SCUOLA DI INGEGNERIA INDUSTRIALE
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EXECUTIVE SUMMARY OF THE THESIS

Over-the-air updates for Connected Cars: a model to assess customer's benefits in a safety recall event

TESI MAGISTRALE IN MANAGEMENT ENGINEERING – INGEGNERIA GESTIONALE

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1. Introduction

The Internet of Things (IoT), Big Data, and Digital Transformation have revolutionized businesses over the past thirty years, affecting also the most traditional physical product-centric industry: the automotive one. This sector moved from merely producing a car to developing an intelligent and connected digital transportation hub, a "connected" vehicle. The Connected Car (CC) is indeed a vehicle capable of accessing the Internet, of communicating with smart devices as well as other cars and road infrastructures, and of collecting real-time data from multiple sources [1].

By incorporating different technologies, Connected Cars offer various benefits to the consumer in terms of safety, for instance through Advanced Driver-Assistance System (ADAS) such as Driver Fatigue Detection, in terms of cost reduction (e.g., Usage-Based Insurance), or in terms of entertainment through infotainment services. Generally, Connected Cars aim both to make driving easier and hassle-free for the driver, facilitating the most complicated operations. The several benefits are enabled by the technologies grounding a modern Connected Car. These vehicles indeed present hundreds of Electronics Control Units (ECUs) resulting in more than 100 million lines of code for performing several controlling functions. The upsurge in the number of lines of code significantly increases the likelihood of software bugs that can pose serious consequences to the safety of the vehicle and its passengers. In fact, when a software issue occurs, Original Equipment Manufacturers (OEMs) have to recall entire fleets of vehicles to upgrade the ECU software. Recalls impact hugely and negatively customer satisfaction, as the consumer must bring the vehicle to the workshop and wait for the completion of the service update. Therefore, it becomes crucial to remotely update the car. On these grounds, Over-the-air (OTA) updates allow for avoiding inconvenient and annoying situations as eventual recalls can be solved remotely and in a short time. OTA software updates are indeed a type of data exchange that allows the software of a digital device to be updated remotely via point-to-point communication over a wireless network. Among the most impactful recalls, safety recalls are the most critical ones. This kind of recall is necessary when there is a defect in a car including any malfunction in performance, component, material or equipment, that poses a severe risk to the vehicle safety. The full potential of OTA updates in the automotive industry is still under analysis as it is a very actual topic. At the same time, it is evident how OTA updates allow the avoidance of costly recalls that pose a cost for the consumer and erode both company's profitability and brand image. OTA updates are estimated to potentially save the global automotive industry more than $35 billion yearly [2].

2. Research Flow

Aiming to have a comprehensive overview of the Connected Cars concept and their positive externalities, the authors started the Research by conducting an extensive literature review over the time horizon 2011-2022. Eighty-one scientific papers were selected and critically reviewed. The authors clustered the articles according to a qualitative framework which enabled to clearly identify the gaps characterizing the actual state of the art. An evident lack of studies investigating the quantification of the economic externalities of convenience services ensured by Connected Cars emerged. In particular, the authors identified no scientific work focused on the quantification of the consumer economic externalities provided by Over-the-air updates.

After depicting the gaps characterizing the scientific literature, the authors carried out an additional and more targeted investigation of the topic of Over-the-air updates applied to the automotive industry through the study of further scientific and white papers. Then, after determining the objectives of the analysis through the Research Questions formulation, the authors designed an analytical model, with the intent to assess the expected convenience of owning a car supporting OTA updates in a safety recall event. Finally, the authors validated the model simulating two different scenarios of a safety recall event in the province of Milan and critically reviewed the results achieved.

3. Objectives and Methodology

The objectives of this dissertation have been formalized with the following two Research Questions.

RQ1: What is the actual state-of-the-art about Over-the-air (OTA) updates?

RQ2: How can benefits generated by a safety recall be quantified?

Furthermore, addressing the research questions appropriately required also answering the following Functional Questions:

FQ1.1: Which are the main typologies of OTA updates available today on Connected Cars and the relative benefits that can be generated for the customer?

FQ2.1: Which are the necessary steps an Italian customer goes through when a safety recall occurs?

The authors addressed the Research Questions and the Functional Questions through different approaches:

- *Literature Review*: this initial step represents a foundational effort aimed at exploring the field of Connected Cars, to establish the boundaries of the analysis and identify the literature gaps.
- *Analysis of secondary sources*: in addition to scientific articles, the authors employed secondary sources, such as web pages, white papers, conference reports, and databases coming from reliable sources, to complement the information and enhance their understanding alongside the literature analysis.
- *Analytical model*: the core of this dissertation is to propose an analytical model to assess the expected convenience of owning a car supporting OTA updates in a safety recall event.
- *Data gathering and management*: the model developed has been validated using datasets coming from reliable databases. Moreover, the authors conducted structured interviews with OEM experts and dealership staff members.

4. Model Design

The primary goal of this section is to introduce all the methodological factors which have been considered to design the model, serving as an introductory part to have a deep understanding of the validation analysis presented in the next section.

4.1. Customer Journey Planning

Firstly, to address the *FQ2.1*, the authors represented what steps the consumer goes through when a safety recall occurs. Since the authors could not rely on any existing scientific work to extract the customer journey, a standard modeling of the safety recall event was designed supported by the qualitative data collected through the interviews with companies and dealerships.

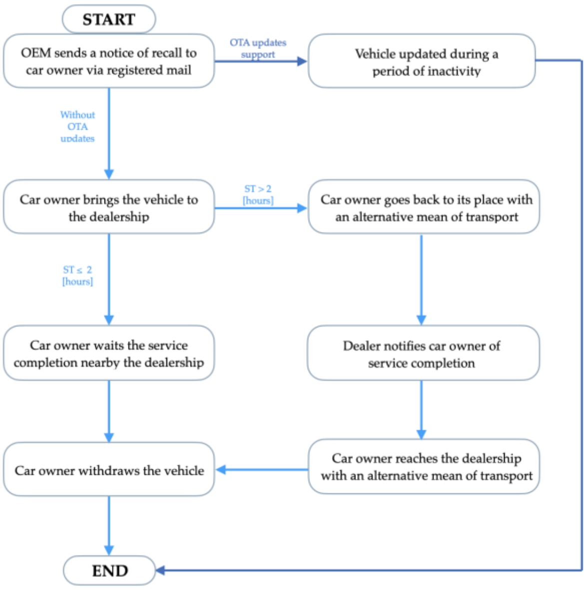

Figure 1: Illustration of the Customer Journey

The car driver (that, by hypothesis, coincides with the owner of the vehicle) enters the system when the OEM notifies that the car needs an update for safety purposes. This notification occurs through various communication channels, such as registered mail. After receiving the recall notification, the consumer must perform the car update as soon as possible. When the vehicle supports OTA updates, the recall can be resolved remotely and the car owner can conveniently perform the update from home during a period of inactivity (for instance, overnight). On the other hand, the consumer owning a car that does not support remote updates will need to bring the vehicle to an authorized dealership to have the necessary operations physically performed. Here a model limitation arises, since the model consider only the case in which the car, despite the recall, is capable of arriving at the dealership without the need for tow truck.

When the customer brings the car to the dealership, the authors designed an additional conditional bifurcation: when the service time to complete the update is high (e.g., more than two hours) the consumer will leave the car at the dealership and will return (using alternative means of transport) to pick it up when notified of service completion (Case 2). Indeed, when the number of vehicles subject to recall is very high or the software requires a long update time, bottlenecks can occur due to the limited capacity of dealerships that cannot perform the update simultaneously on all the cars waiting in the queue. In Case 1 instead the car owner waits the service completion nearby the dealership.

Figure 2: Graphic illustration of Case 1

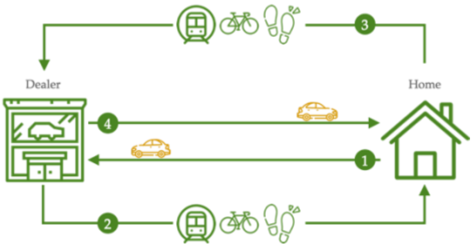

Figure 3: Graphic illustration of Case 2

4.2. Economic Model

This section aims at designing the cost functions representing the main expenses that a consumer copes with when a safety recall occurs. The ultimate goal is to determine the expected cost savings, expressed in euros, that a consumer who owns a car with OTA update support could experience in comparison to a consumer who owns a vehicle that does not support OTA updates. The consumer cost function (1) represents the expected total cost for a safety recall.

$$C = C_R + k \times C_A \tag{1}$$

Where:

- C_R: Costs related to bring the vehicle to the dealership and wait for the update operations.
- C_A: Costs of a car accident.
- k: represents the probability of a car (among those object of the recall) having an accident due to the software failure which is the cause of the recall.

The authors decided to include only the most significant issues impacting a safety recall event. For some other relevant aspects, such as customer satisfaction, the authors did not find any applicable scientific study proposing a model to assess this factor correctly and appropriately.

The model aims to estimate the economic benefit of a vehicle that supports remote updates by comparing the expected cost of remote updates (C_{OTA}) to that of a vehicle that does not support remote updates (C_{wo_OTA}). The former is potentially assumed to be zero, but in some cases, when the issue cannot be resolved remotely, will be equal to C_{wo_OTA}. In particular, the authors defined the relationship between the two cost functions by stating that C_{OTA} is equal to the expected cost of a safety recall for the owner of a vehicle without OTA updates support (C_{wo_OTA}), weighted on the percentage of recalls that cannot be remotely resolved $(1-p)$. Equation (2) depicts this relation:

$$C_{OTA} = (1-p) \times C_{wo\_OTA} \tag{2}$$

Where:

- p: represents the percentage of remotely resolvable recalls.

The equation reasonably highlights that as the number of safety recalls solvable remotely increases, C_{OTA} decreases until becoming equal to zero when all recalls are fixable remotely (p=100%). Consequently to (2), by defining π the expected savings for the consumer owning a vehicle supporting OTA updates, in case of a safety recall event, the authors determined the following gain equation:

$$\pi = C_{\mathrm{wo}\_OTA} - C_{OTA} = p \times C_{\mathrm{wo}\_OTA} \tag{3}$$

4.2.1. Recall

The first component of (1), C_R, aims to represent the monetary expenses that the car owner has to bear when has to bring the vehicle to the dealer and wait for the service update.

$$C_R = TT \times VTT + TC + ST \times VST + SC \tag{4}$$

Where:

- TT: Travel Time
- VTT: Value of Travel Time
- TC: Travel Cost
- ST: Service Time
- VST: Value of Service Time
- SC: Service Cost

The function considers all the journeys the consumer has to travel to reach the dealership and coming back home. *Travel Times* are translated in economic terms through the *Value of Travel Time* (*VTT*) which is a parameter defined by Hössinger *et al.* (2020) [3] as:

$$VTT_{vehicle} = VoL - VTAT_{vehicle} \tag{5}$$

Where:

- *Value of Leisure (VoL):* is the opportunity cost regarding both leisure and work activities [4].
- *Value of Time Assigned to Travel (VTAT)*: is both related to vehicle characteristics and the possibility to carry out alternative activities during the trip.

Secondly, C_R considers the *Travel Cost* that the car owner sustains during the various trips. These expenses consider the contribution of the fuel consumption, the average distance customer-dealership, as well as also the cost of eventual alternative means of transport (e.g., e-bike, subway) necessary when the car is not available. The model is indeed limited to the case where the OEM does not assign a courtesy car to the client.

Then, C_R includes the contribution of the *Service Time* (*ST*) which is the time required by the dealer to carry out the whole service operations for one customer. To model the *ST* computation, the authors chose to use the Queue Theory, assuming that the cars' interarrival times to the dealership are described using the Poisson distribution, being independent and identically distributed random variables. This latter assumption lets the authors represent the system as an M/M/c queueing system with a multiple server configuration with a single queue served with a FIFO discipline. The *ST* is obtained through the computation of the arrival rate of cars to the dealership considering the number of recalled vehicles, available dealerships, servers (c), the campaign penetration rate, and the availability of the dealership. The service rate is computed as the reciprocal of the *Update Time*. To then translate into economic terms the *ST*, the authors assumed that during the service time, the car owner is not able of working, and therefore the *Value of Service Time* (*VST*) was computed as the average net hourly salary in a determined geographical area. The *Service Cost* in the case of a safety recall is zero for the end consumer because the cost is entirely covered by the OEM.

4.2.2. Accident

The second component of formula (1), $k \times C_A$, aims to represent the expected consumer cost associated with a potential software failure-induced accident. Remote updates allow for a significant reduction in the "time-to-market" of an update, thereby decreasing (in practice, resetting) the likelihood of an accident. k represents the probability that a recalled vehicle will undergo an accident due to software failure before the update is performed. After defining R, the number of recalled vehicles, and I, the number of cars involved in car accidents, k can be represented as:

$$k = \frac{I}{R} \qquad (6)$$

The second term, C_A, represents instead the average cost that an individual must bear following a road accident. In turn, C_A is composed of various terms:

$$C_A = C_H + C_{PL} + C_{BA} + C_{Rep} + C_{Ins} \qquad (7)$$

Where:

- C_H: refers to the health care costs the driver has to bear in the case of an accident. The authors modeled this parameter by determining the total cost that the society suffers from road accidents and dividing it by the total population as a first proxy of the pro-capita cost.
- C_{PL}: refers to the loss of productivity. Assuming that the injured person cannot work during the recovery period; this cost is computed by multiplying the average duration of hospitalization with the average net salary in a determined geographical area.
- C_{BA}: refers to the expected cost of an eventual breakdown assistance (BA) intervention.
- C_{Rep}: refers to the costs related to car repair. The model considers the average duration of service that a damaged car requires and the average hourly fee of repair shops. Moreover, the model takes into account the fraction of consumers without "kasko" insurance (which covers all damages suffered by the guilty vehicle).
- C_{Ins}: refers to the upsurge in insurance premiums following a car accident.

5. Model Validation

The authors validated the model by conducting two simulations in two distinct scenarios, in order to have a comprehensive analysis. Both scenarios involve a safety recall event for an automaker in the province of Milan. The difference between the two scenarios lies in the different characteristics of the two players. In the first one, the OEM recalls a more limited fleet of vehicles and has a less extensive dealer network in the territory.

Variable	Scenario 1	Scenario 2
Recalled fleet (R)	1.000	15.000
Dealerships network (D)	8	125
Servers per dealer (c)	2	2
Update Time (UT)	3 hours/car	3 hours/car

Table 1: Scenarios for Model Validation

Considering a remotely resolvable recall rate p of 30% and an accident probability k of 0.01%, the expected total cost in the event of a safety recall for the consumer without OTA support is equal to 146,8€ and 102,8€ in the first and second scenarios respectively. This translates into a value of π higher in the first scenario (44,0€ vs 30,8€). The player in the second scenario has indeed a better structured dealer network in the area, leading to better event management with a lower service time (5,51 hours vs to 5,93 hours). Moreover, the authors compared the results obtained using the Queue Theory with those obtained through an "appointment" method, which ideally determines the *Service Time* as the *Update Time* without additional waiting time. With the latter method the total cost, and in turn π, is reduced by 41% and 53% in the first and second scenarios respectively.

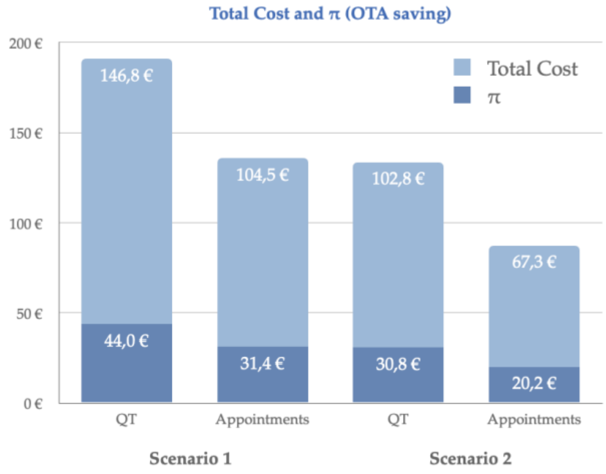

Figure 4: Total Cost (C) and π (p=30%, k=0,01%)

The model reasonably highlights that owning a vehicle that supports OTA updates becomes increasingly convenient as the complexity of the recall event increases.

The authors then performed a sensitivity analysis on p and k to understand how different values may influence the value of π. For both scenarios, when p equals 100%, the savings exceed 100€. The sensitivity analyses reveal a notable finding: when k increases from 0,01% to 1%, π in the second scenario increases more significantly (+91% vs. +64%) than in the first scenario. This result is motivated by the fact that as the number of recalled vehicles (R) grows, π increases more than proportionally.

This result is confirmed by a second analysis the authors conducted by varying the number of recalled vehicles in the second scenario. This analysis highlighted that as R doubles, from 10k to 20k, the consumer cost of the recall, and in turn π, grows almost exponentially, with a growth rate close to 300% (three times the growth rate of R). Consequently, the model points out the increasing convenience of possessing a vehicle supporting OTA updates as the number of recalled vehicles increases.

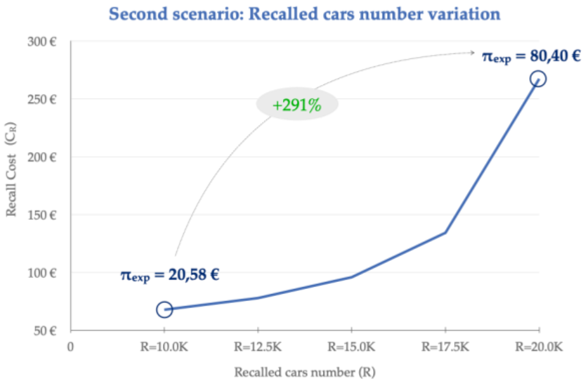

Figure 5: Recalled cars variation impact on C_R

The model findings reveal also that owning a vehicle that supports OTA updates becomes increasingly convenient as the *Update Time* increases. The authors analyzed how the value of C_R varies as the UT varies and the results highlight an increase of C_R and thus, π, more than proportional to UT increase. Moreover, comparing the results of the two scenarios, π variation is more significant in the former scenario (+1.574% vs. +1.282%). This can be attributed to the fact that in the first case, the OEM has a relatively less extensive and effective dealer network, resulting in a higher R/D ratio than in the second scenario.

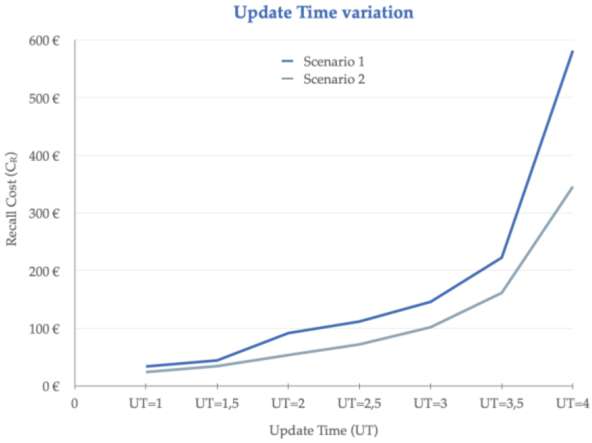

Figure 6: Update Time variation impact on C_R

The authors also analyzed the components that constitute the total cost of a safety recall event. The cost associated with a potential accident remains constant across both scenarios and has negligible effect on the overall cost calculation due to the low likelihood of occurrence (k). The most significant cost element is found to be the expenses related to the recall operations (C_R). The model reveals in both scenarios that for C_R the largest cost component is attributed to the *Service Time* and its translation into monetary terms through the *VST*. In the second scenario, this component is even greater (87%). The greater coverage of the territory by the dealership network in the second scenario results indeed in a smaller average customers-dealership distance (1,00 Km vs 3,96 Km), with a consequent lower contribution of the *Travel Time* and its translation into monetary terms through the *VTT* in the second scenario (32% vs 11%).

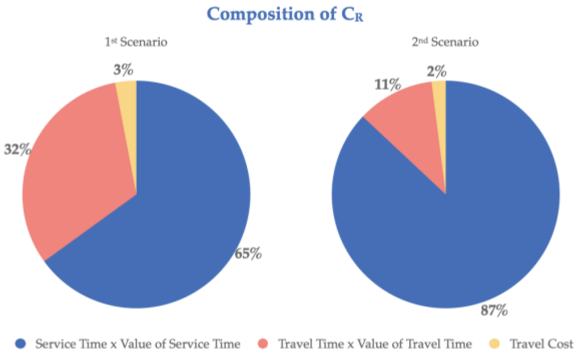

Figure 7: C_R composition in the two scenarios

6. Conclusions

The present study aimed to conduct an extensive convenience analysis of Connected Cars that support Over-the-air updates in safety recall events. The novelty of the topic and the limited existing scientific literature make the findings of this study potentially relevant for further research developments on the subject. OEMs might be interested in the outcome of the model to investigate how safety recalls impact economically on clients with a significant customer dissatisfaction and brand image deterioration.

The authors acknowledge that the assumptions and hypotheses grounding the model may restrict the generalization of the results. Furthermore, the decision to focus solely on safety recall events restricts the model application to this type of recall. At the same time, the model can be applied to any of the major Italian cities for which the authors expect comparable validation outcomes. Nonetheless, the generalizability of the results to foreign countries cannot be guaranteed due to the significant number of input model variables that are contextualized to the Italian setting.

Finally, the achieved results ensure a solid foundation for the further promising development of Over-the-air updates in the automotive industry. After demonstrating the convenience that OTA updates produce for consumers, from an economic point of view, it would be worth extending the cost-benefit analysis to other recall types beyond safety ones. Moreover, OTA updates significantly impact customer satisfaction, maintenance costs, and vehicle obsolescence throughout the whole life cycle of the car. Therefore, extending the cost-benefit analysis also to these topics might provide valuable insights pointing out the great potentialities that OTA technologies offer at the consumer level in the automotive industry.

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Over-the-air updates for Connected Cars: a model to assess customer’s benefits in a safety recall event

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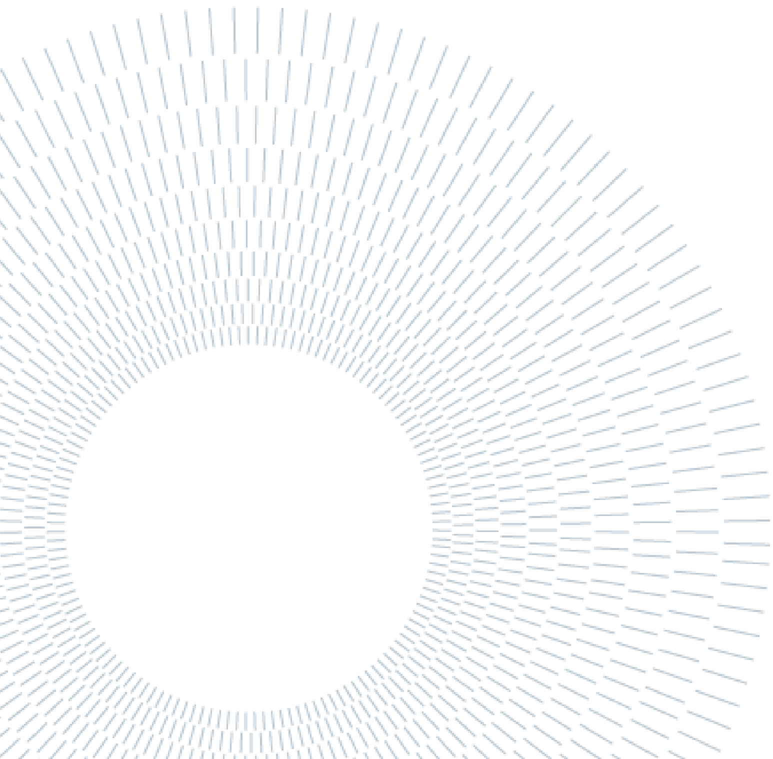


Abstract

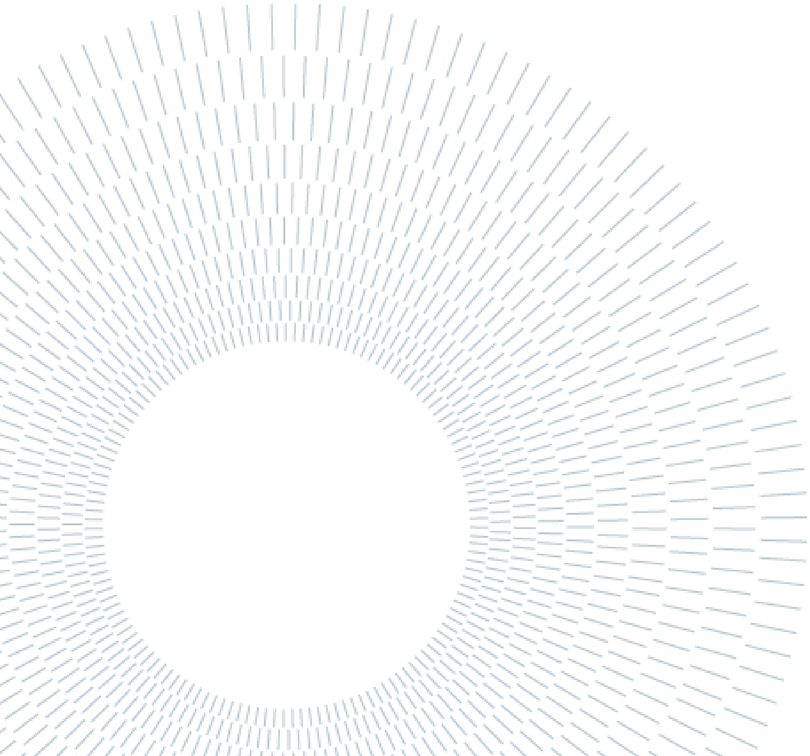
Over-the-air (OTA) updates for Connected Cars have the potential to revolutionize how Original Equipment Manufacturers handle the costly software recall events they have to carry out when vehicles present software faults. Remote management of such events brings high economic benefits to both companies and their customers. This dissertation focuses on assessing the expected convenience of owning a car supporting OTA updates in a safety recall event. To achieve this objective, an analytical economic model was designed, and two distinct simulations were conducted, both replicating a safety recall scenario in the province of Milan. The difference between the two simulations lies in the different characteristics of the two players issuing the recall. In the first simulation, the OEM recalls a more limited fleet of vehicles and has a less extensive dealer network in the territory than in the second one. The final economic results demonstrated unambiguously the convenience of owning a car supporting OTA updates. In both scenarios, the expected total recall cost for the consumer (without a car supporting OTA updates) is over 100 €. In particular, when a recall can be solved remotely, the expect saving from owning a car supporting OTA updates varies from a minimum of 102,8 € in the second simulation to a maximum of 240,5 € in the first one. Moreover, the results highlighted the increasing convenience of possessing a vehicle supporting OTA updates as the number of recalled vehicles increases. Indeed, the cost of the recall is demonstrated to grow more than proportionally to the number of recalled cars. In conclusion, this study provides a promising foundation for OTA updates in the automotive industry. Further cost-benefit analysis could be extended beyond safety recall events, also considering the impact of OTA updates on customer satisfaction, maintenance costs, and vehicle obsolescence, revealing the full potential of this technology from a consumer perspective.

Keywords: Connected Cars, Over-the-air updates, OTA, benefit analysis, safety recall.

Abstract in italiano

Gli aggiornamenti a distanza (Over-the-air, OTA) per i veicoli connessi permettono di rivoluzionare la gestione dei costosi richiami che le case automobilistiche devono effettuare quando i veicoli presentano guasti ai software che li compongono. La gestione da remoto di questi eventi comporta elevati vantaggi economici non solo per le aziende ma anche per i loro clienti. Questo lavoro di tesi si è focalizzato sulla valutazione della convenienza del possedere un'automobile che supporta gli aggiornamenti OTA al verificarsi di un *safety recall* (un richiamo del veicolo dovuto a motivi di sicurezza). Per raggiungere questo scopo, gli autori hanno progettato un modello economico analitico e realizzato due differenti simulazioni, replicando lo scenario di un *safety recall* nella provincia di Milano. La differenza tra le due simulazioni risiede nelle diverse caratteristiche delle due aziende produttrici che effettuano il richiamo. Nella prima, l'azienda richiama una flotta di macchine più limitata ed è caratterizzata da una rete di concessionari meno capillare sul territorio. I risultati economici finali del modello dimostrano in modo inequivocabile la convenienza di possedere un'auto che supporta gli aggiornamenti a distanza. In entrambi gli scenari, il costo totale atteso del richiamo per il consumatore (che possiede un'auto che non supporta aggiornamenti OTA) risulta superiore a 100 €. In particolare, nel caso di un richiamo risolvibile da remoto, il risparmio atteso dal possesso di un'auto che supporta gli aggiornamenti OTA varia da un minimo di 102,8 € nella seconda simulazione a un massimo di 240,5 € nella prima. Inoltre, i risultati evidenziano come all'aumentare del numero di veicoli richiamati il guadagno aumenti più che proporzionalmente. In conclusione, questo studio fornisce una solida base per lo sviluppo degli aggiornamenti Over-the-air nell'industria automobilistica. Ulteriori analisi costi-benefici potrebbero essere estese anche ad altri tipi di richiami, considerando anche l'impatto degli aggiornamenti OTA sulla soddisfazione dei clienti, sui costi di manutenzione e sull'obsolescenza dei veicoli, rivelando il pieno potenziale di questa tecnologia dal punto di vista dei consumatori.

Parole chiave: veicoli connessi, aggiornamenti Over-the-air, analisi dei benefici, richiami per la sicurezza.



Contents

1 Smart and Connected Cars

Over the past 30 years, technological development and the disruptive permeation of the Internet have led to the creation of entirely new businesses. Internet of Things (IoT), Big Data, and Digital Transformation are neologisms that describe the concrete results of these decades of innovations now encompassing whatever sector. These innovations have revolutionized companies' business models, affecting the entire value chains and life cycles of products and services.

These processes of innovation and digitization have impacted everyone, even the most traditional physical product-centric industry: the automotive one. This sector has moved from merely producing a car to creating an intelligent and connected digital transportation hub (Deryabina and Trubnikova 2021), a "smart vehicle".

There is not a univocal definition of smart vehicles, indeed the literature provides multiple concepts and terminologies.

Among these, Park *et al.* (2019) defined smart cars as vehicles characterized by being:

- Autonomous: the vehicle is capable of self-driving, hence without human input.
- Connected: the vehicle is capable of communicating with multiple external entities.
- Electric: the vehicle's fuel is electricity.
- Shared: the same vehicle is shared among a group of users (shared mobility systems: car sharing, carpooling, ridesharing, etc.).

A smart vehicle (for the sake of convenience, hereinafter, "car" and "vehicle" will be used interchangeably) can possess one or more of these characteristics; the quintessential smart car possesses all four.

By incorporating different technologies, smart cars offer various benefits to the consumers in terms of safety (e.g., Collisions Prevention, Driver Fatigue Detection, etc.), cost reduction, (e.g., Usage-Based Insurance), infotainment (e.g., Smartphone Integration, Music Video Streaming, etc.), and various other services. These vehicles have positive externalities not only for drivers and passengers but also for other stakeholders such as car manufacturers, Original Equipment Manufacturers (OEMs), city administrations, insurance companies, tech players, service providers, etc. Moreover, smart vehicles can also have a positive impact on the environment in terms of the reduction of fossil fuel consumption and related emissions.

This research focuses on a specific subgroup of smart cars: Connected Cars.

As for the smart car definition, in the literature, there are many different definitions of a Connected Car. For Coppola and Morisio (2016), “the Connected Car is a vehicle capable of accessing the Internet, of communicating with smart devices as well as other cars and road infrastructures, and of collecting real-time data from multiple sources”. Berdigh and Yassini (2018) proposed the Connected Car as “an embedded system or a multi-layered platform equipped with a wireless network gateway connecting the in-vehicle network to an external network, and data collection, processing systems”.

Therefore, as highlighted by the term *connected*, for these types of vehicles the cruciality is the concept of “connectivity”. In a car, the connectivity is supported by a huge number of sensors enabling communication with all the other entities through WiFi, Bluetooth, GPS, etc. In addition, the vehicle is capable of connecting to the Internet by a transmitter/receiver unit integrated within the vehicle or via third-party systems such as smartphones (Berdigh and Yassini 2018).

The first example of a car with features enabling connectivity was in 1996. The American automotive manufacturing organization General Motors, partnering with Motorola Automotive, developed and launched OnStar service in the new vehicles. In case of an accident, vehicles equipped with OnStar were capable to communicate the GPS location of the accident to a call center aiming to have sooner medical aid.

1.1. Connected Cars Technology

The Internet of Things (IoT) describes all those groups of physical objects capable of connecting and exchanging data with other devices and systems over the Internet or other communications networks. This capability is ensured by sensors, processing abilities, software, and other technologies embodied in the object. Within the IoT world, there are many applications and subworlds. One of these is the so-called “Internet of Vehicles” (IoV).

Before the advent of IoV, vehicles were capable of exchanging information through conventional Vehicle Ad-hoc Networks (VANETs). This latter kind of network model “turns every participating vehicle into a wireless router or mobile node, enabling vehicles to connect to each other and, in turn, create a network with a wide range”

(Yang *et al.* 2014). The limitations of this model, hindering its applications, stand in the fact that "the objects involved are temporary, random and unstable, and the range of usage is local and discrete". A significant issue with VANETs is their limited capacity to effectively handle the large amount of data gathered from various sources, including the network itself, sensors, and mobile devices in the surrounding area (Contreras-Castillo *et al.* 2018).

The Internet of Vehicles instead overcomes these limitations by focusing on the "intelligent integration of humans, vehicles, things, and environments". It is "an open and integrated network system with high manageability, controllability, operationalization, and credibility and is composed of multiple users, multiple vehicles, multiple things, and multiple networks" (Yang *et al.* 2014). Therefore, the concept of IoV, as reported by Contreras-Castillo *et al.* (2018), "integrates two technological visions: (i) vehicle's networking and (ii) vehicle's intelligence".

1.2. Communication Technology

The Internet of Vehicles development played and still plays a crucial role in the growth of Connected Vehicles. Vehicle's networking is ensured by the ability of communicating with the external world.

As previously mentioned, Connected Cars are indeed capable of communicating with many different entities. The communication technologies embedded in the vehicles, enabled by a variety of sensors, are classified concerning the entity the vehicle is communicating with (Park *et al.* 2019). Three major categories have been identified by Park *et al.* (2019), namely Driving Assistance, Infotainment, and IoT Hub, under which the different types of interactions, that a connected vehicle can have, have been identified. Under the umbrella of Driving Assistance:

- Vehicle to Vehicle (V2V)
- Vehicle to Infrastructure (V2I)
- Vehicle to Pedestrian (V2P)
- Vehicle to Everything (V2X)

This assistance provides benefits such as a safer driving environment, driving efficiency, and accident prevention while leaving the opportunity for the driver to be involved in other activities other than driving the vehicle. Under the category of Infotainment:

- Vehicle to Driver

- Vehicle to Cloud (V2C)

Infotainment services provide enhancement of the driver's comfort by allowing her to access information while driving and entertaining all passengers on the road. Moreover, by connecting the vehicle to the Cloud, passengers can instantly exploit connectivity to take advantage of a variety of services, such as watching a streaming movie, working with documents, and making payments and financial transactions to improve their time usage while being in the car. Thanks to AI capabilities, vehicles can also communicate with passengers to recognize and execute commands. Finally, in the IoT Hub there are the below listed connectivity types:

- Vehicle to Office
- Vehicle to Home
- Vehicle to Device

Here a link to the existing IoT systems is created to control all the services offered by the system through the car. An example could be the connection to the home automation appliance to remotely monitor the temperature of the house or the security cameras right from the driver’s seat. Table 1 summarizes the key services categorized by the type of connectivity.

Major connectivity	Service	Explanation	Benefit
Vehicle to Vehicle (V2V) Vehicle to Pedestrian (V2P) Vehicle to Infrastructure (V2I) Vehicle to Everything (V2X)	Driving assistance	Supporting movement and driving	• Safe driving • Efficient driving • Accident prevention
Vehicle to Cloud (V2C) Vehicle to Driver	Infotainment	Enhancing comfort and entertainment while driving	• Experiencing various services during the time spent in the car
Vehicle to Device Vehicle to Home Vehicle to Office	IoT Hub	Utilizing embedded services in the existing IoT system	• Improving quality of life by remotely controlling devices at work or home

Table 1: Key services categorized by type of connectivity (Park et al. 2019)

1.3. Connected and Automated Vehicles (CAVs)

In the first section of this chapter, the pillars of a smart car have been provided: autonomy, connectivity, electricity, and shareability. This research work focuses on the first two points. On these grounds, it is relevant to mention that in the literature, Connected Vehicles are often investigated under the concept of Connected and Automated Vehicles (CAVs).

1.3.1. Connectivity and Automation

Concerning vehicle connectivity, McKinsey consulting firm has developed a framework (reported in Figure 1.1) describing five levels of it, from basic to advanced.

