and yellow colours. This is because, during the first seconds of the evacuation, passengers that were seated on those places were able to rapidly reach the aisle and queue there. This bus configuration does not have standing passengers, which translates in an empty aisle that allowed for passengers to avoid waiting for this zone to clear.

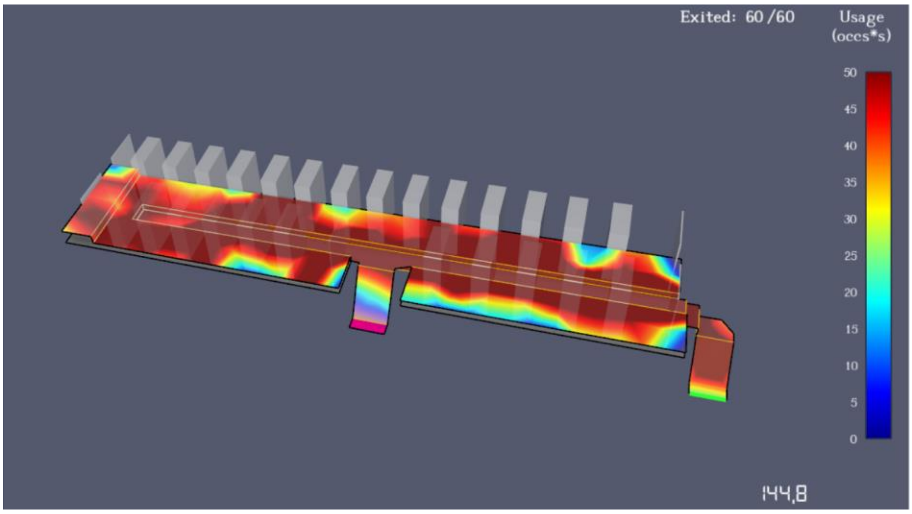

Figure 56: Accumulated usage map of the long-distance bus (Rear door blockage).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 60 occupants evacuated with a flow rate of 0.71 p/s/m.

As there is only one available exit, all passengers were forced to evacuate through it.

The graph (Figure 57) shows two phases. The first one, which lasts until second 66, where there are plenty of small steps with one or two passengers leaving the bus. There can also be seen some small slopes, but it is clear that passengers are interacting between them and delaying the evacuation Then, from this moment until the end of the simulation, the curve follows a linear descent. This reflects that passengers are arranged in the aisle and there is no competition of faster or narrower passengers who tried to avoid other occupants.

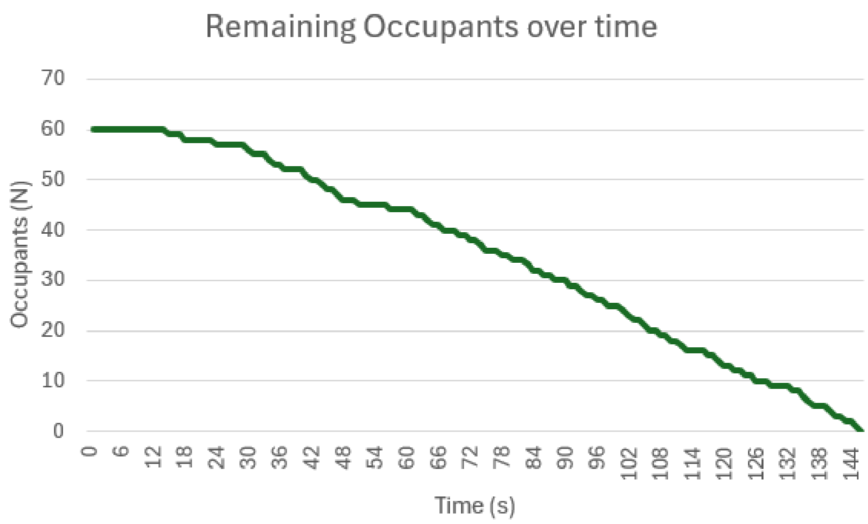

Figure 57: Number of occupants remaining inside the long-distance bus during the simulation (Rear door blockage).

6.4 SCENARIO 4- EXTENDED PRE-MOVEMENT TIME

6.4.1 GLOBAL RESULTS

Vehicle model	Number of passengers	Available exits	Evacuation time (s)
Simple urban bus	96	3 exits of 120 cm	98.0
Double-decker bus	95	2 exits of 120 cm	159.0
Articulated bus	116	3 exits of 120 cm	97.3
Intercity bus	81	1 exit of 120 cm & 1 exit of 65 cm	126.8
Long-distance bus	60	2 exits of 65 cm	144.0

Table 11: Evacuation times obtained for the five vehicle configurations in Scenario 4 (Extended pre-movement).

The obtained results show that extending the pre-movement time increases the evacuation time of all configurations, although it does not have the same impact on all of them.

First of all, the largest increase in the evacuation time occurred in the simple and articulated urban buses (from 68.0 s to 98.0 s and from 70.8 s to 97.3 s, respectively). In both cases where there are no important bottlenecks (all aisles and doors have high usage but there is not a clear dominant one), the evacuation time depends directly on when passengers start moving. Therefore, a longer pre-movement time translates almost directly into a longer evacuation.

Then, the intercity bus and the long-distance bus suffer intermediate increases. The long-distance bus is more affected (from 121.0 to 144.0 seconds). As it is a class III vehicle, more passengers can be asleep during the voyage, so its pre-movement range reaches higher values (up to 120 s). This bus has less occupancy capacity and no standing passengers, and therefore the effect of the pre-movement time is more noticeable.

The double-decker bus is the exception, with the smallest increase (from 151.0 s to 159.0 s). This can be explained by the presence of the stairwell, which acts as the dominant bottleneck. This limits the evacuation rate, which partly absorbs the effect of the extended pre-movement time.

6.4.2 INDIVIDUAL ANALYSIS

6.4.2.1 Simple urban bus

The simple urban bus model has been simulated with a total occupancy of 96 passengers and three available exits of 120 cm. The evacuation time for this configuration in the extended pre-movement time scenario was 98.0 seconds.

The accumulated usage map (Figure 58) shows a very similar distribution to the one of the baseline scenario. However, now all three doors show very high usage and there is no distinction with the front one despite being the least used. The overall colour tones are darker and the PRM seating zones appear in a more intense colour. These changes reflect that passengers remained inside the bus for a longer period due to their extended pre-movement time.

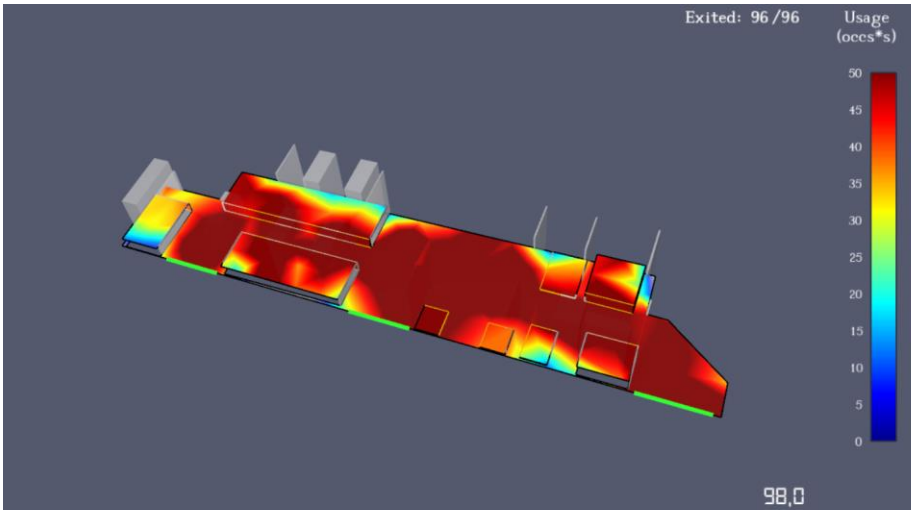

Figure 58: Accumulated usage map of the simple urban bus (Extended pre-movement).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 21 occupants evacuated with a flow rate of 0.21 p/s/m.
- Middle door: 47 occupants evacuated with a flow rate of 0.43 p/s/m.
- Rear door: 28 occupants evacuated with a flow rate of 0.28 p/s/m.

This shows that the front door continued being the least used. However, the number of passengers evacuating through the middle door increased by 5 compared to the baseline. Regarding flow rates, the middle door shows the highest value (0.43 p/s/m), which is consistent with the larger number of passengers that used it.

The graph (Figure 59) shows that the number of passengers decreases in phases with different slope throughout the evacuation. Compared to the baseline, the descent is stretched over a longer period, which reflects that passengers begin to move later due to the extended pre-movement time. The evacuation is completed at 98.0 seconds, 30 seconds later than in the baseline.

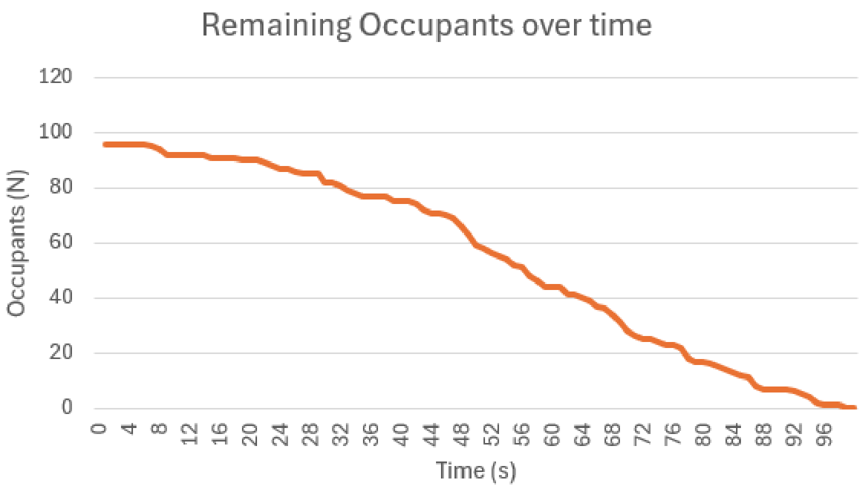

Figure 59: Number of occupants remaining inside the simple urban bus during the simulation (Extended pre-movement).

6.4.2.2 Double-decker bus

The double-decker urban bus model has been simulated with a total occupancy of 95 passengers and two available exits of 120 cm. The evacuation time was 159.0 seconds.

The accumulated usage map (Figure 60) shows a very similar distribution to the one observed in the baseline scenario, with the stairwell remaining as the main bottleneck. The only noticeable difference is that the PRM seating zone appears in a more intense colour than in the baseline. Also, some of the spots on the rear aisle are darker, showing that some passengers took a longer time to react.

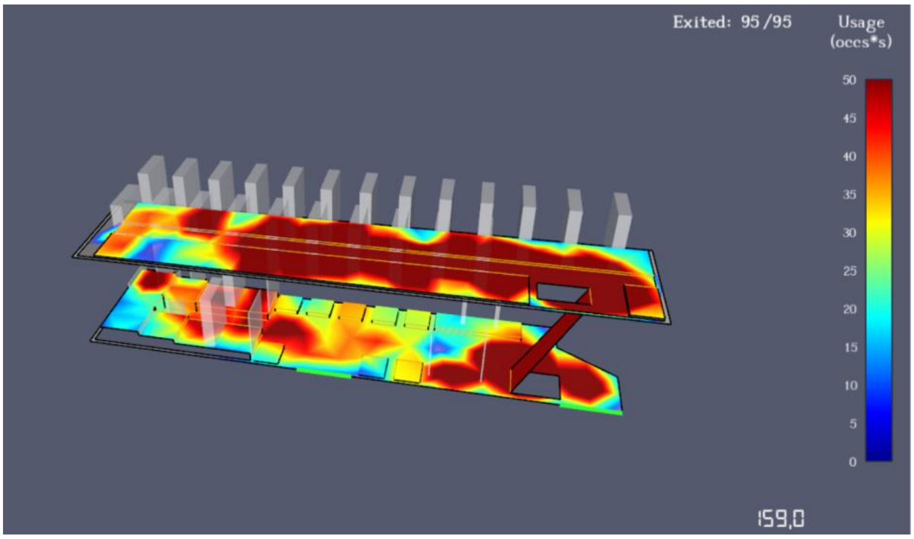

Figure 60: Accumulated usage map of the double-decker bus (Extended pre-movement).

The exit distribution (58 occupants through the front door and 37 through the rear) and the shape of the remaining occupants' graph (Figure 61) are very similar to the baseline. The graph is now shifted slightly to the right, reflecting the longer time occupants take to begin evacuating. This shows that the bottleneck formed in the stair area is the main limiting factor of the evacuation. Therefore, the extended pre-movement time does not have that big of an effect on the final result.

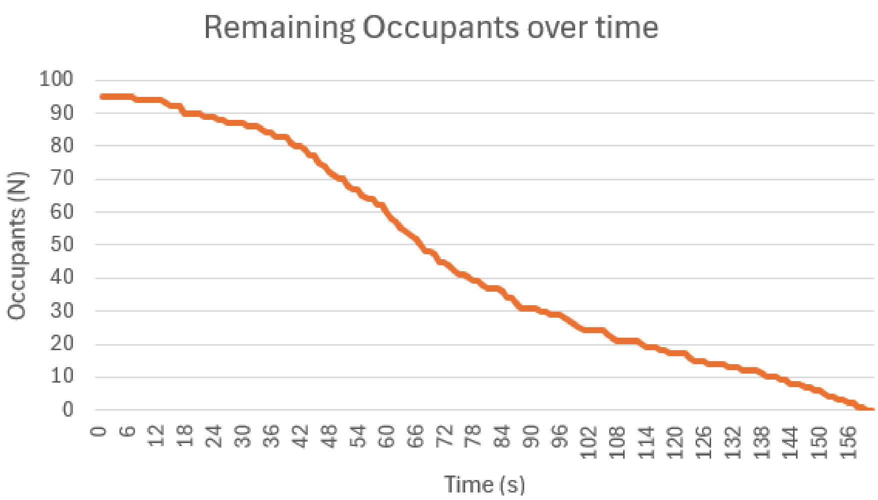

Figure 61: Number of occupants remaining inside the double-decker bus during the simulation (Extended pre-movement).

6.4.2.3 Articulated bus

The articulated bus model has been simulated with a total occupancy of 116 passengers and three available exits of 120 cm. The evacuation time was 97.3 seconds.