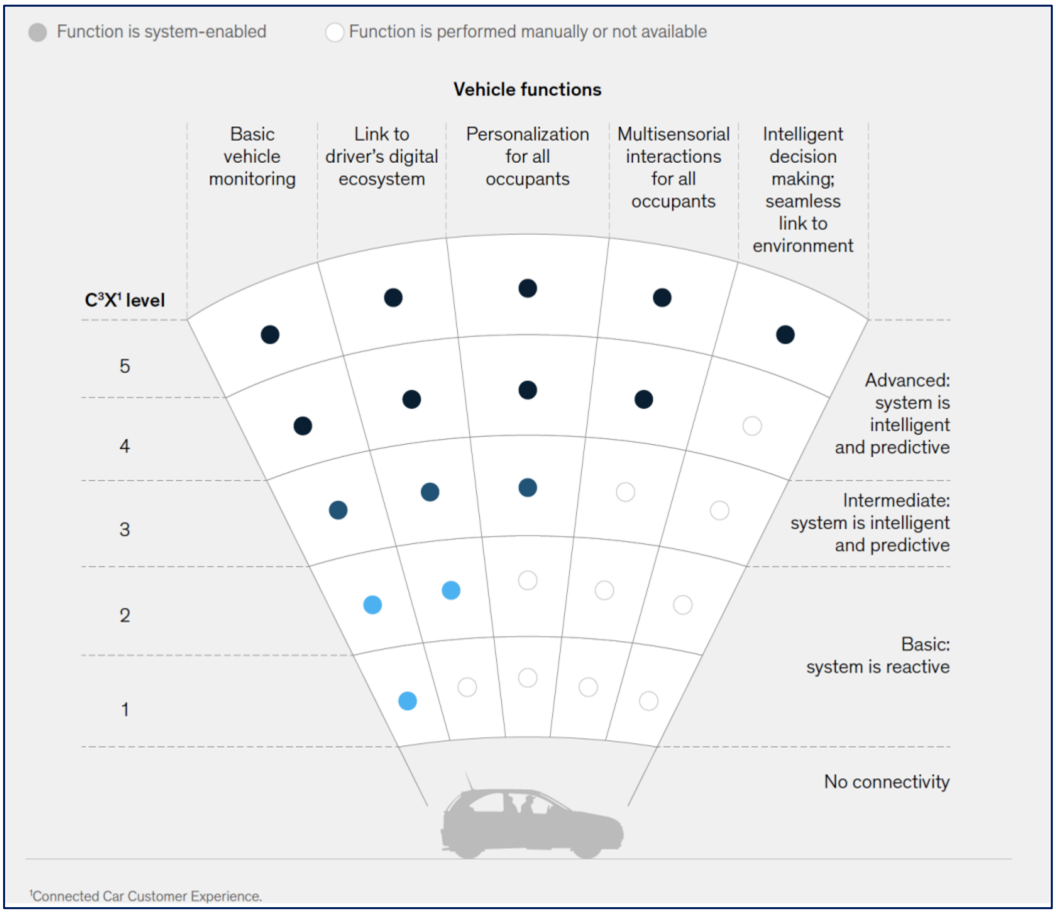


Figure 1.1: The McKinsey Connected Car Customer Experience (C3X) Framework (Unlocking the full life-cycle value from connected-car data, McKinsey & Company, 2021)

In the first level, connectivity is limited around the driver and the simplest services it can provide her (e.g., tracking and monitoring simple vehicle usage data, offering digital services to the driver through external digital platforms, etc.). In the intermediate levels, connectivity deals with occupants by offering personalized infotainment services. At level 4, passengers dialogue in real-time with the vehicle and receive proactive recommendations on services and functions. At the ultimate level, the vehicle is a virtual driver and uses cognitive artificial intelligence to meet the explicit and unstated needs of the passengers.

Connectivity and automation are strictly related. Taiebat *et al.* (2018) report that "vehicle connectivity and automation are separate technologies that could exist independent of each other but entail strong complementary attributes" and that "vehicle connectivity is a key enabler of vehicle automation".

In common parlance, terminologies such as "automated", "autonomous", and "self-driving" are often interchangeably used and thus erroneously. This can lead to misunderstandings and therefore, it is immediately necessary to provide standard and scientific terminologies, and definitions. The study of Shladover and Greenblatt (2017) for the U.S. Department of Energy's (DOE) Vehicle Technologies Office - SMART Mobility has been used for the following definitions. Autonomy implies independency and self-sufficiency while automation refers to the substitution of human labor with electronic and/or mechanical systems. Therefore, it is possible to understand how autonomous vehicles, which are capable of self-driving without human input, are a subgroup of automated ones.

Moreover, it is worth to provide the SAE's (Society of Automotive Engineers) classification of the levels of automation (SAE International, 2016) presented in Table 2, in the following page. It presents six different levels, ranging from no automation to full automation. This classification system reflects the amount of driver intervention and attentiveness required, rather than the vehicle capabilities, although these are very closely related.

To conclude, it is possible to define Connected and Automated Vehicles as vehicles with connectivity capabilities and a high level of automation. For sake of simplicity hereinafter the authors will use the terms CAVs, "Connected Cars" (CC), and "Connected Vehicles" (CV) interchangeably. Moreover, to avoid misunderstandings, it is important to highlight that when the authors use the term "vehicle", they refer to it as "car".

SAE Level	**Name**	**Narrative Definition**	**Execution of Steering and Acceleration**	**Monitoring of Driving Environment**	**Fallback Performance of Dynamic Driving Task**	**System Capability (Driving Modes)**
Human driver monitors the driving environment						
0	No Automation	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	N/A
1	Driver Assistance	The driving mode specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver will perform all remaining aspects of the dynamic driving task	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	The driving mode specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver will perform all remaining aspects of the dynamic driving task	System	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitorsthe driving environment						
3	Conditional Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene	System	System	Human driver	Some driving modes
4	High Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene	System	System	System	Some driving modes
5	Full Automation	The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environment conditions that can be managed by a human driver	System	System	System	All driving modes

Table 2: SAE's classification (source: SAE International, 2016)

1.4. Benefits of Connected Cars

Connected Cars offer a wide variety of benefits. These positive externalities can be classified in terms of the entity that is receiving the perk: drivers, passengers, pedestrians, OEMs, environment, etc.

The first concept of a Connected Car (OnStar by General Motors) aimed at reducing fatal accidents on the roads. In fact, the primary goal of the adoption of CCs is to reduce and avoid collisions and the consequent fatalities. Indeed, most of the solutions aim to enhance vehicle safety for example with predictive maintenance or other systems (e.g., Driver Fatigue Detection).

Generally, Connected Cars also aim both to make driving easier and hassle-free for the driver, facilitating the most complicated operations (e.g., parking assistance), and to make the car journey fun or at least less boring as possible with infotainment (combination of information and entertainment) functionalities. In fact, drivers and passengers are capable of integrating their smartphones with the vehicle enjoying the drive with music and videos.

It is possible even to consider the Connected Car as an extension of one's home from which performing many tasks remotely such as setting and programming the heating of the house is very easy. These kinds of services can be classified as "convenience benefits".

CC solutions can have an economic impact on consumers and companies, such as insurance packages based on actual vehicle usage (Usage-Based Insurance) or Eco Driving modality which permits minimizing fuel usage.

Communication between the vehicles themselves and the road network has a positive impact in terms of traffic efficiency. A concrete example of this is what is known as platooning: by communicating cars can reduce the distances between them, increasing road capacity, reducing traffic jams, and allowing more non-road spaces which then can be converted into more pavements, cycle lanes, parks, etc.

The usage of CC can also positively impact the environment. In fact, smart cars can suggest to the driver fuel-efficient routes based on traffic information or can offer Eco Driving modalities that can significantly lower fuel consumption (e.g., the Start and Stop function) and thus the related CO_2 emissions.

1.5. The Connected Cars market

The Connected Cars market is steadily increasing. By 2030, more than 95% of the sold vehicles will be connected (*Unlocking the full life-cycle value from connected-car data*, McKinsey & Company, 2021). A study from the Fortune Business Insights journal (Market Research Report 2021) sized the Connected Car market USD 55,56 billion in 2020. COVID-19 has negatively impacted with a 12,1% reduction from the previous year, but the market's demand and growth are projected to bring to a size of USD 191,83 billion in 2028.

It is possible to observe a similar trend in the Italian ecosystem. In fact, in 2021, the Connected Car solutions market (including Advanced Driver-Assistance Systems, ADAS) presented an 8% growth over the previous period, reaching a value of EUR 1.92 billion (*Osservatorio Connected Car & Mobility*, Report 2022, Politecnico di Milano).

This solid growth of the sector needs a parallel infrastructural development. Many areas on Earth still present network connection gaps, which makes it difficult for vehicles to connect to the cloud, especially in rural areas. A stronger 4G/5G data network coverage in these areas would allow even stronger market growth.

These numbers point out how this market offers a huge value in terms of revenue opportunities. Along the whole new value chain of the industry, incumbents and newcomers have to react to the rapid tech innovations and consumers-shifts behaviours by establishing sustainable business models.

1.6. Connected Cars & Business Models

Connected Cars have revolutionized the automotive ecosystem. The industry's value chain has seen the entry of many new players (Figure 1.2 on the next page). In fact, connected vehicle services enable revenue and cost benefits for different types of companies in the industry (OEMs, insurance companies, tech firms, advertising companies, etc.). These perks are enabled by the huge amount of data generated by the vehicle. Original Equipment Manufacturers can leverage Connected Car services to generate new and recurrent revenue streams throughout the whole life cycle of the vehicle. Examples of this are Over-the-air (OTA) updates (e.g., updates that add new features or functionalities such as acceleration updates) or mobile charging/refueling services. Moreover, beyond providing additional sources of revenue, these recurrent services and interactions with the customer enhance brand loyalty (McKinsey & Company, 2021).

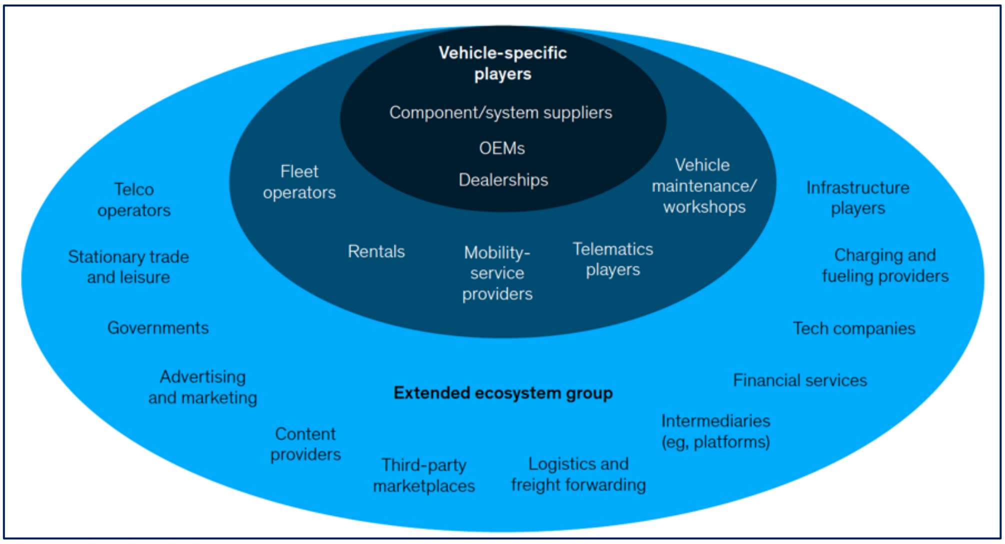


Figure 1.2: Automotive industry ecosystem (non-exhaustive). (Source: Unlocking the full life-cycle value from connected-car data, McKinsey & Company, 2021)

Insurance companies can nowadays exploit data to tailor insurance rates based on the driving styles of the car owner. Advertising agencies can exploit a new touch point inside the vehicle.

Therefore, it is evident how the advent of connectivity has led to the creation of entirely new business models in the automotive landscape. Looking at the renowned definition from Osterwalder and Pigneur (2010), "a business model describes the rationale of how an organization creates, delivers, and captures value", it is possible to understand how, with the advent of CC, the automotive ecosystem changed its processes of value creation, delivery, and capture. The value proposition represents the offered value to the customer, and in this sense, the industry moved from merely offering an "owned mobility" product (Bohnsack *et al.* 2021) to an "owned mobility digital service". Digitally oriented business models replaced physically oriented ones.

As mentioned before, the value network (how the value is created and delivered) of the CC ecosystem has changed being fragmented into a variety of different stakeholders. OEMs must be able to establish partnerships with the other players along the value chain to present a digital and sustainable service offering to the customers and to capture the full value enabled by connected vehicles data. In fact, as reported by Sterk *et al.* (2022), "strategic partnerships enable companies to maximize their value proposition by operating complex services that they cannot realize on their own, such as usage-based insurance models or predictive maintenance approaches".

However, OEMs are still struggling with connectivity, with few players realizing and reacting to the immense potential of connected vehicles, and with even fewer fully monetizing their car data (Sterk *et al.* 2022). Moreover, while OEMs launched digital services such as "BMW ConnectedDrive" and "Mercedes me connect", major tech companies such as Google or Apple are threatening the incumbents by introducing their own car operating systems.

Looking at how the value can be captured, many new revenue streams are popping up. OEMs can sell additional services (e.g., OTA updates, usage-based pricing) and rely on additional revenue models such as freemium, add-on, or razor & blade. Moreover, OEMs can also monetize the data generated by the vehicle by selling them through third-party platforms, such as Caruso, a German-based platform enabling third parties to consume data standardized across multiple vehicle manufacturers.

1.7. Regulatory framework

The high level of connectivity in connected vehicles introduces a wide variety of new security threats and privacy challenges. Therefore, it is necessary a robust security architecture for sustaining the connected vehicle concept (Halder *et al.* 2020). Moreover, the amount of car data collected grows significantly, and consequently, privacy and ethical issues may arise. Companies must be able to exploit the data to improve the end-users experience without undermining their trust (e.g., sending the car speed data to the police for checking compliance with speed limits).

Connected and autonomous cars, therefore, require careful and clear regulation that can enable the use of these technological innovations. Institutions have the difficult task of enabling the development of these vehicles, through real-world testing, while always ensuring the maximum safety of the cars as a means of transport.

On 14 July 2022, the European Union changed the regulations and gave the green light for the circulation of self-driving cars on the road. The different countries will now have to adapt to the new directives. Nowadays in Italy, only cars that are equipped with auxiliary instruments and that fall within levels 1-2 of automation (of the SAE classification presented in section 1.3.1) can circulate on roads. Current Italian regulation does not yet allow vehicles with higher levels of autonomous driving to enter the market. Vehicles in levels 1-2, being equipped only with one or more driver assistance systems, are not considered true autonomous vehicles, since they require the presence of an active driver. Therefore, in Italy, a highly autonomous vehicle, i.e., one that is equipped with technologies capable of adopting driving behavior without the active intervention of a driver, cannot yet be homologated.

2 Literature Review

A literature review, as stated by Houser (2018) is a “critical component of the research process that provides an in-depth analysis of recently published research findings in specifically identified areas of interest”.

For the authors of this work, it has been a powerful tool, used to explore the topic of Connected cars and automated vehicles, which has already been previously investigated, that involved the collection, selection, classification, evaluation, and analysis of the found information, aimed at identifying gaps in the literature to be filled in order to contribute to the research community.

Over the past 30 years with the advancements in computing and networking technologies and the decreasing costs of various electronic devices and systems, the stage seems to be set for making vehicles an inevitable part of the connected world. As mentioned in the first chapter, the Connected Car market is steadily increasing with the belief that by 2030 95% of the world's car fleet will be connected. Hence, being a sector of strong interest, thanks to the literature review, the authors of this work were able to better understand the various facets of this new technology and the whole ecosystem being built around it, to be able to proactively contribute to research by investigating further a meagre area of this vast and extensive topic.

The fragmentation and the width of the literature body make it necessary to perform and follow a structured and solid methodology to fulfil the goals of the dissertation. Therefore, the objective of this performed literature review is to deeply understand the level of advancement of literary studies performed by the research community in the area of "Connected Cars” (and CAVs) and to consequently identify potential gaps to be filled with an original and unique contribution in terms of economic and societal benefits of the overmentioned technology.

The first step performed in that direction was to generally collect all the available information, whether in conference proceeding papers or journal articles, to then secondly perform an in-depth analysis, on the only inherent and then selected ones.

The collected literature was then analysed and clustered according to the papers' main characteristics.

2.1. Methodology

The framework used to perform this literature review is a multi-step methodology used by analogous research such as Perego *et al.* (2011) and Mangiaracina *et al.* (2015). The structured approach can be visually understood in Figure 2.1. The selected methodology led to a final sample of 81 Papers, published between 2011 and 2022, spread across 73 international journals and conferences.

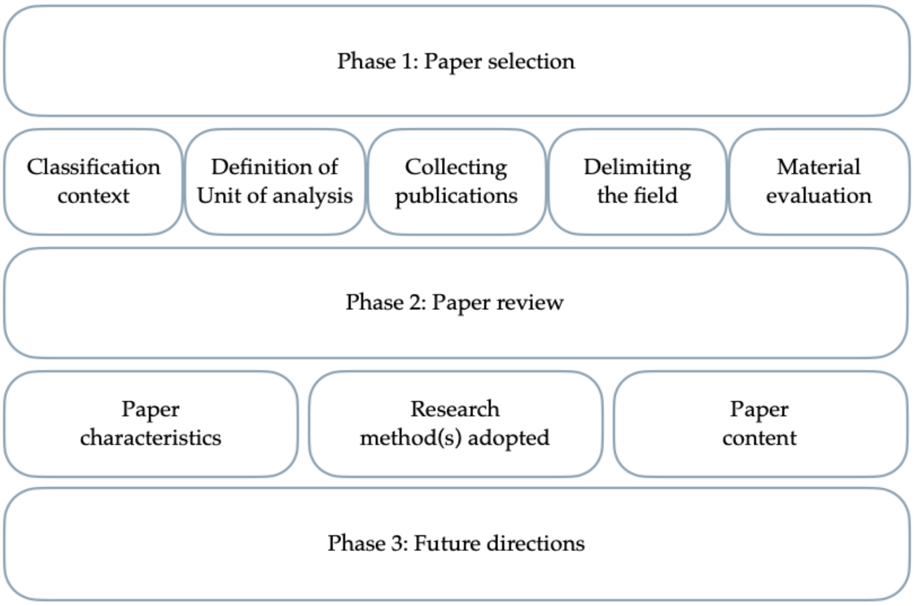


Figure 2.1: Methodology framework (Mangiaracina et al. 2015)

2.2. Phase 1: Paper Selection

The steps used for article selection were as follows:

- *Classification context*: the classification context has been identified by the authors to classify the material gathered. Connected Cars and related benefits were identified as the reference for the research process.
- *Definition of the unit of analysis*: the unit of analysis was identified as articles, conferences, and technical reports published in international academic literature.
- *Collecting publications*: the most popular and relevant online databases selected to gather all the prominent articles were Scopus and Google Scholar. To select the fundamental keywords, it has been considered that the subject of

investigation is relatively new, thus the literature uses multiple terms to refer to the same technology. Therefore, the selected keywords used to perform the research were the following ones, either singularly or combined: “connected_cars”, “connected_vehicles”, “connected_automated_vehicle”. Furthermore, to obtain the maximum coverage of the area of interest, according to Marchet *et al.* (2015), backward research has been done to investigate references and cited contributions, and to include additional papers in the analysis if regarded as relevant.

- *Delimiting the field*: this stage aims at performing a punctual choice of the most inherent papers. To do so, it was necessary to filter and select only the papers consistent with the theme of the thesis. While the first step encompasses a general overview of the topic with the usage of keywords like “connected_automated_vehicle”, then thanks to the knowledge acquired by the authors the research spectrum has broadened by choosing more specific keywords concerning specific technological aspects. According to this, new keywords were added to the research: “business_model”, “benefits”. Moreover, to be consistent with the focus of the thesis, additional keywords addressing potential implications for the owner of the vehicle, that emerged from the initial general evaluation, were cross added to the above-mentioned keywords. Therefore, keywords such as “over-the-air”, “updates”, “customer_satisfaction” and “customer_experience” were included. Lastly, papers whose research area was computer science were excluded as categorized out of focus for this work.
- *Material evaluation*: the selected literature was reviewed and categorized according to the features of the papers. Second, the literature was classified according to the themes that emerged to get an overview of meaningful and worthwhile topics. Finally, the classification and evaluation of the papers allowed the authors to highlight possible gaps and directions for future research (Meixell and Norbis 2008).

The final number of papers to be obtained was not established a priori; on the contrary, it was the outcome of iterations and combined research. From the initial sample, once all the steps defined by Phase 1 were performed, 81 papers were selected for an in-depth review. The authors believe that the final number of publications obtained is appropriate, considering the breadth of the topic investigated.

At the end of this first step, all publications in the obtained sample were summarized to outline the content addressed by each article and support the classification task.

2.3. Phase 2: Paper Review

To conduct a descriptive analysis of the chosen papers, the approaches developed by Meixell and Norbis (2008), Perego *et al.* (2011), and Mangiaracina *et al.* (2015) were first explored.

As part of this literature review, the selected works were classified according to:

1. Paper characteristics analysis (e.g. year of publication, country, publisher)
2. Research method(s) adopted
3. Paper content analysis

This explorative path led to the detection of possible gaps in the current literature body, which will be thoroughly investigated in Section 2.4.

2.3.1. Paper Characteristics

The selected publications were ranked according to these attributes: authors, publication type, publisher, country, and year of publication. The 81 selected papers were published by 73 different scientific publishers. Among them, the major contributor was the journal "Transportation Research Record: Journal of the Transportation Research Board", with a total of 3 articles published. Considering the dispersed distribution of publications among 73 distinct journals, the authors deemed it unnecessary to provide a graphical representation of this information. Moreover, the prevailing area of interest identified was Connected Vehicles (47,5%), followed by Connected and Automated vehicles (CAVs) (26,3%) and Vehicle Information Systems (10%). Analysing the year of publication, the authors realized that most of the papers belong to the last five years, especially 80,2% of the papers were published from 2017 onward. However, the first publications started in 2011, and this paper analysed all papers published in the total span of 11 years, starting from the first published paper until the end of 2022.

Figure 2.2 shows the temporal distribution of articles examined in the years under analysis. There is a visible upward trend in publications, confirming the growing interest of the research community over time in this topic. The declining trend of the line in 2022 is associated with the fact that this literature review was performed in the middle of the year, limiting the material available for 2022. In any case, the imperfect trend in the line is mainly due to the sample taken as a reference, which is a subset of all results made available by the research platforms used as sources for this dissertation.

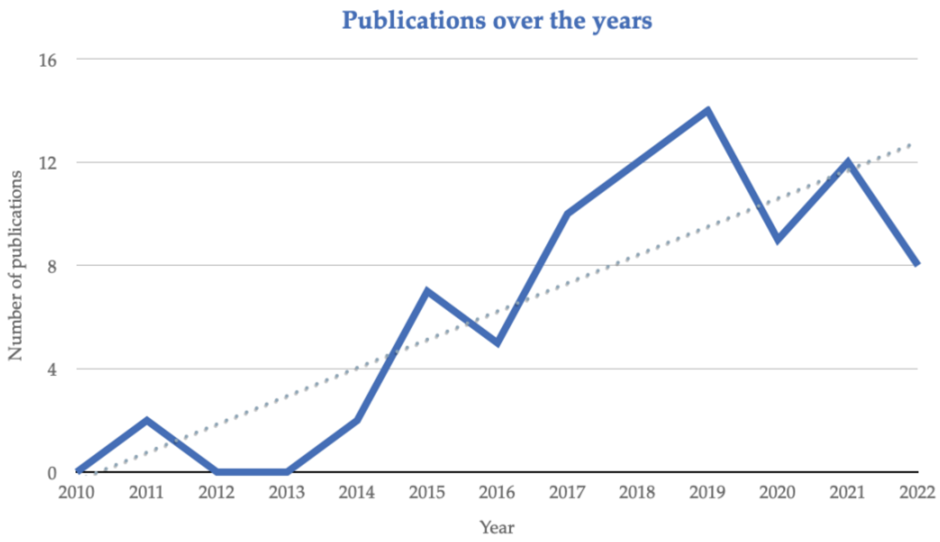


Figure 2.2. Distribution of publications over the years

In order to improve the quality of the graph, a global perspective should be taken into account, to overcome the funnel methodology adopted in this work. Considering the country of publication, the papers have been classified considering as a reference the country in which most of the authors belong, being very common the presence of international research teams. Most of the publications were published in the USA, which counts for 21% of the overall sample (17 papers), immediately followed by Germany with 18,5% (15 papers), UK with 8,6% (7 papers), and China with 7,4% (6 papers). These results and those related to other countries are illustrated in Figure 2.3.

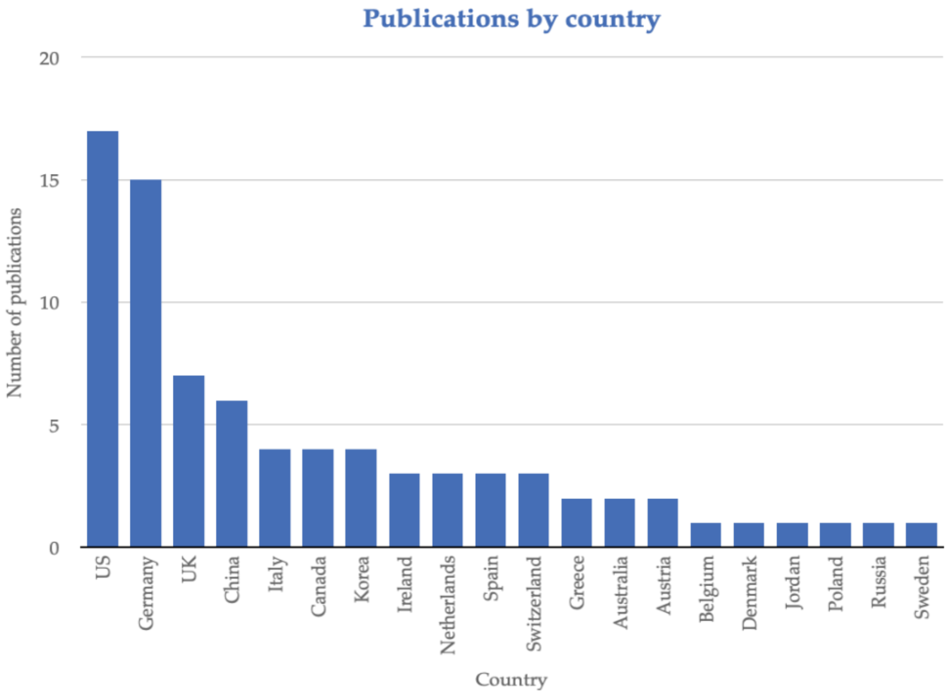


Figure 2.3: Number of published articles by Country

For a more comprehensive view, it is also important to make some considerations at the continent level rather than at the country level. The Figure 2.4 provides an overview of the breakdown of the analysed documents by continent. Despite the primacy in the number of publications for the US, Europe is the continent with the highest research commitment towards the Connected Cars topic, counting for 58% of the overall collection. The authors expected the leading country to be the United States, for several reasons. The United States has been at the forefront of automated vehicle (AV) research and, as described by Andersson and Mattsson (2015), continues to be a pivotal contributor to the development and implementation of Connected Car solutions in the market.

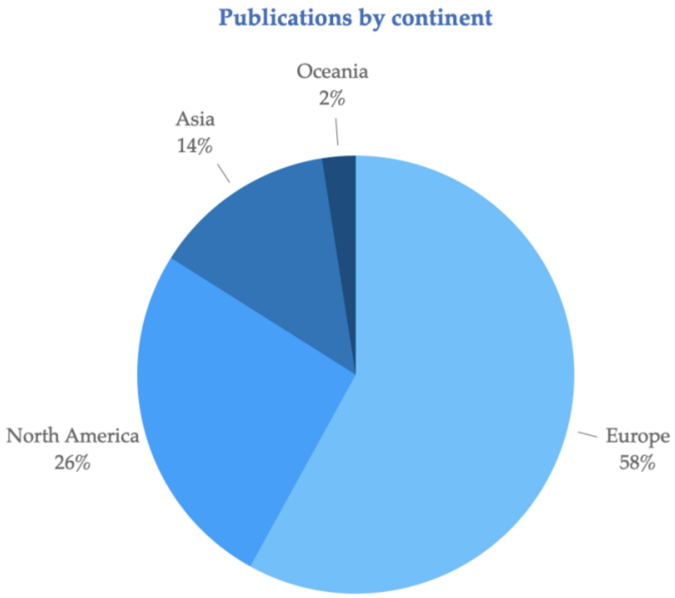


Figure 2.4. Number of publications by continent

Furthermore, according to Statista, the number of Connected Cars on American roads was approximately 84 million in 2021, with an estimated projected figure of over 305 million by 2035, thereby establishing the United States as the largest market for connected vehicles. This partly justifies the significant research workforce focused on this country, as our sample of articles shows. Moreover, it can be said that the second country in terms of publication contribution is Germany, which brings up the number of publications of articles on Connected Cars in Europe landscape. This can be easily justified as Germany is known for its strong presence in the automotive industry and its advanced research in technology. Germany is world leader in automotive manufacturing, with many major companies based in the country, including Volkswagen, BMW, Mercedes-Benz, and Audi. In addition, Germany has a strong tradition of automotive research and development, with many research centers and universities focusing on innovation in the automotive industry. This includes research on connected vehicles, which is an important part of the development of the car of the future. In addition, the German government has invested in research projects for the development of connected vehicles and the Internet of Things (IoT) for mobility, incentivizing companies to invest in this area. Figure 2.5, from Statista, depicts the above discussed numbers about connected car fleets by world region.

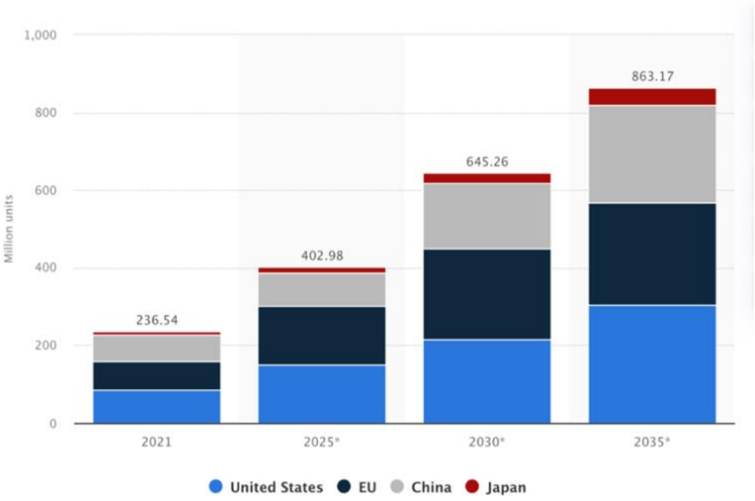


Figure 2.5: Size of the global Connected Car fleet in 2021, with a 2025, 2030, 2035 forecast, by region (in million units). Source: Statista

2.3.2. Research Method Adopted

The selected papers were also classified according to the research method used by the authors. To do so, seven different categories were chosen on the base of the study conducted by Meixell and Norbis (2008), who analysed the different research methods that can be used to address a Research Question. Here are the methods listed below:

- *Analytical method:* scientific analysis methodology which allows solving a problem by means of a well-defined analytical mathematical calculation procedure.
- *Conceptual framework*: it gives an abstract and qualitative representation of a problem and its solution. It is more easily visualized and understood than its literal counterparts thanks to the use of causal maps, matrixes, and diagrams to give the reader a better understanding of the topic.
- *Research framework*: is a qualitative way to explain and foresee future tendencies through critical, deductive assumptions.

- *Case study:* Empirical analysis that investigates a contemporary phenomenon in its real-world context. It is typically used to validate a model previously defined in a real setting.
- *Literature review:* literature analysis that collects previously published studies and papers on a given topic, aiming at identifying gaps and future trends.
- *Survey:* statistical survey directed to a predetermined sample of people and aimed at collecting a set of opinions, preferences, and/or behaviours in relation to the purposes for which it is conducted. It can be structured, semi-structured, and unstructured, depending on the margin of discretion given to the interviewee.
- *Simulation:* model of reality that makes it possible to evaluate and predict the dynamic unfolding of a series of events or processes following the imposition of certain conditions by the analyst or user.

It is worth to be mentioned that many works are developed by combining more than one research method. In fact, the authors realized during the research that frequently papers laid out following the analytical method framework then have been concluded by testing it through a simulation (Jiang *et al.* 2017). Therefore, given the scope of identifying the most recurrent method in literature, for papers presenting a double classification, it was considered only the prevailing research method between the two. The following Figure 2.6 gives a graphic overview of the number of publications for each of the research methods presented. There is a good balance between the methods, with a spark for "conceptual framework" and "case study".

Figure 2.6: Number of publications by research method adopted

The conceptual framework method has been the largely adopted one in the paper sample, with as many as 16 articles under this category, being the 20% of the total sample. These articles focus their attention on the applications and impacts of CAVs (Yang *et al.* 2014, Swan 2015, Stocker *et al.* 2017, Putz *et al.* 2019, Llopis-Albert *et al.* 2021, Kaiser *et al.* 2019), but also formalize potential business model archetypes for new value creation around different CAVs applications (Andersson and Mattsson 2015, Bohnsack *et al.* 2021, Grieger and Ludwig 2019, Kaiser *et al.* 2021, Kukkamalla *et al.* 2020, Kim and Yang 2021, Mikusz *et al.* 2015, Mikusz 2016, Sterk *et al*. 2022, Zhao *et al.* 2020).

The case studies, which account for 16%, were helpful for the authors to gain insights on real applied models in specific contexts and circumstances. Among them, five studies (Bahaaldin *et al.* 2017, Bethaz *et al.* 2021, Olia *et al.* 2014, Shannon *et al.* 2021, Zhao and Kockelman 2018) have quantified the results specifically to assess the potential impacts of connected vehicles on mobility scenarios, to then qualitatively delineate the benefits stemming from it.

The papers, on the other hand, which used the analytical model as methodology of study are 12, accounting for 15% of the overall sample. These mainly represent the quantitative effort of the sample of articles selected by the authors, besides the simulation ones. This category of articles encompasses all those that contain a mathematical framework within. The authors identified a recurring pattern in these papers, which typically starts by introducing and explaining the analytical model, followed by its application in a real-world context and a discussion of the results obtained. The topics covered by these papers, which make up a significant portion of the overall literature review, span across different CAVs applications. A more in-depth analysis of their content will be provided in the next chapter.

Concerning Surveys, they characterize 14% of the overall material gathered. This method allows the collection of qualitative information from both the end users'/consumers' points of view and OEM ones. Athanasopoulou *et al.* 2019, Karmanska 2021, Piccinini *et al.* 2015, Rahman and Tadayoni 2018, and Mayer and Siegel 2015 with their articles, contributed to the assessment of yet-to-be-explored benefits and impact of this digital disruption within the current automotive industry. On the other hand, Bosler *et al.* 2017, Goikoetxea-Gonzalez *et al.* 2022, Halder *et al.* 2020, Kim *et al.* 2019, Park *et al.* 2019, Shin *et al.* 2015, and Toglaw *et al.* 2018 have collected useful information to understand end consumers' preferences in terms of willingness to pay, perception of safety and security, and technological bundles that consumers would like to be offered to improve the experience and performances of their connected vehicles.

The simulation papers account for 14%, and provide the quantitative results of the sample, along with those from the articles that used the analytical method. In all these papers, the simulations conducted are used to estimate the possible benefits of traffic congestion (Neufville *et al.* 2022, Makridis *et al.* 2018, Hensher 2018), road safety (Genders and Razavi 2016), in terms of accident frequency and severity (Mathew and Benekohal 2022, Sinha *et al.* 2020) through the use of Connected Cars in real-world settings. Often the real-world applications are set in Asian or American cities, and this is explained because there is already an extensive use of connected vehicles than in European cities, a continent that nevertheless remains the second largest contributor to scientific research related to connected vehicles.

Research framework articles are the least in the sample of papers that the authors selected. Only 7 articles have been drafted using this method, which aims to provide general trends and possibilities enabled by the use of Connected Cars. In fact, Arena *et al.* 2020, Coppola and Morisio 2016, He *et al.* 2019, Jadaan *et al.* 2017, and Kaiser *et al.* 2017 all provide an overview of the possibilities offered by Connected Cars in terms of services and related benefits and provide an overview of the current status and future perspectives of smart cars, taking into account technological, transport, and social features. Only Deryabina and Trubnikova 2021 analyze how digital transformation is changing the traditional business model and presents many emerging trends in the value chain applications in the automotive industry.

The authors included in their paper samples, 10 literature reviews that helped them to have a comprehensive view of the topic. They span and cover a variety of topics, ranging from the history of the early application of wireless communication technologies in vehicles in early 1990, in America and Japan with Chan (2011), an overview of the state-of-the-art wireless solutions to vehicle-to-sensor, vehicle-to-vehicle, vehicle-to-Internet, and vehicle-to-road infrastructure connectivity thanks to Lu *et al*. (2014), and false myths about CAVs and a critical examination of some typical misconceptions referring to CAVs' development and adoption readiness in the paper of Nikitas *et al.* (2019). Hanelt *et al.* (2015), Kaiser *et al.* (2017), Shah *et al.* (2018), and Sterk *et al.* (2022) instead, carried out literature reviews focusing on the potential business model innovations driven by the digital technology trends affecting nowadays the global automotive manufacturing environment.

Kaiser *et al.* (2018) and Mahdavian *et al.* (2019) studies explore the impact of CAV in the future, considering the ecosystem that has to be created around them to safely exploit the emerging opportunities. Only Taiebat *et al.* (2018) conduct a literature review to assess the environmental interaction and impacts of CAVs, with their positive and negative impacts.

A noteworthy point is the existence of one article within the category of "others", published in 2015. Piccinini *et al.* using the Delphi method asked a group of 35 automotive experts to assess the impact of digital transformation in automotive organizations in the future, with a focus on the possible new nuances of business models and the way in which the OEM companies gather value thanks to their developed Connected Cars.