The accumulated usage map (Figure 62) is, as expected, very similar to the one of the baseline scenario, with the red tones being darker and the PRM zones appearing in a more intense colour. The articulated zone appears as in the baseline scenario in a blue colour, which means that passengers do not stay there but rather use it to reach the middle zone.

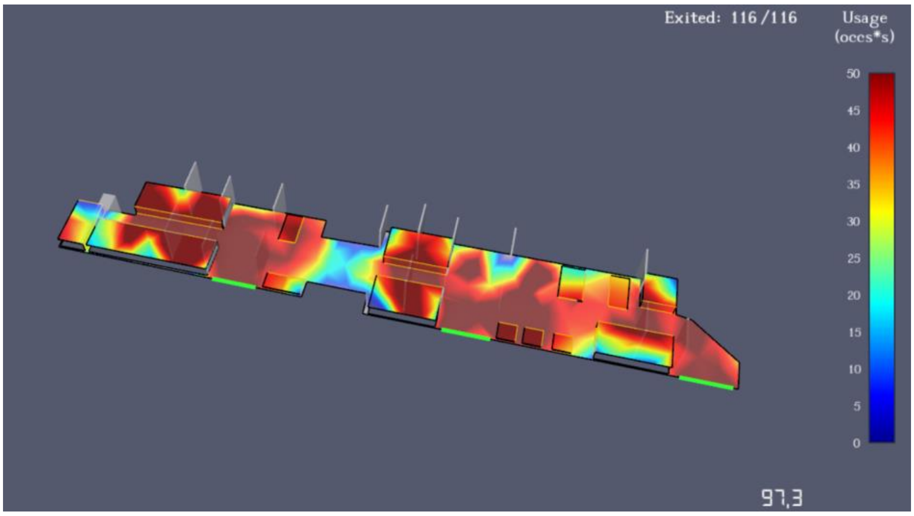

Figure 62: Accumulated usage map of the articulated bus (Extended pre-movement).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 22 occupants evacuated with a flow rate of 0.22 p/s/m.
- Middle door: 51 occupants evacuated with a flow rate of 0.47 p/s/m.
- Rear door: 43 occupants evacuated with a flow rate of 0.41 p/s/m.

The exit distribution is very similar to the baseline with the middle and rear doors again being used by most of the passengers and the front door remaining the least used. The main difference is that the flow rates are lower than in the baseline across all three doors, as the extended pre-movement time reduces the intensity at which each door is used.

The graph (Figure 63) follows the same shape as the baseline, but it is stretched over a longer period of time. This again reflects that passengers begin to move later due to the extended pre-movement time.

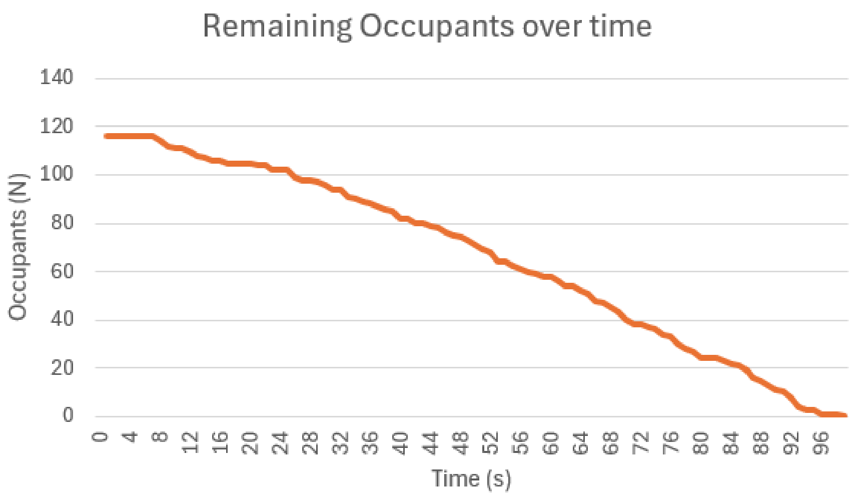

Figure 63: Number of occupants remaining inside the articulated bus during the simulation (Extended pre-movement).

6.4.2.4 Intercity bus

The intercity bus model has been simulated with a total occupancy of 81 passengers and two available exits. The evacuation time was 126.8 seconds.

The accumulated usage map (Figure 64) is very similar to the baseline, with the rear aisle and middle door area remaining the darkest zones. The main difference is that the PRM seating zone appears more intense, reflecting its extended pre-movement time.

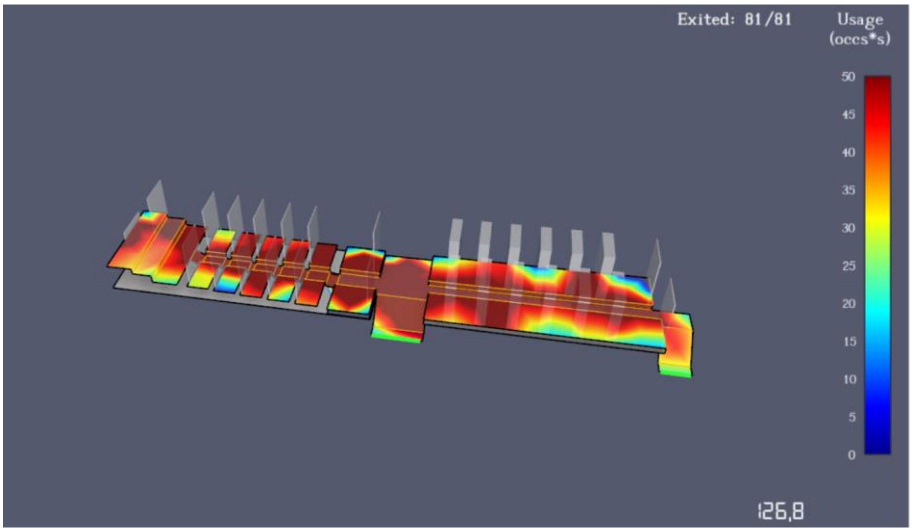

Figure 64: Accumulated usage map of the intercity bus (Extended pre-movement).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 22 occupants evacuated with a flow rate of 0.38 p/s/m.
- Rear door: 59 occupants evacuated with a flow rate of 0.42 p/s/m.

The rear door, as in the baseline, is the most used door. However, the number of passengers that chose this exit has increased by 4 occupants. This change can be explained by some passengers taking longer to react and forming a longer queue for the front door, which forced passengers to use the rear door. The flow rate is quite similar in both exits, which can be explained by the difference in door width and in their active period (the rear door was used for 30 more seconds).

The graph (Figure 65) shows the same two-phase shape observed in the baseline. However, now the whole curve is shifted to the right, reflecting the longer time occupants take to begin to evacuate.