2.3.3. Paper Content

This section aims at providing an exhaustive overview of the key topics discussed in the selected papers regarding Connected Cars and related benefits. The ultimate goal of the following analysis is to identify potential areas for further exploration, potentially through quantitative analysis, and to add unique insights to the existing literature. In order to maintain a rational and objective approach, a classification scheme was applied to all the collected papers. No existing classification was suitable for our innovative examination of the benefits of Connected Vehicles, so a custom clustering method was crafted. It is important to note that the classification was not determined beforehand but rather adjusted after reviewing the research and content of the papers to provide a comprehensive framework for understanding all the papers.

Despite this, the authors found a recent scientific article by Sterk *et al.* (2022) that conducted a literature review on "Data-Driven Business Models in the Connected Car Domain." This work analyzed the existing body of literature on the data-driven business models in the Connected Car context and structure it according to four dimensions: value proposition, value architecture, value network, and value finance. Inspired by this literature review, which focuses on a sub-topic related to Connected Cars (only data-driven business models), section 2.3.3.2 replicates a similar categorization of the selected papers, expanding the scope to all topics related to connected vehicles.

2.3.3.1. Connected Car Definition

In the first chapter, the authors presented some definitions of Connected Car, but it is interesting and worthy to see and classify the different definitions of “Connected Cars” provided by the selected sample of scientific papers. In this way, it is possible to get a comprehensive snapshot of all the different standpoints regarding the topic of connected vehicles, without missing any aspect.

Within the selected sample, some papers propose their own definition for "Connected Car" (or “Connected Vehicle” or “Connected and Automated Vehicle”), while others do not propose a new definition but rather adopt a conceptualization crafted from previous works. Among the 81 selected studies, only 20 provide a definition, as Table 3 reports.

Author(s)	**Year**	**Defintion**
Andersson and Mattson	2015	The Connected Vehicle case concerns a fairly new process leading to the emergence of systems in which cars and trucks increasingly become connected to the internet and to wireless networks.
Bohnsack *et al.*	2021	Connected cars—referring to cars being connected to the internet and the associated applications, such as emergency assistance systems or remote parking—originate from telematics, a field at the intersection of vehicle technologies with telecommunications, computer science, and electrical engineering.
Cao *et al.*	2021	Intelligent connected vehicles (ICVs) are a new type of vehicles which integrate navigation, autonomous driving, digital info-entertainment systems and mobile communication technologies.
Coppola and Morisio	2016	The connected car is a vehicle capable of accessing the Internet, of communicating with smart devices as well as other cars and road infrastructures, and of collecting real-time data from multiple sources.
Genders and Razavi	2016	The foundation of Connected Vehicle is the ability for vehicles to establish ad-hoc, wireless communication networks. Connected vehicles use wireless communication technologies to collect, transmit, and receive pertinent transportation information such as vehicle position, velocity, and travel time.
Halder *et al.*	2020	The connected vehicle is one of the applications of Internet of Things, that has transformed the driving experience of customers. Connected vehicles provide high levels of safety and comfort. The vehicle is able to anticipate the current traffic condition due to the enhancement in the degree of automation, that has led to the reduction in the workload of the driver. The automobile companies are manufacturing vehicles having advanced driver assistance.
He *et al.*	2019	Connected vehicles uses vehicle to everything (V2X) communication technology to communicate with other road users and networks, including V2V, V2P and V2I.
Jadaan *et al.*	2017	A Connected Car may therefore be defined as “the presence of devices in an automobile that connect devices within the car/vehicles together or with devices, networks and services outside the car including other cars, home, office or infrastructure.
Karmanska *et al.*	2021	A conneceted car can be defined as a new form of the vehicle that combines ICT technology with automobiles.
Kim *et al.*	2019	CAVs mean a vehicle that provides a connection with another vehicle or an urban traffic control system
Lu *et al.*	2014	Connected vehicles on the go are proactive, cooperative, well informed, and coordinated and will pave the way for supporting various applications for road safety (e.g., collision detection, lane change warning, and cooperative merging), smart and green transportation (e.g., traffic signal control, intelligent traffic scheduling, and fleet management), location-dependent services (e.g., point of interest and route optimization), and in-vehicle Internet access.
Mishra *et al.*	2020	The advances in connected vehicle systems (CVS) allow vehicles to communicate with each other and with infrastructures via wireless communication networks. This technology enables vehicles to detect potential hazards on the road, generate warnings, and assist the driver in taking preventive actions.
Olia *et al.*	2014	Connected vehicle is a new paradigm aiming at developing and deploying a fully connected transportation system that enables data exchange among vehicles, infrastructure, and mobile devices to improve safety, mobility, and adverse environmental impacts of the transportation systems.
Pütz *et al.*	2019	Vehicles that can communicate with each other and with infrastructure to provide information on location, speed etc.

Table 3: Connected Car definitions

Author(s)	Year	Defintion
Shannon *et al.*	2021	CAVs can be defined as the set of vehicles that can facilitate the connection to, and communication with, other vehicles and the surrounding infrastructure, as well as maintaining the ability to perform autonomous functions.
Shah *et al.*	2018	A connected vehicle is a vehicle with technology that enables it to communicate and exchange information wirelessly with other vehicles, infrastructure, other devices outside the vehicle and external networks. An autonomous vehicle is a vehicle that is, in the broadest sense, capable of driving itself without human intervention.
Shin *et al.*	2015	Connected vehicles (CVs) are equipped with onboard technologies to communicate wirelessly with each other, with infrastructure, and with other means of mobility.
Sterk *et al.*	2022	We refer to the connected car as a vehicle capable of accessing the internet, communicating with its ecosystem, and generating and transmitting realtime data.
Swan	2015	The connected car means that vehicles are now part of the connected world, continuously Internet-connected, generating and transmitting data.
Toglaw *et al.*	2018	Vehicles equipped with Internet access, and usually with a wireless local area network in order to share access with other devices inside and outside the vehicle.

Table 3: Connected Car definitions

By analysing these definitions, clear differences and recurring elements emerge. The authors have identified 4 macro-themes present: communication, data, integration, and internet. It is worth pointing out how some papers address more than one theme within the proposed definition. As Figure 2.7 points out, the majority (about 65%) focuses on "communication", which refers to the vehicle's ability to communicate and exchange information with other devices, with the external ecosystem it is part of, through wireless communication networks. The communication technologies embodied in the vehicle enable to "detect potential hazards on the road, generate warnings, and assist the driver in taking preventive actions" (Mishra *et al.* 2020). Around the concept of communication, there is the exchange of information with external entities that allow the vehicle "to collect, transmit, and receive pertinent transportation information such as vehicle position, velocity, and travel time" (Genders and Razavi 2016).

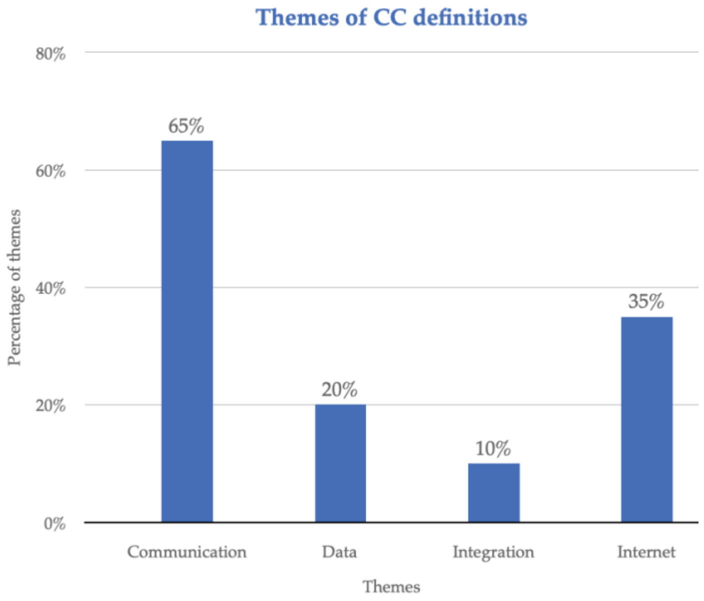


Figure 2.7: Percentage of macro-themes of CC definitions

Other definitions (35%) are based on the theme of the Internet, specifically on the ability of the vehicle to access it, being an application of the Internet of Things. This internet access permits "high levels of safety and comfort" (Halder *et al.* 2020), offering services such as emergency assistance or remote parking (Bohnsack *et al.* 2021).

Other articles (20%) focus on the theme of data, as connected vehicles generate a large amount of data as they are capable of generating and transmitting real-time data (Swan 2015, Sterk *et al.* 2022). Finally, few articles focus on the ability of connected vehicles to "integrate" various functionalities, from "navigation, autonomous driving, digital info-entertainment systems, and mobile communication technologies” (Cao *et al.* 2021).

However, it is important to note that all these different themes are closely interconnected. In fact, the internet is a technology that, among its applications, allows the vehicle to communicate with the outside world, exchanging information and therefore data. One of the most interesting and complete definitions, and therefore often cited by other works, is that of Coppola and Morisio (2016), also presented in the first introductory chapter, which embraces all themes: "The Connected Car is a vehicle capable of accessing the Internet, communicating with smart devices as well as other cars and road infrastructures, and collecting real-time data from multiple sources".

2.3.3.2. Connected Car Benefits Classification

This section aims at classifying the selected papers in clusters based on the type of Connected Car’s benefit they talk about.

Inspired by the work of Sterk *et al.* (2022), which focuses on data-driven business models in the Connected Car domain, the authors replicated a similar classification of the articles, broadening the scope to encompass all topics related to connected vehicles. Sterk *et al.* (2022) reproduced the business model framework proposed by Al-Debei and Avison (2010) and applied it to the domain of the Connected Cars focusing on data-driven business model. This framework encompasses four areas: value proposition, value architecture, value network, and value finance. In line with the purpose of this research work, the authors decided to focus on the first area.

Sterk *et al.* (2022) propose five classes of value proposition that a connected vehicle can offer: safety, convenience, cost reduction, traffic efficiency, and infotainment. Connected vehicles indeed offer various services and features to different stakeholders (e.g., the vehicle owner, passengers, society as a whole...). This classification is significant as it provides a quick snapshot of the most studied clusters in literature, thereby identifying potential areas that are still under development and require further attention in the coming years. Furthermore, the authors decided to create a new category to add to the five value propositions proposed by Sterk *et al.* (2022): environment. Noticing that many articles addressed the issue of environmental impact that a connected vehicle can have, it seemed reasonable to add this category not addressed in the clusters of the framework proposed in the reference paper.

Upon analyzing the content of each article in our sample, each paper was assigned to its respective cluster. It is worth noting that some articles focus on a specific topic, while others discuss more general aspects of connected vehicles and thus one paper may belong to multiple classes.

Before entering the detail of each cluster, it is worth providing a brief explanation of each one (Sterk *et al.* 2022):

- *Safety*: connectivity enables a multitude of opportunities to enhance both vehicle and traffic *safety*. The first concept of Connected Car, General Motors' OnStar, aimed to reduce fatal accidents on the roads and indeed the primary goal of adopting Connected and Automated Vehicles (CAVs) is to minimize collisions and resultant fatalities.
  Many studies emphasize the importance of detecting driving styles as a means to promote safer and more conscious driving practices. One of the most frequently cited safety-enhancing services is the intelligent emergency call (eCall) system. In the event of a collision, eCall automatically initiates contact with an emergency response center and conveys the location of the vehicle along with relevant information such as the time of the accident and the type of vehicle involved. Predictive Maintenance, Driver Fatigue Detection, and Remote Diagnostics are other examples of Connected Car services aimed at reducing and avoiding collisions.
- *Convenience*: connected vehicle services also aim at making driving easier and hassle-free for the driver, facilitating the most complicated and annoying operations (e.g., parking). It is even possible to consider the Connected Car as an extension of one's home from which performing many tasks remotely such as setting and programming the heating of the house is very easy (Barron 2021). Therefore, CC services also enhance the overall driving and vehicle usage experience. For example, BMW offers remote services such as vehicle locking and unlocking, displaying the vehicle's location via an app, and remotely controlling the vehicle's climate system. In 2014, Volvo tested a service that went even further by utilizing remote keyless entry for digital food delivery into the car. Another example of a *convenience* benefit is Over-the-air updates

and upgrades which ensure the vehicle is always revised with the latest software update without the need of bringing the car to a dealership.

- *Cost Reduction*: connectivity on board also ensures monetary benefits for consumers, OEMs, and third-party companies, such as improved fuel efficiency, automated payment systems for road tolls, usage-based insurance (UBI), or fleet management solutions.
- *Traffic Efficiency*: inter-vehicular communication and communication between vehicles and the road network can have a positive impact on *traffic efficiency*. An illustrative example of this is platooning, where vehicles can communicate to decrease the distances between them, leading to increased road capacity, reduced traffic congestion, and the creation of more non-road spaces for pedestrian walkways, cycling lanes, parks, and other similar amenities. Other applications like dynamic routing, real-time traffic updates, and parking assistance help to decrease travel time. Then, a prominent example of this is the Google Maps app, where users share their personal data through their smartphones, while also using aggregated real-time traffic information from other users for navigation purposes.
- *Infotainment*: CC services can also enhance the driving experience by providing *infotainment* (a combination of information and entertainment) features. Drivers and passengers can integrate their smartphones with the vehicle, allowing them to enjoy music and videos during the journey. Modern vehicles' *infotainment* systems already have a wealth of applications, including music and video streaming, internet access through an in-car hotspot, and integration with in-car smartphones. Examples of the latter include third-party options like Google Android Auto and Apple CarPlay, which allow the driver to use smartphone apps through the car's head unit.
- *Environment*: CAVs usage can also have a positive impact on the *environment*. Connected cars can indeed suggest fuel-efficient routes to the driver based on traffic information or offer eco-driving modes that can significantly reduce fuel consumption and related CO_2 emissions (such as the Start and Stop function).

2.3.3.2.1. Safety

Connected cars have the potential to significantly improve road safety. According to a report by the National Highway Traffic Safety Administration (NHTSA), Connected Cars can reduce the number of crashes caused by human error, which is a major factor in more than 90% of road accidents. Toglaw *et al.* (2018) reported that, approximately, 1,2 million people are killed every year due to human error in car accidents. The primary goal of adopting Connected, and Automated Vehicles (CAVs) is to minimize collisions and resultant fatalities, by enhancing vehicle safety.

Connected vehicles can indeed improve road safety by enabling advanced driver assistance systems (ADAS). An example of these systems is the so-called "Lane Assist", which uses a camera located near the internal rear-view mirror and behind the windshield to detect and recognize the solid and dotted lines on the road surface, determining the lane in which the vehicle is traveling (Arena *et al.* 2020). Coppola and Morisio (2016) described this same system (under the different name of Lane Keeping and Departure Warning systems) as a means of preventing drivers from veering off the correct trajectory, "with the aid of cameras detecting lane markings ahead and in the meantime interpreting eye and head dynamics to predict the driver's intention to change direction".

Another ADAS is the adaptive cruise control (ACC), which serves as a convenient electronic tool, particularly while driving on highways. The ACC operates by maintaining a constant speed while respecting a pre-determined minimum distance between the vehicle and the one in front of it. The system is considered adaptive as it automatically adjusts the speed of the car to match that of the leading vehicle (Arena *et al.* 2020).

Shelly (2015) reported that in 2014, on the US roadways, more than 3.300 deaths could be attributed to driver distraction issues. Among their benefits, Connected Cars sensors aim at preventing distracting situations by alerting drivers to potential hazards and taking action to avoid them. The use of connected vehicle technology to detect and respond to driver fatigue has been proposed as a promising solution to this problem. The technology can utilize various sensors and data analysis techniques to monitor the driver's behavior and physical states, such as their eye movements, heart rate, and body temperature. If the system detects signs of fatigue, it can alert the driver or even take control of the vehicle to prevent an accident. An example of these systems is the so-called Driver Fatigue Detection service: the car detects if the driver is falling asleep and takes corrective actions (Athanasopoulou *et al.* 2019). Therefore, the ability to identify and respond to driver fatigue through connected vehicle technology has the potential to greatly improve road safety and reduce the number of accidents caused by fatigue. This highlights the importance of incorporating such technology into future vehicles to ensure the safety of drivers and passengers on the road (Swan 2015).

The implementation of vehicle communication has the potential to greatly improve road safety by providing real-time information about accidents and enabling faster and more effective responses. In turn, this can lead to more efficient rescue efforts and potentially save lives. Furthermore, vehicle communication can also be used to monitor the vehicle's performance and identify potential issues before they lead to accidents, further increasing road safety. The ability of vehicles to communicate is indeed a key aspect of road safety. By transmitting vehicle data to original equipment manufacturers (OEMs), vehicle communication enhances customer safety. As pointed out by Bosler *et al.* (2017), in the event of an accident, specific information is transmitted to the emergency call center of the OEM, allowing for necessary actions to be taken based on that information, such as triggering an emergency call (eCall) or activating a breakdown service. To highlight the benefit of the eCall systems, Coppola and Morisio (2016) cited a 2013 study by the European Commission which estimated that promptness in making emergency calls can save up to 2.500 lives every year in Europe alone. Kaiser *et al.* (2017) pointed out the example of the Intelligent Emergency Call of BMW ConnectedDrive (*"BMW Connected is a personal mobility assistant which facilitates everyday mobility and assists drivers in reaching their destinations relaxed and on time"*): whenever an airbag is deployed, the BMW Call Centre is contacted via an accident-proof telephone unit (pre-installed in the vehicle) and the precise location of the car is communicated, including relevant accidental data.

Martens and Mueller-Langer (2020) discussed the privacy issues regarding the emergency call. In the EU, the mandatory eCall emergency road assistance system for drivers was introduced in accordance with Regulation EU 758/2015. In fact, from March 31, 2018, in the European Union manufacturers must install the eCall system in all new models of passenger cars and light commercial vehicles. In the event that the driver does not react after a serious accident event, the eCall system automatically issues an emergency call (Pütz *et al.* 2019). This has led to quicker implementation of telematics capabilities in vehicles from 2018 onwards. However, to safeguard drivers' privacy, the data transfers made through eCall are strictly restricted to only what is necessary for emergency services and determining the location.

Moreover, the car can communicate also with other vehicles, alerting them about possible dangers. For instance, Nielson *et al.* (2019) reported that when a connected vehicle detects an accident on the road or a hazardous situation, such as reckless driving or adverse weather conditions, it can alert other nearby vehicles to slow down or take appropriate action to avoid damage or collisions.

Kaiser *et al.* (2021) emphasized how connectivity enables the possibility to develop data-driven services. The collection of data onboard vehicles can indeed provide valuable information to the car manufacturer for advanced diagnostics and detection of malfunctions with the so-called Predictive Maintenance and Remote Diagnostics systems (Athanasopoulou *et al.* 2019, Goikoetxea-Gonzalez *et al.* 2022, Rahman and Tadayoni 2018 and Sterk *et al.* 2020). Coppola and Morisio (2016) observed how this information can help prevent unexpected car breakdowns and provide timely assistance to drivers. Llopis-Albert *et al.* (2021) pointed out how Predictive Maintenance is enabled by the car's intelligent components and ubiquitous connectivity which allow certain parts to send a signal when they need maintenance or replacement. Another analogous benefit is what Sterk *et al.* (2020) called the "Service Reminder" system, as Connected Cars offer the significant advantage of being able to alert customers and service dealerships to poor and failing performances in the vehicles (Andersson and Mattsson 2015).

Additionally, in the event of theft, CC support certain actions such as blocking the car or contacting the authorities, to protect the vehicle (e.g., Stolen Vehicle Recovery System, Toglaw *et al*. 2018, Swan 2015).

The work of Olia *et al.* (2014) aimed to thoroughly quantify the potential impacts of connected vehicles on three key areas: mobility, safety, and the environment. The focus of the study was on micro-modeling and quantifying these impacts, particularly in non-recurrent congestion scenarios such as accidents, lane closures, and construction work zones. Regarding safety, Olia *et al.* (2014) developed a sophisticated modeling framework using traffic micro-simulation techniques. This framework was designed to accurately imitate the communication between Connected Cars and simulate their behavior in various congestion scenarios. To quantitively assess safety benefits, they used a Time to Collision (TTC) indicator (converted then in a probability of an accident), which is defined as the time left to collide between two following vehicles if the relative speed remains constant, taking into consideration also the market penetration of CC. The results of this work indicate a strong positive relationship between the penetration rate of connected vehicles and the safety index. The study found that as the number of connected vehicles on the road increases, the safety index improves by 45% (as depicted in Figure 2.8 on the next page). This confirms that connected vehicles, equipped with Vehicle-to-Vehicle (V2V) communication technology, are capable of avoiding sudden evasive movements, taking alternate routes to avoid congestion, and preventing sudden breaks and lane changes. The communication between vehicles also enables them to receive information about downstream hazards such as construction zones and accident areas, which increases the awareness of drivers and reduces their likelihood of aggressive behavior. This increased awareness and decreased aggressiveness lead to an improvement in road safety and a reduction in the probability of accidents.

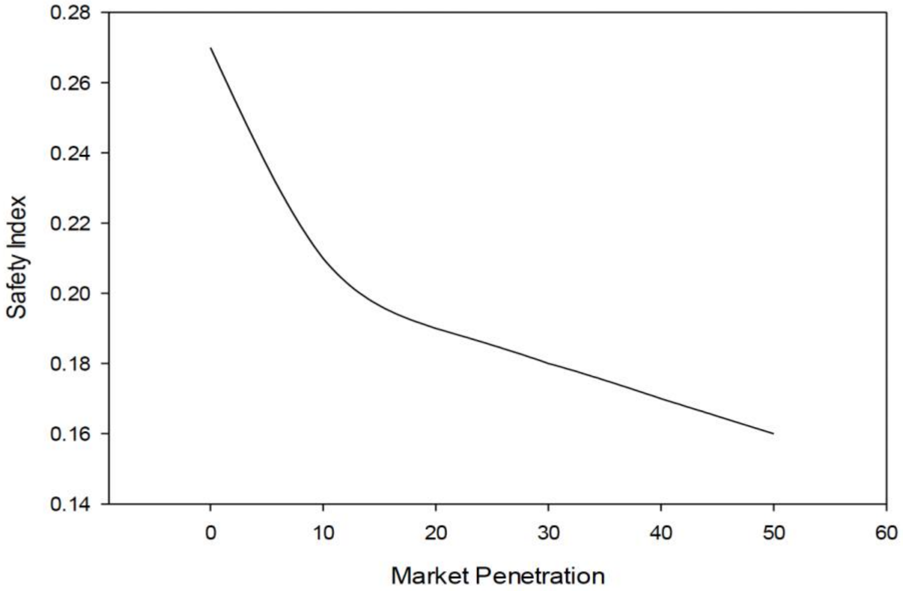


Figure 2.8: Impact of Connected Vehicles' Penetration on Safety Index (Olia et al. 2014)

In some other papers, the authors tried to ask directly to consumers and professionals in the automotive industry which are the most relevant benefits of Connected Vehicles. Kim *et al.* (2019) conducted a survey to assess the differences in perception regarding the benefits and concerns of connected vehicles among 98 individuals on the demand side and 46 experts on the supplier side. The results showed that safety was the most important benefit and concern for both groups, although the priority given to different benefits varied between individuals and experts. Karmanska (2021) conducted a similar survey to determine the top benefits of connected vehicles as perceived by respondents. The results indicated that the top-ranked benefit was in the area of safety and navigation, with a mean score of 4,25 (the answers could range from 1, “strongly disagree”, to 5, “strongly agree”). The second highest benefit was location and condition monitoring of the vehicle, with a score of 4,19. Conversely, the least important benefits were environmental aspects and access to the Internet and the possibility of working while driving, both with scores of 3,61 and 3,79, respectively.

2.3.3.2.2. Convenience

As reported by Deryabina and Trubnikova (2021), entertainment and convenience are becoming crucial factors for consumers as they are seeking a comprehensive service that goes beyond just the simple purchase of a vehicle. This shift in customer expectations highlights the importance of providing a well-rounded, enjoyable customer experience that meets the changing needs of today's consumers. Connected cars offer indeed a range of convenience benefits that enhance the driving experience and make it more comfortable and hassle-free. Arena *et al.* (2020) proposed an interesting standpoint towards connected vehicles: the car is losing, at least in part, "its status symbol function and will be transformed from a means of transport into an extension of the living space". They defined future smart cars as a sort of "protective bubble to escape from the chaos of surrounding environment", where you can work, relax and socialize.

Many papers report the ability of Connected Cars to perform many services from distance (defined as "remote services" by Sterk *et al.* 2022). For instance, drivers can remotely unlock their cars, check the status of batteries in electric cars, and find the location of the car (Andersson and Mattson 2015, Athanasopoulou *et al.* 2019 and Mikusz *et al.* 2015). Kaiser *et al.* (2017) point out BMW ConnectedDrive's ability to lock and unlock the vehicle, indicating the vehicle's location by honking the horn or flashing the lights, and activating the vehicle's climate control immediately or on schedule.

Park *et al.* (2019) and Coppola and Morisio (2016) also observed the integration of connected vehicles with smart home functionalities. For instance, "on the way home from work, passengers can check whether the air conditioning at the office has been turned off, turn on the air conditioning at home, and remotely control a rice cooker to have it finish cooking around the time they arrive home" (Park *et al.* 2019). Coppola and Morisio (2016) highlighted two examples of automobile manufacturers working for integration with smart home environments. Ford, for instance, has established a connection between the steering wheel and Amazon's Alexa, providing access to devices on the platform such as garage doors and lighting systems. Mercedes-Benz instead has become part of Nest's developer platform, enabling drivers to control the heating systems in their homes while operating their vehicles. Deryabina and Trubnikova (2021) highlighted how the car's integration with IoT enhances the personalization of the experience as the consumer can integrate all her mobile devices into the car. Coppola and Morisio (2016) also mentioned the integration of the vehicle with wearable devices in order to obtain smarter and safer mobility services (e.g., wearable devices can be effectively used for the detection of driver fatigue and drowsiness). They reported the example of Ford which presented the integration of augmented vision glasses with its cars alongside systems monitoring blood sugar levels and heart rate of the driver through information gathered from smartwatches.

Connected Vehicles let do actions through voice command, for instance, the so-called "hands-free calls" (Athanasopoulou *et al.* 2019). OEMs nowadays provide specific interfaces that ensure hands-free control for many car subsystems as climate management, music selection, voice calls, and message reading if a smartphone is connected (Coppola and Morisio 2016).

Another key convenience benefit of Connected Cars is their ability to improve the parking experience. CC can indeed provide maps of available parking spots based on real-time information (Coppola and Morisio 2016). Kaiser *et al.* (2017) reported the example of Mercedes me' service of Daimler Group with its "Parked Vehicle Locator": from the mobile app, you can easily see where you parked the vehicle. Athanasopoulou *et al.* (2019) mention also a possible CC service, the Parking Spot Locator which enables you to see from the in-vehicle monitor where you can find an available parking lot for your car.

Among the selected papers, a few articles presented another convenience benefit enabled by vehicle connectivity: Over-the-air (OTA) updates. This procedure lets to update of the software embodied in the vehicle completely remotely, without the need of bringing the vehicle to the dealership (Andersson and Mattsson 2015, Athanasopoulou *et al.* 2019). This leads to higher customer satisfaction, lower maintenance expenses, quality refinement, and, last but not least, a rise in sales for OEMs without too much cost (Efstathiadis *et al.* 2021). OTA procedure to install the software in an ECU (Electronic Control Unit) offers the most convenient, fastest, and cost-effective mode of delivering software updates to vehicles, ensuring saving the visiting time of the customers for rectifying trivial bugs in the software (Ghosal *et al.* 2022). Therefore, the digitalization of vehicles avoids also costly recalls for the manufacturers (Bosler *et al.* 2017).

Vehicle lifecycle data can be used to enable a broad portfolio of value-added consumer services including concierge services (Stocker *et al.* 2017). By concierge services, the driver can receive remote and location-independent assistance around the clock, among others enabled by interlinked and intelligent vehicular sensors and actuators, and eventually brought out by specialized service providers (e.g., hotel booking, etc.).

Kaiser *et al.* (2017) brought the example of BMW ConnectedDrive's concierge services. The vehicle's owner can select travel destinations and get information, connect with call-center agents to look for the nearest services or to book services, and the addresses are sent directly to the navigation system.

2.3.3.2.3. Cost Reduction

Connected cars offer significant cost reduction benefits for various stakeholders in the automotive industry. Starting from the consumers' standpoint, Connected Cars can reduce maintenance costs by providing real-time information about the vehicle's health, enabling predictive maintenance, which can prevent breakdowns and costly repairs. Goikoetxea-Gonzalez *et al.* 2022 motivate the cost reduction benefit ensured by CC by the fact that connected vehicles are IoT devices that can remind and alert the owner to perform a certain maintenance activity. In this way, the car keeps always working well reducing the possibility of vehicle breakdown.

Goikoetxea-Gonzalez *et al.* 2022 also mention that fuel consumption is enhanced. Indeed, Connected Cars can improve fuel efficiency by optimizing driving patterns and reducing unnecessary idling, leading to lower fuel consumption and cost savings. Many papers recall the Eco Driving modality embodied in most of the Connected Cars. Mikusz and Herter (2016) suggests that vehicle-to-vehicle communication enables the “eco-driving analysis function” by which people can compare their driving behavior with other drivers and optimize it, to get fuel-saving recommendations (using sensor data). Coppola and Morisio (2016) highlight that the interfaces between electric vehicles and smart homes, along with vehicle-to-home (V2H) communication systems, can enable to program of cost-effective charging and discharging schedule for the vehicle.

Always looking at the consumers’ benefits, Deryabina and Trubnikova (2021) report that Connected Car customization enables consumers to design individual vehicles resulting in an increase in the car service life of the latter and in a reduction of the car replacement cost.

Nikitas *et al.* 2019 report another interesting economic benefit deriving from CC usage. Connected Vehicles' benefits result in significant time savings and, moreover, “people can use the in-vehicle time to do productive activities instead of driving” with a consequent productivity gain for vehicle owners and users.

Coppola and Morisio (2016) propose another cost benefit for consumers, “algorithm-based vehicle pricing”. Connectivity can indeed enable to price used cars with an evaluation based on “a set of dynamic information that accurately describes the vehicle (in a more detailed way than the simple count of traveled kilometers can do). This way, the buyer of the car can make a better-informed choice”.

Many papers mention the insurance based on personalized data, also known as Usage-Based Insurance (UBI), enabled by connectivity (Athanasopoulou *et al.* 2019, Coppola and Morisio 2016, Deryabina and Trubnikova 2021, Kaiser *et al.* 2017, Kaiser *et al.* 2018, Karmanska 2021, Martens and Mueller-Langer 2020, Mikusz and Herter 2016, Mikusz *et al.* 2015, Pütz *et al.* 2019, Remane *et al.* 2016, Stocker *et al.* 2017, Toglaw *et al.* 2018). This kind of insurance provides insurance policies and alternative options based on a driver's on-road behaviors and movement frequency. As reported by Karmanska (2021) connectivity can indeed allow "the usage of dynamic measures (hour and length of each trip, actual total distance traveled, driving conditions for the area, and driver's ability and behavior, such as speed, acceleration, hard braking, phone use while driving), to determine motor insurance policy premium". To perform this kind of insurance, information needs to be collected by "black-boxes, OBD dongles, and contemporary smartphones" (Coppola and Morisio 2016).

Moreover, the application of Usage-based insurance (UBI or "Pay-as-you-go" insurance, Athanasopoulou et al. 2019) has been found to establish a closer link between driving habits and insurance premium rates for motor insurance. Studies have indicated that drivers with UBI policies generally exhibit more cautious driving behaviors, resulting in a noticeable enhancement in road safety standards. This demonstrates that UBI can positively impact the overall improvement of road safety by promoting safer driving practices (Karmanska 2021).

Connected Vehicles offer several cost reduction benefits also to organizations. Connectivity enables transmitting and receiving data. This data can be used to improve the efficiency and safety of fleet management operations carried out, for instance, by shared mobility operators (Andersson and Mattson 2015, Athanasopoulou *et al.* 2019, Stocker *et al.* 2017). CC can provide real-time information on vehicle location, status, and maintenance needs, as well as driver behavior and safety data. This information can be used to optimize fleet routing and reduce fuel consumption. Furthermore, the data collected from Connected Cars can be integrated with other fleet management systems, such as asset management and maintenance tracking, to provide a comprehensive view of fleet operations. Karmanska (2021) investigates the main advantages of fleet management systems within an organization and reports that "purchasing, placement, and maintenance of the fleet and allows businesses in a variety of industries to keep track of their fleet in a convenient and cost-effective manner".

Contreras-Castillo *et al.* (2018) highlight the economic benefits of the application of the Internet of Vehicle solutions reporting the study of Cisco IBSG Automotive and Economics (2011) which quantified the monetary benefits (per year) for several stakeholders:

- Vehicle owner/ user: $550 USD due to lower insurance rates, lower operation costs, and less time spent in traffic.
- Society: $420 USD from reduced expenses related to traffic management, accidents reduction, improved control of traffic congestion, and a decrease in CO_2 emissions.
- IoV Service Providers: around $160 USD through traffic guidance, navigation, emergency services, and location-based services.
- OEMs: they could save around $300 USD through lower service/ warranty costs and new profit pools amortized over eight years.

Moroever, regarding OEMs, Halder *et al.* (2020) report that by using Over-the-air updates to solve vehicle software bugs, automakers will save $35 USD billion in 2022, up from $2,7 USD billion in 2015.

2.3.3.2.4. Traffic Efficiency

Communication between the vehicles themselves and the road network has a positive impact in terms of traffic efficiency. A concrete example of this is what is known as platooning (Adler *et al.* 2019, Auld *et al.* 2017, He *et al.* 2019, Kuang *et al.* 2018, Kuang *et al.* 2019, Lioris *et al.* 2017, Mahdavian *et al.* 2019, Makridis *et al.* 2018, Martin-Gasulla *et al.* 2019, Neufville *et al.* 2022, Taiebat *et al.* 2018): by communicating cars can reduce the distances between them, increasing road capacity, reducing traffic jams, and allowing more non-road spaces which then can be converted into more pavements, cycle lanes, parks, etc.

He *et al.* (2019) state that platooning has a large potential of increasing traffic capacity and fuel efficiency by employing a short vehicle space. The vehicles in the platoon move at a consistent speed and maintain the desired spacing. Adler *et al.* 2019 cite a study by Boston Consulting Group that estimate that platooning on highways can increase capacity by up to 500%. Mahdavian *et al.* 2019, beyond pointing out the several benefits deriving from platooning, such as the capacity expansion of the roads with consequently reduced congestion and pollution emissions, present a possible further risk introduced by platooning: increased crash severity.

Bahaaldin *et al.* (2017) realize a quantitative study to assess the impact of CV technologies on traffic performance during no-notice evacuation events. The study compares the average speed, average delays, and total delays. The evaluation of these performance measures results that the presence of 30% of Connected Vehicles could significantly reduce evacuation traffic delays, compared to a scenario with no-CV.

Kuang *et al.* 2018 state that a reduction in average travel time by up to 36.28% and an increase in average travel speed by up to 56,65% may be achieved with Connected Car technologies, assuming that all the running vehicles on urban roads are equipped. Nevertheless, the effects are much smaller on highways and rural roads, owing to the similarity between their real traffic flow and free flow scenario. Olia *et al.* (2014) quantitively analyzed that connectivity between vehicles can improve corridor travel times by up to 37% by providing more informative routing choices to drivers.

Coppola and Morisio (2016) report that CC can provide navigation information also presented on a "contact analog head-up display, thus presenting augmented reality information in the driver's principal sight and therefore avoiding distracting her from driving". The same study highlights that vehicle-to-infrastructure (V2I) communication technologies can be leveraged to gather information (anonymously, by every car on the road) about position, speed, and points of origin and destination of cars, and to send them to other applications in order to prevent road congestions.

Many papers present another traffic-related benefit enabled by connectivity: dynamic routing (Dimitrakopoulos 2011, Genders and Razavi 2016, Grieger and Ludwig 2019, Mikusz *et al.* 2015, Mikusz and Herter 2016, Mikusz *et al.* 2017, Neilson *et al.* 2019). Dynamic routing features in modern Connected Cars offer a range of benefits for drivers. By utilizing real-time data on traffic, road closures, and construction sites, these systems can provide drivers with optimal routes, reducing travel time and improving fuel efficiency. Additionally, dynamic routing systems can help drivers avoid accidents and hazards, further improving safety on the road. One of the key advantages of this technology is its ability to adapt to changing conditions and update routes accordingly, ensuring that drivers always have the most efficient and effective route to their destination. As such, dynamic routing features have the potential to revolutionize the way we navigate our roads, making travel faster, safer, and more environmentally friendly. This kind of feature is enabled by the fact that "Connected Cars are open and linked-up systems that merge the physical and the virtual world" (Mikusz *et al.* 2017).

As stated by Nielson et al. 2019, CV can share traffic conditions to help drivers find the most efficient routes to their destinations. Moreover, emergency vehicles may receive real-time assistance in getting to the needed locations quickly and safely.

Finally, it is worth mentioning that in the survey carried out by Karmanska (2021), The top benefit of Connected Cars, as perceived by the respondents, was navigation and road traffic monitoring.

2.3.3.2.5. Infotainment

Infotainment systems in Connected Cars refer to the various digital technologies and services that are integrated into a vehicle to provide entertainment, information, and communication to drivers and passengers.

The emergence of the current concept of infotainment in cars is often attributed to Ford's introduction of SYNC (Coppola and Morisio 2016), which was a software platform designed for in-vehicle communication and entertainment. It was pre-installed on Ford vehicles and based on Windows Embedded Automotive, allowing third-party developers to build various infotainment systems.

These systems, nowadays, are designed to offer a range of features and functions, such as music streaming, navigation, communication, and multimedia content (Coppola and Morisio 2016).