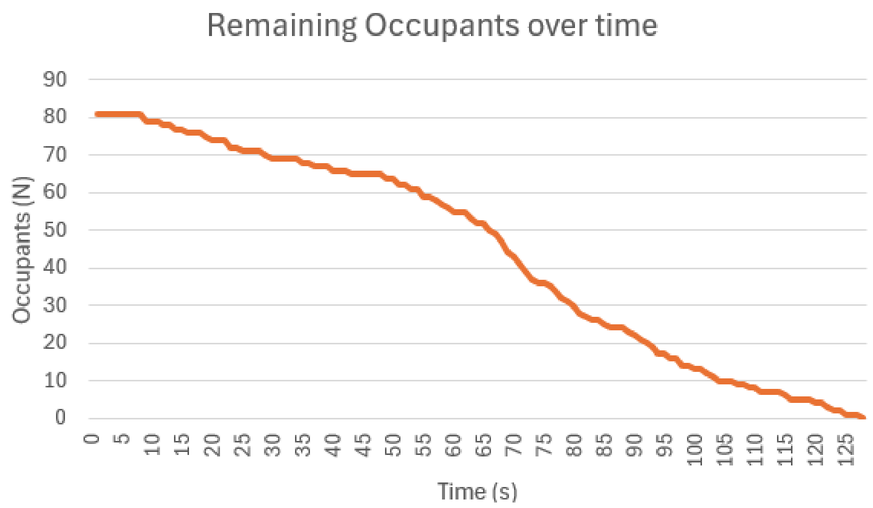

Figure 65: Number of occupants remaining inside the intercity bus during the simulation (Extended pre-movement).

6.4.2.5 Long-distance bus

The long-distance bus model has been simulated with a total occupancy of 60 passengers and two available exits of 65 cm. The evacuation time was 144.0 seconds.

The accumulated usage map (Figure 66) shows a much darker distribution compared to the baseline. The rear door area and rear aisle keep showing the highest usage, while the front door remains the least used. There are some random dark spots at the front seating area, which show that some passengers took longer to react.

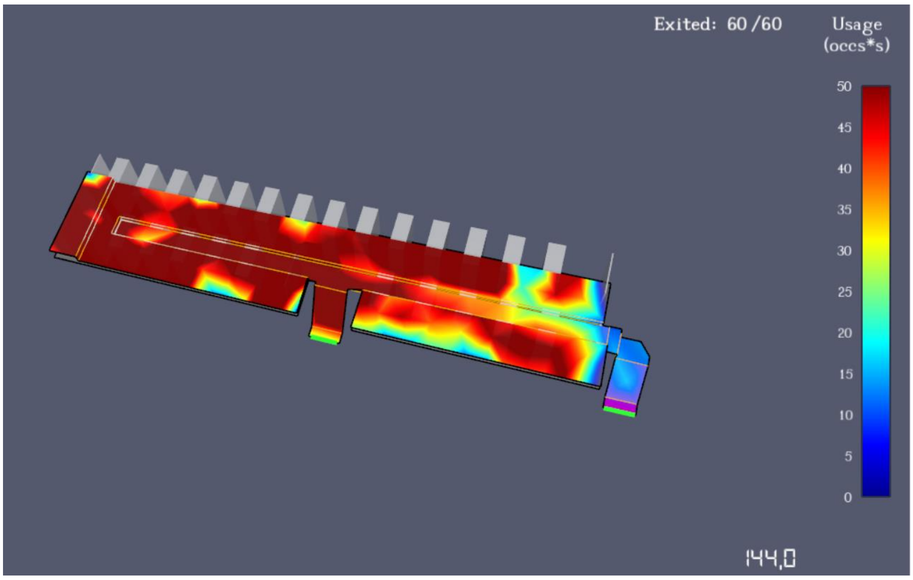

Figure 66: Accumulated usage map of the long-distance bus (Extended pre-movement).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 13 occupants evacuated with a flow rate of 0.18 p/s/m.
- Middle door: 47 occupants evacuated with a flow rate of 0.28 p/s/m.

The middle door was used by most of the passengers, while the front door was used by very few during a long period, which resulted in a low flow rate. The distribution is very similar to the baseline (14 and 46, respectively), showing that the extended pre-movement time affected when passengers evacuated but not the exit chosen to evacuate.

The graph (Figure 67) shows the same pattern of small steps of one or two passengers that was observed in the baseline. The curve is stretched over a longer period explained by the wide range of pre-movement times. In this scenario, the evacuation now takes noticeably longer than the baseline.

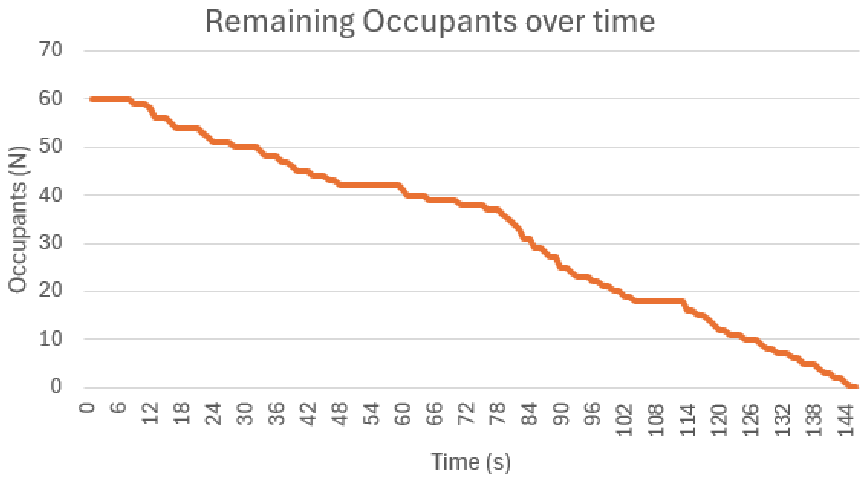

Figure 67: Number of occupants remaining inside the long-distance bus during the simulation (Extended pre-movement).

6.5 SCENARIO 5- CRITICAL SCENARIO

6.5.1 GLOBAL RESULTS

Vehicle model	Number of passengers	Available exits	Evacuation time (s)
Simple urban bus	96	2 exits of 120 cm	122.5
Double-decker bus	95	1 exit of 120 cm	186.8
Articulated bus	116	2 exits of 120 cm	156.8
Intercity bus	81	1 exit of 65 cm	211.3
Long-distance bus	60	1 exit of 65 cm	152.5

Table 12: Evacuation times obtained for the five vehicle configurations in Scenario 5 (Critical scenario).

The obtained results show that this scenario results in the highest evacuation times of the whole study. This is consistent with the combination of a blocked rear door and an extended pre-movement time. However, the effect of adding the extended pre-movement time to the scenario with the rear blocked door is different for each configuration.

First of all, there are some buses where the increase of the evacuation time with respect to the rear door blockage scenario is not very big. In this category there can be found both the long-distance and the double-decker buses. In the long-distance bus, the low occupancy capacity and the absence of standing passengers results in the smallest increase (from 144.8 to 152.5 seconds). The first passengers to react can move quickly to the aisle and evacuate using the front door, while passengers with a higher reaction time remain seated without obstructing the aisle. In the double-decker, whose evacuation time goes from 179.5 to 186.8 seconds, the stairwell remains the dominant bottleneck, so the effect of the extended pre-movement time is not very noticeable, as in previous scenarios.

The articulated bus shows an intermediate increase (from 143.3 s to 156.8 s).

Finally, the simple urban and intercity buses suffer the largest increases in their evacuation times (from 102.0 s to 122.5 s and from 187.0 s to 211.3 s, respectively). In both cases, their high occupancy and especially the presence of standing passengers results in occupants needing to queue for a long time. Therefore, the extended pre-movement time adds a very noticeable delay to the congestion that is already caused by the blocked door. This effect is even more noticeable in the intercity bus, which only has a single 65 cm exit in scenarios 3 and 5, making it reach 211.3 seconds, the highest evacuation time of the entire study.

6.5.2 INDIVIDUAL ANALYSIS

Since this scenario combines the two most demanding conditions already studied separately (the rear door blockage and the extended pre-movement time), the results are very similar to those of the rear door blockage scenario. In all configurations, the usage maps appear almost entirely in dark red and the remaining-occupants graphs follow the same shape as that scenario. Therefore, the analysis below focuses on the exit distribution and on the specific differences of each configuration, rather than repeating the full description already provided in previous scenarios.

6.5.2.1 Simple urban bus

The simple urban bus model has been simulated with a total occupancy of 96 passengers and two available exits of 120 cm, as the rear door has been blocked. The evacuation time was 122.5 seconds.

The accumulated usage map (Figure 68) shows almost the entire vehicle in dark red, indicating very high usage. Compared to the rear door blockage scenario, the colours are even more intense, reflecting that passengers remained inside the bus for a longer period due to the extended pre-movement time.

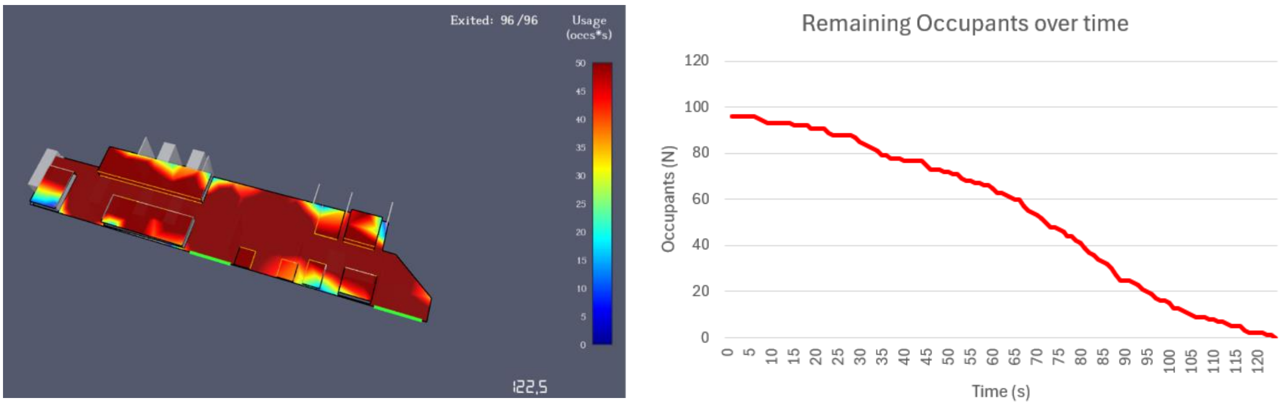

Figure 68 : Accumulated usage map and remaining occupants graph of the simple urban bus at the end of the simulation (Critical scenario).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 29 occupants evacuated with a flow rate of 0.34 p/s/m.
- Middle door: 67 occupants evacuated with a flow rate of 0.58 p/s/m.

As in the rear door blockage scenario, the middle door handled most of the evacuation. The distribution is very similar to the one of that scenario (28 and 68, respectively), showing that the extended pre-movement time did not affect the exit they chose.

The graph has a similar shape to the rear door blockage scenario, but it is stretched over a longer period as passengers begin to move later. The evacuation is completed at 122.5 seconds.

6.5.2.2 Double-decker bus

The double-decker urban bus model has been simulated with a total occupancy of 95 passengers and one available exit of 120 cm at the front, as the rear door has been blocked. As in the rear door blockage scenario, the PRM passenger is evacuated by the driver through the narrow aisle using an Assisted Evacuation Team. The evacuation time was 186.8 seconds.

The accumulated usage map (Figure 69) is very similar to the one of the rear door blockage scenario, with the upper deck and the stairwell area appearing in dark red as the dominant bottleneck. Also, the lower deck shows dark red tones through almost all the floor except from the rear area, where there are some blue and green spots.

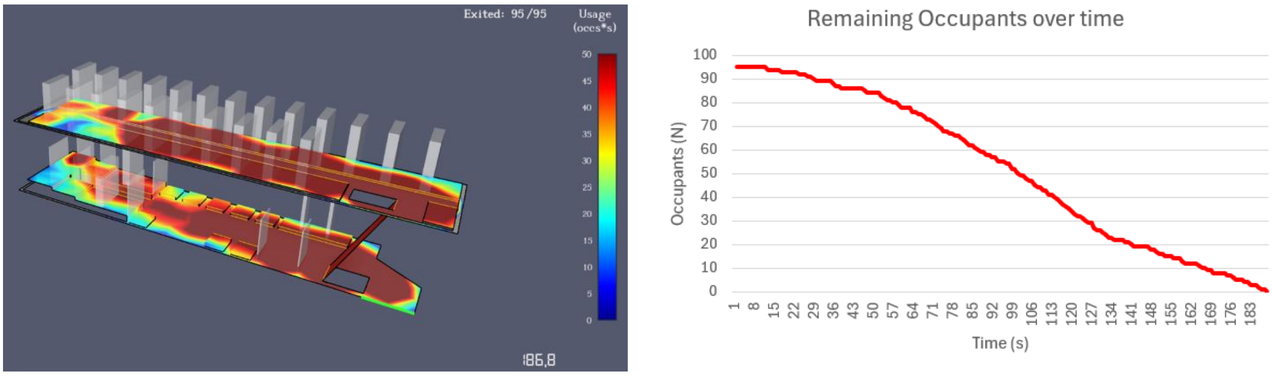

Figure 69: Accumulated usage map and remaining occupants graph of the double-decker bus at the end of the simulation (Critical scenario).

As there is only one available exit, all 95 passengers evacuated through the front door, with a flow rate of 0.45 p/s/m.

The graph has the same shape as the rear door blockage scenario. However, the first phase is stretched over a longer period as passengers begin to move later. As in the other scenarios, the stairwell remains the main limiting factor, so the extended pre-movement time has a limited effect on the final result. The evacuation is completed at 186.8 seconds.

6.5.2.3 Articulated bus

The articulated bus model has been simulated with a total occupancy of 116 passengers and two available exits of 120 cm, as the rear door has been blocked. The evacuation time was 156.8 seconds.

The accumulated usage map (Figure 70) combines the effects seen in the rear door blockage and the extended pre-movement scenarios. In the rear door blockage scenario, the rear and middle zones (including the articulated area) already appeared in dark red, while the front section showed lighter red tones, as those passengers were able to leave earlier. In this scenario, the extended pre-movement time also delays the front passengers, so the entire vehicle now appears in dark red.