Coppola and Morisio (2016), comprises also “In-car Wi-Fi networks” and “Social Network” as infotainment services to be offered within a connected vehicle. The former refers to the possibility of recreating Wi-Fi networks with wireless routers installed in the car. The latter, instead, can provide extensive connections between cars and vehicle-to-vehicle communication to allow for social interactions among drivers on the road. This would enable people to share information about their travel plans, connect with similar users, and ask for support when needed. Additionally, they could share experiences through existing social networks such as Facebook, Twitter, and Instagram, which can be integrated into car dashboards (Athanasopoulou et al. 2019).

Infotainment systems typically include a range of hardware components, such as a touchscreen display, speakers, microphones, and sensors, as well as software applications that enable users to interact with the system. Some infotainment systems are also designed to integrate with a driver's smartphone, enabling them to use their preferred apps and services in the car (Andersson and Mattson 2015, Bosler *et al.* 2017, Coppola and Morisio 2016, Martens and Mueller-Langer 2020, Rahman and Tadayoni 2018).

One notable example of software that enables integration with a smartphone is the third-party options of Google Android Auto and Apple CarPlay. These platforms provide drivers with the ability to utilize their smartphone applications through the car's head unit. Android Auto and CarPlay allow for seamless access to popular features such as navigation, music streaming, and messaging, without the need to handle a mobile device while driving. As a result, they are increasingly popular among drivers looking for a more convenient and safer in-car digital experience.

However, the relationships between the OEMs and the mobile operators' industry organizations have to be reconsidered. Indeed, the mobile operators' industry organization has called for business model innovation, noting that the strategic positioning of automakers on telematics and infotainment services is essential in defining their value proposition and business model. Traditionally, automakers have assumed the role of owner and the final customer of the entire process. However, given the greater complexity of forthcoming services and the need for swift deployment, this positioning may need to be rethought. Expanded value chains will be required to create multiple revenue streams. Automakers will need to determine how to pursue their core interests while building the strategic alliances necessary for a fast time to market (Andersson and Mattson 2015).

With the increasing use of infotainment services in Connected Cars, concerns have been raised regarding their impact on driver safety. While these services provide convenience and entertainment, they also introduce distractions that can impair a driver's ability to focus on the road. As pointed out by Coppola and Morisio (2016), various regulations have been put in place to measure and restrict the amount of distraction that in-vehicle infotainment (IVI) systems can cause while driving. The literature has introduced a classification of levels of operations that are required to be performed while driving a vehicle; primary tasks are operations related to car maneuvering, secondary tasks involve actions that are relevant to driver safety, and tertiary tasks refer to all other functions that do not fall under the first two categories. According to this categorization, infotainment applications are classified as tertiary tasks. To address the issue of distracted driving caused by in-car components, the NHTSA has issued design guidelines aimed at reducing distractions while driving.

2.3.3.2.6. Environment

Transportation is a sector that heavily relies on fossil fuels, making it a significant contributor to carbon emissions. In 2021, transportation accounted for 37% of CO_2 emissions from end-use sectors, the highest percentage of any industry. The continued reliance on fossil fuels poses a significant challenge to efforts aimed at mitigating the effects of climate change. The transportation industry must take bold steps to reduce its carbon footprint, such as adopting more sustainable and low-carbon energy sources and transitioning to cleaner modes of transportation.

Olia *et al.* 2014 state that "connected vehicle technology is an innovative and a new paradigm initiated to develop and deploy fully connected transportation system in order to foster safer roads and at the same time improved mobility and green environment". A microscopic model developed by the authors called PARAMICS, led to the results that 50% Connected Cars populated transport network allows to reduce CO_2 emissions from 177 to 124 gram/km. The observed effect has been commented by the authors as not surprising, as connected vehicles have the ability to receive up-to-date travel time information, enabling them to make more informed decisions regarding route selection. This results in several benefits, including improved vehicle speeds, reduced traffic congestion, minimized stop-and-go traffic conditions, and ultimately reduced emission rates and fuel consumption.

Nonetheless, Arena *et al.* (2020) underscored in their study that transitioning entirely to electric vehicles, while a desirable solution for a more sustainable and green future, presents challenges that require thoughtful consideration and resolution. The authors further analyzed the matter and came to the following conclusions. Should electric vehicles replace the current fleet of cars, the distribution network must be able to support the significant energy demand. Furthermore, in rural areas and small towns, residential garages with electrical outlets for recharging vehicles may be more commonplace, while in urban areas, finding adequate charging facilities may be more challenging. To address these challenges, a significant public intervention will be required to improve both renewable energy production and the recharge capacity of the grid. It is worth noting that transitioning to electric vehicles will only be environmentally beneficial if the energy used to power them is produced from renewable sources, rather than simply shifting emissions from the point of use to the point of energy production. On another hand, Taiebat *et al.* 2018 have estimated the environment Connected Cars benefits at the vehicle, transportation system and urban system level. From the first level analysis they grasped that with the use of "partial automation in conjunction with connectivity" fuel consumption can be reduced by 5-7%. At the level of the transportation system, CAV technology can bring environmental benefits through optimized fleet operations, improved traffic behavior, efficient vehicle utilization, and the provision of shared mobility services. Shared mobility and CAV technology have positive and mutual impacts.

At the urban system level, CAVs can reshape cities by altering land-use patterns and transportation infrastructure. This could lead to energy savings, for example, the reduction of street lighting and traffic signals that might become unnecessary under a CAV system. However, the use of radar, sensors, and high-speed internet connectivity for CAVs may increase energy consumption, offsetting the potential gains in energy efficiency.

Regarding the net effect of CAV technology on energy consumption and emissions, it is uncertain whether the increase in vehicle energy consumption due to CAV features will offset the gains in energy efficiency. Nonetheless, if the negative effects are minimized and the positive effects are fully realized, CAV technology has the potential to lead to significant improvements in fuel economy and reductions in emissions (Taiebat *et al.* 2018).

Jiang *et al.* 2017 propose in their work an eco-driving system for an isolated intersection under partially connected automated vehicles (CAV) environment, tested through a microscopic simulation. The simulation results presented confirm that the system can decrease fuel consumption and emissions while also maintaining optimal traffic flow. The results demonstrate that the proposed system has the potential to reduce fuel usage by as much as 58%, lower emissions by up to 33%, and enhance traffic throughput up to 11%.

The validity of this research and the effectiveness of the proposed system are reliant upon the existence of connected and automated vehicles (CAVs) within the traffic network. As the quantity of such vehicles increases, the advantages conferred by the system amplify, with benefits plateauing at an MPR (market penetration rate) of approximately 40%. This implies that the proposed system may be implemented with immediacy, even amidst low MPRs of connected and automated vehicles, and may be executed with greater expediency in real-world traffic relative to analogous applications of connected and automated vehicles. Making a further step in the technology adoption, arriving to the use of connected fully autonomous vehicles (ConFAVs), Neufville *et al.* 2022 investigated the potential of these type of vehicles in providing an environmentally conscious transport solution, by quantifying the results through a simulation procedure applied in England.

The findings indicate that the introduction of a significant number of ConFAVs can result in a notable decline in vehicular delay, with reductions of up to 100% observed. This decrease in delay can correspondingly lead to a considerable reduction in greenhouse gas emissions, holding the promise of a more sustainable road transportation system.

2.3.3.3. Results

At the end of this section, Table 4 lists all the papers selected with the cluster themes they focus on (each paper can threat multiple themes). Moreover, the authors analyzed and reported for each paper whether a quantitative study was carried out.

As pointed out by Figure 2.9, the most recurrent topic in the 81 selected papers is the *Safety* one, with 54 papers (67%) discussing the safety benefits of Connected Cars. The authors explain this by noting that safety topics have always been the hottest in the automotive field. Many papers report data on road accidents that cause the loss of life for many people each year. Therefore, it is logical that the scientific community is mostly focused on analyzing and studying technologies that can limit and reduce fatal accidents on the streets.

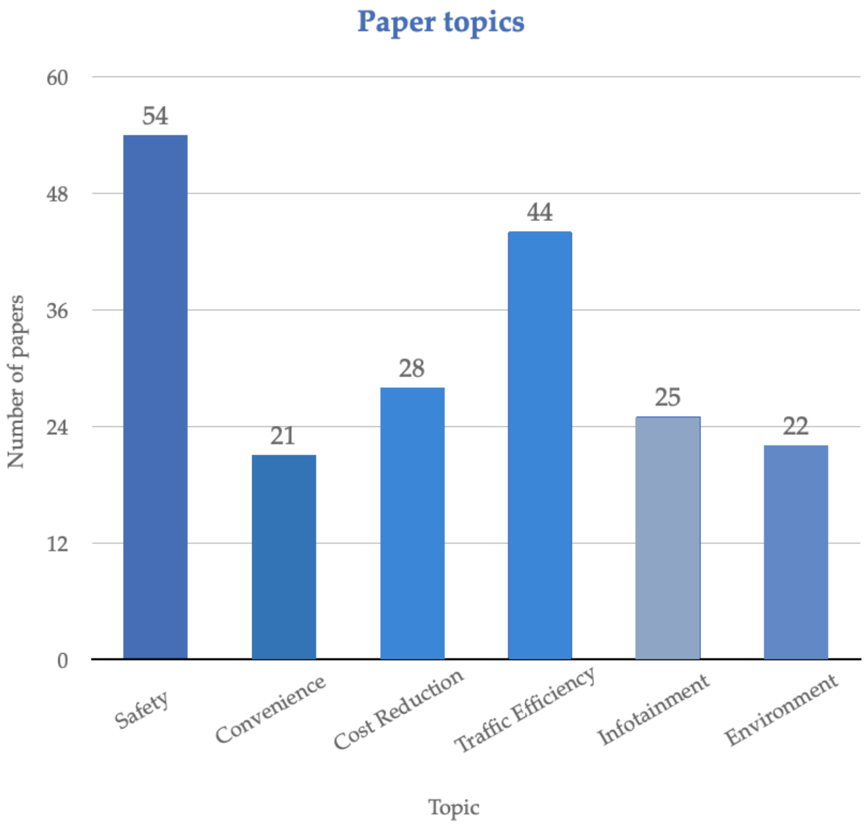


Figure 2.9: Number of papers covering each topic

The second most discussed topic is *Traffic Efficiency* with 44 papers, which translates to a percentage of 54%. Following this, *Cost Reduction* and *Infotainment* are respectively covered in 28 and 25 papers (35% and 31%). *Environment* and *Convenience* are the least discussed topics with 22 and 21 articles. The majority of articles (79%) simultaneously address 1 to 3 themes, while only 21% address 4 or more themes. Only one article (Karmanska 2021) covers all 6 thematic areas. The average for the sample of 81 papers is 2.4 clusters per article. Analyzing the number of papers that offer a quantitative study of the topic, a clear minority emerges with only 21 articles (26%). On the next page, Figure 2.10 illustrates how many quantitative studies are present in the sample divided by thematic area. It is worth noting that two articles, Olia *et al.* (2014) and Neufville *et al.* (2022), simultaneously conduct a quantitative analysis on multiple topics. It emerges that the most discussed topics in order are Traffic Efficiency, Safety, and Cost Reduction (the latter includes some studies that analyze the socio-economic impact of CAV). The thematic areas of Convenience and Infotainment do not have any articles with quantitative analysis.

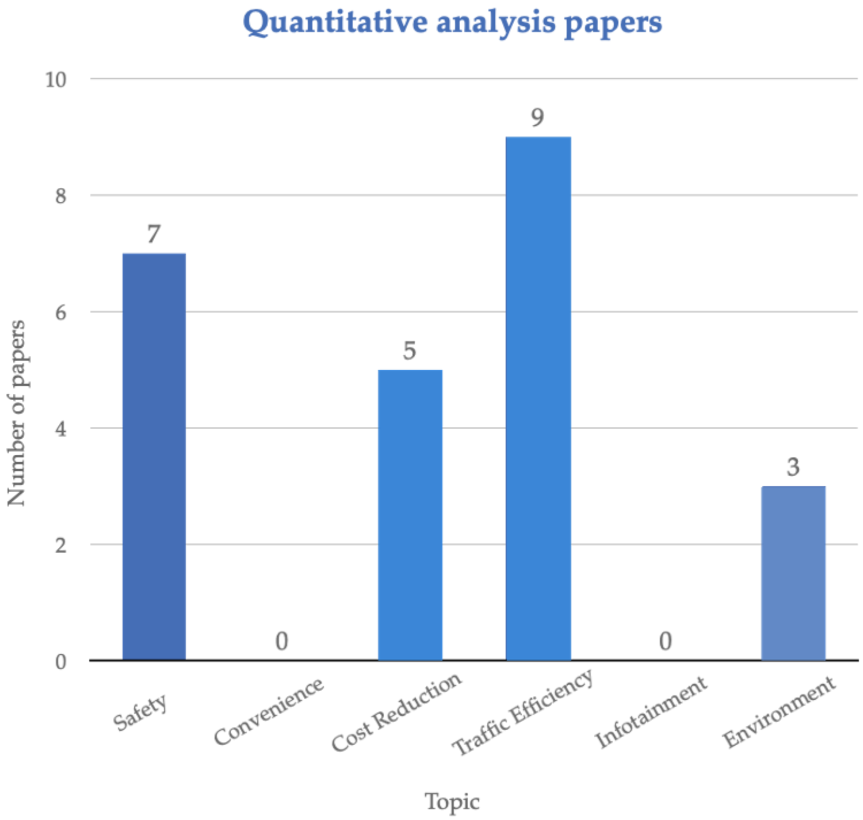


Figure 2.10: Number of papers covering each topic through a quantitative analysis

In Table 4, on the following page, the qualitative or quantitative nature of each of the 81 papers, belonging to the selected sample, is reported along with the classification based on the treated topics.

Author(s) and Year	QNT/QAL	Safety	Convenience	Cost Reduction	Traffic Efficiency	Infotainment	Environment	Σ (✓)
Adler et al. 2019	QAL	✗	✗	✓	✗	✗	✓	2
Andersson and Mattsson 2015	QAL	✓	✓	✓	✗	✓	✗	4
Arena et al. 2020	QAL	✓	✗	✗	✗	✓	✓	3
Athanasopoulou et al. 2019	QAL	✓	✓	✗	✓	✓	✓	5
Auld et al. 2017	QNT	✗	✗	✗	✓	✗	✗	1
Bahaaldin et al. 2017	QNT	✗	✗	✗	✓	✗	✗	1
Barron 2021	QAL	✓	✗	✗	✓	✗	✗	2
Bethaz et al. 2021	QNT	✓	✗	✓	✗	✗	✗	2
Bohnsack et al. 2021	QAL	✗	✗	✓	✗	✗	✗	1
Bolser et al. 2017	QAL	✓	✓	✗	✓	✓	✗	4
Contreras-Castillo et al. 2018	QAL	✓	✗	✓	✗	✗	✗	2
Cao et al. 2021	QNT	✓	✗	✗	✗	✗	✗	1
Chan 2011	QAL	✓	✗	✗	✗	✗	✗	1
Coppola and Morisio 2016	QAL	✓	✓	✓	✓	✓	✗	5
Deryabina and Trubnikova 2021	QAL	✓	✓	✓	✗	✓	✓	5
Dimitrakopoulos 2011	QAL	✗	✗	✗	✓	✗	✓	2
Efstathiadis et al. 2021	QAL	✗	✓	✗	✗	✗	✗	1
Genders and Razavi 2016	QNT	✓	✗	✗	✓	✗	✗	2
Ghosal et al. 2022	QAL	✗	✓	✗	✗	✗	✗	1
Goikoetxea-Gonzalez et al. 2022	QNT	✗	✗	✓	✗	✗	✓	2
Grieger and Ludwig 2019	QAL	✓	✗	✗	✓	✗	✓	3
Halder et al. 2020	QAL	✗	✓	✗	✗	✗	✗	1
Hanelt et al. 2015	QAL	✓	✓	✗	✗	✗	✗	2
He et al. 2019	QAL	✓	✗	✗	✓	✗	✗	2
Hensher 2018	QAL	✗	✗	✗	✓	✗	✓	2
Jadaan et al. 2017	QAL	✓	✗	✗	✗	✗	✓	2
Jiang et al. 2017	QNT	✗	✗	✗	✓	✗	✓	2
Jun et al. 2022	QNT	✓	✗	✗	✓	✗	✗	2
Kaiser et al. 2017	QAL	✓	✓	✓	✓	✓	✗	5
Kaiser et al. 2017	QAL	✓	✗	✓	✗	✓	✗	3
Kaiser et al. 2018	QAL	✓	✗	✓	✗	✓	✗	3
Kaiser et al. 2019	QAL	✗	✗	✓	✗	✗	✗	1
Kaiser et al. 2021	QAL	✓	✗	✓	✓	✗	✗	3
Karmanska 2021	QAL	✓	✓	✓	✓	✓	✓	6
Kim and Yang 2021	QAL	✓	✗	✗	✓	✗	✗	2
Kim et al. 2019	QAL	✓	✗	✓	✓	✗	✓	4
Koch et al. 2020	QAL	✓	✗	✗	✗	✗	✗	1
Kuang et al. 2018	QNT	✗	✗	✗	✓	✗	✗	1
Kuang et al. 2019	QNT	✓	✗	✓	✓	✗	✓	4
Kukkamalla et al. 2020	QAL	✓	✗	✗	✗	✗	✗	1

Table 4: Papers classification by threated topics

Author(s) and Year	QNT/QAL	Safety	Convenience	Cost Reduction	Traffic Efficiency	Infotainment	Environment	Σ (✓)
Lioris et al. 2017	QNT	✗	✗	✗	✓	✗	✗	1
Liu et al. 2018	QAL	✗	✗	✗	✓	✗	✗	1
Llopis-Albert et al. 2021	QNT	✓	✗	✗	✗	✓	✓	3
Lu et al. 2014	QAL	✓	✗	✗	✓	✓	✗	3
Mahdavian et al. 2019	QAL	✗	✗	✗	✓	✗	✓	2
Makridis et al. 2018	QNT	✗	✗	✗	✓	✗	✓	2
Marquez-Barja et al. 2021	QAL	✗	✗	✗	✓	✗	✗	1
Martens and Muller-Langer 2020	QAL	✓	✗	✓	✗	✓	✗	3
Martin-Gasulla et al. 2019	QNT	✗	✗	✗	✓	✗	✗	1
Mathew and Benekohal 2022	QNT	✓	✗	✗	✗	✗	✗	1
Mayer and Siegel 2015	QAL	✓	✗	✗	✓	✗	✓	3
Mikusz and Herter 2016	QAL	✓	✓	✓	✓	✗	✗	4
Mikusz et al. 2015	QAL	✓	✓	✓	✓	✗	✗	4
Mikusz et al. 2017	QAL	✓	✓	✓	✓	✗	✗	4
Mishra et al. 2020	QNT	✓	✗	✗	✗	✗	✗	1
Neilson et al. 2019	QAL	✓	✗	✗	✓	✗	✓	3
Neufville et al. 2022	QNT	✗	✗	✗	✓	✗	✓	2
Nikitas et al. 2019	QAL	✓	✗	✗	✓	✗	✓	3
Olia et al. 2014	QNT	✓	✗	✗	✓	✗	✓	3
Park et al. 2019	QAL	✓	✓	✗	✗	✓	✗	3
Petry and Moormann 2020	QAL	✗	✓	✗	✗	✗	✗	1
Piccinini et al. 2015	QAL	✗	✗	✗	✗	✓	✗	1
Pütz et al. 2019	QAL	✓	✗	✓	✗	✗	✗	2
Rahman and Tadayoni 2018	QAL	✓	✗	✗	✗	✓	✗	2
Remane et al. 2016	QAL	✗	✗	✗	✗	✓	✗	1
Schellekens 2022	QAL	✓	✗	✗	✗	✓	✗	2
Shah et al. 2018	QAL	✗	✗	✗	✗	✓	✗	1
Shannnon et al. 2021	QNT	✓	✗	✓	✓	✗	✗	3
Shelly 2015	QAL	✗	✗	✗	✗	✓	✗	1
Shin et al. 2015	QAL	✓	✗	✗	✓	✗	✗	2
Sinha et al. 2020	QNT	✓	✗	✗	✗	✗	✗	1
Soley et al. 2018	QAL	✓	✗	✓	✗	✓	✗	3
Sterk et al. 2022	QAL	✓	✓	✓	✓	✓	✗	5
Sterk et al. 2022	QAL	✓	✓	✓	✓	✓	✗	5
Stocker et al. 2017	QAL	✓	✓	✓	✓	✗	✗	4
Swan 2015	QAL	✓	✓	✓	✓	✓	✗	5
Taiebat et al. 2018	QAL	✓	✗	✗	✓	✗	✓	3
Toglaw et al. 2018	QAL	✓	✓	✓	✓	✗	✗	4
Yang et al. 2014	QAL	✓	✗	✗	✗	✗	✗	1
Zhao and Kockelman 2018	QNT	✗	✗	✗	✓	✗	✗	1
Zhao et al. 2020	QAL	✗	✗	✗	✗	✓	✗	1
Tot		***54***	***21***	***28***	***44***	***25***	***22***	

Table 4: Papers classification by threated topics

2.4. Phase 3: Future Directions

The authors conducted this literature review with the utmost thoroughness as possible in order to provide a comprehensive overview of the benefits of Connected Vehicles, which is a high novelty topic.

The review accurately represents the current state-of-the-art in the field and identifies areas that require further research and exploration. Specifically, the publication years of the articles included in the sample demonstrate a clear upward trend in the topic of Connected Cars, highlighting the growing interest of the research community over time. Upon analyzing the diverse research methodologies utilized in the sample of 81 papers, as delineated in section 2.3.2 of this chapter, it is discernible that a considerable proportion of the studies were conducted through qualitative research methods such as "conceptual framework" and "case study," which collectively account for 36% of the sample. As a result, a conspicuous deficiency in the literature pertaining to quantitative research is noticeable, with the latter representing a mere 26% of the analyzed articles.

The literature review revealed that the research community mainly focuses on vital mobility issues, including vehicle safety and reducing traffic and CO_2 emissions. However, as reported by many articles, smart cars are no longer merely a means of transportation but are increasingly becoming a true "extension" of the home, with various types of comfort services. Notably, the literature review exposes a significant gap in the quantification of time and cost benefits of *Convenience* and *Infotainment* services enabled by Connected Cars. This deficiency is particularly evident regarding Over-the-air updates, a recurring *Convenience* topic, with three articles published in the last three years (Halder *et al.* 2020, Efstathiadis *et al.* 2021, and Ghosal *et al.* 2022). None of these articles provided a quantitative analysis of the benefits that Over-the-air updates can offer to the consumer (the vehicle owner), and therefore the authors deem this gap to be significant and potentially intriguing to explore, given the current up-to-date relevance of the topic.

In conclusion, it is important to note that this study may have some limitations. Although the authors have made every effort to be comprehensive in their approach, there is a possibility that some relevant papers may have been unintentionally excluded (others might be excluded for their unavailability). Nonetheless, the authors are confident that their review provides an accurate representation of the current state-of-the-art regarding the benefits of Connected Cars technologies. As such, the results of this study can be considered reliable.

N	Authors	Year	Country	Title	Research method
1	Adler et al.	2019	Netherlands	*Autonomous, connected, electric shared vehicles (ACES) and public finance: An explorative analysis*	Analytical method
2	Andersson and Mattsson	2015	Sweden	*Service innovations enabled by the "internet of things*	Conceptual framework
3	Arena et al.	2020	Italy	*An Overview on the Current Status and Future Perspectives of Smart Cars*	Research framework
4	Athanasopoulou et al.	2019	Netherlands	*What technology enabled services impact business models in the automotive industry? An exploratory study*	Survey
5	Auld et al.	2017	US	*Analysis of the Effects of Connected–Automated Vehicle Technologies on Travel Demand*	Simulation
6	Bahaaldin et al.	2017	US	*A Case Study on the Impacts of Connected Vehicle Technology on No-Notice Evacuation Clearance Time*	Case study
7	Barron	2021	UK	*The Road to a Smarter Future: The Smart City, Connected Cars and Autonomous Mobility*	Case study
8	Bethaz et al.	2021	Italy	*Empowering Commercial Vehicles through Data-Driven Methodologies*	Case study
9	Bohnsack et al.	2021	Germany	*Re-examining path dependence in the digital age: The evolution of connected car business models*	Conceptual framework
10	Bolser et al.	2017	Germany	*Platforms and Ecosystems for Connected Car Services*	Survey
11	Cao et al.	2021	China	*The development and validation of the perceived safety of intelligent connected vehicles scale*	Analytical method
12	Chan	2011	US	*Connected vehicles in a connected world*	Literature review
13	Contreras-Castillo et al.	2018	US	*Internet of Vehicles: Architecture, Protocols, and Security*	Research framework
14	Coppola and Morisio	2016	Italy	*Connected Car: Technologies, Issues, Future Trends*	Research framework
15	Deryabina and Trubnikova	2021	Russia	*The Impact of Digital Transformation in Automotive Industry on Changing Industry Business Model*	Research framework
16	Dimitrakopoulos	2011	Greece	*Intelligent transportation systems based on internet-connected vehicles: Fundamental research areas and challenges*	Case study
17	Efstathiadis et al.	2021	Greece	*Smart Cars and Over-the-Air Updates*	Case study
18	Genders and Razavi	2016	Canada	*Impact of Connected Vehicle on Work Zone NetworkSafety through Dynamic Route Guidance*	Simulation
19	Ghosal et al.	2022	Ireland	*Secure over-the-air software update for connected vehicles*	Analytical method
20	Goikoetxea-Gonzalez et al.	2022	Spain	*The Role of IoT Devices in Sustainable Car Expenses in the Context of the Intelligent Mobility: A Comparative Approach*	Survey

Table 5: Summary of reviewed papers

N	Authors	Year	Country	Title	Research method
21	Grieger and Ludwig	2019	Germany	*On the move towards customer-centric business models in the automotive industry - a conceptual reference framework of shared automotive service systems*	Conceptual framework
22	Halder et al.	2020	Italy	*Secure over-the-air software updates in connected vehicles: A survey*	Survey
23	Hanelt et al.	2015	Germany	*Digital transformation of primarily physical industries-exploring the impact of digital trends on business models of automobile manufacturers*	Literature review
24	He et al.	2019	UK	*Cooperative Connected Autonomous Vehicles (CAV): Research, Applications and Challenges*	Research framework
25	Hensher	2018	Australia	*Tackling road congestion – What might it look like in the future under a collaborative and connected mobility model?*	Simulation
26	Jadaan et al.	2017	Jordan	*Connected Vehicles: an Innovative Transport Technology*	Research framework
27	Jiang et al.	2017	US	*Eco approaching at an isolated signalized intersection under partially connected and automated vehicles environment*	Analytical method
28	Jun et al.	2022	Korea	*Impact of the connected & autonomous vehicle industry on the Korean national economy using input-output analysis*	Simulation
29	Kaiser et al.	2021	Germany	*Conceptualising value creation in data-driven services: The case of vehicle data*	Conceptual framework
30	Kaiser et al.	2017	Austria	*Digital vehicle ecosystems and new business models: An overview of digitalization perspectives*	Literature review
31	Kaiser et al.	2017	Switzerland	*Quantified Cars: An exploration of the position of ICT start-ups vs. car manufacturers towards digital car services and sustainable business models*	Research framework
32	Kaiser et al.	2019	Germany	*Understanding Data-driven Service Ecosystems in the Automotive Domain*	Conceptual framework
33	Kaiser et al.	2018	Austria	*A Research Agenda for Vehicle Information Systems*	Literature review
34	Karmanska	2021	Poland	*The benefits of connected vehicles within organizations*	Survey
35	Kim and Yang	2021	Korea	*A Smart City Service Business Model: Focusing on Transportation Services*	Conceptual framework
36	Kim et al.	2019	Korea	*Identifying and prioritizing the benefits and concerns of connected and autonomous vehicles: A comparison of individual and expert perceptions*	Survey
37	Koch et al.	2020	Germany	*Towards Data-driven Services in Vehicles*	Analytical method
38	Kuang et al.	2019	China	*Assessing the socioeconomic impacts of intelligent connected vehicles in China: A cost-benefit analysis*	Simulation
39	Kuang et al.1	2018	China	*Intelligent Vehicles' Effects on Chinese Traffic: A Simulation Study of Cooperative Adaptive Cruise Control and Intelligent Speed Adaption*	Simulation
40	Kukkamalla et al.	2020	Spain	*The new BMW: business model innovation transforms an automotive leader*	Conceptual framework

Table 5: Summary of reviewed papers

N	Authors	Year	Country	Title	Research method
41	Lioris et al.	2017	US	*Platoons of connected vehicles can double throughput in urban roads*	Analytical method
42	Liu et al.	2018	US	*Distributed Conflict Resolution for Connected Autonomous Vehicles*	Analytical method
43	Llopis-Albert et al.	2021	Spain	*Impact of digital transformation on the automotive industry*	Conceptual framework
44	Lu et al.	2014	China	*Connected Vehicles: solutions and challenges*	Literature review
45	Mahdavian et al.	2019	US	*Assessing the long-and mid-term effects of connected and automated vehicles on highways' traffic flow and capacity*	Literature review
46	Makridis et al.	2018	Switzerland	*Connected and Automated Vehicles on a freeway scenario. Effect on traffic congestion and network capacity*	Simulation
47	Marquez-Barja et al.	2021	Belgium	*Enabling cross-border tele-operated transport in the 5G Era: The 5G Blueprint approach*	Analytical method
48	Martens and Muller-Langer	2020	UK	*Access To Digital Car Data and Competition in Aftermarket Maintenance Services*	Case study
49	Martin-Gasulla et al.	2019	US	*Investigation of the Impact on Throughput of Connected Autonomous Vehicles with Headway Based on the Leading Vehicle Type*	Simulation
50	Mathew and Benekohal	2022	US	*Quantifying the Extent to Which Connected and Autonomous Vehicles Reduce Accidents at Railroad Grade Crossings: A Machine Learning Approach*	Simulation
51	Mayer and Siegel	2015	US	*A Survey of the Connected Vehicle Landscape - Architectures, Enabling Technologies, Applications, and Development Areas*	Survey
52	Mikusz and Herter	2016	Germany	*How do consumers evaluate value propositions of connected car services?*	Conceptual framework
53	Mikusz et al.	2015	Germany	*Business Model Patterns for the Connected Car and the Example of Data Orchestrator*	Conceptual framework
54	Mikusz et al.	2017	Germany	*Transforming the Connected Car into a Business Model Innovation*	Case study
55	Mishra et al.	2020	US	*The Prediction of Collisions in Connected Vehicle Systems with A Long Short-Term Memory Model*	Analytical method
56	Neilson et al.	2019	Canada	*Systematic Review of the Literature on Big Data in the Transportation Domain: Concepts and Applications*	Analytical method
57	Neufville et al.	2022	UK	*Potential of Connected Fully Autonomous Vehicles in Reducing Congestion and Associated Carbon Emissions*	Simulation
58	Nikitas et al.	2019	UK	*Examining the myths of connected and autonomous vehicles: Analysing the pathway to a driverless mobility paradigm*	Literature review
59	Olia et al.	2014	Canada	*Assessing the potential impacts of connected vehicles: mobility, environmental, and safety perspectives*	Case study
60	Park et al.	2019	Korea	*Exploring the key services and players in the smart car market.*	Survey

Table 5: Summary of reviewed papers

N	Authors	Year	Country	Title	Research method
61	Petry and Moormann	2020	Germany	*Mobile Payment in the Connected Car: Developing Services Based on Process Thinking*	Case study
62	Piccinini et al.	2015	Germany	*Transforming industrial business: The impact of digital transformation on automotive organizations*	Other
63	Pütz et al.	2019	Ireland	*Connected automated vehicles and insurance: Analysing future marketstructure from a business ecosystem perspective*	Conceptual framework
64	Rahman and Tadayoni	2018	Denmark	*Digital Transformation of Automobiles - From product to service*	Survey
65	Remane et al.	2016	Germany	*Changes in digital business model types–a longitudinal study of technology startups from the mobility sector*	Case study
66	Schellekens	2022	Netherlands	*Data from connected cars for the public cause*	Case study
67	Shah et al.	2018	UK	*Innovation and I4.0 Management in Connected and Autonomous Automotive Manufacturing*	Literature review
68	Shannon et al.	2021	Ireland	*Connected and autonomous vehicle injury loss events: Potential risk and actuarial considerations for primary insurers*	Case study
69	Shelly	2015	US	*Addressing Challenges in Automotive Connectivity: Mobile Devices, Technologies, and the Connected Car*	Analytical method
70	Shin et al.	2015	US	*User Acceptance and Willingness to Pay for Connected Vehicle Technologies*	Survey
71	Sinha et al.	2020	Australia	*Crash Severity and Rate Evaluation of Conventional Vehicles in Mixed Fleets with Connected and Automated Vehicles*	Simulation
72	Soley et al.	2018	US	*Value in vehicles: economic assessment of automotive data*	Analytical method
73	Sterk et al.	2022	Germany	*Monetizing Car Data: A Literature Review on Data-Driven Business Models in the Connected Car Domain*	Literature review
74	Sterk et al.	2022	Germany	*Understanding Car Data Monetization: A Taxonomy of Data-Driven Business Models in the Connected Car Domain*	Conceptual framework
75	Stocker et al.	2017	Switzerland	*Quantified Vehicles: Novel Services for Vehicle Lifecycle Data*	Conceptual framework
76	Swan	2015	UK	*Connected Car: Quantified Self becomes Quantified Car*	Conceptual framework
77	Taiebat et al.	2018	US	*A Review on Energy, Environmental, and Sustainability Implications of Connected and Automated Vehicles*	Literature review
78	Toglaw et al.	2018	Canada	*Connected, autonomous and electric vehicles: The optimum value for a successful business model*	Survey
79	Yang et al.	2014	China	*An overview of Internet of Vehicles*	Conceptual framework
80	Zhao and Kockelman	2018	US	*Anticipating the regional impacts of connected and automated vehicle travel in Austin, Texas*	Case study
81	Zhao et al.	2020	China	*Analysis of the Business Models of the Intelligent and Connected Vehicle Industry*	Conceptual framework

Table 5: Summary of reviewed papers

3 Over-the-air Updates for Connected Cars

This chapter aims to provide a deeper analysis of the gap identified in the scientific literature regarding Over-the-air (OTA) updates for connected vehicles. In the following sections, the authors present the most relevant issues related to OTA updates by conducting a focused study on the topic using both scientific and non-scientific sources. The overview presented in this chapter serves as a critical foundation for the research contribution that this thesis aims to provide in the following chapters.

3.1. Overview of OTA updates

The Internet of Things solutions have already digitized an increasing number of functionalities of modern-day society, impacting applications areas such as healthcare, surveillance, agriculture, personal fitness, and home and industry automation (Bauwens *et al.* 2020). This trend has led to an enormous expansion in the number of devices per person, thereby raising the necessity for well-designed and maintainable IoT solutions. However, the specific device limitations, fast technology evolution, and increasing pace at which new devices are rolled out in difficult-to-reach areas raise questions concerning the long-term sustainability of previously installed IoT networks (Bauwens *et al.* 2020). For instance, security issues or bugs are often detected post-deployment, thereby hindering operational IoT networks. Moreover, already deployed devices cannot take advantage of new features and/or optimizations, or even adapt to new application requirements. The local update method was the traditional software update technique, where the manufacturer communicated with the object owner via physical letter, email, or in-object notification system for bringing the device to the service center or authorized workshop. The main drawback of the local update method is that it is not time and resource efficient, resulting in a high cost of labor and customer dissatisfaction. On the contrary, with Over-the-air software updates (henceforth, OTA updates), the device owners have the freedom to update the software without having to go to the authorized workshop or repair shop. Efstathiadis *et al.* (2021) define an OTA update as “a wireless delivery of new software or data to mobile devices. Wireless carriers and original equipment manufacturers (OEMs) use OTA to send updated data to cars on the fly”. Over-the-air software updates are indeed a type of data exchange that allows the software of a digital device to be updated remotely via point-to-point communication over a wireless network. This type of remote update makes it possible to repair bugs and upgrade the product with new features in a matter of moments.

3.1.1. OTA updates in the automotive industry

The automotive industry's first aim is always to maximize vehicle safety e comfort, and this can be pursued only with the most updated and innovative technological instruments. This has led to an increasing number of Electronics Control Units (ECUs) which are “embedded systems in automotive electronics that control one or more of the electrical systems or subsystems in a vehicle” (Efstathiadis *et al.* 2021). Indeed, in a modern connected and automated vehicle, hundreds of ECUs control a multitude of car functionalities, from the correct functioning of engines to the proper working of the windscreen wipers or window lifters (Studnia *et al.* 2013).

The ECUs are interconnected via a Controller Area Network (CAN) and/or Local Interconnect Network (LIN). Since the past decade, computer-based ECUs have substituted many in-vehicle mechanical control systems. And this is the reason why, nowadays, a Connected Car, as already mentioned, consists of a significant amount of software with millions of lines of code (from tens of Megabytes to even Gigabytes) for performing certain controlling functions (Halder *et al.* 2020). The car has indeed become an authentic smart computer on four wheels, as it comprises over 100 million lines of code, which is more than a mission-critical fighter jet (Khurram *et al.* 2016). The upsurge in the number of these electronic components and the consequent line of code significantly increases the likelihood of software bugs that OEMs must carefully monitor and correct to avoid serious consequences. In fact, the OEMs of each ECU are obliged to maintain the software efficiency and security throughout the whole life cycle of the vehicle. When a software issue occurs, OEMs have to recall entire fleets of vehicles in order to upgrade the ECU software or fix firmware bugs. This process, commonly called "recall", is a considerable cost to the OEMs. Moreover, recalls impact hugely and negatively customer satisfaction, as the consumer must take the vehicle to the workshop and wait for the realization of the service. In such a complex automotive electronics and software setup, it is crucial to remotely manage and update the vehicle ECU software (Halder *et al.* 2020). On these grounds, Over-the-air update allows avoiding this inconvenient and annoying situation as problems are solved remotely and in a short time.

In addition to remotely resolving ECU software issues, OTA updates offer new profit opportunities for OEMs and suppliers by allowing players to sell features throughout the whole vehicle's life cycle. In fact, through OTA updates (in this case it is better to use the terms upgrades or unlocks), OEMs can add new software-based features to the cars (e.g., new and better acceleration performances), even those already in the fleet, after the start of production (McKinsey, 2021). Obviously, a car, to enable OTA updates requires to be conceived and manufactured to support them. Therefore, OEMs and suppliers must define an end-to-end architecture and create modular-vehicle software that can be upgraded (McKinsey, 2021). Moreover, producers must ensure upgradability and maintainability through hardware-abstraction layers and create hardware with sufficient performance reserves. Parallelly, back-end systems and the related infrastructure must be designed to support regular OTA updates and other critical functions.

Finally, it is worth pointing out the significant differences between OTA updates for connected vehicles and connected devices like smartphones, laptops, and smart watches/televisions in terms of reliability, heterogeneity, installation procedures, and usage (Halder *et al.* 2020). Table 6 summarizes a comparative study of OTA updates between a connected device and a Connected Car.

Parameter	**Connected Device**	**Connected Vehicle**
Mobility	Low	High
Daily traffic pattern	Predictable	Unpredictable
Connectivity with cellular network	Always	Shorter duration, typically, 1 h per day
Heterogeneity	Low to Medium	Medium to High
Volume of OTA download	Kilobytes to Megabytes	Megabytes to Gigabytes
Ratio of uplink to downlink traffic volume	High	Low
Average lifetime	4,7 years	11 years

Table 6: Comparison between OTA update in connected devices and vehicles (Halder et al. 2020)

3.2. OTA update procedure

There are several entities involved in the OTA update procedure. Indeed, the ecosystem of software updates for cars includes: Car, Cloud Servers, Mobile Phone, OEMs, Spare part OEMs, Software Developer/Vendor, Car Owner, Service Centers, Cellular Operator, Insurance Companies, and Law and Enforcement Personnel (Cebe *et al.* 2018).

Generally, as presented by Halder *et al.* (2020), car software updates result necessarily in four scenarios:

- *Update for safety purposes*: the car presents a defect as any malfunction in performance, component, material, or equipment. A safety defect is generally defined as "a fault that is present in the vehicle, or in a component of the vehicle that poses a risk to the safety of the vehicle and may pose security risks for a set of vehicles of similar design, or in the list of equipment of the similar type and manufacturer" (Halder *et al.* 2020).
- *Update operations for non-safety purposes*: this is the case when some problems affect the performance of the car, however, without compromising the safety related to the driver, the passengers, and the external entities such as pedestrians and other vehicles. For instance, problems related to pieces of equipment such as batteries or brake pads do not affect car safety. Referring to this type of problem, there is no existing regulation, except for those covered by the warranty period of the vehicle. Polluting emissions control is a category of non-safety related issues which is under regulation in many countries. In the US, for example, vehicles must be compliant with the requirements defined by the Environmental Protection Agency (EPA) which is a branch of the Office of Transportation and Air Quality.
- *Updates for performance improvements*: performance improvements comprise all those issues that are not connected to security, safety, or environmental risks. Examples of performance improvements include updating the infotainment system or upgrading the attributes of the vehicles such as rate of acceleration and maximum speed. Another example is the upgrade of the navigation map information.
- *Security risk preventive measures*: the current wireless connections enable hackers to attack car's software and thus take control of the vehicle locks and brakes. Therefore, OEMs must prevent these situations by always controlling and

monitoring security risks and when a possible fragility of the software is identified, a prompt update must be carried out.

The procedure for OTA update varies from manufacturer to manufacturer and differs depending on the scenario we are coping with. Tesla, for example, which does not have its own dealer network, sends a message on the vehicle's computer screen whenever a new software update is available. Other major manufacturers, such as General Motors, instead use dealer networks to inform the car owner about the release of a new software package. Despite these differences between manufacturers and types of scenarios, it is possible to present a general overview of the several steps involved during an OTA update. The following is a summary of the general procedure described by Halder *et al.* (2020).

Every time a new software version has been released and is available for download from the cloud server, the car manufacturer informs each registered owner, for instance through an in-vehicle notification. Once notified, car owners can decide to reject/delete, recall later, or agree to the software update. In the former case, the update will not take place via OTA, but the vehicle will have to be brought to the respective dealer to perform the update at a later date or will have to wait for the new notification. If instead, the driver provides consent for the software update there is an automatic assessment of the status of various systems parameters in order to understand if the car is capable of performing the whole downloading process. If the vehicle does not meet the necessary conditions (e.g., the battery charge is too low, the ambient temperature is not suitable for the battery, or network connectivity is poor...), the car generates a message revealing that the conditions are not ideal and the system will attempt in a successive moment. Instead, when the car meets all the required conditions the new software package is downloaded, usually via the cellular network. In case the vehicle loses connectivity, the download automatically stops and restarts when the conditions are newly met. It is worth pointing out how during the download the vehicle can continue its normal use. Once the download is concluded, the driver is asked to accept the installation of the updated software package. Before installation, downloaded software packages undergo extensive security checks to prevent the installation of malicious software updates. Unlike the downloading phase, during installation, the car is disabled and cannot be operated for the safety of passengers. Completed the installation, the driver receives a success or error message. In the event of an error, the car activates the necessary measures, including re-downloading and/or reinstalling the new software package. After, a post-check is performed to confirm that the software update to the necessary ECUs was successfully completed.

3.2.1. OTA update techniques

There are several approaches and techniques to perform an OTA update, and the scientific literature provides many studies on the various secure approaches. Although this technical topic is beyond the scope of this thesis work, it is nevertheless interesting to depict what are these techniques and their differences. To do so, the authors report in the following Table 7 the comparative analysis of the approaches studied in the literature proposed by Halder *et al.* (2020).

Approach	**Strenghts**	**Weaknesses**
Symmetric key	• Resource efficient and fast execution • Establish a secure link with the vehicle before software update • Send redundand copy of software	• Require significant bandwidth • Require memory buffers for redundant copy of software • Significant scalability issues
Hash function	• Computational lightweight • Downloaded software is vefiried before it is installed • Designed approach is scalable	• Significant memory overhead • Susceptible to DoS attack • Unable to detect the reliability of the source
Blockchain	• Ensure a tamper-proof software update • Used overlay network to improve scalability	• High resource consumption • Slow in delivering the sofwtare update
RSA and steganography	• Only autheticated software will be downloaded into the vehicle • Decryption process is time consuming	• Significant scalability issue • High memory overhead
Symmetric & Asymmetric key	• Support parallel software updates • Designed approach is scalable	• Require additional memory for cryptographic operation • Significant communication latency
Hardware secutiry module	• Resistance against physical tampering • Provide secure execution environment	• Each ECU requires an HSM, incurred additional cost of implementation • Does not support parallel software updates
Secure update framework	• Support parallel software updates • Designed method is scalable • Practical software update framework	• Vulnerable to rollback attack • Lack of suitable update verification method
TMDSP	• Designed method is scalable • Reduced average download startup delay • Suitable for heterogeneous scenarios	• Imbalance in the OTA update distribution along the schedule •Proposed solution require significant memory and computation time
BRKGA	• Allows opportunistic use of available cellular cell capacity • Reduction of network load during busy hours • Designed method is scalable	• OTA update heavily dependent on the cellular operator • Lack of security measures

Table 7: OTA software update techniques: a comparative summary (Halder et al. 2020)

3.3. OTA updates benefits

In this section, the authors present the various benefits that OTA updates bring for Connected Cars, both from the manufacturers' and consumers' (car owners, driver, passengers) perspectives. The benefits presented were identified through a literature search on the topic, as well as the study of some relevant and reliable white papers. Table 8 shows a classification of these papers according to the benefits they discuss.

Topic		**Scientific papers**								**White paper**
		Ghosal et al. (2022)	Efstathiadis et al. (2021)	Halder et al. (2020)	Scheuble (2020)	Mirfakhraie et al. (2018)	Riggs et al. (2018)	Khurram et al. (2016)	Hesham and Subra	McKinsey (2021)
RECALL	• Cost reduction for OEMs	✓	✓	✓	✓	✓	✓	✓	✓	✓
	• Time saving for customers	✓	✓	✓	✓	✓	✓	✗	✓	✓
	• Cost saving for customers	✓	✓	✓	✓	✓	✓	✗	✓	✓
	• Customer satisfaction	✗	✓	✓	✓	✓	✗	✓	✓	✓
SAFETY	• Improved safety	✓	✓	✓	✗	✗	✗	✗	✗	✗
CAR VALUE	• Improved car quality/Increased car value/Reduced obsolescence	✗	✓	✓	✗	✗	✗	✓	✗	✗
MAINTENANCE	• Maintenance costs reduction	✗	✓	✗	✗	✓	✓	✗	✓	✓
UPGRADEABILITY	• New revenues opportunities for OEMs	✗	✗	✓	✗	✗	✗	✗	✗	✓
	• Customer experience	✗	✗	✗	✗	✗	✗	✗	✗	✓

Table 8: Summary of reviewed papers on OTA updates benefits

3.3.1. Recall

As described in the previous sections of this chapter, OTA updates allow the customer to avoid bringing the vehicle to the dealer every time a car software needs an update. In fact, each time a customer brings the vehicle to the dealership for a recall, it is the manufacturing company that has to bear the cost of the service. In addition, the process takes time, and if several vehicles need the service, it can "create bottlenecks in dealerships across the country and be very expensive" (Riggs *et al.* 2018).

Minimizing recalls through OTAs thus substantially reduces costs for OEMs. The IHS Markit (2016) report predicted that OTA upgrades could save the global automotive industry more than $35 billion by 2022.

It is worth mentioning the famous "Dieselgate", the Volkswagen emissions scandal of 2015 when the company had to recall the 11 million vehicles it has sold in the previous 8 years due to a bug in the emissions control software. If the problem was coped with an OTA software update, the overall process would have involved much less cost and time. Thus, it is possible to clearly understand the significance of remote software updates Over-the-air (OTA). The mere amount of time it takes to travel to the dealer is enough of a motivator to implement OTA updates, as it saves customers from having to make trips just to fix minor software bugs (Ghosal *et al.* 2022). Consumers do not have the hassle of having to take their car to the dealership and at the same time can receive the latest information and safety updates without even being aware of it. A real-life example is Tesla, which provides OTA updates in many of its cars, and has reported a high level of customer satisfaction and usability. The large number of consumer orders for Tesla vehicles in recent times reflects their high satisfaction and success of OTA updates (Halder *et al.* 2020). In a nutshell, the quicker and more secure the update delivery, the greater the cost savings, the fewer recalls, the stronger the brand image, and the higher the customer satisfaction (Scheuble 2020). On the other hand, it is worth highlighting how OTA updates cannot resolve all the recalls; ABI Research's market analysis in 2016 examined that around one-third of the recalls in that year could have been resolved remotely. This can be explained by the fact that most of the vehicles on the road have been designed with an architecture that does not support OTA updates, but it is more than reasonable to assume that the percentage of recalls that can be resolved via OTA will strongly increase in the upcoming years.

3.3.2. Safety

The introduction of new software capabilities has led to the rapid improvement in crash-avoidance features, such as lane departure warnings and adaptive cruise control. All these new features are modifying the way customers assess vehicles, giving more importance to user experience and improved safety.

Many in-vehicle systems, such as steering, braking, and acceleration, are electronically controlled. These safety systems can be updated promptly through OTA if issues are detected (Halder *et al.* 2020). These software-reliant systems generally need continuous updates, such as route map changes, road construction information, and changes to safety features. OTA updates support in a vehicle, allow manufacturers to update software as frequently as necessary in near real-time and transmit the latest information and safety updates to all vehicles, whether in the parking lot or on the road and avoid the customer bringing the vehicle to the dealer while still comfortably benefit from these safety features without any effort.

As Efstathiadis *et al.* 2021 state in their publication, this method of installation could guarantee that a vehicle is always updated to the latest software and that the update’s time to market (TTM) is reduced. This decrease in the TTM is crucial, because it is very likely that important security updates will be installed much sooner than expected, and many accidents due to faulty software may be avoided sooner than would be possible with dealer installation of firmware updates by cable.

3.3.3. Maintenance

With the development of connected vehicle technology and the increase in functionality offered by automobiles, the number of ECUs is increasing significantly.

Today, vehicles can have over 100 electronic control units (ECUs) that control a range of functions from essential systems such as engine control and power steering, to comfort features like power windows, seats, and heating, ventilation, and air conditioning (HVAC). ECUs also manage safety features like airbags and basic active safety features such as automatic emergency braking, playing a crucial role in ensuring the proper functioning of various systems within a vehicle.

This is a result of the trend to shift vehicle functions from mechanics to electronics. This means that automobiles are becoming more sophisticated and offer more services and features for drivers and passengers. The growing number of ECUs creates a complex network structure that can lead to serious technical faults in vehicles. It is thus likely that these faults can also impact the engine's fuel timing and settings, which can negatively affect the overall performance of the vehicle as the ECUs are interconnected, having the potential to cause unwanted acceleration, increased fuel consumption, unintended airbag deployment, and decreased vehicle performance. If the multiple ECUs in a vehicle fail to function together, the consequences can be severe. Therefore, this proliferation of ECUs leads to a greater maintenance effort and a regular need for software updates to ensure that the cars function optimally. However, with traditional maintenance, customers often have to bring their vehicles to a service centre, which can be time-consuming and inconvenient. Whenever the fault is remotely solvable, over-the-air technology could come to the rescue, becoming increasingly common making the process more efficient and enhancing customer satisfaction (Efstathiadis *et al.* 2021). On the other hand, when it is not possible to solve the ECU failure remotely, technology can also be of help. In fact, instead of issuing a car recall, a two-way connectivity gateway can be developed.

This technology can handle predictive maintenance by analysing sensor data along with delivering firmware updates for ECUs (Mirfakhraie *et al.* 2018). There is a significant opportunity to reduce maintenance costs and extend warranties. By adding new features and remotely troubleshooting faulty systems, vehicle performance can be improved, offering a competitive advantage.

The use of Over-the-air (OTA) technologies can result in a reduction of maintenance costs for both customers and Original Equipment Manufacturers (OEMs). OTA updates provide a convenient and cost-effective solution for customers, who no longer need to physically bring their vehicles to a dealership for software issues. Remote solutions save time and money and offer a seamless experience for the owner. Similarly, OEMs can save on the costs associated with transporting and repairing vehicles by remotely diagnosing and resolving issues. OTA updates also streamline the maintenance and troubleshooting process, leading to increased efficiency and lower costs for the automotive industry.

To further decrease maintenance costs, vehicle connectivity can be leveraged to proactively schedule repairs, optimizing repair slots to suit drivers' calendars. Additionally, vehicles can assist with inventory management for dealer service departments and workshops by notifying them about upcoming repairs. Finally, vehicles can actively reduce maintenance costs by adjusting their settings based on data, lowering wear and tear. These measures result in even greater cost savings for both customers and OEMs, highlighting the potential of OTA technologies to revolutionize the maintenance and repair process for connected vehicles (McKinsey, 2021).

3.3.4. Car Value

OTA updates for connected vehicles have the potential to reduce the obsolescence of the vehicle and increase its value. According to a study conducted by the Boston Consulting Group, connected vehicles are expected to generate over $250 billion in revenue by 2030, with over-the-air updates playing a significant role in this growth. As Halder *et al.* (2020) state, "By consistently maintaining in-vehicle software systems with OTA updates, the overall value of the car increases and opens new revenue opportunities to automakers. Also, software configuration costs decrease when multiple software solutions use a single, compatible Operating System (OS)".

By providing timely updates to the software and hardware systems of the vehicle, manufacturers can ensure that their vehicles remain technologically current and competitive in the market. Additionally, over-the-air updates can resolve any issues with the vehicle's performance and improve its overall functionality, providing owners with a better driving experience. In addition to these technical benefits, research conducted by consulting firm McKinsey & Company found that OTA updates can significantly increase customer satisfaction and loyalty. By reducing the need for time-consuming and costly trips to the dealership for software upgrades, OTA updates provide a convenient and hassle-free solution for consumers, increasing the car value thanks to an intangible benefit (McKinsey, 2021).

In the current environment, connected services offer a quick opportunity for revenue and profit generation. They require a smaller initial investment and have quicker development times compared to other technologies such as advanced driver-assistance systems, which can require massive investments (McKinsey, 2021). For these reasons, connected services are especially appealing as they offer high-profit margins and recurring revenue streams. A strong offering can also increase retention, as around a third of customers are willing to switch car brands for better connectivity.

3.3.5. Upgradeability

OTA updates in Connected Cars offer several upgradability features that provide a range of benefits for both manufacturers and consumers.

1. Remote software upgrades: OTA updates allow for remote software upgrades, which means that the software on a Connected Car can be improved or updated without having to physically visit a dealership. This is a convenient and time-saving feature for consumers and reduces costs for manufacturers.
2. Improved performance: OTA updates can improve the performance of a vehicle by fixing software bugs and improving the functionality of the car's systems. This can help to enhance the overall driving experience and increase customer satisfaction.
3. Enhanced security: OTA updates also provide an opportunity to enhance the security of Connected Cars by fixing vulnerabilities and updating the car's systems to the latest security protocols. This is particularly important in the era of Connected Cars, where cyber threats are becoming increasingly prevalent.
4. Increased efficiency: OTA updates can also improve the efficiency of a vehicle by fixing software bugs and enhancing the functionality of the car's systems. This can help to reduce emissions and improve the vehicle's overall performance.
5. New features: OTA updates can also add new features to a Connected Car, such as the latest infotainment systems or advanced driver-assistance systems

(ADAS). This helps to keep vehicles up-to-date with the latest technology and provides a more enjoyable driving experience for consumers.

To capture new opportunities, OEMs are looking at OTA feature updates and connected service unlocks to generate new revenue streams throughout a vehicle's life cycle. By paid over-the-air (OTA) upgrades companies can profit from these features, adapting their business model to capture new revenue streams in unconventional ways. Some players already sell software features, such as acceleration updates for their existing vehicle fleets. Some also offer their connectivity packages and ADAS systems by subscription and plan to roll out similar offerings for ADAS features. For instance, a Chinese EV OEM offers mobile-charging services to customers, and a US start-up provides a similar service for refuelling. Beyond generating revenues, these services provide players with recurring interactions with their customers that may increase brand loyalty (McKinsey, 2021).

The results of McKinsey's 2020 ACES consumer survey indicate that respondents, from all over the world, are willing to pay approximately $13 per month for advanced map and personalized navigation features or features related to fuel and cost efficiency and as cited "this willingness to pay for connectivity features is increasing, especially for differentiating features".

3.4. OTA updates for Safety Recall events

As presented by Halder *et al.* (2020), an OEM needs to carry out a safety recall when the car presents a safety defect as any malfunction in performance, component, material, or equipment. A safety defect is generally defined as a fault that is present in the vehicle, or in a component of the car that poses a risk to the safety of the vehicle and may pose security risks for a set of vehicles of similar design, or in the list of equipment of the similar type and manufacturer.

When certain vehicles present this kind of defect, the manufacturer must identify all individuals owning cars with the malfunction and must notify them by registered mail. Then, the consumer is the first responsible for vehicle update duty (at the dealership or remotely). In fact, in Italy, for instance, Article 2054 of the Civil Code states that the car owner is legally primarily responsible for the proper functioning of the vehicle and can therefore be sanctioned if he does not update the car.

When a software breakdown occurs, the manufacturer must use any means to update the cars in order to avoid accidents that might result in the death of vehicle passengers.

This criticality of the event also leads companies to take decisions that produce very significant costs that can in turn also impact the customer who will have to follow instructions to upgrade their car. Therefore, it is reasonable to consider the safety recall as the most relevant and impactful for both companies and consumers. Indeed, for instance, according to the National Highway Traffic Safety Administration (NHTSA), there were approximately 53 million vehicles recalled in the United States in 2019 alone, with safety issues being the leading cause.

To understand how widespread and impactful this phenomenon is on the business of automakers some examples of safety recalls that have occurred in recent years are provided (Halder *et al.* 2020):

- 2023: Tesla solved a safety recall for 362.000 US vehicles offering a free-of-charge Over-the-air software update, in order to cope with a NHTSA's complaint about Tesla software that allowed to exceed speed limits in an unlawful or unpredictable manner increasing the risk of deadly crashes.
- 2022: Ford Motor recalled more than 634.000 sport utility vehicles (SUVs) worldwide over fire risks from possible cracked fuel injectors.
- 2022: Fiat recalled all the Fiat 500 Hybrid vehicles manufactured between January and June 2022 as a consequence of the risk of fire due to a broken circuit in the electrical connection of the auxiliary battery.
- 2018: Honda recalls 232.000 hybrid cars due to a software glitch that provoke malfunctioning of the rear camera display.
- 2017: FCA recalls 1,25 million trucks due to a software bug that might momentarily disable the side airbag and deployment seat of belt pretensioners.
- 2016: FCA recalls 1,1 million cars to add additional transmission control software to prevent inadvertent rollways.
- 2015: Jaguar Land Rover recalls more than 65.000 Range Rover sport utility cars due to a software bug that might cause unlatch vehicles' doors unexpectedly.
- 2015: FCA recalls 1,4 million vehicles equipped with Uconnect radio head units to fix a software hole that allowed hackers to remotely control various vehicle control systems.

These examples are just some of the cases that have occurred in the recent past, but they give an insight into the scale of these critical events. Only the first example, the Tesla recall of 2023, was remotely resolved via OTA updates. For all other safety recall events examples, if the problem was coped with an OTA software update, the overall process would have involved much less cost and time. Thus, it is possible to clearly understand the significance of Over-the-air technologies to solve safety recalls.

3.5. Security issues, challenges, and requirements for OTA updates

Nevertheless, any connection with an external network is by default at risk, and subject to vulnerability. Although OTA updates appear to be a solution to many problems, they can still present new security vulnerabilities. An attacker could potentially take control of a vehicle by introducing a malicious update, either through the back-end system or while the update is being transmitted.

As Efstathiadis *et al.* (2021) state in their article, history has shown that software systems are most at risk of lapses in safety and security when undergoing change, and being an OTA update a substantial change security becomes a vital aspect to be taken into consideration.

European Union Agency for Cybersecurity (ENISA) issued a report last year (2022) where relevant security threats and cybersecurity risks associated with smart vehicles are examined and various measures to mitigate these risks are proposed. The report considers the unique characteristics of this highly complex, heterogeneous, and ever-changing environment and acknowledges that no modern system can be evaluated in isolation. This analysis presents the interconnection between various components of a smart vehicle, including sensors, artificial intelligence, machine learning algorithms, cloud computing, and connectivity, and thoroughly examines potential threats arising from these components.

There are multiple reasons why a car could be targeted by an attacker, as categorized by Efstathiadis *et al.* (2021):

1. Theft: vehicles are often stripped down into spare parts, with those in good condition being sold to illegal traders, while the others are either repaired and sold at a lower price or used for scrap. This is particularly concerning given the high prices associated with new electronic parts, resulting in a heightened demand for spare parts.
2. Planned accidents: this can be achieved through various means, such as locking the brake system, stopping the engine while the car is in motion, or blocking the steering system.

3. Interception of personal data: information such as paired phones, call history, geolocation data, and installed applications are considered sensitive and can potentially lead to data leaks.
4. ECU source code theft: hackers motivated by rival motor industries may also pose a threat through the theft of ECU source codes. They may do so to copy patented methodologies.
5. Ethical hacking: hacking smart cars as a challenge and help companies guard against potential threats by finding new vulnerabilities.
6. Tuning and other improvements: upgrading horsepower or reducing mileage, can also be compromised if the car's operating system is hacked. This can allow unauthorized individuals to bypass software restrictions and install spare parts on smart cars.

For these reasons, it is imperative to ensure that the distribution of software during Over-the-air (OTA) updates is structured in a manner that guarantees high levels of security, minimizes latency, and consistently protects data, while also being designed to withstand various security threats such as spoofing, tampering, repudiation, information leakage, denial-of-service, among others.

Here listed are some reasons why a Connected Car can be attacked through its software:

1. Unsecured software: If the software used in the car is not properly secured, it can become vulnerable to hacking attempts.
2. Lack of encryption: Without proper encryption, the data transmitted between the car and other systems can be intercepted and manipulated by attackers.
3. Inadequate software updates: Failing to perform regular software updates can leave the car vulnerable to known security weaknesses that have already been addressed in more recent versions of the software.
4. Remote access: The ability to remotely access and control a car through its software can create opportunities for unauthorized access by hackers.
5. Interconnected systems: With the increasing number of interconnected systems in modern vehicles, the attack surface is expanding and creating new opportunities for attackers.

6. Integration of third-party components: Integrating third-party components into the car's software can increase the attack surface and create new vulnerabilities if those components are not properly secured.
7. Supply chain attacks: The use of third-party suppliers for software components can create opportunities for attackers to introduce malicious code into the car's software via the supply chain.

3.6. OTA updates Market for Connected Cars

The global market for over-the-air (OTA) updates in connected vehicles is rapidly growing, with projections indicating that it will reach approximately 10.35 billion dollars by 2027 (Statista). Data shows that the market is growing at a compound annual growth rate (CAGR) of 19% between 2020 and 2027. The increasing demand for OTA updates in connected vehicles is driven by the need for more efficient and cost-effective software updates, as well as the growing importance of cybersecurity in the automotive industry. Because software are becoming more and more crucial and critical components in a connected vehicle, the latter have to be intended as much as possible as a mobile device and treated like that, providing the needed means through which regular updates can be transmitted. Until now, updates for automotive software or firmware have primarily been conducted through physical visits to repair shops. This approach is resource-intensive, complex, and has limited scalability. Additionally, it is restricted to a local level, with only authorized workshops able to perform authenticated and security-critical updates. With the advent and widespread use of connected and automated vehicles, at the same pace, the need for software updates has increased. In fact, reflecting the previous shown data on the global market of OTA updates, there is a trend in the global automotive software and electronics market, that as stated in the white paper of McKinsey 2023, is expected to reach $462 billion by 2030, representing a 5,5 percent CAGR from 2019 to 2030.

Supporting these trends, Original Equipment Manufacturers (OEMs) are heavily investing in Over-the-air (OTA) updates technologies as they realize the potential benefits of this software-driven approach. For instance, the BMW Group set a goal of having the largest OTA upgradeable fleet of any manufacturer by the end of last year, with more than 3.8 million vehicles from the BMW brand able to receive remote software upgrades. Meanwhile, Stellantis executed over 6 million OTA updates during 2021, and Ford aims to have 33 million OTA-enabled Ford and Lincoln vehicles on the road by 2028.

Worth mentioning is the case of Tesla, known for its innovative approach to vehicle technology, and one of its most notable features is the OTA updates that it provides for its electric vehicles. Recently, in February 2023, Tesla solved a safety recall for 362.000 US vehicles offering a free-of-charge over-the-air software update, in order to cope with a NHTSA's complaint about Tesla software that "allowed to exceed speed limits in an unlawful or unpredictable manner increasing the risk of deadly crashes" (The Guardian, 2023). In fact, over the past years, Tesla has performed several OTA updates on its vehicles, with the number of updates increasing each year. These updates have covered a wide range of areas, including improvements to the battery management system, autopilot functionality, and entertainment features. This success of Tesla's OTA updates has also inspired other automakers to adopt similar practices, demonstrating the impact that Tesla has had on the industry. The cost savings potential of OTA updates is substantial; in recent years, software-related glitches have accounted for about half of all vehicle recall cases, and it is estimated that these issues can be solved remotely, potentially resulting in annual savings of around $15 billion. The automotive industry is increasingly becoming a software-driven industry, with many OEMs and suppliers investing in rebuilding their organizations to put software first.

In conclusion, the investment trend in OTA updates technology by OEMs reflects the recognition of its benefits and the transformation of the automotive industry towards a software-enabled one.

4 Research Questions and Methodology

The objective of this chapter is to clarify the purpose of this dissertation and establish the key research questions that the model is built around. The research questions are of paramount importance, as they serve the dual purpose of furnishing the reader with an initial understanding of the topics that will be expounded upon in the ensuing chapters and laying the foundation for the model configuration. This chapter concludes with a brief summary of the methodologies that will be employed to tackle the research questions.

It should be noted that this thesis is part of a broader research initiative carried out by the Osservatorio Connected Car & Mobility of Politecnico di Milano. As a result, this work is the outcome of continuous collaboration with the aforementioned observatory.

4.1. Research Questions Formulation

The scientific literature on the exploitation of Over-the-air (OTA) updates on connected vehicles is presently characterized by a gap in knowledge, prompting the present dissertation to address this shortcoming by providing an analytical model to quantify the monetary benefits that end-users can derive from owning a Connected Car that supports OTA updates. In particular, the authors decided to build a model quantifying the benefits in the event of a safety recall. The focus of the model on safety recalls is motivated by the fact that it is the most relevant and prevalent case in the real world. For instance, according to the National Highway Traffic Safety Administration (NHTSA), there were approximately 53 million vehicles recalled in the United States in 2019 alone, with safety issues being the leading cause. Additionally, as presented in Chapter 3, safety recalls have been shown to have significant economic implications for both automakers and consumers.

Therefore, this study endeavors to bridge this gap by conducting a thorough analysis of the positive externalities that OTA updates can offer in a designated area of Italy, Milan, thereby providing insights into the economic implications of this technology supporting Connected Cars.

The literature review has revealed that scholars are primarily focused on exploring the integration of emerging technologies as a means to extract economic advantages for OEMs. While research has demonstrated the potential for emerging technologies to yield economic advantages for automakers, less attention has been given to how such technologies can be leveraged to offer tangible benefits to consumers.

The adoption of Over-the-air updates for managing automotive safety recalls is increasing, but it is not yet widespread. There are still some technical challenges, such as the need to ensure the security and reliability of the data transmitted during the update, that must be addressed before this technology can be fully adopted. Additionally, the involvement of various stakeholders, such as car manufacturers, component suppliers, connectivity service providers, and regulatory agencies, can be a barrier to its widespread adoption. However, the adoption of OTA updates for managing safety recalls represents a significant opportunity to improve the efficiency and safety of automobiles while reducing the costs and downtime associated with traditional automotive recall activities. For these reasons the scientific literature body still focuses on technological development rather than deployment, thereby limiting research on the benefits related to the application of these technologies.

This dissertation aims to address this gap in the literature by providing a detailed analysis of the monetary benefits that end-users can realize through the support of OTA updates in Connected Cars, thereby offering insights into the potential economic implications for end-users, while also increasing awareness of this new technology being commercialized.

Finally, as the prevalence of the Connected Car in Italy is far lower than in North America, where most of the papers and articles analyzed come from, the authors believe that the application of the model in Milan, Italy, can contribute to increased awareness of the benefits that Connected Cars supporting this technology can bring to the end consumers.

The above discussion has given rise to the formulation of two Research Questions that this dissertation aims to address.

RQ1: What is the actual state-of-the-art about Over-the-air (OTA) updates?

Moreover, a further step can be performed by proposing the following research question advancement:

RQ2: How can benefits generated by a safety recall be quantified?

Addressing the first research question also required the definition of the following Functional Question:

FQ1.1: Which are the main typologies of OTA updates available today on Connected Cars and the relative benefits that can be generated for the customer?

Furthermore, considering the territory-specific factors related to Italy, and particularly to Milan, addressing the second research question appropriately required answering the following additional Functional Question as a preliminary step.

FQ2.1: What are the necessary steps an Italian consumer goes through when a safety recall occurs?

4.2. Methodology

This section outlines the various methodologies employed to answer the research questions. The authors undertook an in-depth investigation using the following strategies:

- *Literature Review:* this initial step represents a foundational effort aimed at exploring the field of Connected Cars, to establish the boundaries of the analysis and identify the literature gap for investigation. In total, eighty-one publications were examined and classified, using two primary research engines (Scopus and Google Scholar).
- *Analysis of secondary sources:* in addition to scientific articles, the authors employed secondary sources, such as web pages, white papers, conference reports, and databases coming from reliable sources, to complement the information and enhance their understanding alongside the literature analysis. Specifically, the Istat database and NHTSA reports related to mobility were extensively examined to address the research and functional questions presented. Moreover, the authors decided to provide a further chapter (Chapter 3) to offer a deeper analysis of the gap identified in the scientific literature regarding Over-the-air (OTA) updates for connected vehicles serving as a critical foundation for the research contribution that this thesis aims to provide in the following chapters.
- *Analytical model:* the core of this dissertation is to propose an analytical model for evaluating the economic externalities for end-users linked to Over-the-air (OTA) updates support in Connected Cars in a “safety recall” case, thereby

allowing to answer to the second Research Question outlined in the previous section of this chapter.

- *Data gathering and management:* at the end of the dissertation, the model developed has been validated using datasets coming from databases such as Istat, and insights collected through structured interviews with OEM experts and dealers' staff. The information gathered has been filtered and adjusted to make them suitable to be used in the model.

5 Model Design

The primary goal of this chapter is to introduce all the methodological factors which have been considered to design the model, serving as an introductory part to have a deep understanding of the validation analysis presented in Chapter 6. As anticipated in the previous section, the model of this dissertation is focused on the quantification of the economic externalities linked to the possession of a Connected Car that supports Over-the-air updates, in the event of a safety recall. In order to do that, the authors, following the information about the topic gathered in Chapter 3, modeled the "safety recall" system involving different stakeholders, with a primary focus on the consumer, aligned with the second research question (and the functional questions 2.1) and the purpose of this work. Then, this section proposes the main contribution of this dissertation, the Economic Model with its functioning and limitations.

5.1. System Model

Before defining the Economic model that aims to provide a mathematical framework to estimate the benefits of a consumer owning a car that supports OTA updates in the event of a safety recall, it is necessary to model the system the consumer goes through when her vehicle is recalled for safety purposes. The authors decided to define this latter as the "safety recall system".

5.1.1. Preliminary Consideration

Before delving into details, the authors would like to stress that the aim of this work is to propose a model that is as comprehensive as feasible so that it can be adaptable and replicable under any conditions and in any geographical area. However, considering the Italian geographical area on which the model is tested and validated, some influences due to this might arise.

Furthermore, in order to define and validate the reasoning and formulas underlying the model and to evaluate all the most pertinent elements, the authors conducted interviews with OEMs and dealerships. These interviews also ensured to obtain some indications on quantitative parameters necessary for model application presented in the next chapter. In particular, the authors held meetings with two OEM's that operate on the Italian territory and with a major dealer operating in the central Italy territory.

5.1.2. Customer definition

The model of this research work aims at providing the quantification of the consumer economic externalities linked to the possession of a Connected Car that supports Over-the-air updates in the event of a safety recall. Therefore, to ensure the model is customer-centric, it is crucial to identify who is precisely the customer.

In this case, the B2C Connected Car market is the focus, where the consumer is the private owner coinciding also with the car driver. A vehicle indeed is often used by various members of the same family group, but, for sake of simplicity, the authors have chosen to introduce the following hypothesis:

HP1: The driver and the owner of the car are the same person

Hereinafter the terms "consumer", "customer", "driver", and "car owner" will be used interchangeably.

5.1.3. Journey Planning

Since the authors could not rely on any existing scientific work to extract the customer journey in the "safety recall system", the authors provide standard modeling of the safety recall event.

As presented in Chapter 4, a safety recall is necessary when there is "a defect in a vehicle that includes any malfunction in performance, component, material or equipment... that poses a risk on the safety of the vehicle and may pose security risks for a set of vehicles of similar design, or in a list of equipment of similar type and manufacturer" (Halder *et al.* 2020). However, it is important to emphasize that each country has its own legal requirements that define how the notification and repair are carried out in the event of a safety recall.

The authors decided to design the "safety recall system" from the consumer standpoint starting from the study of Halder *et al.* (2020), which points out the standard and general safety recall procedure shown in the following figure (Figure 5.1).

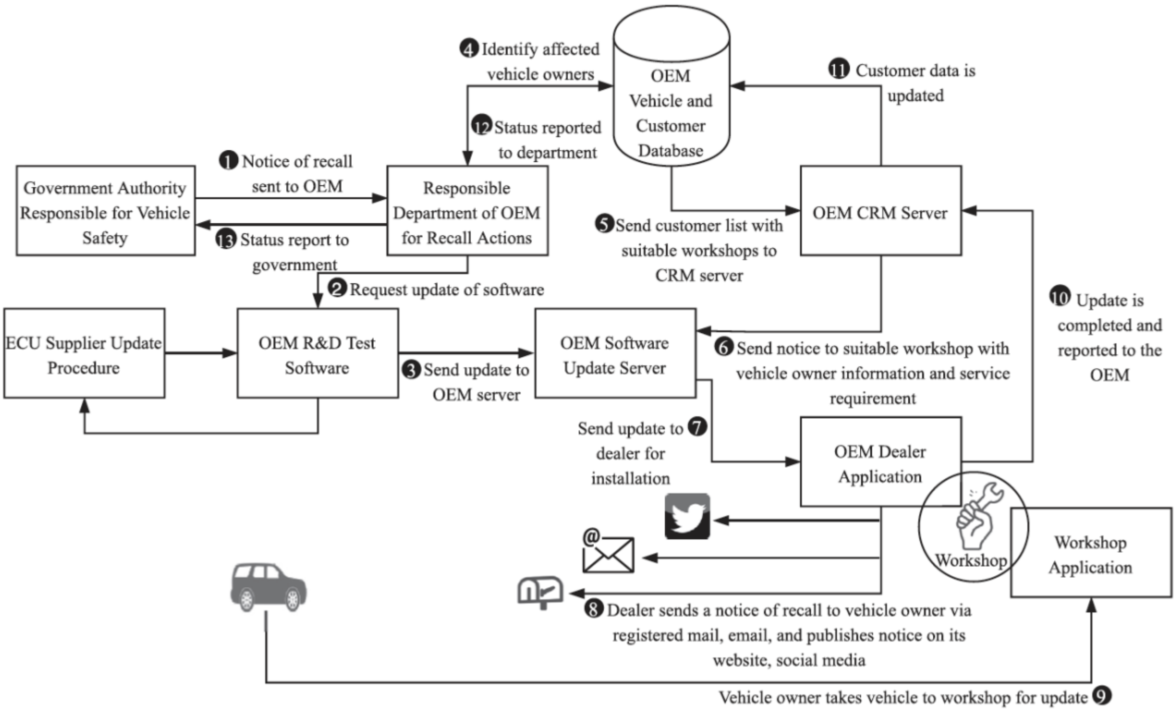


Figure 5.1: Safety Recall procedure (Halder et al. 2020)

Coherently to the second Research Questions, the authors built the "Customer Journey" of the safety recall event (remotely resolvable) as pointed out by Figure 5.2 on the next page.