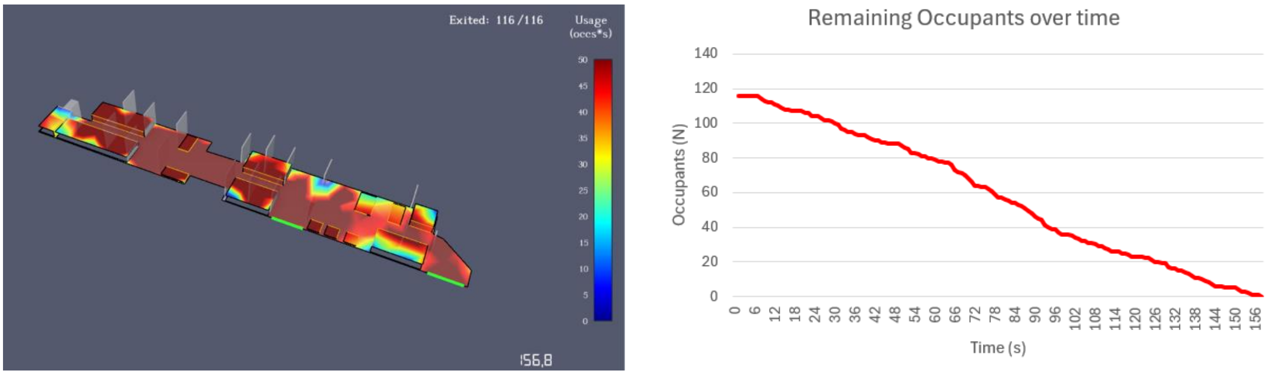

Figure 70: Accumulated usage map and remaining occupants graph of the articulated bus at the end of the simulation (Critical scenario).

The distribution of evacuated passengers and flow rate by exit was as follows:

- Front door: 25 occupants evacuated with a flow rate of 0.16 p/s/m.
- Middle door: 91 occupants evacuated with a flow rate of 0.51 p/s/m.

As in the rear door blockage scenario, the middle door handled most of the evacuation, since passengers from the rear section are forced to cross the articulated zone towards it. The distribution is the same as in the rear door blockage scenario, but both flow rates are smaller as expected.

The graph has the same shape as the rear door blockage scenario, stretched over a longer period as passengers begin to move later. The evacuation is completed at 156.8 seconds.

6.5.2.4 Intercity bus

The intercity bus model has been simulated with a total occupancy of 81 passengers and one available exit of 65 cm at the front, as the rear door has been blocked. As in the rear door blockage scenario, the PRM passenger is evacuated by the driver through the narrow aisle using an Assisted Evacuation Team. The evacuation time was 211.3 seconds, the highest of the entire study.

The accumulated usage map (Figure 71) is very similar to the one of the rear door blockage scenario, with the entire vehicle appearing in dark red due to the extreme congestion caused by evacuating 81 occupants through a single 65 cm door.

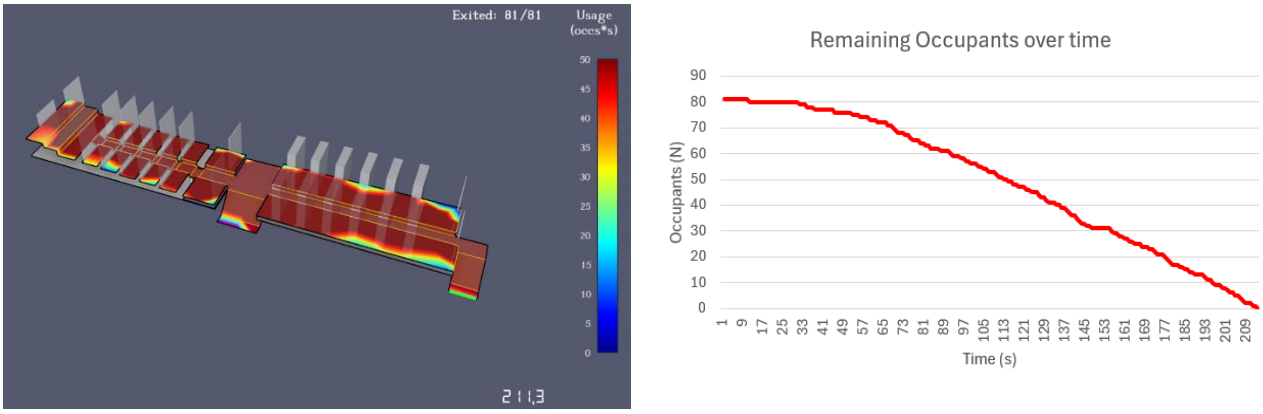

Figure 71: Accumulated usage map and remaining occupants graph of the intercity bus at the end of the simulation (Critical scenario).

As there is only one available exit, all 81 passengers evacuated through the front door, with a flow rate of 0.62 p/s/m.

The graph has the same shape as the rear door blockage scenario, stretched over a longer period as passengers begin to move later. Between seconds 145 and 153 no passenger left the bus. This is due to the fact that the assisted evacuation team helped the PRM during those seconds. The evacuation is completed at 211.3 seconds.

6.5.2.5 Long-distance bus

The long-distance bus model has been simulated with a total occupancy of 60 passengers and one available exit of 65 cm at the front, as the rear door has been blocked. The evacuation time was 152.5 seconds.

The accumulated usage map (Figure 72) is very similar to the one of the rear door blockage scenario, with almost the entire vehicle appearing in dark red.

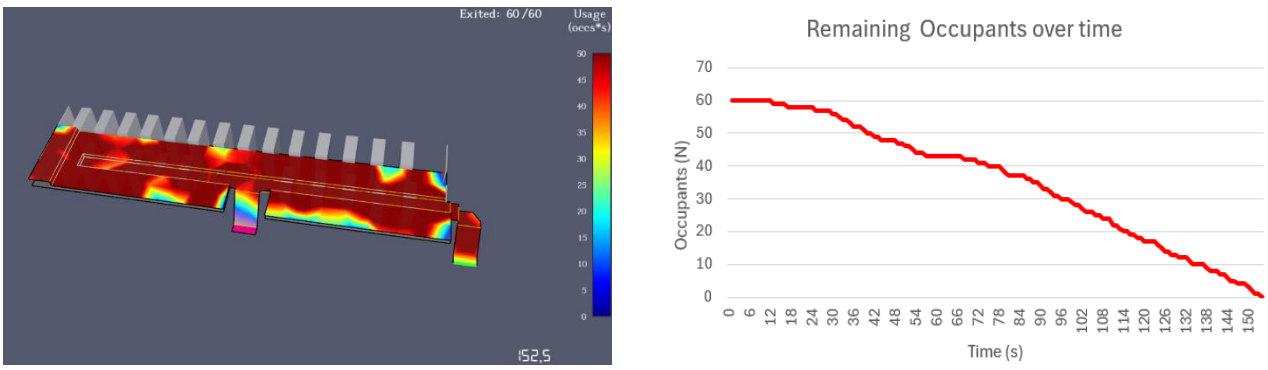

Figure 72: Accumulated usage map and remaining occupants graph of the long-distance bus at the end of the simulation (Critical scenario).

As there is only one available exit, all 60 passengers evacuated through the front door, with a flow rate of 0.66 p/s/m.

The graph has the same shape as the rear door blockage scenario, stretched over a longer period as passengers begin to move later. The evacuation is completed at 152.5 seconds.

Chapter 7. CONCLUSIONS

7.1 GENERAL SYNTHESIS OF THE WORK

Throughout this dissertation, the main objective has been to analyse the evacuation process in bus transport. To do so, a numerical analysis has been developed, focusing on the impact that the interior design and the conditions during an emergency have on the total evacuation time. Unlike in aviation, where a maximum evacuation time is established by regulation, there is no time limit established for buses and coaches at the moment. For this reason, this study has focused on a comparative analysis between vehicle configurations instead of a verification of whether each of these configurations exceeds a fixed regulatory threshold.