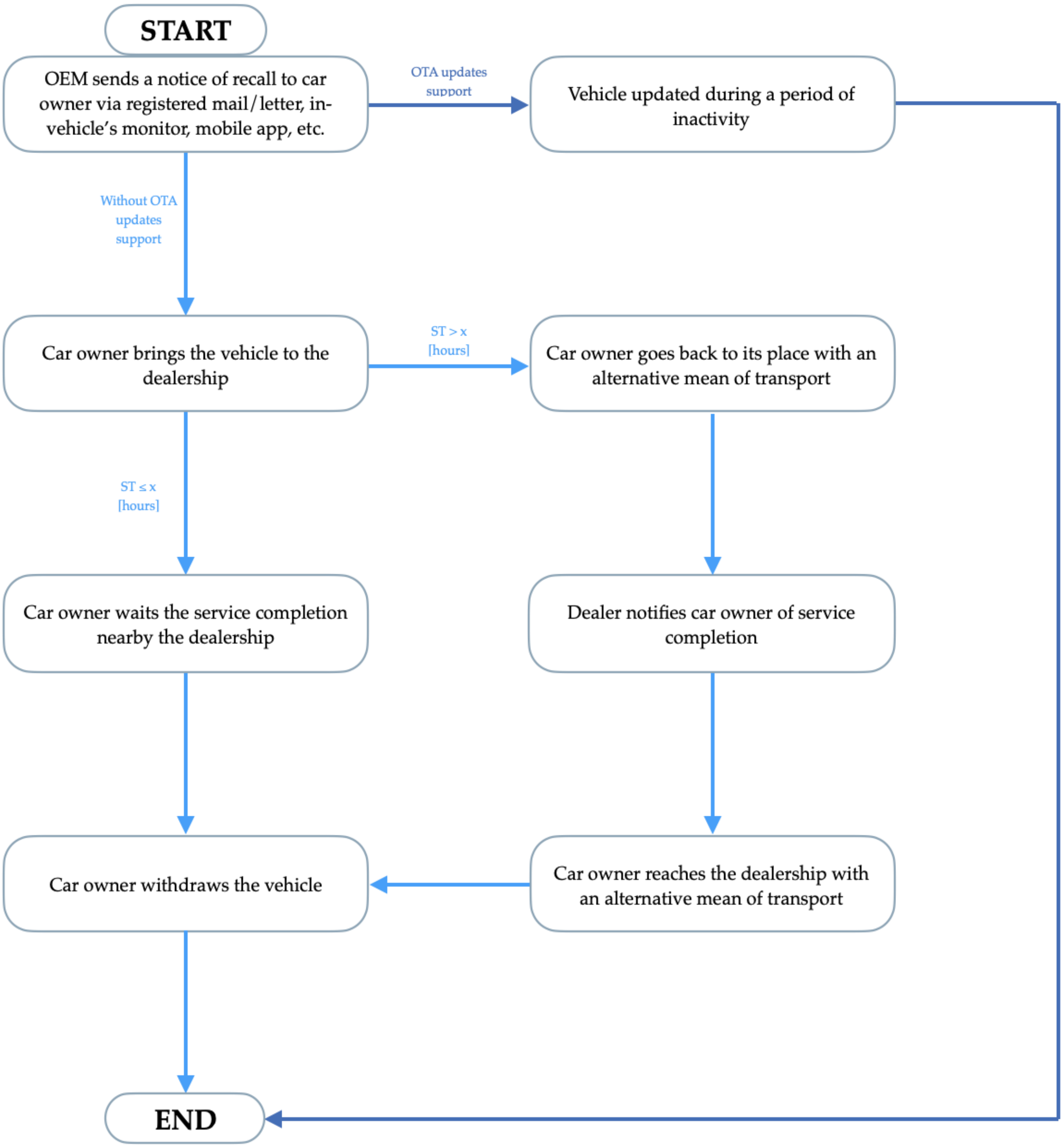


Figure 5.2: Customer Journey in the safety recall event

The consumer (i.e., the car owner) enters the safety recall system when the Original Equipment Manufacturer notifies that her vehicle needs an update for safety purposes. This notification can occur through various communication channels (also simultaneously), such as notifications sent through the mobile application or displayed on the vehicle's onboard monitor. For the purpose of this work, the method by which the vehicle owner is notified is irrelevant.

After receiving the recall notification, the consumer must perform the vehicle update as soon as possible. This is where the first switch point of the journey pops up:

- If the consumer owns a vehicle that supports Over-the-air updates and, at the same time, the recall can be resolved remotely, then the vehicle owner can conveniently update the vehicle from home during a period of inactivity (for instance, overnight), following hypothesis number 2:

  HP2: In the case of remote updates, the consumer performs the update during a period of inactivity (i.e., overnight)

- If the consumer owns a vehicle that does not support remote updates, she will need to bring the vehicle to an authorized dealership to have the necessary operations performed.

In the first case, immediately after the update event, the car owner's journey within the safety recall system ends. On the other hand, in the second case, the consumer must physically bring the vehicle to an authorized dealership within T days of receiving the notification. The ensuing hypothesis then follows:

HP3: The consumer brings the vehicle to the dealership within T days

Another assumption rising at this point is that, despite the recall, the car is capable of arriving at the dealership without the need for breakdown assistance.

HP4: Despite the recall, the car is capable to reach the dealership without the need for a breakdown truck

At this point, in the second option, there is a further bifurcation:

- If the service time to complete the update is less than a certain number X of hours, the consumer waits for the service completion nearby the dealership.
- If the service time to complete the update is greater than a certain number X of hours (for instance, due to high demand generated by a large number of recalled vehicles), the consumer leaves the vehicle at the dealership and will return to pick it up when notified of service completion.

This last bifurcation arises from the interviews conducted by the authors with dealerships. It emerged that when the number of vehicles subject to recall is very high, bottlenecks can occur due to the limited capacity of dealerships that cannot perform the update simultaneously on all the vehicles waiting in the queue.

In the case where the vehicle owner leaves the vehicle at the dealership, the authors assume that they will return to the same point from which they started the journey, using alternative means of transportation (the same goes for the journey to go back to the dealership to pick up the vehicle) before taking the car to the repair shop. The reasoning behind this is based on the following hypotheses:

HP5: The starting point before bringing the vehicle to the dealership coincides with the point of arrival after picking up the car

HP6: The consumer, during the period when the vehicle is at the dealership, uses alternative means of transportation

5.2. Economic model

This chapter represents the primary element of this dissertation since it illustrates the design of the model used in order to answer *RQ2*. Therefore, this section offers the formulas underlying the model, while the next chapter will detail the process of how the necessary data was acquired.

The ultimate goal of this model is to determine the potential cost savings, expressed in euros, that a consumer who owns a car with OTA update support could experience in comparison to a consumer who owns a vehicle that does not enable OTA updates in the event of a "safety recall". In order to accomplish the intended objective, the first step involves elaborating the model to accurately determine the economic savings in terms of time and cost for travel and services related to the update operations. Subsequently, the model considers the cost savings associated with preventing accidents by owning a vehicle that supports OTA updates and is continuously updated with the latest security features. Finally, the overall benefit is ascertained by combining both contributions.

The foundation of the model is built on the subsequent equation, which calculates the expected cost of a safety recall for car owners, combining the two aforementioned contributions:

$$C = C_R + k \times C_A \tag{1}$$

Where:

- C_R : Cost to bring the vehicle to the dealership for the update.
- C_A : Cost of car accident.

- k: Probability of a car (among those object of the recall) having an accident due to the software failure cause of the recall.

As shown in (1) the economic model is grounded around two main contributions: the cost to bring the vehicle to the dealership for the update and the cost of a car accident, weighted by the probability of having the accident due to the software failure (which is the cause of the recall). The former one has been modeled by the authors following the safety recall journey the owner of the vehicle passes through when experiencing a "safety recall", presented in section 5.1. On the other hand, the second term contribution will be actively present in the equation whenever the recalled car undergoes an accident caused by the software failure for which the recall was induced.

Moving forward the authors have separated the equation into two case scenarios: the expected cost of a safety recall for the owner of a car that support OTA updates (C_{OTA}), versus the expected one for the owner of a car that does not support them (C_{wo_OTA}).

$$C_{OTA} = C_{R\_OTA} + k_{OTA} \times C_{A\_OTA} \tag{2}$$

$$C_{wo\_OTA} = C_{R\_wo\_OTA} + k_{wo\_OTA} \times C_{A\_wo\_OTA} \tag{3}$$

The model proposed by the authors aims to estimate the economic benefit of a vehicle that supports remote updates by comparing the cost of remote updates (C_{OTA}) to that of a vehicle that does not support remote updates (C_{wo_OTA}). For the former, the cost of a remote update is assumed to be zero, but in some cases, when the issue cannot be resolved remotely, there will be a cost equal to that of a vehicle that does not support OTA updates.

In particular, the authors defined the relationship between the two cost functions by stating that the expected cost of a safety recall for the owner of a vehicle with OTA updates support is equal to the expected cost of a safety recall for the owner of a vehicle without OTA updates support, weighted on the percentage of recalls that cannot be remotely resolved $(1-p)$.

In the equation (4) this relation is depicted:

$$C_{OTA} = (1-p) \times C_{wo\_OTA} \tag{4}$$

Where:

- p : percentage of remotely resolvable recalls.

In this equation, p represents the percentage of remotely resolvable recall. The complementary value, therefore, has been multiplied by the expected cost sustained in the case without OTA updates support in the previous equation. The equation of the formula reasonably highlights that as the number of safety recalls solvable remotely increases, C_{OTA} decreases until it becomes equal to zero when all recalls are fixable remotely (*p = 100%).*

By combining (2), (3) and (4) the authors defined the gain equation, through which the $RQ2$ has been answered.

Finally, the expected gain for a vehicle owner that supports OTA updates is:

$$\pi = C_{\text{wo\_}OTA} - C_{OTA} = p \times C_{\text{wo\_}OTA} \tag{5}$$

Where:

- π: represents the expected savings for the consumer owning a vehicle supporting OTA updates, in case of a safety recall event.

From this equation, the consumer's monetary gains will be obtained, in terms of euros saved. It is noteworthy that the impact of supporting this new technology on connected vehicles goes beyond economic gains and encompasses other unquantifiable benefits such as enhancing customer satisfaction and improving the end-user experience with the vehicle. These aspects cannot be easily modeled and therefore for the purpose of this research they are just qualitatively discussed in Chapter 3.

5.3. Recall

By delving deeper into the contribution that a safety recall provides in equation (1), this has been fragmented into six equation terms to better visualize the single different contributions that each required step brings to the overall cost.

In the absence of OTA updates support, the cost of a recall for a car can be attributed to the time and monetary expenses involved in the car owner's journey to the dealer.

The C_R can be thus represented as the sum of:

$$C_R = TT\ [h]\ \times\ VTT \left[\frac{€}{h}\right] +\ TC\ [€] + ST\ [h]\ \times\ VST \left[\frac{€}{h}\right] + SC\ [€] \tag{6}$$

Where:

- $TT\ (Travel\ Time)$: time needed to reach the dealership.
- $VTT\ (Value\ of\ Travel\ Time)$: factor that translates the travel time into economic terms.
- $TC\ (Travel\ Cost)$: monetary expenses incurred by the traveler during their journey depending on the mode of transportation under consideration.
- $ST\ (Service\ Time)$: is the service time required by the dealer to carry out the software update operations, including the update time and the waiting time of the car in the queue.
- $VST\ (Value\ of\ Service\ Time)$: factor that translates the service time into economic terms.
- $SC\ (Service\ Cost)$: is the cost of the service performed by the dealer, which, however, in the case of a safety recall is 0 for the end consumer because it is entirely borne by the OEMs.

The following paragraphs provide a detailed analysis of each equation term.

5.3.1. Travel Time

In this paragraph, the authors examined the travel time required for a driver to take their vehicle to a dealership for the software update. This time spent to reach the designated dealership to perform the software update is dependent upon the service time. As already presented in the "Journey planning" section (5.1.3), when the waiting time is equal to or less than a certain number of x hours (e.g., 2 hours), the vehicle owner will remain in the vicinity of the dealership until the update is completed. On the other hand, if the service time is greater than x hours, the vehicle owner will not wait in the dealership neighborhood but will return after X hours or days to pick up the vehicle. In this second case, the time spent in travel due to the recall will not only be represented by the round-trip time by car, but also by the time required to return home and travel back to the dealer using alternative means of transportation.

The fundamental relationship to express this contribution is:

- *CASE 1: (ST <= x [h])*

$$TT = T_{o1} + T_{r1}$$

(7)

- *CASE 2: (ST > x [h])*

$$TT = T_{o1} + T_{r1} + T_{o2} + T_{r2}$$

(8)

Where:

- ST: Service Time
- x: service time threshold after which the customer returns home to wait for the service to be completed.
- T_{o1}: time to get to the dealership from home with driver's own car.
- T_{r1}: time to return back to home from the dealership (in CASE 2, with an alternative mean of transfer).
- T_{o2}: time to return back to the dealership from home with an alternative mean of transfer.
- T_{r2}: time to return back home after picking up the vehicle to the dealership.

The next two figures (Figure 5.3 and Figure 5.4) depict the two different cases.

Figure 5.3: Graphic illustration of Case 1

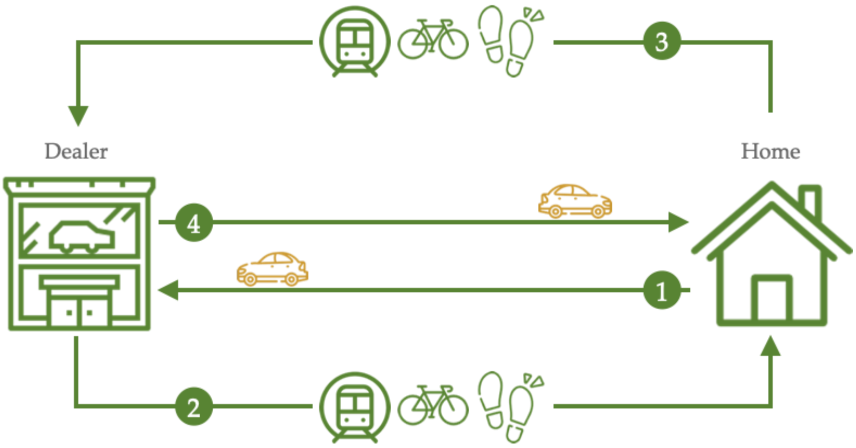


Figure 5.4: Graphic illustration of Case 2

The authors assume that the place of departure and arrival, after vehicle pickup, coincide and that also travel times of same distances covered by the same mean of transport coincide.

HP7: the place of departure coincides with the place of arrival after vehicle pickup, therefore $T_a = T_r$ *(for same mean of transport)*

Hence, it ensues that:

- In CASE 1:
  - $T_{o1} = T_{r1}$

- In CASE 2:
  - $T_{o1} = T_{r2}$
  - $T_{r1} = T_{o2}$

In particular, the contribution of time needed to reach the dealership from the vehicle owner's house will be generally described by the following base relationship derived from the speed definition:

$$T = \frac{d}{s} \tag{9}$$

Where:

- d is the average distance home-dealership [m].
- s is the average speed calculated in the home-dealership route [km/h].

For the speed computation, the authors assume it to be the average speed in a given geographical area, taking into account the speed limits present in urban areas. Moreover, to calculate distance, d, the authors propose the following modeling.

5.3.1.1. Distance

Considering a certain surface, A, (i.e., that of the Municipality of Milan) and the number of authorized dealers (D) to operate the update service for a certain car manufacturer in that specific area, it is possible to derive the "covered area" by a dealer (S). To obtain the distance, the authors assume reasonable for simplicity and effectiveness to approximate S to a circle of radius r. The dealer is considered the center of the circle. Assuming a homogeneous distribution of the population within surface

A and, in turn, within *S*, it follows that the average distance from the center of the circle and therefore from the dealership will be equal to half the radius.

Defined:

- A_j: area of municipality j [Km²].
- D_{k_j}: number of authorized dealerships for the OEM *k* in the municipality *j* [d].
- S_{k_j}: area covered by an authorized dealership for the OEM *k* in the municipality *j* [Km²/d].
- r_{k_j}: radius of S_{k_j} area [Km].
- d_{k_j}: average distance consumer-dealership (*k*) in the municipality *j*.

Mathematically, it ensues:

$$S_{k\_j} = \frac{A_j}{D_{k\_j}} \tag{10}$$

$$r_{k\_j} = \sqrt{\frac{S_{k\_j}}{\pi}} \tag{11}$$

$$d_{k\_j} = \frac{r_{k\_j}}{2} \tag{12}$$

5.3.2. Value of Travel Time (VTT)

In order to translate in economic terms the value of travel time, the homonym factor has been developed by taking inspiration from different scientific papers and the thesis work accomplished by the assistant researchers Alessandro Branca and Federico Brianza for the Connected Car & Mobility Observatory of Politecnico di Milano titled "Mobility as a Service applications in an urban environment: evaluation of social benefits".

Before delving into the subject matter, it is important to clarify that the multiplication between the travel time and its economic value, is a vector multiplication because the value of travel time varies depending on the vehicle used to cover the distance home-dealership. Therefore, the total contribution in the calculation of the expected cost of a safety recall will be the sum of the different trips involved.

In equation 13, this relationship is expressed in mathematical terms:

$$Travel\ Time\ \times\ Value\ of\ Travel\ Time\ (VTT) = \sum_{i} TT_i\ \times\ VTT_i$$

(13)

The Value of Travel Time (VTT) concept was initially introduced in the 1960s following the development of the Time Allocation Model (Athira *et al.* 2016). This model suggests that consumers allocate their time and cost to various activities by maximizing their utility under time and budget constraints. In-depth studies conducted by Hössinger *et al.* (2020) and Fournier & Christofa (2021) have extensively analyzed the concept of VTT. Both these studies concurred to the definition of the VTT, which can be defined as the difference between the travel opportunity cost (VoL) and the utility gained from spending time in travel (VTAT), which can be demonstrated through the following equation:

$$VTT_{vehicle} = VoL - VTAT_{vehicle}$$

(14)

Where:

- *Value of Leisure (VoL)*: is the opportunity cost regarding both leisure and work activities.
- *Value of Time Assigned to Travel (VTAT)*: is both related to vehicle characteristics and the possibility to carry out alternative activities during the trip.

5.3.2.1. Value of Leisure (VoL)

Differently from the second term of the equation, the VTAT, this term contribution is independent from the type of vehicle used.

In fact, it depends on:

- *Trip characteristics*: distance and travel purpose.
- *Personal traveler characteristics*: gender, age, income, and marital status.

Some of these variables are continuous, like distance, age, and income, while the others (travel purpose, gender, and marital status) are discrete.

Given the complexity of analyzing the impact of all these variables simultaneously, the authors consulted various studies in the scientific literature, including those conducted by Athira *et al.* (2016), Fournier & Christofa (2021), Hössinger *et al.* (2020), Máca & Kohlová (2019), Poudel & Singleton (2022) and Sartori *et al*. (2015). Through a comprehensive analysis of these studies, the authors identified as key variables influencing VoL:

- Income
- Travel distance
- Travel purpose

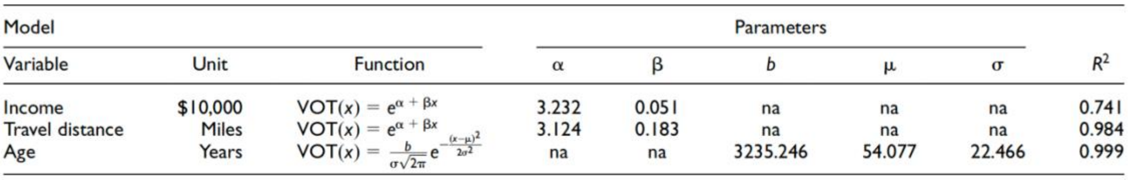
Income is considered the most appropriate variable to express the opportunity cost of travel, which represents the potential income that the user could earn if the time spent on travel was utilized for work. According to Athira *et al.* (2016), income has a substantial influence on VoL and can be measured as the ratio (15) between:

- δ_{time}: represents the marginal utility of time, which is measured in utility per hour. It captures the additional satisfaction that an individual obtains from spending an extra unit of time on a particular activity.
- δ_{money}: denotes the marginal cost per unit of money, which is expressed in utility per euro. This variable is closely linked to the income level of the decision-maker, as it reflects the amount of utility that a given amount of money can generate for that individual.

$$VoL = \frac{\delta_{time}\left[\frac{U}{hour}\right]}{\delta_{money}\left[\frac{U}{€}\right]} = \left[\frac{€}{hour}\right] \tag{15}$$

The marginal unit of cost, δ_{money}, has a greater impact on the value of life (VoL) than the marginal utility of time, δ_{time}. This is due to the fact that while the marginal utility associated with each hour of time is similar across individuals (as each person typically has 24 hours available per day), δ_{money} varies widely depending on the income level of the user. Therefore, the values of δ_{money} can differ significantly among individuals, leading to a greater influence on VoL than δ_{time}.

Athira *et al.* (2016) and Fournier & Christofa (2021) have both examined the relationship between income and VoL. While the former study simply states an upward trend in VoL as income increases, the latter study provides a more detailed analysis by establishing a mathematical relationship between the two variables (Figure 5.5).



Model			Parameters					
Variable	Unit	Function	α	β	b	μ	σ	R^2
Income	\$10,000	$VOT(x) = e^{\alpha + \beta x}$	3.232	0.051	na	na	na	0.741
Travel distance	Miles	$VOT(x) = e^{\alpha + \beta x}$	3.124	0.183	na	na	na	0.984
Age	Years	$VOT(x) = \frac{b}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$	na	na	3235.246	54.077	22.466	0.999

Figure 5.5: Summary of parametric variables for VoL computation (Fournier & Christofa 2021)

To derive this relationship, Fournier & Christofa (2021) conducted a survey of 14.159 trips, thus providing a richer dataset for their analysis.

Here is the function that links the two variables:

$$VoL(x) = e^{\alpha+\beta x} \tag{16}$$

Where:

- x = income [one unit = 10.000€]
- α = 3,232
- β = 0,051

Travel distance is the length of the trip undertaken by the consumer to reach the dealership. Similar to the analysis of income, the authors draw upon the works of Athira *et al.* (2016) and Fournier & Christofa (2021) to investigate the relationship between travel distance and VoL. Specifically, Athira *et al*. (2016) found a positive correlation between travel distance and VoL, while Fournier & Christofa (2021) developed a functional relationship between the two variables based on a survey of 14.159 trips.

Here is the function that links the two variables:

$$VoL(x) = e^{\gamma+\theta x} \tag{17}$$

Where:

- x = travel distance [Km]
- γ = 3,124
- θ = 0,183

Differently from income and travel distance, *travel purpose* is a discrete variable that denotes the reasons why a consumer travels. While there are various travel purposes, the authors utilized this distinction to model if the trips towards a dealership in case of a "safety recall" are accomplished during working hours or during bank holidays. For this reason, the following two categories of travel purposes have been taken into consideration: business trips and not business trips. The classification is based on Athira *et al.* (2016) findings that distinguish the assessment of Value of Time (VoL) between these two categories. Specifically, VoL for business trips should be evaluated based on income, while VoL for not business trips should consider the willingness to pay for saved time that can be spent on leisure activities. In addition to these authors' views, the literature exhibits a divergence of thought on whether the economic value of not business trips can be inferred from income, with some authors arguing for it (Fournier & Christofa 2021) and others against. In order to bridge this research gap, referring to the study by Sartori *et al.* in 2015, the authors of this thesis estimated the Value of Leisure for non-business trips as a proportion of the outcomes calculated for business trips.

5.3.2.1.1. VoL for Business trips

Once defined the variables that influence the model, the authors' objective was to estimate the Value of Leisure (VoL) while simultaneously considering the influence of both travel distance and income. Fournier & Christofa's (2021) contribution to the model is significant as they provided functions (16) and (17), which were described earlier. These functions are important as they enable the authors to determine the VoL for any income and travel distance value, without relying on the intervals established by Fournier & Christofa (2021). Table 9 displays the income and travel distance ranges taken into account.

VoL_{ij} [€/hour]	Income Ranges [€]					
Distance Ranges [Km]	<25 K	25K - 49,9K	50K - 74,9K	75K - 99,9K	100K - 124,9K	>125K
<0,5	-	-	-	-	-	-
0,5 - 1	-	-	-	-	-	-
1,1 - 2	-	-	-	-	-	-
2,1 - 3	-	-	-	-	-	-
3,1 - 4	-	-	-	-	-	-
4,1 - 5	-	-	-	-	-	-
5,1 - 6	-	-	-	-	-	-
6,1 - 7	-	-	-	-	-	-
7,1 - 8	-	-	-	-	-	-
8,1 - 9	-	-	-	-	-	-
9,1 - 10	-	-	-	-	-	-

Table 9: Ranges of travel distance and income considered

To fill in each cell of the table, a relationship that links the two variables must have been established. The authors used the following relationship defined by a previous thesis work, which condensates the two fundamental formulas (16) and (17) in a unique one, considering both variables' independents.

$$VoL_{ij} = W_{distance_i} \times VoL_{distance_i} + W_{income_j} \times VoL_{income_j} \tag{18}$$

Where:

- i: distance range
- j: income range
- VoL_{ij}: Value of Leisure calculated for each combination of distance-income range.
- $W_{distance_i}$: weight of travel distance compared to the income in the computation of VoL_{ij}.
- W_{income_j}: weight of income compared to the distance in the computation of VoL_{ij}.
- $VoL_{distance_i}$: absolute Value of Leisure related to the distance range i.
- VoL_{income_j}: absolute Value of Leisure related to the income range j.

The calculation of VoL_{income_j} and $VoL_{distance_i}$ values within the relevant range is a crucial step in the analysis, which can be achieved through point-by-point calculations using equations (16) and (17). As shown in Table 10, the values are calculated with Microsoft Excel by varying the independent variable of 0,1 Km and 0,1*10.000€ respectively.

Income [10.000€]	*VoL income [€/hour]*	*Distance [Km]*	*VoL distance [€/hour]*
0,1	25,46	0,1	23,00
0,2	25,59	0,2	23,26
0,3	25,72	0,3	23,53
….	….	….	….
30	116,98	10	70,91

Table 10: Values of VoL_{income} and $VoL_{distance}$ when income and distance vary by 0,1 units

The calculation of the average values for VoL_{income} and $VoL_{distance}$, based on the data presented in Table 10, is performed for each income and travel distance range specified in Table 9. The outcomes of this computation are reported in the following Tables 11 and 12, respectively.

Income ranges [€]	*VoL income j [€/hour]*
<25 K	27,01
25K - 49,9K	30,61
50K - 74,9K	34,86
75K - 99,9K	39,70
100K - 124,9K	44,99
>=125K	77,41

Table 11: Average VoL_{income} per income range

Distance ranges [Km]	*$VoL_{distance\ i}$ [€/hour]*
<0,5	23,53
0,5-1	24,91
1,1-2	27,13
2,1-3	30,40
3,1-4	34,07
4,1-5	38,17
5,1-6	42,77
6,1-7	47,92
7,1-8	53,69
8,1-9	60,16
9,1-10	67,40

Table 12: Average $VoL_{distance}$ per distance range

The last step to reach the goal of calculating the VoL_{ij} is to define the two weights $W_{distance_i}$ and W_{income_j} for each cell in Table 12.

To do so, a coefficient p_{ij} has been defined, using the data of Table 11 and 12. The values obtained for p_{ij} are shown on Table 13 on the following page.

$$p_{ij} = \frac{VoL_{distance_i}}{VoL_{income_j}} \tag{19}$$

p_{ij}	Income Ranges [€]					
Distance Ranges [Km]	<25 K	25K - 49,9K	50K - 74,9K	75K - 99,9K	100K - 124,9K	>125K
<0,5	0,87	0,77	0,67	0,59	0,52	0,30
0,5 - 1	0,92	0,81	0,71	0,63	0,55	0,32
1,1 - 2	1,00	0,89	0,78	0,68	0,60	0,35
2,1 - 3	1,13	0,99	0,87	0,77	0,68	0,39
3,1 - 4	1,26	1,11	0,98	0,86	0,76	0,44
4,1 - 5	1,41	1,25	1,09	0,96	0,85	0,49
5,1 - 6	1,58	1,40	1,23	1,08	0,95	0,55
6,1 - 7	1,77	1,57	1,37	1,21	1,07	0,62
7,1 - 8	1,99	1,75	1,54	1,35	1,19	0,69
8,1 - 9	2,23	1,97	1,73	1,52	1,34	0,78
9,1 - 10	2,50	2,20	1,93	1,70	1,50	0,87

Table 13: Values of p_{ij} for each combination of $VoL_{distance\_i}$ and VoLincome_j

By using the values of p_{ij}, the corresponding $W_{distance_i}$ and W_{income_j} values can be obtained through a system of two equations with two unknown variables:

$$\begin{cases} \dfrac{VoL_{distance_i}}{VoL_{income_j}} = p_{ij} \\ VoL_{distance_i} + VoL_{income_j} = 1 \end{cases} \tag{20}$$

The solutions for the system of equations, for each combination of $VoL_{distance_i}$ and VoL_{income_j}, are presented in the following Table 14.

	<25 K		25K - 49,9K		50K - 74,9K	
	$W_{distance\,i}$	$W_{income\,j}$	$W_{distance\,i}$	$W_{income\,j}$	$W_{distance\,i}$	$W_{income\,j}$
<0,5	46,6%	53,4%	43,5%	56,5%	40,3%	59,7%
0,5 - 1	48,0%	52,0%	44,9%	55,1%	41,7%	58,3%
1,1 - 2	50,1%	49,9%	47,0%	53,0%	43,8%	56,2%
2,1 - 3	53,0%	47,0%	49,8%	50,2%	46,6%	53,4%
3,1 - 4	55,8%	44,2%	52,7%	47,3%	49,4%	50,6%
4,1 - 5	58,6%	41,4%	55,5%	44,5%	52,3%	47,7%
5,1 - 6	61,3%	38,7%	58,3%	41,7%	55,1%	44,9%
6,1 - 7	63,9%	36,1%	61,0%	39,0%	57,9%	42,1%
7,1 - 8	66,5%	33,5%	63,7%	36,3%	60,6%	39,4%
8,1 - 9	69,0%	31,0%	66,3%	33,7%	63,3%	36,7%
9,1 - 10	71,4%	28,6%	68,8%	31,2%	65,9%	34,1%

Table 14: $W_{distance\_i}$ and W_{income_j} for each combination of $VoL_{distance\_i}$ and VoL_{income_j}

	75K - 99,9K		100K - 124,9K		>125K	
	$W_{distance\,i}$	$W_{income\,j}$	$W_{distance\,i}$	$W_{income\,j}$	$W_{distance\,i}$	$W_{income\,j}$
<0,5	37,2%	62,8%	34,3%	65,7%	23,3%	76,7%
0,5 - 1	38,5%	61,5%	35,6%	64,4%	24,3%	75,7%
1,1 - 2	40,6%	59,4%	37,6%	62,4%	26,0%	74,0%
2,1 - 3	43,4%	56,6%	40,3%	59,7%	28,2%	71,8%
3,1 - 4	46,2%	53,8%	43,1%	56,9%	30,6%	69,4%
4,1 - 5	49,0%	51,0%	45,9%	54,1%	33,0%	67,0%
5,1 - 6	51,9%	48,1%	48,7%	51,3%	35,6%	64,4%
6,1 - 7	54,7%	45,3%	51,6%	48,4%	38,2%	61,8%
7,1 - 8	57,5%	42,5%	54,4%	45,6%	41,0%	59,0%
8,1 - 9	60,2%	39,8%	57,2%	42,8%	43,7%	56,3%
9,1 - 10	62,9%	37,1%	60,0%	40,0%	46,5%	53,5%

Table 14: $W_{distance\_i}$ and W_{income_j} for each combination of $VoL_{distance\_i}$ and VoL_{income_j}

By calculating $VoL_{distance_i}$, VoL_{income_j}, $W_{distance_i}$, and W_{income_j}, it is possible to use equation (14) to fill the empty cells in Table 9. The resulting VoL_{ij} values for business trips are then presented in the next Table 15, which shows the values for each income and distance range.

VoL_{ij} [€/hour]	Income Ranges [€]					
Distance Ranges [Km]	<25 K	25K - 49,9K	50K - 74,9K	75K - 99,9K	100K - 124,9K	>125K
<0,5	25,39	27,53	30,30	33,69	37,62	64,85
0,5 - 1	26,00	28,05	30,72	34,00	37,83	64,63
1,1 - 2	27,07	28,98	31,48	34,60	38,27	64,36
2,1 - 3	28,81	30,51	32,79	35,67	39,11	64,15
3,1 - 4	30,95	32,43	34,47	37,10	40,28	64,16
4,1 - 5	33,55	34,81	36,59	38,95	41,86	64,45
5,1 - 6	36,67	37,70	39,22	41,29	43,91	65,08
6,1 - 7	40,38	41,17	42,42	44,20	46,50	66,13
7,1 - 8	44,76	45,31	46,28	47,74	49,72	67,69
8,1 - 9	49,89	50,19	50,88	52,03	53,67	69,86
9,1 - 10	55,85	55,91	56,31	57,14	58,43	72,75

Table 15: VoL for each combination of distance and income range for business trips

5.3.2.1.2. VoL for non-business trips

As previously described, to estimate the Value of Leisure (VoL) for non-business trips the authors intend to calculate it as a proportion of the outcomes calculated for business trips (values reported in Table 15), following the study by Sartori *et al.* (2015). To determine this percentage, the authors refer again to the results of Fournier and Christofa (2021) as presented in below Table 16, which provides data from the same sample of participants used for the estimation of VoL for business trips.

Trip Purpose	***VoL[$/hour]***
Work/school	70,20
Recreation	54,60
Shopping/errands	42,20
Other	41,50

Table 16: VoL based on the trip purpose (Fournier & Christofa 2021)

As the estimation of these values is solely based on the travel purpose and is independent of factors such as income and travel distance, they can be utilized to determine the percentage i for computing the VoL for non-business trips:

$$i = \frac{VoL_{NBU}}{VoL_{BU}} = \frac{46{,}1}{70{,}2} = 65{,}67\% \tag{21}$$

Where VoL_{NBU} is equal to the average of the Fournier and Christofa (2021) values of VoL for "Recreation", "Shopping/errands" and "Other", while on the other hand VoL_{BU} is equal to the "Work/school" VoL (Table 17).

Trip Purpose	***VoL[$/hour]***
Business trips	70,20
Non-business trips	46,10

Table 17: VoL for business and not business trips

Subsequently, the authors estimated the VoL for non-business trips by multiplying the VoL for business trips with the previously calculated percentage i from equation (17), as reported in Table 18.

VoL ij [€/hour]	Income Ranges [€]					
Distance Ranges [Km]	<25 K	25K - 49,9K	50K - 74,9K	75K - 99,9K	100K - 124,9K	>125K
<0,5	16,67	18,08	19,90	22,12	24,70	42,59
0,5 - 1	17,08	18,42	20,17	22,33	24,84	42,44
1,1 - 2	17,78	19,03	20,67	22,72	25,13	42,26
2,1 - 3	18,92	20,03	21,53	23,43	25,68	42,13
3,1 - 4	20,32	21,30	22,64	24,36	26,45	42,14
4,1 - 5	22,03	22,86	24,03	25,58	27,49	42,32
5,1 - 6	24,08	24,75	25,75	27,12	28,83	42,74
6,1 - 7	26,52	27,04	27,86	29,02	30,54	43,43
7,1 - 8	29,39	29,75	30,39	31,35	32,65	44,45
8,1 - 9	32,76	32,96	33,41	34,17	35,24	45,88
9,1 - 10	36,68	36,72	36,98	37,52	38,37	47,78

Table 18: VoL for each combination of distance and income range for not business trips

5.3.2.2. Value of Time Assigned to Travel (VTAT)

Calculating Value of Travel Time (VTT) requires taking into account two key components, one of which is the Value of Time Assigned to Travel (VTAT), which pertains primarily to mode-specific transportation characteristics. As noted by Hössinger *et al.* (2020), computing this factor necessitates gathering data from a comprehensive survey of a large number of individuals. However, the authors of this thesis have decided to use the data already obtained by Hössinger *et al.* (2020), displayed in Table 19, and substitute it into formula (14). Although this approach may potentially influence the model outcomes due to the specific context of the survey conducted by Hössinger *et al*. (2020), the authors have chosen to utilize these values rather than disregard the factor entirely.