All of the simulations were carried out using Pathfinder, an agent-based evacuation simulator with each passenger being modelled as an independent agent defined by its walking speed, physical dimensions and reaction time. In order to cover the main bus configurations that are found on roads and used daily by thousands of people, five configurations were selected: a simple urban bus, a double-decker bus, an articulated bus (Class I), an intercity bus (Class II) and a long-distance coach (Class III). As the main objective has been to see the impact of passenger capacities, number of doors and layouts, a geometric model was built for each of the configurations. The proportions of the vehicle were replicated and a walking speed, body size and pre-movement time were established for each occupant.

Then, in order to evaluate the impact of different emergency situations, each configuration was tested under five scenarios: a baseline case with the bus at full occupancy and all doors available, a low occupancy case, a rear door blockage case, an extended pre-movement time case and a critical case that combined scenarios 3 and 4 (the blocked door with the extended pre-movement time). The combination of these five scenarios in each of the five configurations resulted in a matrix of 25 cases. All of them were analysed in chapter 6 and will be interpreted throughout this final chapter.

7.2 GLOBAL EVALUATION AND SUMMARY OF RESULTS

In order to compare the evacuation times of the five configurations under each of the five scenarios, the following table (Table 13) gathers information of the 25 cases. This global summary helps us analyse the results between scenarios and between configurations.

Vehicle model	Scenario 1: Baseline	Scenario 2: Low occupancy	Scenario 3: Rear door blockage	Scenario 4: Extended pre-movement	Scenario 5: Critical scenario
Simple urban bus	68.0	65.8	102.0	98.0	122.5
Double-decker bus	151.0	87.0	179.5	159.0	186.8
Articulated bus	70.8	67.3	143.3	97.3	156.8
Intercity bus	108.8	73.3	187.0	126.8	211.3
Long-distance bus	121.0	99.8	144.8	144.0	152.5

Table 13: Summary of evacuation times (in seconds) for the 25 simulated cases.

Looking at the scenarios, it is clear that the lowest evacuation times for the five configurations are obtained in the second scenario. This is consistent with the reduced number of passengers. On the other hand, the highest evacuation times are obtained in the critical scenario (scenario 5). The combination of both the rear door blockage and the extended pre-movement time results in the most demanding situation of the whole study. The other three scenarios have evacuation times between these two scenarios.

Looking at the configurations, the results show that each vehicle acts in a very different way under each of the scenarios. None of the configurations have the best performance in all five situations. For example, the double-decker bus starts with the highest baseline time (151.0 s), but it is the least affected by the extended pre-movement time. This shows that the performance of each configuration depends on both the situation and on how its interior design responds to each specific factor.

The different behaviour of each configuration depends on the most important factor: the presence or, on the other hand, the absence of a dominant bottleneck. When a configuration has a strong geometric bottleneck, for example the stairwell on the double-decker bus, the effect of other factors does not have such a big impact, as the evacuation rate is already limited by the presence of that bottleneck. When a configuration does not have a strong geometric bottleneck, for example in the urban and articulated bus, where all doors have high usage, the evacuation time is more influenced by other factors such as occupancy or pre-movement time. Figure 73 shows these results graphically, where the different behaviour of each configuration across the five scenarios can be clearly observed.

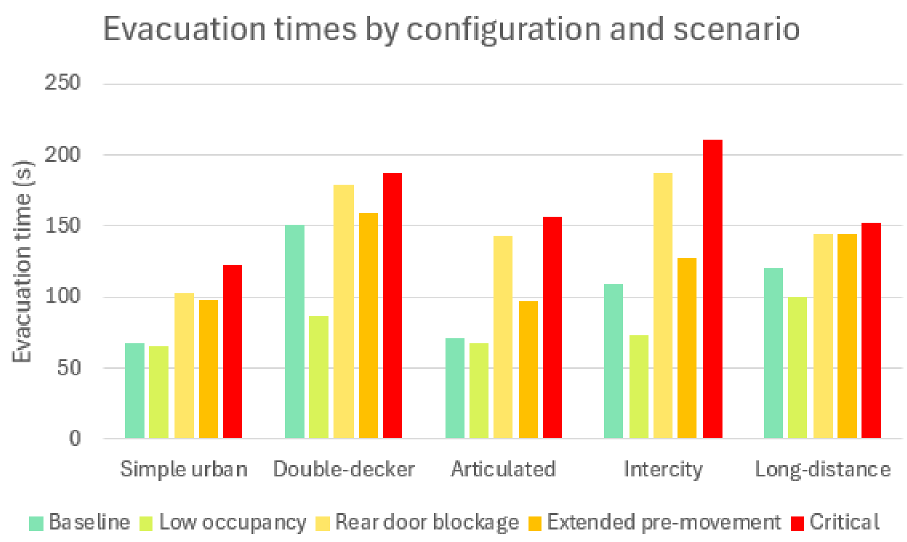

Figure 73: Evacuation times obtained for each configuration under the five scenarios.

7.3 ANALYSIS OF THE KEY FACTORS AFFECTING THE EVACUATION

7.3.1 EFFECT OF REDUCED OCCUPANCY

The effect of occupancy was studied by comparing the baseline scenario with the low occupancy scenario, in which the number of passengers was reduced to 50%. The following table (Table 14) shows the difference between both scenarios for each configuration.

Vehicle	Baseline (s)	Low occupancy (s)	Difference (s)	Difference (%)
Simple urban bus	68.0	65.8	2.2	3%
Double-decker bus	151.0	87.0	64	42%
Articulated bus	70.8	67.3	3.5	5%
Intercity bus	108.8	73.3	35.5	33%
Long-distance bus	121.0	99.8	21.2	18%

Table 14: Effect of reduced occupancy (Scenario 2 vs baseline).

First of all, it can be seen that the configurations that have the least improvement when the occupancy is reduced by half are both the urban and articulated buses with a 3% and a 5% reduction, respectively. This can be explained because, in the baseline scenario, these configurations were very close to their maximum efficiency. The evacuation on these types of buses depends primarily on the walking and the pre-movement times instead of depending on the formation of queues that collapse the aisles. Therefore, removing passengers does not have a big impact on the result.

On the other hand, the configurations that have the best improvement are the intercity and the double-decker buses. The first one improves considerably (a 33% reduction) because reducing the number of occupants and especially the number of standing ones help reduce the congestion in the aisle. The double-decker bus shows the largest reduction (42%), as the lower occupancy helps decrease the queue that is formed on the upper deck and, therefore, the stairwell bottleneck. The long-distance bus shows an intermediate reduction of an 18%, as its evacuation time is very influenced by the pre-movement time of its passengers.

In summary, reducing the occupancy is only beneficial when the configuration was already limited by congestion.

7.3.2 EFFECT OF EXIT AVAILABILITY AND WIDTH

The effect of the number of available exits and its width was studied by comparing the baseline scenario with the rear door blockage scenario, in which the rear door was disabled. The following table (Table 15) shows the difference between both scenarios for each configuration.

Vehicle	Baseline (s)	Rear door blockage (s)	Difference (s)	Difference (%)
Simple urban bus	68.0	102.0	34	50%
Double-decker bus	151.0	179.5	28.5	19%
Articulated bus	70.8	143.3	72.5	102%
Intercity bus	108.8	187.0	78.2	72%
Long-distance bus	121.0	144.8	23.8	20%

Table 15: Effect of the rear door blockage (Scenario 3 vs baseline).