	Bike	***Car***	***Subway***	***Walk***
VTAT [€/hour]	-3,03	-4,23	0,27	-4,13

Table 19: VTAT for each the transport solution (Hössinger et al. 2020)

Upon reviewing the findings presented in the above table, it becomes apparent that the VTAT for subway travel substantially varies from the other modes of transportation. This difference is primarily due to the superior comfort provided by subway travel, which enables travelers to engage in secondary activities during their journey. Compared to driving and biking, subway travel eliminates the need for the consumer to operate a vehicle and removes exposure to the traffic stress that is typical of urban areas. After calculating the values of VoL and VTAT, the VTT can be obtained through the equation (14). Depending the VTAT on the mean of transport used to travel the home-dealer route, four different VTT values can be computed, according to the following formulas:

- $$VTT_{bike} = VoL - VTAT_{bike} \tag{22}$$
- $$VTT_{car} = VoL - VTAT_{car} \tag{23}$$
- $$VTT_{subway} = VoL - VTAT_{subway} \tag{24}$$
- $$VTT_{walk} = VoL - VTAT_{walk} \tag{25}$$

5.3.3. Travel Cost

In this section, the authors modeled the costs that the car owner sustain during the trip to the dealership in case of a "safety recall".

The expenses involved in renting a bike, taking the subway and walking can be easily calculated using equations (26), (27), and (28).

- $TC_{bike} = \frac{c\left[\frac{€}{min}\right] \times 60 \left[\frac{min}{h}\right] \times d\,[Km]}{s\left[\frac{Km}{h}\right]}$

(26)

- $TC_{subway} = subway\ ticket\ cost$

(27)

- $TC_{walk} = 0$

(28)

On the other hand, estimating the costs incurred while driving the car to the dealer from home is a little bit more complex. In fact, to calculate it the following formula has been developed by the authors:

$$TC_{car} = d\,[Km] \times TC_{car\_fuel}\left[\frac{€}{Km}\right] \tag{29}$$

Where:

- $TC_{car\_fuel}\left[\frac{€}{Km}\right] = \sum_{fuel} TC_{fuel}\left[\frac{€}{Km}\right] \times \%\ Concentration_{fuel}$

(30)

  It represents the travel cost component for fuel consumption and it's a weighted average of the percentage concentration of differently fueled vehicles.

With:

- $TC_{fuel}\left[\frac{€}{Km}\right] = Consumption_{fuel}\left[\frac{l/KWh/Kg}{Km}\right] \times Price_{fuel}\left[\frac{€}{l/KWh/Kg}\right]$

(31)

- $\%\ Concentration_{fuel} = \frac{\#\ vehicles\ per\ fuel\ type}{total\ vehicles\ recalled}$

(32)

In particular, TC_{fuel} refers to the money spent to travel 1 Km with that specific fuel, while $\%\ Concentration_{fuel}$ stands for the percentage concentration of vehicles powered by different types of power supply, within a particular set of vehicles subject to recall.

In order to calculate TC_{fuel}, prices and consumption measures of different types of fuels are needed (Table 20). The authors analyzed the consumption, taking into account 15 different city car models included in the article by Motor1 and prices by combining the information coming from "Ministero dell'Ambiente e della Sicurezza Energetica" (MISE) website, and average self-service fuel prices in Italy during March 2023 (for the cost of electricity, the value of Public AC charging, Enel X was taken as reference).

Vehicle power supply	*Consumptions*		*Prices*	
	Unit of measure	Values	Unit of measure	Values
Diesel	[l/Km]	0,048	[€/l]	1,816
Electricity	[KWh/Km]	0,148	[€/KWh]	0,58
Liquified Petrol Gas (LPG)	[l/Km]	0,074	[€/l]	0,788
Methane	[Kg/Km]	0,037	[€/Kg]	2,458
Petrol	[l/Km]	0,054	[€/l]	1,761

Table 20: Average values of fuel consumption and price for each type of power supply

5.3.4. Service Time

The Service Time represents the total service time that the vehicle owner will have to wait before being able to withdraw their car. It is important to underline that this quantity differs from the update time because the dealer will have to execute updates on multiple vehicles, potentially resulting in a queue of vehicles waiting for service.

To model this part, the authors decided to use Queueing Theory. In particular, the following scientific sources on the topic were used:

- Fundamentals of Queueing Theory, by D. Gross, J. Shortle, J. Thompson, and C. Harris (Wiley Series in Probability and Statistics, 4th edition).
- Basic Queueing Theory, János Sztrik.

As defined in Fundamentals of Queueing Theory, "A queueing system can be described as customers arriving for service, waiting for service if it is not immediate, and if having waited for service, leaving the system after being served. The term customer is used in a general sense and does not imply necessarily a human customer".

To represent a queueing system, it is crucial to identify the probabilistic properties of the arrival flow of requests, service times, and service disciplines. The arrival process can be characterized by the distribution of the interarrival times of the customers. In queueing theory these interarrival times are usually described using the Poisson distribution, assuming that arrival times are independent and identically distributed random variables. This can reasonably describe the "safety recall" system underlying this model, as it is reasonable to assume that the arrival of each car to the dealership is an independent and random variable. Below is the hypothesis just discussed:

HP8: the car interarrival times to the dealership are described using the Poisson distribution, being independent and identically distributed random variables

Moreover, to depict a queueing system, it is necessary to define the "service discipline" that determines the rule according to which the next customer is served. Consistent with the system underlying the model and as emerged from meetings with dealerships, in the case of a safety recall, the dealer updates the vehicle that arrives first at the dealership, following a FIFO (First In, First Out) logic, also known as FCFS (First Come, First Served).

A queueing system can be featured by six parameters, following the below well-known Kendall's classification:

$$A\ /\ B\ /\ m\ /\ K\ /\ n\ /\ D$$

Where:

- A: distribution function of the interarrival times.
- B: distribution function of the service times.
- m: number of servers.
- K: capacity of the system, the maximum number of customers in the system including the one being served.
- n: population size, number of sources of customer.
- D: service discipline.

Exponentially distributed random variables are notated by M, meaning Markovian or memoryless. Furthermore, if the population size and the capacity is infinite, the service discipline is FIFO, then they are omitted.

For the purpose of this research, an M/M/c system is well representing the “safety recall” system, denoting a system with Poisson arrivals, exponentially distributed service times, and c servers, serving with a FIFO service discipline. M/M/c is a classical multiple-servers configuration with a single queue.

Moreover, it is worth presenting some parameters used in the solving formulas for M/M/c queueing systems:

- λ: arrival rate [car/h] representing the hourly demand per dealership.
- μ: service rate [car/h].
- n: number of customers (cars) in the system (including the ones in the queue).
- L_q: average number of customers waiting in the queue.
- L_s: average number of customers waiting in the system.
- W_s: average system throughput time (average time spent in the system by a customer).
- ρ: traffic intensity of the system.
- c: number of servers in the dealership.

Therefore, it is possible to state that the Service Time coincides with the average waiting time in the system (W_s) which represent the time from when the vehicle arrives at the dealership to when it is picked up by the owner, including both the waiting time and the actual time to perform the update. It is worth highlighting that the system expected throughput time is a representation of the "average" customer.

The variable c represents the number of servers present in the dealership, therefore representing the number of cars that the dealer shop can serve simultaneously.

Before introducing the queueing theory formulas necessary to calculate W_s, it is worth defining some additional variables:

- UT: update time [h/car].
- R: number of recalled cars.
- pr: average penetration rate of a safety recall campaign.
- D: number of dealerships.
- WH: daily working hours of the dealership [h/day].
- T: number of days within which the update must be performed [day].

The Update Time (UT) indicates the exact time it takes a dealership to perform the vehicle update operation. R represents the precise number of vehicles that have been recalled by the automaker for the update. It is worth pointing out that D represents the number of dealerships authorized to perform the vehicle service. It is worth emphasizing that not all customers who are “recalled” then actually bring the vehicle to the dealership. In fact, the interviews conducted showed that each recall campaign has a certain *penetration rate*. Campaigns for safety-related recalls have higher penetration rates, both because the customer is more sensitive and because the OEM uses various instruments to push the consumer to make the update as soon as possible. For instance, Honda Italy for a safety recall that happened in 2022 offered Amazon vouchers to customers who brought their vehicles to update the software. Therefore, the model considers the penetration rate as the cars that will actually go to the dealer to perform the update will be the number of recalled cars, *R*, multiplied by the penetration rate.

At this point, it is appropriate to introduce two assumptions underlying the model:

HP9: customers are evenly distributed among the D dealerships

HP10: the customers arrive at the dealership uniformly during the period T

It follows that the arrival rate, which is the average hourly number of vehicles arriving at the dealership for the update, is defined by the following formula:

$$\lambda\left[\frac{car}{h}\right]=\frac{\frac{pr\times R}{D}}{T\times WH} \tag{33}$$

The service rate coincides with the reciprocal of the update time, representing the hourly number of vehicles that a dealership (each server) can serve.

$$\mu\left[\frac{car}{h}\right]=\frac{1}{UT} \tag{34}$$

At this point, it is appropriate to introduce another fundamental quantity that describes a queueing system, ρ, the "traffic intensity", defined as the ratio of arrival and service rate.

$$\rho=\frac{\lambda}{\mu} \tag{35}$$

The formula to calculate the average system throughput time ($W_s = ST$) is as follows:

$$W_s[h]=\frac{L_q}{\lambda}+\frac{1}{\mu}=ST \tag{36}$$

Therefore, to calculate W_s, it is necessary to comprehend the average number of customers waiting in the queue, L_q, which can be derived from the following formulas:

$$L_q=L_s-\rho \tag{37}$$

$$L_s=\frac{\rho^{c+1}}{(c-1)!\,(c-\rho)^2}\,P_0+\rho$$

(38)

$$P_0 = \frac{1}{\left(\sum_{i=0}^{c-1} \frac{\rho^i}{i!}\right) + \frac{\rho^c}{c!\,(1 - \frac{\rho}{c})}}$$

(39)

5.3.5. Value of Service Time

To convert the service time into monetary terms, the authors define a quantity called "Value of Service Time" (VST) that represents the monetary value of the vehicle owner's time. This value represents the productivity loss caused by the time "lost" waiting for the completion of the service. The following assumption underlies this reasoning:

HP11: During the service time, the vehicle owner does not work

To determine the Value of Service Time (VST), in monetary terms per hour (€/h), the authors consider the average net salary in a specific geographic area (where the recall takes place) and the average working hours per year (in the same geographical area).

Therefore, the Value of Service Time in the geographical area j [€/h] can be defined as follow:

$$VST_j = \frac{YNS_j}{YWH_j}$$

(40)

Where:

- YNS_j: Yearly average Net Salary in the geographical area j [€/y].
- YWH_j: Yearly Working Hours in the geographical area j [h/y].

5.3.6. Service Cost

The update operations, in case of a safety recall, are entirely covered by the OEMs, i.e., the vehicle manufacturer. This can be easily extracted from government agency websites, such as the US NHTSA, or from automotive company websites, such as Tesla, which specifies that "if your Tesla is included in a recall, service to address the issue will be provided for free regardless of age or mileage".

Therefore, for the purpose of this model, it is legitimate to consider the Service Cost for the car's owner as zero.

5.4. Accidents

This section depicts the second part of the formula underlying the model, formula (1), which is reported below.

$$C = C_R + k \times C_A \tag{1}$$

The purpose of the model is to estimate the expected cost associated with a potential software failure-induced accident (which is the reason for the recall) for the car owner. As highlighted in Chapter 3, remote updates allow for a significant reduction in the "time-to-market" of an update, thereby decreasing (in practice, resetting) the likelihood of an accident occurring before the update is carried out in the case of a safety recall.

The first term of the second part of the equation, *k*, represents the probability that a recalled vehicle will undergo an accident due to software failure before the update is performed. Mathematically, it can be represented as follows:

$$k = \frac{I}{R} \tag{41}$$

Where:

- I: number of vehicles involved in car accidents
- R: number of recalled cars

The term, C_A, represents instead the average cost that an individual must bear following a road accident. In turn, C_A is composed of various terms that characterize road accidents and their related expenses:

$$C_A = C_H + C_{PL} + C_{BA} + C_{Rep} + C_{Ins} \tag{42}$$

Where:

- C_H: Health Care cost
- C_{PL}: Productivity Loss cost
- C_{BA}: Breakdown Assistance cost
- C_{Rep}: Car Repair cost
- C_{Ins}: Insurance cost

When a recall occurs, the manufacturer identifies all vehicles that require an update and, by cross-referencing chassis data in databases, locates and contacts the owner of the vehicle. The owner has the duty to bring the vehicle to the dealership as soon as possible. For instance, in Italy, according to Article 2054 of the Civil Code, the owner of the vehicle is legally responsible for the safe functioning of their own car. Moreover, failure to carry out the recall campaign may result in administrative sanctions for the consumer (Art. 79 c.4 of the *Codice della Strada*). Nevertheless, from interviews conducted with companies, it has emerged that in the judgment phase, the responsibility for the accident can be attributed to either the consumer or the manufacturer based on specific circumstances. The aim of this work is to propose a solution to the general and theoretical case. Therefore, unable to consider specific circumstances, the model considers the theoretical case where the consumer is legally responsible for the proper functioning of their vehicle.

5.4.1. Health Care Cost

Exploring the first equation (42) term, health care costs refer to the driver's own injury costs that she has to bear in the case of an accident induced by the software failure, for which the safety recall was prompted. In fact, in Italy, third-party or passenger injuries and unintended damages are covered by compulsory RC (*Responsabilità Civile*) insurance that all vehicles on the road must have, even whether the vehicle is stationary or parked.

As a result, the equation for determining the average healthcare costs is as follows:

$$C_H = m \times (1 - i) \times c_h \tag{43}$$

Where:

- m: represents the percentage of accidents in which the driver of the guilty vehicle is injured.
- i : percentage of consumers with policy add-on "driver's injury coverage" (in Italian: "*infortunio conducente*").
- c_h: average individual cost for medical expenses following the injury.

The estimation of the health care costs that a driver would have to bear after a road accident in which they sustain an injury depends on multiple factors. Firstly, it depends on the severity of the injury, as the length of hospitalization, needed following therapies, and necessary physiotherapy would vary between a minor injury, which may not even require hospitalization, and a severe injury, which would inevitably result in higher costs.

Another factor that influences medical costs is the geographical location, as different countries have adopted various welfare policies regarding national healthcare. For instance, in Italy, the National Health Service (SSN) is a system of facilities and services that aim to ensure universal access to fair healthcare services for all citizens, in accordance with Article 32 of the Italian Constitution, which states that "the Republic safeguards health as a fundamental right of the individual and as a collective interest, and guarantees free medical care to the indigent. No one can be obliged to undergo a specific healthcare treatment except by law. The law cannot violate the limits imposed by the respect of the human person”. In other countries, such as the United States, Mexico, and Turkey, there is no universal healthcare coverage, but rather a system of private insurance that provides different healthcare coverage levels based on the plan selected by the insured.

In the case of national healthcare coverage, obviously, a notable aspect in defining medical expenses amount is the income of the injured party, which, combined with the benefits provided by the national healthcare coverage, results in the various amounts that the citizen must pay to receive the necessary medical support in any circumstance, including in the event of an accident.

Given the involvement of multiple elements and the complexity of determining each of them, the authors have chosen a different strategy to estimate the average medical costs. In fact, while the straight estimation of the above parameters can be considered a "direct" method, the authors have opted for an "indirect" approach. Many scientific studies estimate the societal cost associated with road accidents (e.g.: PoliS Lombardia -Valutazione economica dell’incidentalità stradale, analisi dei costi sanitari per il 2020 e confronto con il 2019, 2021 and Grosse and Krueger 2011). Inspired by these papers, the authors have decided to deduce the average cost of medical expenses that a driver involved in a car accident must bear in case of self-injury, from the total societal cost of accidents.

The literature regarding the societal cost assessment related to road accidents provides various methodologies. Based on the available data, the authors concluded that the Human Capital approach (HCA) was the most dependable method (Grosse and Krueger 2011).

The HCA allows determining the collective welfare loss based on the assessment of the economic consequences of road accidents (e.g., loss of productivity). In this way, the authors by determining the total cost that the society will suffer from road accidents and dividing it by the total population can obtain a first proxy of per-capita healthcare-related costs in case of a car accident.

To estimate the social costs of car accidents, the HCA divides them into two main categories:

- *Fatal car crashes*: refer to the financial harm that society incurs due to a deadly road accident.
- *Car crashes with injuries*: refer to the financial burden imposed on society due to a non-fatal road accident, resulting in injuries to at least one person.

The authors have decided to focus exclusively on the second category because, since the model aims to find the expense for the consumer and in case of death, it would be irrational to calculate an individual consumer cost, they assume that for the person involved in the accident the expenses can be approximated just with the second category of costs.

In the following sections, the authors assessed the social healthcare costs of injuring accidents.

5.4.1.1. Social Cost per Slightly Injured person involved in a Car Crash

In assessing the expenses borne by the community for individual accidents, healthcare costs are the primary expense item contributing to them. As reported by Miller (2004) healthcare costs can be divided in: ambulance, ER (Emergency Room), therapies, and hospitalization. For a slightly injured person involved in an accident, just ER and ambulance costs have been taken into consideration, considering that hospitalization and therapies are typically not expected to be necessary for an injury of this type.

Given Italy's unified healthcare system, the authors of this work used Lombardy's ER and ambulance costs per person as a benchmark, believing that is a reliable and scalable estimation that can eventually be applied nationwide. These data were gathered from the *"Valutazione economica dell'incidentalità stradale - Analisi dei costi sanitari per il 2020 e confronto con il 2019"* published by Regione Lombardia and PoliS Lombardia in November 2021.

$$C_{h_{slight\,injury}} = ER + Ambulance = 153{,}51\text{ €} + 243{,}09\text{ €} = 396{,}6\text{ €}$$

(44)

5.4.1.2. Social Cost per Severe Injured person involved in a Car Crash

On the other hand, to estimate the social cost per severely injured person involved in a car crash, further considerations are needed to add to the computation of the hospitalization cost. To determine the average unit cost of hospitalization per seriously injured person, this study took the output of the cost analysis conducted at a regional level in Lombardy for 2020.

$$C_{h_{severe\,injury}} = ER + Ambulance + Hospitalization = 153{,}51\,€ + 243{,}09\,€\ +\ 5.607\,€ = 6.003{,}6\,€ \tag{45}$$

Subsequently, here is presented the Average Unit Social Cost C_h, which is a weighted average of the healthcare expenses that the community bears for a slight and severe injury.

$$C_h = \ C_{h_{slight\,injury}} \times \%\,of\ slight\ injuries + \ C_{h_{severe\,injury}} \times \%\,of\ severe\ injuries \tag{46}$$

Where:

- $\%\,of\ slight\ injuries$: is the percentage of slight injury accidents over total accidents that occurred.
- $\%\,of\ severe\ injuries$: is the percentage of severe injury accidents over total accidents that occurred.

Thus:

$$C_h = 396{,}6\,€ \times\ 0{,}774 + 6.003{,}6\,€ \times\ 0{,}226 = 1.663{,}78\,€ \tag{47}$$

In order to determine the percentages, in equation 46, of slightly and severely injured persons in car accidents, the authors retrieved the data from the same report above referenced (*"Valutazione economica dell'incidentalità stradale - Analisi dei costi sanitari per il 2020 e confronto con il 2019"*, 2021). According to the report, the percentage of slightly injured individuals is 77,4%, while the percentage of severely injured individuals is 22,6% in 2020.

In the following Table 21, a recap on the average cost per slight/severe injury is reported.

Social cost per injury		*Formula*	*Avg Unit Cost [€]*
Average cost per slight injury			
Expenses upon the community	Healthcare	Ambulance + ER	396,6
Average cost per severe injury			
Expenses upon the community	Healthcare	Ambulance + ER + Hospitalization	6.003,6

Table 21: Average cost per slight/severe injury

5.4.1.3. Number of car accidents with injuries

From the Istat database of road accidents, the authors effectively ascertained the yearly occurrence of accidents in Italy and gathered the number of individuals who suffered injuries in 2019. Although this work has being carried out in the middle of 2023, the authors have deemed more appropriate to use accident data from 2019, the year prior to the outbreak of the Covid-19 pandemic. This decision was made to avoid potential bias in the more recent years' data, as the pandemic's impact, including the implementation of various lockdowns and curfews throughout Italy, has significantly distorted accident statistics. Therefore, utilizing 2019 data allows for a more accurate and reliable analysis of road accidents in Italy.

In particular, in 2019, there were 172.183 road accidents resulting in injuries in Italy, slightly lower than in 2018 (-0,2%), with 3.173 fatalities (deaths occurring within 30 days of the event) and 241.384 injured individuals (-0,6%).

Therefore, it can be calculated the total society cost that the collectivity would bear for the total number of injured persons in 2019:

$$C_{h_{total}} = C_h \times \#of\ total\ injured\ people = 1.663{,}78\ \text{€}\ \times 241.384 = 401.610.354{,}29\ \text{€} \tag{48}$$

Since this model is designed to estimate the individual cost for the consumer, the total healthcare society cost is divided by the number of inhabitants of Italy able to drive, to obtain the individual expected cost. Although the authors acknowledge that this modeling may not reflect the actual cost associated with healthcare costs sustained by the driver, they are confident that it provides a reliable approximation (“proxy”). The authors determined the number of individuals in Italy who are eligible to drive by calculating the difference between the total Italian population and the population below the legal driving age. A further expedient is to also eliminate from the calculation all persons aged 90 years and older, who are often no longer able to drive given their age and thus are not part of the drivers who may be involved in an accident.

In Table 22, the calculation needed to arrive at the final number of eligible drivers has been detailed.

2022	***Number [persons]***
Total population in Italy	59.030.133
People under legal driving age (18 years old)	9.218.914
People over 90 years old	820.351
Number of persons elegible to drive in Italy	48.990.868

Table 22: Number of eligible drivers in Italy

Accordingly, the term c_h in the (49) equation will be calculated as:

$$c_h = \frac{C_{h_{total}}}{Italy\ elegible\ driving\ population} = \frac{401.610.354{,}29\ €}{48.990.868} = 8{,}20\ {}^{€}/_{person} \tag{49}$$

5.4.2. Productivity Loss Cost

The productivity loss cost refers to the loss of utility for the injured person. For this section, the primary underlying assumption is that during the injury recovery period following the accident, the consumer will be unable to work. In order to model this cost, the authors have settled to consider the average duration of hospitalization and convalescence following a road accident in a specific geographic area and multiply this value by the average monetary value of the time. Mathematically, the Productivity Loss cost due to the involvement in a car accident can be defined as:

$$C_{PL} = t_{hosp} \times VT_j \tag{50}$$

Where:

- t_{hosp}: average hospital stay time.
- VT_j: value of time in the geographical area j [€/h].

In turn, VT_j can be computed as:

$$VT_j = \frac{YNS_j}{YWH_j} \tag{51}$$

Where:

- YNS_j: Yearly Net Salary in the geographical area j [€/y].
- YWH_j: Yearly Working Hours in the geographical area j [h/y].

5.4.3. Breakdown Assistance Cost

This section proposes a model to estimate the expected cost of a breakdown assistance (BA) intervention following an accident.

$$C_{BA} = [p_{BA\_WD} \times ba_{wd} + p_{BA\_NH} \times ba_{nh}] \times ba \times \frac{1}{2} \tag{52}$$

Where:

- p_{BA_WD}: base price of breakdown assistance intervention on working days.
- ba_{wd} : percentage of breakdown assistance interventions on working days.
- p_{BA_NH} : base price of breakdown assistance intervention on night/holidays.
- ba_{nh} : percentage of breakdown assistance interventions on night/holidays.
- ba : percentage of accidents that required breakdown assistance intervention.

The formula takes into account several aspects. Firstly, the tariff is differentiated between working hours and non-working hours, and the percentage of interventions that occur during each specific time slot is weighted. It is important to highlight the following logical relationship between ba_{wd} e ba_{nh}:

$$ba_{nh} = 1 - ba_{wd} \tag{53}$$

Moreover, assuming that not all accidents require a breakdown assistance intervention, the average price is weighted by the probability, ba, that a BA is needed. This can be obtained from statistical data, as follows:

$$ba = \frac{BA_j}{A_j} \tag{54}$$

Where:

- BA_j: total number of BA interventions in geographical area j per year.
- A_j: total number of accidents in geographical area j per year.

The last term of equation (52), $\frac{1}{2}$, represents the fact that when an accident occurs between two vehicles, breakdown assistance may only be necessary for one of the two vehicles. Therefore, assuming that the probability of it being needed for one or the other is the same, it is reasonable to consider this safety factor as well.

5.4.4. Car Repair Cost

In the case of road accidents, consumers who cause the accident and do not have insurance for damages to their own vehicle may incur significant costs related to the repair of the vehicle. The following equation illustrates the costs related to car repair activities following a road accident.

$$C_{Rep} = \left(sh \times c_{ser\_j} + \sum_{i}^{N} c_{comp_i} \right) \times \left(1 - kasko_j\right) \tag{55}$$

Where:

- sh: average service hours required for car repair.
- c_{ser_j}: average dealership hourly service cost in the geographical area j.
- c_{comp_i}: cost of the i-th car’s component to be substituted.
- N: number of components to be substituted.
- $kasko$: % of vehicles with kasko insurance in the geographical area j.

The formula takes into account the average duration of service that a damaged vehicle requires and the average hourly fee of a repair shop in a given geographic area. In addition, the formula includes the cost of any components of the vehicle that may need to be replaced as a result of the accident. Finally, since some consumer have insurance that covers damages to their own vehicle even if they are the cause of the accident (in Italy this is called “kasko” insurance that covers all damages suffered by the vehicle, including those that do not involve other vehicles or third parties due to a risky maneuver or distraction), the formula takes into account the percentage of consumer who may incur a vehicle repair cost, $1 - kasko$, i.e. those who do not have this type of insurance.

5.4.5. Insurance Cost

The formula also takes into account the cost related to insurance. In fact, among the significant costs that road accidents can impose on consumers, another particularly onerous factor is the upsurge in insurance premiums following the accident, which can last for years. Road accidents are in fact one of the primary factors that impact the increase in insurance premiums for liability insurance, which covers damages to third parties.

The following equation illustrates the formula for calculating the insurance cost related to the increase in premium following a road accident:

$$C_{Ins} = c_{ins\_j} \times \Delta_{premium\_j} \tag{56}$$

Where:

- c_{ins_j}: average car insurance premium in the geographical area j.
- $\Delta_{premium\_j}$: average % increase of car insurance premium after a car accident in the geographical area j.

5.5. Model Design Assumptions and Limitations

In order to exhaustively comprehend how the model functions, the authors would like to conclude this chapter by summarizing the assumptions and hypotheses underlying the model design.

Firstly, given the newness of the topic and the fact that OTA updates for solving safety recall are still a developing issue without yet clear and standardized procedures, either at regulation or OEMs levels, the authors could not rely on scientific frameworks modeling the event of a safety recall from the consumer's point of view. To overcome this barrier, the authors had to propose general modeling of the safety recall event starting from the work of Halder et al. (2020), presented in section 5.3 ("Journey planning"). Therefore, it is worth pointing out that different modeling of the journey might lead to different results.

Moreover, in an effort to enhance comprehension of the model, the authors have formulated multiple hypotheses as its underlying foundations, which are succinctly presented in Table 23, provided below.

N	Hypothesis
1	*The driver and the owner of the car are the same person*
2	*In the case of remote updates, the consumer performs the operation during a period of inactivity (i.e., overnight)*
3	*The consumer brings the vehicle to the dealership within T days*
4	*Despite the recall, the car is capable to reach the dealership without the need for a breakdown truck*
5	*The starting point before bringing the vehicle to the dealership coincides with the point of arrival after picking up the car*
6	*The consumer, during the period when the vehicle is at the dealership, uses alternative means of transportation*
7	*The place of departure coincides with the place of arrival after vehicle pickup, therefore Ta = Tr (for same mean of transport)*
8	*The car interarrival times to the dealership are described using the Poisson distribution, being independent and identically distributed random variables*
9	*The customers are evenly distributed among the D dealerships*
10	*The customers arrive at the dealership uniformly during the period T*
11	*During service time, the vehicle owner does not work*

Table 23: Model Design hypotheses

Hypothesis number 4 limits the model application to recalls that do not require a tow truck to take the vehicle to the dealer. In fact, sometimes the defect causing the recall may result in the car being unable to be ridden. Following the interviews, the authors realized that this type of event is rare and therefore decided to introduce hypothesis number 4.

Hypothesis number 8 was introduced to be able to model the Service Time through the Queue Theory. In reality, some customers arrange appointments to have their vehicles updated by the dealer. In the latter case, the recall event management is less chaotic and allows the service time to be reduced. The authors decided to opt for Queue Theory because it is a scientific method that allows a good approximation for the management of critical services such as a safety recall. However, in the next validation chapter, the authors compared the results obtained using the Queue Theory with those obtained through an 'appointment' method, which ideally determines the service time as the update time without additional waiting time.

The last hypothesis, regarding the inactivity of the consumer during the service time, allows the authors to attribute an economic value to waiting service time. In reality, during the service time, for certain classes of jobs, it would be possible for the consumer to work, and especially in the case where the time is greatly extended, it is reasonable to assume that the consumer can work during the wait. Therefore, the assumption of considering the whole service time as an unproductive period of time might amplify the economic results.

As presented in the previous sections, the aim of this work is to propose a solution to the general and theoretical case. Therefore, unable to consider specific circumstances, the model considers the theoretical case where the consumer is legally responsible for the proper functioning of their vehicle.

Another noteworthy observation pertains to the authors' choice of deriving the consumer healthcare cost associated with a car accident from the broader societal costs. This constraint was driven by the fact that there were no studies available proposing a model to estimate the cost of a car accident for the consumer involved in it. Despite the limitations posed by this approach, the authors are confident that this is an adequate method to obtain a proper approximation of the cost to the consumer.

The authors have grounded the model on the two most noteworthy factors affecting the safety recall event: the costs related to the recall operations and the eventual accident. As presented in Chapter 3, several papers present many other benefits of OTA updates for the car owner. For example, reduced maintenance costs (Efstathiadis *et al.* 2021, Mirfakhraie *et al.* 2018, Riggs *et al.* 2018, Odat and Ganesan 2014), increased vehicle value (Efstathiadis *et al.* 2021, Halder *et al.* 2020, Khurram *et al.* 2016), increased customer satisfaction (Efstathiadis *et al.* 2021, Halder *et al.* 2020, Khurram *et al.* 2016). The authors have decided to include in the model only the most significant issues impacting a safety recall event. Moreover, for some aspects, such as customer satisfaction and experience, estimating the economic value through an economic model is exceptionally challenging, especially without scientific studies to rely on as references. Therefore, the authors have just discussed these topics qualitatively in the previous chapters.

6 Model Validation

The aim of this chapter is to validate the theoretical model presented in Chapter 5, whose aim is to answer the *RQ2* presented in section 4.1. In particular, the model that the authors developed at the theoretical level is intended to assess how much the consumer owning a Connected Car that supports OTA updates saves in case of a "safety recall" event, compared to a consumer with a vehicle that does not support them. Through model validation, the authors applied the model to a real case scenario in order to quantify the economic benefits of OTA updates support. The purpose of model validation is to ensure that the model accurately represents the real-world system that the model attempts to simulate.

The process of model validation involved the following steps which will be the core of the next sections:

1. Collect validation data: this first step consisted in collecting the data that were used to test the model's capability. This activity involved conducting interviews and gathering data from reliable sources. Section 6.1 will outline the data collection methods utilized and provide an overview of all the data collected.
2. Perform model simulations: the model is then run using the validation data to generate simulated results. The model has been tested in the metropolitan city of Milan.
3. Analyze and interpret results: the final step regarded the analysis of the model simulation results and the interpretation of the model findings. This step will be outlined by the authors in Section 6.3.

The specific urban reality chosen by the authors to apply the model is the metropolitan city of Milan. The reasons behind this choice are multiple. Firstly, Milan is one of the most populated and advanced cities in Italy with a high level of car ownership, making it an ideal setting for studying the potential benefits of Over-the-air updates.

Additionally, Milan is widely acknowledged as one of the most technologically advanced and innovative cities in Italy, including being a leader in the adoption of electric cars and the development of sustainable transport solutions, which enhances the likelihood of early adoption of new technologies, such as Connected Cars with OTA capabilities.

Furthermore, this master thesis project is being developed in collaboration with "Osservatori Digital Innovation" of Politecnico di Milano. This partnership has facilitated data gathering for validating the proposed model, and it is another reason why Milan was chosen as the application environment for the project. The Osservatorio has extensive contacts within the municipality and provides valuable insights into the local market and technological trends.

In conclusion, the convergence of a large potential market, technological advancement, and collaboration with Osservatori Digital Innovation of Politecnico di Milano make Milan an ideal location to evaluate the benefits of these cars supporting OTA updates in a real-world scenario.

At the conclusion of this chapter, in Section 6.3, the authors comment the model findings and readers will possess a firm grasp of the intricate computations that constitute the model's operation.

6.1. Input Data

In this section, the methodology for acquiring the required data is presented.

First of all, it must be clarified that the model calculations will be performed for the scenario in which the owner possesses a car without OTA updates support. This is because the model intends to calculate the gain that the consumer has in owning a Connected Car comparing the case with and without OTA support. To do so, the authors developed the gain formula (5) which states that the payoff of having a Connected Car that supports OTA updates in a case of a safety recall event is precisely equal to a portion of the cost that the driver must sustain if owning a car without OTA support. This proportion depends on the percentage of remotely resolvable recall, as mechanical recalls necessitating manual intervention by workshop personnel will inevitably entail costs, regardless of the scenario.

In addition, the model will be applied in different case scenarios that the authors modeled to test and apply the model in as many cases as possible. In particular, the variables that will vary accordingly to the scenarios will be the input data to apply queue management and the way in which the customer shows up at the dealership.

Multiple sources were utilized to procure input data for the various scenarios investigated through the model. First of all, interviews were conducted with specialists from OEMs, as well as with representatives from dealerships, to obtain valuable insights and gather pertinent information. The aim was to glean as much relevant data as possible, which could then be utilized to refine and adjust the model. The interviews were instrumental in enabling the authors to enhance the accuracy of the model by inserting numerical data and testing it accordingly. By eliciting input from individuals with practical experience and expertise in the field, the authors sought to ensure that the model was grounded in empirical reality and reflective of the current state of affairs. Subsequently, multiple online databases have been consulted, such as the Istat database which is the Italian National Institute of Statistics, primary source of official statistics in Italy, or the "Open Data Lombardia" the open data portal of the Lombardy region with more than 5.000 datasets, the "ACI Automobile Club d'Italia", and also the "IVASS Istituto per la Vigilanza sulle Assicurazioni" website where are reported data and statistics about car insurances in Italy.

As this dissertation was collaboratively developed with Politecnico di Milano, the model will be applied in Milan, Italy. To apply the model to the different explained above scenario, a common urban area needed to be selected. In addition, to determine the number of dealerships operating in the region, it was necessary to select the Original Equipment Manufacturers (OEMs), to take as reference. To do so, the authors compared the annual number of registered cars by brand in Italy, to then select two different clusters of them to apply the model to. The first group pertains to car manufacturers that have registered fewer than 1.000 vehicles per month on average in Italy. For instance, in 2022, carmakers such as Honda, Seat, and Volvo, who have had limited market penetration in Italy, may fall under this category. In contrast, the second cluster comprises automakers that have registered an average of 10.000 cars per month in Italy. Prominent examples include Fiat and Volkswagen.

For the first scenario application, the information gathered from the interviews, therefore, helped the authors to apply the model in a real case scenario to better validate it. For the second scenario, the online data and information about such large and widespread automakers facilitated the application of the model to the second cluster.

The citizen of Milan who earns an average salary in the area was chosen as the average customer. This was needed to compute the specific VoL, the Value of Service Time, and the Productivity Loss cost.

6.2. Model Validation Scenarios

The authors opted to validate the model designed by conducting two simulations in two distinct scenarios. By doing so, the authors assert that this approach provides a more comprehensive validation of the model, while comparing the outcomes of the two scenarios to gain a greater insight into the model's reliability. The first scenario involves a safety recall event for an automaker with less than 1.000 registrations per month on average in Italy, occurring within the province of Milan, spanning an area of 1.575 square kilometers.

In this scenario, the number of recalled vehicles is estimated to be around 1.000 units, with a network of 8 dealerships in the area. These specific figures were selected by the authors, as they are representative of a player belonging to the first cluster operating within the target territory. Furthermore, the authors made the assumption that each dealership would have access to two diagnostics, namely two computers through which the update can be transmitted to the vehicles, to update the recalled vehicles. Based on the interviews, the update time for a safety recall was found to range from 2 to 4 hours, leading the authors to select a duration of 3 hours for this simulation. This duration has implications for the consumer's journey, which was presented in the previous chapter; in fact, the consumer would return home after dropping off the vehicle at the dealership and come back to withdraw it as soon as the update is completed, since the authors assumed as reasonable that if the waiting time exceeds 2 hours the driver would return home (Case 2 of Journey Planning, section 5.1.3). To assess the recall campaign's impact, a penetration rate of 90% was assumed, which was derived from interview findings. As for *k*, estimating the average number of accidents resulting from untimely updates was found to be challenging from the interviews with industry players. Therefore, the authors assumed that 1 in 10.000 of the recalled vehicles would be involved in an accident. The value of *k* depends on several factors, including the importance of the safety recall, the malfunction's impact on the vehicle if not updated, and the risk the driver incurs while driving the car, even if it is subject to recall. With respect to *p*, which represents the percentage of remotely resolvable recalls, the interviews revealed that it varied among players, with a minimum of 10%. However, it was evident from the interviews that the number of remotely resolvable recalls would increase in the short term. Therefore, for this simulation, the authors used a value of 30%. It is worth mentioning that a sensitivity analysis was conducted by the authors, where the values of *k* and *p* were varied to investigate how the cost of a safety recall and the savings for a vehicle owner who supports OTA updates change. This was done to gain a better understanding of the impact of *k* and *p* on the results.