First of all, it can be seen that the configurations that have the least increase in their evacuation time when the rear door is blocked are both the double-decker and long-distance buses, with a 19% and a 20% increase, respectively. In the first case, this can be explained because the main bottleneck already was the stairwell. Therefore, reducing the number of available doors does not have a big impact. For the long-distance bus, the small increment is explained by the fact that its baseline evacuation time was already high due to the queue that formed at the rear door, which was used by most passengers from both sections. When the rear door is blocked, these passengers are simply redirected towards the front door, so the single queue is not very different from the one that already governed the baseline evacuation. In addition, the low occupancy and the absence of standing passengers prevent this queue from becoming critical.

The simple urban bus shows an intermediate increase of a 50%. This can be explained by the availability of two remaining exits, which have enough capacity to reabsorb the flow that would have used the rear door.

On the other hand, the configurations that suffer the biggest increase are the intercity and the articulated buses, with a 72% and a 102% increase, respectively. In the articulated bus, the baseline evacuation did not form large bottlenecks, as there were three clear sections and passengers barely moved between zones, they just evacuated through the door of their own section. When the rear door is blocked, the passengers from the rear section are forced to cross the entire articulated zone and join the passengers of the middle section to use the middle door. This increases the distance they need to travel and creates a severe bottleneck at that aisle and middle exit. In the intercity bus, the blockage leaves a single narrow exit of 65 cm for 81 passengers, many of them standing, so the aisle collapses from the beginning of the evacuation. The intercity bus is the most affected of all if it is only considered the absolute difference, increasing its time by more than 78 seconds.

7.3.3 EFFECT OF PRE-MOVEMENT TIME

The effect of the pre-movement time was studied by carrying out two analysis. First, the baseline scenario was compared with the extended pre-movement scenario, in which the reaction times of the passengers were increased. Then, the rear door blockage scenario was compared with the critical scenario, in order to see the combination of the pre-movement time with a blocked door.

Unlike the previous factors, the pre-movement time was extended by the same amount for all configurations. Therefore, the effect is analysed in absolute terms instead of using a percentage.

The following table (Table 16) shows the difference between the baseline and the extended pre-movement scenario for each configuration.

Vehicle	Baseline (s)	Pre-movement time (s)	Difference (s)
Simple urban bus	68.0	98.0	30.0
Double-decker bus	151.0	159.0	8.0
Articulated bus	70.8	97.3	26.5
Intercity bus	108.8	126.8	18.0
Long-distance bus	121.0	144.0	23.0

Table 16: Effect of the pre-movement time (Scenario 4 vs baseline).

First of all, it can be seen that the configuration that has the least increase in its evacuation time when the pre-movement time is extended is the double-decker bus, with only 8 more seconds. In this case, the stairwell remains the main bottleneck. Therefore, increasing the initial delay just changes the location in which passengers wait before evacuating. In the baseline scenario they remain in the queue for a longer period, whereas in this scenario they wait longer in their seats before moving.

The intercity and long-distance buses both have intermediate increases (18 and 23 seconds, respectively). In these cases, the narrower exits already introduce a certain limitation on the flow, which partly reduces the effect of the extended pre-movement time compared to the urban and articulated buses.

On the other hand, the configurations that have the biggest increase are the simple urban and articulated buses (30 and 26.5 seconds). In these types of buses, the absence of a dominant bottleneck means that the evacuation time highly depends on when passengers start moving.

The following table (Table 17) shows the difference between the rear door blockage scenario and the critical scenario for each configuration.

Vehicle	Rear door blockage (s)	Critical scenario (s)	Difference (s)
Simple urban bus	102.0	122.5	20.5
Double-decker bus	179.5	186.8	7.3
Articulated bus	143.3	156.8	13.5
Intercity bus	187.0	211.3	24.3
Long-distance bus	144.8	152.5	7.7

Table 17: Effect of the pre-movement time (Scenario 5 vs Scenario 3).

When these values are compared with the ones from the first part of the analysis, it can be seen that in most configurations the pre-movement time has a smaller impact when it is combined with the blocked door than when it acts alone. One example where this is clear is the articulated bus, which adds 26.5 seconds to the evacuation when it happens alone and 13.5 seconds when it is combined with the blockage. This shows that the two effects are not summed up. The blocked door results in high congestion at the aisles and remaining exits and, therefore, part of the extended delay is absorbed by the queues that are already formed, instead of extending the total evacuation time.

The intercity bus is the only exception. When the pre-movement time is combined with the blocked door it adds 24.3 seconds versus the 18 seconds that added when it was only applied the extended delay. Its single 65 cm exit and high occupancy create such an extreme congestion that the vehicle cannot absorb any additional delay, making this the most critical case of the entire study.

7.3.4 PRESENCE OF PRM

The presence of people with reduced mobility does not have a very big impact on the final evacuation time. However, their presence has some particular effects that should be mentioned. First of all, PRM need help from the driver or from other passengers to leave the bus, as it is not feasible to deploy the ramp during an emergency situation. In this dissertation, they are assigned a higher pre-movement time to simulate this. Therefore, they are usually among the last passengers to evacuate.

This can be seen in some graphs where the curve remains at one or two passengers during some of the final seconds of the evacuation. They also modify the flow rate of the door they use to evacuate (usually the middle/rear door) as they occupy it for a longer period.

In scenarios where the rear door is blocked and the only remaining exit obliges them to use the aisle to reach it, the Assisted Evacuation Team was modelled. As the wheelchair is wider than the aisle, they need to be carried by the driver. This can interrupt the flow of passengers for a few seconds, as seen in the intercity bus during the critical scenario. Therefore, PRM can represent a critical factor, especially during very demanding and difficult evacuations.

7.4 DESIGN RECOMMENDATIONS

The result of this study makes it possible to establish some recommendations for bus companies. First, it is important to include enough doors as wide as possible. Configurations that have several doors evacuate faster and are safer in case of the blockage of one of their doors. Second of all, it is important to test every bus configuration under plenty of different scenarios, not only under normal operation. At full occupancy, the urban and articulated buses have a similar behaviour. However, when one of the doors is blocked, the evacuation changes a lot and the evacuation times of both configurations do not behave the same way. Another important thing to consider is the strong bottlenecks caused by bus geometry. For example, the stairwell in the double-decker bus limits the evacuation, regardless of any improvement.

In addition, if a regulation that established a maximum evacuation time for buses was created, it would allow manufacturers to carry out the necessary evacuation tests and verify that their configurations meet the required safety levels.

7.5 LIMITATIONS AND FUTURE WORK

This study has some limitations that are important to mention. First of all, it assumes that passengers behave in a rational way, without considering panic or falls that could happen during a real emergency. The evacuation of PRM is also a simplification. In real life, the assistance could be slower, resulting in a bigger delay and it could be necessary the help of other passengers depending on the type of mobility impairment. In addition, the simulations do not model the effects of fire, smoke or toxic gases directly, instead, the pre-movement time is modified to replicate the adverse effects of all of this factors. Finally, when the evacuation starts, the bus is assumed to be stopped. However, if a fire starts when the bus is moving, the driver will need to react and completely stop the bus before any passenger can start to evacuate.

With regard to future work, the software could be used to simulate other bus configurations such as two-doors simple urban buses. It could also include a wider range of pre-movement times. Finally, future models could include the dynamic effects of fire and smoke instead of only their influence on the pre-movement time.

CHAPTER 8. REFERENCES

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