Regarding the second scenario, the authors aimed to replicate a player belonging to the second cluster, with a wider range of recalled vehicles and a more extensive network of authorized dealers in the province of Milan. Specifically, they selected a fleet of 15.000 recalled vehicles and a dealer network exceeding 100. To facilitate comparison with the first scenario, the authors kept consistency in other parameters such as the number of servers (*c*), update time (*UT*), campaign penetration rate (*pr*), *p*, and *k*.

The following two parameters are also set as the basis for both scenarios: the timeframe given to the vehicle owner to bring their car to the dealership (*T*=30 days) and the daily operating hours of the dealership (*WH*=8 hours per day). Table 24 provides a summary snapshot of the two scenarios.

Variable	**Scenario 1**	**Scenario 2**
Where	Milan (province)	Milan (province)
Recalled fleet (R)	$\sim 10^3$	$\sim 10^4$
Dealerships network (D)	$\sim 10^1$	$\sim 10^2$
Servers per dealer (c)	2	2
Update Time (UT)	3 hours/car	3 hours/car
Penetration Rate (pr)	90%	90%
k	0,01%	0,01%
p	30%	30%
T	30 days	30 days
WH	8 hours	8 hours

Table 24: Scenario 1 and 2 input data

The authors chose to conduct the two distinct scenarios to compare the effects of a safety recall on customers of the two different clusters of players, with the aim of analyzing which type of player's customers may be more affected by a safety recall event.

6.3. Calculations and Results

In this chapter, the authors will guide the reader into the calculations that make up the core of the model. These calculations are crucial in determining the output of the model and comprehending them is essential for gaining a profound understanding of the model's functioning.

The subsequent subchapters in this section will present a comprehensive categorization of the mathematical operations utilized to process input data. These calculations will be arranged coherently with the theoretical model described in the preceding chapter (Chapter 5).

Moreover, since the calculations to be carried out in the first and second scenarios are the same, the authors present in this section the calculations solely for the first scenario. It is also important to specify that the expected cost of the eventual accident (C_A), remains unchanged for both scenarios because it is not affected in any way by the characteristics of the player under consideration. The results of the second scenario will be discussed and compared with those of the first scenario in Section 6.4 "Model findings," and a detailed account of the related calculations is provided in the Annexes.

6.3.1. Recall

This subchapter aims to quantitatively calculate the first component of the formula in the abovementioned first scenario. This component consists of six equation terms, each of which will be investigated individually and with detailed mathematical determination.

The general formula (6), that is here reported, will serve as the starting point for this analysis:

$$C_R = TT\ [h] \times VTT \left[\frac{€}{h}\right] + TC\ [€] + ST\ [h] \times VST \left[\frac{€}{h}\right] + SC\ [€]$$

6.3.1.1. Travel Time and Value of Travel Time

Before calculating the Travel Time (TT), the authors first defined in which of the two journey cases the ideal customer is. As a result of the systematic organization of the dissertation, the Service Time (ST) calculation will be presented later on. However, it is important to note that the authors have already conducted the calculations in parallel and found that the average ST, both in the first and second scenarios, exceeds 2 hours. This conclusion is based on the observation that the Update Time alone takes on average 3 hours, as evidenced by data gathered from industry expert meetings. Moreover, given the increasing number of vehicles per inhabitant and the growing rate of Connected Car adoption, the authors assume reasonable potential bottlenecks in the case of a safety recall at the dealerships, leading to a convergence towards CASE 2. In particular, in CASE 2 the owner of the car will not wait in the dealership neighborhood but will return after a certain number of hours or days to pick up the vehicle. As already presented in Chapter 5, the time spent in travel due to the recall will not only be represented by the round-trip time by car but also by the time required to return home and travel back to the dealer using alternative means of transportation. Thus, the formula for the TT will be:

$$TT = T_{o1} + T_{r1} + T_{o2} + T_{r2}$$

To calculate each travel time contribution, the base relationship derived from the speed definition has been used. In order to do so, the average distance between the dealership and the house has to be calculated. Taking into consideration the Milan province, here in Table 25 the numbers are shown:

d - Distance home-dealership		
Variable	Value	Unit of Measure
A	1.575	Km^2
D	8	-
S	196,88	Km^2/dealership
r	7,92	Km
d	3,96	Km

Table 25: Distance calculation input values

Where A is the area encompassed by the province of Milano and D is the number of dealerships/authorized workshops for a reference automaker of the first cluster, in the province of Milan. The authors proceeded to select one OEM from the first cluster mentioned earlier, to then specifically use precise and real numbers in the model. Therefore, Honda was chosen as the preferred option for this purpose. By surfing the Italian official website Honda, the authors gathered the number of dealerships allowed to perform mechanical interventions on the cars. Specifically, there are 8 authorized dealerships within the province boundaries of Milan, counting an area of 1.575 Km^2. Accordingly, S has been calculated as the ratio between A and D, to obtain the coverage area of each single dealership. By approximating S to a circle of radius r, assuming that the dealer is at the center of the circle and there is a homogeneous distribution of the population within surface A and, in turn, within S, it follows that the average distance from the center of the circle and therefore from the dealership will be equal to half the radius, which in our case is 3,96 Km.

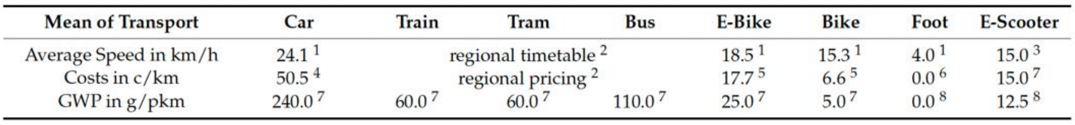
To then calculate $T_{o1} = T_{r2}$ (see hypothesis in chapter 5.3.1) the average Milan urban area speed has been gathered, from the TomTom traffic index 2022, which states that the average speed in rush hours in Milan is 18 Km/h. By dividing the average home-dealership distance by the average speed of Milan, the average travel time spent in the car to reach the workshop for a recall has been obtained (Table 26).

$\mathbf{TT_{car}}$ **- Car Travel Time**		
Variable	Value	Unit of Measure
s	18	Km/h
d	3,96	Km
TT_{car}	0,22	h

Table 26: Car Travel Time input data

Subsequently, $T_{r1} = T_{o2}$ have been calculated as a weighted average of the time spent traveling 3,96 Km with the three different alternative means of transport. In particular:

- $T_{bike} = \frac{d}{s_{bike}} = \frac{3{,}96\ Km}{16{,}9\ {Km}/{h}} = 0{,}23\ h$, where the average speed of a bike in an urban environment has been gathered from the work of Edel et al. (Table 27), which collected the average speed in Km/h of e-bikes (18,5 Km/h) and bikes (15,3 Km/h). Given that the customer has an equal chance of choosing either the first or second type of bicycle, the authors believe it to be reasonable to use the average speed between the two.



Mean of Transport	Car	Train	Tram	Bus	E-Bike	Bike	Foot	E-Scooter
Average Speed in km/h	24.1[1]	regional timetable[2]			18.5[1]	15.3[1]	4.0[1]	15.0[3]
Costs in c/km	50.5[4]	regional pricing[2]			17.7[5]	6.6[5]	0.0[6]	15.0[7]
GWP in g/pkm	240.0[7]	60.0[7]	60.0[7]	110.0[7]	25.0[7]	5.0[7]	0.0[8]	12.5[8]

Table 27: Average bicycle speed (Edel et al. 2021)

- $T_{subway} = 0{,}30\ h$ has been calculated by assuming that the yellow metro line of Milan (M3) has a length of 17,1 Km with 21 stops along the journey; dividing the length by the number of stops it has been calculated that on average the subway line travels for 0,814 Km between two consecutive stops. By saying so, to travel for 3,96 Km the driver has to cross 5 stops. The authors used the travel time between the Centrale FS and Missori subway stops on the yellow subway line as a reference point, which was estimated to be 8 minutes according to Google Maps. Since the dealer or the driver's home may not be exactly at the metro exit, the authors added to this travel time 5 minutes to walk to the metro stop from the consumer's house and another 5 minutes to walk to the dealer from the metro stop (or vice versa) for a total of 10 minutes. These three contributions make up the total subway travel time in the abovementioned case.

- $T_{walk} = \frac{d}{s_{walk}} = \frac{3{,}96\ Km}{5{,}16\ ^{Km}/_{h}} = 0{,}77\ h$, where the average speed of a human walking has been gathered from a meta-analysis of 41 prior studies, which was conducted by Bohannon and Williams Andrews (2011). The meta-analysis findings revealed that the average walking speed ranged from 143,4 cm/second for men aged 40 to 49 years to 94,3 cm/second for women aged 80 to 99 years. Considering that vehicle owners predominantly fall in the former age range, the authors opted to utilize the first value as a point of reference for walking speed. Therefore, the reference value for walking speed in this study was established as 5,16 Km/h.

The authors estimated that these three ways to travel the distance home dealership by alternative means of transportation are chosen evenly by consumers, and therefore with equal probability (of 33,33%). Thus, $T_{r1} = T_{o2}$ will be equal to:

$$T_{r1} = T_{o2} = 0{,}23\ h * 33{,}33\% + 0{,}30\ h * 33{,}33\% + 0{,}77\ h * 33{,}33\% = 0{,}43\ h$$

Therefore, the total TT in CASE 2 for the ideal customer is:

$$TT = 0{,}22\ h + 0{,}43\ h + 0{,}43\ h + 0{,}22\ h = 1{,}30\ h = 77{,}90\ min$$

To then translate the time into economic terms, the TT of each mean of transport must be multiplied by the correspondent VTT. The total contribution in the calculation of the expected cost of a safety recall will be the sum of the vector multiplication of the different trips involved.

To calculate the VTT, the authors used the formula (14) here reported:

$$VTT_{vehicle} = VoL - VTAT_{vehicle}$$

The Value of Leisure computation has been done following the formulas of Fournier & Christofa (2021), presented in chapter 5.3.2. To apply the two formulas, the distance and income value of the ideal customer were selected. The distance of course is the above assessed one; for the income, the average gross income earned in Milan was taken into account, to then derive the net one using the pmi.it website. The gross value of 35.724 €/year has been gathered from the JP Geography Index 2022 drafted by Osservatorio Job Pricing. Then after using the PMI platform, filled in with the most general factors to represent the average customer, the net value obtained is 25.050 €/year.

Thus, the $\text{VoL}_{\text{distance}}$ and $\text{VoL}_{\text{income}}$ have been calculated as:

$$VoL_{distance} = 35{,}67\text{ €}$$
$$VoL_{income} = 28{,}78\text{ €}$$

To then combine these two values to obtain a unique Value of Leisure, able to capture the opportunity cost regarding both leisure and work activities, the formula (18) has been used, using the corresponding values of $W_{distance_i}$ and W_{income_j} specific of the case.

The final value of VoL for business trips is:

$$\begin{aligned} VoL_{ij} &= W_{distance_i} \times VoL_{distance_i} + W_{income_j} \times VoL_{income_j} \\ &= 52{,}7\% \times 35{,}67\text{ €} + 47{,}3\% \times 28{,}78\text{ €} = 32{,}41\text{ €} \end{aligned}$$

As the authorized dealers of the first cluster's OEM of choice do not offer services during bank holidays, the calculation of VoL for non-business trips was not required.

Afterwards, by subtracting the VTAT values obtained by Hössinger *et al.* (2020) from the VoL obtained, the VTT values have been obtained accordingly:

- $VTT_{bike} = VoL - VTAT_{bike} = 32{,}41 + 3{,}03 = 35{,}44\text{ €}$
- $VTT_{car} = VoL - VTAT_{car} = 32{,}41 + 4{,}23 = 36{,}64\text{ €}$
- $VTT_{subway} = VoL - VTAT_{subway} = 32{,}41 - 0{,}27 = 32{,}14\text{ €}$
- $VTT_{walk} = VoL - VTAT_{walk} = 32{,}41 + 4{,}13 = 36{,}54\text{ €}$

Overall, the contribution of the first two terms of the equation that estimate the expected cost for the consumer in case of a safety recall amounts to:

$$TT \times VTT = \sum_i TT_i \times VTT_i = 0{,}44\ h \times 36{,}64\ {}^{€}/_{h} + 0{,}15\ h \times 35{,}44\ {}^{€}/_{h} + 0{,}20\ h \times 32{,}12\ {}^{€}/_{h} + 0{,}51\ h \times 36{,}54\ {}^{€}/_{h} = 46{,}45\ €$$

In Table 28, the different means of transport contributions to the C_R calculation were split:

Vehicle	**TT$_i$**	**VoL**	**VTAT$_i$**	**VTT$_i$**	**TT$_i$*VTT$_i$**
Car	0,44	32,41 €	-4,23 €	36,64 €	16,11 €
Bike	0,15	32,41 €	-3,03 €	35,44 €	5,48 €
Subway	0,20	32,41 €	0,27 €	32,14 €	6,36 €
Walk	0,51	32,41 €	-4,13 €	36,54 €	18,49 €

Table 28: Different means of transport contributions to the Recall Costs calculation

6.3.1.2. Travel Cost

In order to estimate the costs stemming from the travel between the dealership and the car owner's house, the expense that the car owner sustains during the trip to the dealership in case of a safety recall needs to be taken into account. Being in the CASE 2 scenario, in which the car owner undertakes 4 trips, two of which with her own car and the intermediate ones with an alternative mean of transport of her choice, four contributions must be taken into account. The burden related to bike renting, taking the subway, or walk home, has been easily calculated as:

- $TC_{bike} = \dfrac{c\left[\frac{€}{min}\right] \times 60\left[\frac{min}{h}\right] \times d\,[Km]}{s\left[\frac{Km}{h}\right]} = \dfrac{0{,}2\,\frac{€}{min} \times 60\left[\frac{min}{h}\right] \times 3{,}96\,Km}{16{,}9\,\frac{Km}{h}} = 2{,}81\ €$
- $TC_{subway} = subway\ ticket\ cost\ = 2{,}20\ €$
- $TC_{walk} = 0$

The cost per minute of shared bike services has been calculated as the average cost among the available sharing services in Milan (Lime, Ridemovi, BikeMi). In parallel, the cost incurred while driving the car to the dealer from home has been estimated by gathering fuel consumption and pricing, previously shown in chapter 5.3.3.. Thus TC_{fuel} has been calculated for each fuel type taken into consideration using the formula:

$$TC_{fuel}\left[\frac{\text{€}}{Km}\right] = Consumption_{fuel}\left[\frac{l/KWh/kK}{Km}\right] \times Price_{fuel}\left[\frac{\text{€}}{l/KWh/Kg}\right]$$

Then, Table 29 summarizes the total cost per fuel type:

Vehicle power supply	**Consumptions**		**Prices**		**TC_{fuel}**
	Unit of measure	*Values*	*Unit of measure*	*Values*	
Diesel	[l/Km]	0,048	[€/l]	1,82	0,087 €
Electricity	[KWh/Km]	0,148	[€/KWh]	0,58	0,086 €
Liquified Petrol Gas (LPG)	[l/Km]	0,074	[€/l]	0,79	0,058 €
Methane	[Kg/Km]	0,037	[€/Kg]	2,46	0,091 €
Petrol	[l/Km]	0,054	[€/l]	1,76	0,095 €

Table 29: Total Cost per fuel type

To then derive the percentage concentration of differently fueled vehicles among the ones subject to the recall, the authors used the information collected in the online database Open Data of Regione Lombardia, in which the distribution of the power supply types of cars are analyzed in Lombardy. As an approximation, the percentage of vehicles by fuel type in the province of Milan has been defined by using the corresponding figures for the Lombardy region (Table 30).

Vehicle power supply	**Province of Milan**	**Distribution**
Diesel	3.275.075	38,56%
Electricity	40.516	0,48%
Liquified Petrol Gas (LPG)	258.988	3,05%
Methane	14.205	0,17%
Petrol	4.668.726	54,97%
Other	235.463	2,77%
Total	8.492.973	100,00%

Table 30: Percentage of vehicles per fuel type in the province of Milan

To normalize the percentages, in order to not take into account the vehicles classified as "other", the values have been standardized (Table 31).

Vehicle power supply	Concentration	Normalized values
Diesel	38,6%	39,7%
Electricity	0,5%	0,5%
Liquified Petrol Gas (LPG)	3,0%	3,1%
Methane	0,2%	0,2%
Petrol	55,0%	56,6%
Other	2,8%	-

Table 31: Normalization of the fuel concentration percentages

Subsequently, the TC_{car_fuel} value has been calculated as the summation of the different weighted contributions of fuel cost:

$$TC_{car\_fuel}\left[\frac{€}{Km}\right] = \sum\nolimits_{fuel} TC_{fuel}\left[\frac{€}{Km}\right] \times \%\, Concentration_{fuel} = 0{,}091\ {}^{€}\!/_{Km}$$

Finally, to have the travel cost by car the following formula has been applied:

$$TC_{car} = d\,[Km] \times TC_{car\_fuel}\left[\frac{€}{Km}\right] = 3{,}96\ Km \times 0{,}091\ {}^{€}\!/_{Km} = 0{,}36\ €$$

Therefore, the total travel cost for CASE 2 will be:

$$\begin{aligned} Travel\ Cost\,[€] &= TC_{car} + 2 \times \frac{1}{3}\left(TC_{subway} + TC_{bike} + TC_{walk}\right) + TC_{car} \\ &= 0{,}36\ € + 2 \times \frac{1}{3}(2{,}20\ € + 2{,}81\ € + 0\ €) + 0{,}36\ € = 4{,}06\ € \end{aligned}$$

6.3.1.3. Service Time and Value of Service Time

To calculate the Service Time, the authors employed the Queue Theory formulas presented in the previous chapter. To ensure the accuracy of the calculations, they developed a model on Microsoft Excel and verified it using freely available software (Omnicalculator.com). Before using the Queue Theory formulas, the authors computed the arrival rate (λ) and service rate (μ) values, which were used in the calculations, as shown below:

$$\lambda = \frac{\frac{pr \times R}{D}}{T \times WH} = \frac{\frac{90\% \times 1.000\ cars}{8}}{30\ days \times 8\ {}^{h}/_{day}} = 0{,}46875\ cars/h$$

$$\mu = \frac{1}{UT} = \frac{1}{3\ {}^{h}/_{car}} = 0{,}33333\ cars/h$$

Using the obtained values, the average waiting time ($W_s = ST$, service time) for the average customer in a system with two servers c (modeled as an M/M/2 system) was calculated (Table 32):

$$W_s = ST = 5{,}93337\ h/car$$

Scenario 1		
Variable	Value	Unit of Measure
λ - Arrival Rate	0,46875	cars/h
μ -Service Rate	0,33333	cars/h
c - Servers	2	-
R - Recalled vehicles	1.000	-
D - Dealerships	8	-
W_s = Service Time (ST)	5,93	h/cars

Table 32: Input data for Service Time computation

Moreover, the authors opted to determine the service time by utilizing another technique, simpler and more approximate that considers the service time almost equivalent to the update time (considering a security coefficient of 10%). This method enabled to draw a comparison with an ideally highly efficient scenario, wherein the customer schedules an appointment at the dealership and undergoes no wait time for service. As a result, the authors could compare the outcomes obtained from both the methods used in the model. The Service Time obtained using this method is as follows:

$$ST = UT \times (1 + sec.\ coeff.) = 3\ h \times (1 + 10\%) = 3{,}30\ h$$

To then convert the Service Time in monetary terms, the Vale of Service Time has been calculated (Table 33). The authors used the average net salary in the specific Milan area, as described above in the VoL calculation. For the yearly working hours, the authors relied on the data published by Truenumb3rs in 2022, stating that in 2020 the yearly average working hours in Italy were 1.558,7.

Value of service time - VST		
Variable	Value	Unit of Measure
YNS	25.050	€/year
YWH	1558,7	h/year
VST	16,07	€/h

Table 33: Value of Service Time calculation input data

By doing the math, the Value of Service Time results in 16,07 €/h which multiplied by the average Service Time calculated in both cases, accounts respectively for a contribution in the calculation of the expected cost due to a safety recall for the car owner of:

$$ST(queue) \times VST = 5{,}93\ h \times 16{,}07\ {}^{€}/_{h} = 95{,}36\ €$$

$$ST(app.) \times VST = 3{,}30\ h \times 16{,}07\ {}^{€}/_{h} = 53{,}03\ €$$

6.3.1.4. Service Cost

To conclude the calculation of each equation term of C_R, as already discussed in chapter 5.5.6 for the purpose of this model, it is legitimate to consider the Service Cost for the car's owner as zero, since in the case of a safety recall the update operation costs are entirely covered by the OEM.

6.3.2. Accidents

This subchapter aims to quantitatively compute the second part of the formula underlying the model. This second component consists of five equation terms, each of which will be investigated individually and with detailed mathematical determination, and a parameter that multiplies the overall contribution.

The parameter, k, represents the probability that a recalled vehicle will undergo an accident due to software failure before the update is performed. Mathematically, it can be represented by formula (41) presented in the previous chapter and here reported:

$$k = \frac{I}{R}$$

The authors endeavored to explore how the k parameter could be estimated. Subsequently, through interviews conducted with industry experts, it became evident that arriving at an average number of accidents caused by a delayed update is exceedingly challenging, owing to various factors such as the relevance of the safety recall, the impact of the malfunction if not updated, and the risks involved in driving a vehicle subject to recall. Additionally, in certain situations, the malfunction leading to the recall may not be the primary cause of the accident but only a secondary cause. Due to these complexities, the authors employed a value of 0,01%, which corresponds to one crashed vehicle out of every 10.000 vehicles, in the simulation. They further conducted a sensitivity analysis by varying this value.

Moreover, during the interviews, the authors sought to gauge the appropriateness of this value, by questioning the industry experts, and the feedback received affirmed that this average value could be considered a reasonable approximation of reality.

For the overall individual cost of an accident, the general formula (42), that is here reported, will serve as the starting point for this analysis:

$$C_A = C_H + C_{PL} + C_{BA} + C_{Rep} + C_{Ins} \tag{42}$$

6.3.2.1. Health Care Cost

By delving deeper into the first equation term, health care costs refer to the drivers' injury costs that they have to bear in the case of an accident induced by the software failure, for which the safety recall was prompted. Accordingly, equation (43) has been developed by the authors.

To calculate the overall impact of this voice of cost, the percentages m and i must be identified. First, the i percentage has been found by surfing the internet, through the website SoStariffe.it which states that in 2017 the penetration percentage of the "driver's injury coverage" insurance (in Italian: "*infortunio conducente*") subscribed in Italy was of 13,2%. Even though this information might be outdated, the authors believe that this is a good approximation and a good proxy to take into account in the simulation in absence of updated data. Afterwards, the m value has been calculated by using the information inside the Istat report "Incidenti stradali 2019", where accident numbers are reported. Specifically, the record of drivers involved in car accidents during 2019 has been reported, including their respective outcomes of being unharmed, injured, or deceased (Table 34).

Drivers involved in accidents in 2019	
Total	316.206
Unharmed	149.479
Dead or injured	166.727
% D or I	52,7%
m	26,4%

Table 34: m calculation input data

Thus, the authors derived from that data the percentage of drivers involved in car accidents that ended up injured or dead.

As the authors were unable to determine the distribution of fatalities and injuries within the number of drivers injured or dead, they opted to use the percentage that encompassed both deceased and injured drivers, which was deemed a reliable approximation for injured ones. Moreover, to account for the likelihood that the guilty vehicle driver is the one who sustains injuries in a collision, the percentage obtained must be multiplied by 50%. Finally, the percentage m is represented by 26,4%.

$$m = \frac{166.727}{316.206} \times 50\% = 52{,}7\% \times 50\% = 26{,}4\%$$

Being the average individual cost for medical expenses following the injury, c_h, already calculated in chapter 5.4.1, the authors can now multiply the factors to conclude the expected healthcare costs that a driver has to bear in the case of an accident induced by the software failure, for which the safety recall was proclaimed, by using the equation (43):

$$C_H = m \times (1 - i) \times c_h = 26{,}4\% \times (1 - 13{,}2\%) \times 8{,}2\ € = 1{,}88\ €$$

6.3.2.2. Productivity Loss Cost

To then investigate the productivity loss cost that the injured person incurs, first of all, the authors estimated the average hospital stay time (t_{hosp}) in case of a car accident. The information was obtained from the Regione Lombardia and PoliS Lombardia report "*Valutazione economica dell'incidentalità stradale -Analisi dei costi sanitari per il 2020 e confronto con il 2019*" published in November 2021. Inside the report, the average hospitalization in terms of days has been reported by age group. The authors made an average taking into account the age gap between 18 and 90 years old, to limit the analysis to individuals who are eligible to drive a car and therefore could potentially be involved as drivers in an accident. Therefore, the value of t_{hosp} can be assumed as 9,43 days, which in turn if multiplied by 8 h/day (according to Legislative Decree No. 66 of April 8, 2003, the full-time contract has a normal average duration of 40 hours/week spread across 5 working days per week which means 8 h/day) represents 75,41 lost working hours. To then calculate the C_{PL} with the formula (50), the authors used the value of service time (VST) already calculated to convert the service time in monetary terms, to express the value of time (VT) to take into account in this formula.

In turn, the overall contribution of this term is:

$$C_{PL} = t_{hosp} \times VT_j = 75{,}41\,h \times 16{,}07\ {}^{€}/_{h} = 1.211{,}97\ €$$

6.3.2.3. Breakdown Assistance Cost

To estimate the expected cost of a breakdown assistance intervention following an accident, the authors developed equation (52) which is here reported:

$$C_{BA} = [p_{BA\_WD} \times ba_{wd} + p_{BA\_NH} \times ba_{nh}] \times ba \times \frac{1}{2}$$

First of all, the base price of a breakdown assistance intervention on working days and nights/holidays has to be gathered. In Italy, the *Italian decree 401 – 4th of September 1198 of the Ministry for Transportation and Navigation* defines it for vehicles under 1,5 tons (usually the weight of a hatchback car is around 1.344 Kg) as shown in Table 35.

Breakdown intervention tariffs	
$p_{BA\text{-}WD}$	117,69 €
$p_{BA\text{-}NH}$	152,99 €

Table 35: Breakdown Assistance intervention tariffs

Moreover, assuming that not all accidents require a breakdown assistance intervention, the average price is weighted by the probability, ba, that a breakdown assistance truck is needed. This value has been obtained, by using the total number of accidents in 2019, which was 172.183 (gathered from the Istat 2019 "Incidenti stradali" report), and by using the data about breakdown assistance interventions of 2019 obtained by ACI, as per Table 36 below:

ISTAT and ACI data in 2019	
BA_j	96.000
A_j	172.183
ba	55,75%

Table 36: Istat and ACI data in 2019 for ba percentage calculation

By dividing the first term by the second one, the ba value has been calculated as:

$$ba = \frac{BA_j}{A_j} = \frac{96.000}{172.183} = 55{,}75\%$$

From the same ACI report of before, the authors also gathered information about how many breakdown assistance interventions occurs during night/holidays and consequently how many during working days (in 2019), shown in Table 37.

Variable	Value	Unit of measure
ba_{wd}	78%	-
ba_{nh}	22%	-

Table 37: Breakdown intervention distribution

Therefore, the cost item related to breakdown assistance can now be calculated as:

$$C_{BA} = [p_{BA\_WD} \times ba_{wd} + p_{BA\_NH} \times ba_{nh}] \times ba \times \frac{1}{2}$$
$$= [117{,}69\,€ \times 78\% + 152{,}99\,€ \times 22\%] \times 55{,}75\% \times \frac{1}{2} = 34{,}97\,€$$

In accordance with the information presented in Chapter 5.4.3, the coefficient of $\frac{1}{2}$ signifies that in the event of a collision between two vehicles, only one of them may require breakdown assistance. As such, assuming an equal likelihood of either vehicle requiring assistance, it is appropriate to account for this safety factor.

The calculations performed are summarized by Table 38.

C_{BA} - Breakdown assistance cost		
Variable	Value	Unit of measure
p_{BA_WD}	117,69	€
ba_{WD}	78%	-
p_{BA_NH}	152,99	€
ba_{NH}	22%	-
ba	55,75%	-
Coefficient	0,5	-
C_{BA}	34,97	€

Table 38: Breakdown Assistance cost calculation input data

6.3.2.4. Car Repair Cost

To estimate the costs to fix the damages following a car accident, the authors developed formula (55), that is here reported:

$$C_{Rep} = \left(sh \times c_{ser\_j} + \sum_{i}^{N} c_{comp_i} \right) \times (1 - kasko_j)$$

To gather the required info, the authors conducted phone interviews with the Honda dealerships located within the boundaries of the province of Milan.

For the purpose of evaluating the mean service hours required to repair a damaged vehicle, the typical hourly service rate of dealerships within the Milan region, and the average cost of components with a high probability of requiring replacement following an accident, a total of 8 Honda authorized dealerships were interviewed. The values that the authors have been able to gather are summarized in the following Table 39.

Telephone investigation			
Dealerships	Hourly rate [€/h]	Average cost per part	*sh*
Dealership 1	50	2.000/7.000€	10
Dealership 2	45	2.000/7.000€	10
Dealership 3	65	5.000/6.000€	20
Dealership 4	65	5.000/6.000€	15
Dealership 5	45	6.000 €	5
Dealership 6	45	7.000 €	8
Dealership 7	40	4.000/5.000€	8
Dealership 8	50	4.000/5.000€	5
Average	*50,63 €*	*4.500 €*	*10*

Table 39: Information gathered through telephone investigation

The authors have estimated that the number of components to be replaced could be two, based on the assumption that at least both airbags may deploy in the event of an accident.

Moreover, since some consumers have insurance that covers damages to their own vehicle even if they are the cause of the accident (in Italy it is called "kasko" insurance), the percentage of drivers who subscribed to this type of coverage has been gathered. The authors have gathered this data from the website SoStariffe (as of before) which states that in 2017 the penetration percentage of the "Kasko" insurance subscribed in Italy was 9,4% for the "Kasko collisioni" insurance and 5,39% for the "Kasko complete" insurance. The sum of these two percentages has been used as a reference value for the simulation case. Even though this information might be outdated, the authors believe that this is a good approximation and a good proxy to take into account in the simulation in absence of updated data.

Overall, the value of car repair costs can be calculated as:

$$\begin{aligned} C_{Rep} &= \left(sh \times c_{ser\_j} + \sum_{i}^{N} c_{comp_i} \right) \times \left(1 - kasko_j\right) \\ &= \left(10\, h \times 50{,}63\, {}^{€}/_{h} + 4500\, {}^{€}/_{comp} \times 2\, comp\right) \times (1 - 14{,}63\%) \\ &= 8.115{,}49\ € \end{aligned}$$

Table 40 summarizes the input data for the computation of Repair Costs.

C_{Rep} - Repair cost		
Variable	Value	Unit of measure
sh	10	h
C_{ser}	50,63	€/h
C_{comp}	4.500	€
N	2	-
$kasko$	14,63%	-
C_{Rep}	8.115,49	€

Table 40: Car repair cost calculation input data

6.3.2.5. Insurance Costs

Last but not least, the costs linked to the upsurge of the insurance premium following an accident will be calculated. The formula requires first of all the average car insurance premium in the geographical area of Milan, c_{ins_j}. The authors used the "*Istituto per la vigilanza sulle assicurazioni – IVASS*" quarterly reports, on the analysis of car insurance prices in Italy, to collect the average "RC auto" prices in the first three quarters of 2022 in the province of Milan. The value obtained amounts to 336, 33 € as depicted by Table 41.

IVASS	**Italy**	**Milan (province)**
I trimester	353,00 €	333,50 €
II trimester	353,00 €	332,60 €
III trimester	362,00 €	342,90 €
Average	*356,00 €*	*336,33 €*

Table 41: IVASS average car insurance prices in Italy and Milan in 2022

This value must be then multiplied by the average percentage increase of car insurance premiums after a car accident in Milan, $\Delta_{premium\_j}$. As stated by Facile.it (Italy's leading insurance comparison web company since 2011) predicting the exact amount of increase in car insurance after an accident is not possible in a certain way as it can range from 30% to 240%, which is a significant variation. For a driver with over 20 years of experience, who drives conservatively, has a clean driving record, and belongs to the first merit class for several years (ideal customer), the authors estimated that the insurance premium would be increased by a percentage of 30%. In Table 42 the Insurance Costs' calculation input data are summarized.

C_{Ins} - Insurance cost		
Variable	Value	Unit of measure
c_{ins}	336,33	€
Δ premium	30%	-
C_{ins}	*100,90*	€

Table 42: Car insurance cost calculation input data

Therefore, the value of insurance costs following an accident amounts to:

$$C_{Ins} = c_{ins\_j} \times \Delta_{premium\_j} = 336{,}33\text{ €} \times 30\% = 100{,}90\text{ €}$$

6.3.3. Consumer cost results

In this section, the final C_R and $C_A$values calculated in the first scenario will be presented. In Table 43, the primary factors that contributed to the expected costs for safety recall operations and accidents were shown. Subsequently, using the two corresponding values of C_R and C_A, calculated based on two different methods of ST estimation, the total expected cost incurred by a consumer with a vehicle that does not support OTA updates, in an event of a safety recall, was determined using the fundamental formula (1).

Scenario 1			**Scenario 1**		
Queue Theory			***Appointments***		
Variable	Value	Unit of measure	Variable	Value	Unit of measure
TT x VTT	46,45	€	TT x VTT	46,45	€
TC	4,06	€	TC	4,06	€
W_s x VST	95,36	€	W_s x VST	53,03	€
SC	0	€	SC	0	€
C_R	**145,86**	**€**	**C_R**	**103,54**	**€**
C_A	**9.465,21**	**€**	**C_A**	**9.465,21**	**€**
k	0,01%	-	k	0,01%	-
C_{tot}	**146,81**	**€**	**C_{tot}**	**104,49**	**€**
p	30%	-	p	30%	-
π_{exp}	**44,04**	**€**	**π_{exp}**	**31,35**	**€**

Table 43: Main contributions to costs and savings

6.4. Model Findings

In this Section, the authors aim to point out and discuss all the results reached by applying the model presented in the previous sections. Starting from the results of the two scenarios' simulations the authors want to perform a comparative analysis of the findings of the two different scenarios in order to have a comprehensive understanding and validation of the proposed model. To do so, the authors applied the model and performed the related calculations, also for the second scenario, whose input data are displayed in Table 44.

	Scenario 1	**Scenario 2**	
Variable	Value	Value	Unit of measure
R	1.000	15.000	cars
D	8	125	dealerships
c	2	2	servers
UT	3	3	hours
pr	90%	90%	-
T	30	30	days
WH	8	8	hours/day

Table 44: Scenarios input data (Queue Theory)

The reference OEM, belonging to the second cluster, that has been selected for the 2nd scenario is Fiat. This second cluster comprises automakers that have registered an average of 10.000 cars per month in Italy and considering that Fiat holds a dominant position in the Italian market, it was selected as the subject of this study due to the availability of necessary information required for applying the model.

Moreover, both "Queue Theory" and "appointment" methods have been applied to scenario 2 to calculate the ST; however, for the purpose of the subsections the queue theory scenario and numbers have been taken into account to perform the following comparisons, while the "appointment" model results have been analyzed in the ad hoc sub-section 6.4.1.1. As already mentioned, all the related calculations are available in the Annexes.

The authors conducted various analyses on the fundamental parameters of the model in order to observe and examine the variations in the results with the changing parameters. Consequently, this section is structured into multiple sub-sections, each of which addresses a specific analysis performed.

6.4.1. Consumer benefits

The first analysis aims to clearly answer *RQ2* underlying the model: "*How can benefits generated by a safety recall be quantified?*".

Considering a remotely resolvable recall rate *p* of 30% and an accident probability *k* of 0.01% the expected total cost in the event of a safety recall for the consumer without OTA support is equal to 146,81€ and 102,81€ in the first and second scenarios, respectively. Consequently, the expected savings (π_{exp}) for the owner of a vehicle supporting OTA updates is higher in the first scenario (44,04€ vs 30,84€).

The authors considered the results, summarized in Table 45, reasonable and realistic because the player with greater market share possessed a more comprehensive and well-structured dealer network in Italy, leading to better event management and a reduced waiting time in the system of the average customer (5,51 hours vs to 5,93 hours) in the second scenario.

Scenario 1			**Scenario 2**		
Queue Theory			*Queue Theory*		
Variable	Value	Unit of measure	Variable	Value	Unit of measure
TT x VTT	46,45	€	TT x VTT	11,17	€
TC	4,06	€	TC	2,12	€
W_s x VST	95,36	€	W_s x VST	88,57	€
SC	0	€	SC	0	€
C_R	**145,86**	**€**	**C_R**	**101,86**	**€**
C_A	**9.465,21**	**€**	**C_A**	**9.465,21**	**€**
k	0,01%	-	*k*	0,01%	-
C_{tot}	**146,81**	**€**	**C_{tot}**	**102,81**	**€**
p	30%	-	*p*	30%	-
π_{exp}	**44,04**	**€**	**π_{exp}**	**30,84**	**€**

Table 45: Comparison of consumers' benefits in scenario 1 and 2

6.4.1.1. Queue Theory vs Appointments

The authors conducted a comparison between the total cost obtained using the service time calculated with Queue Theory and an approximate method that assumes the absence of any waiting time for the consumer and service time coinciding precisely with the update time. The latter approach was referred to as the "appointment approach," as it represents the optimal scenario in which the consumer schedules an appointment with the dealer and the service is carried out efficiently. As expected, in both scenarios (Table 46 and Table 47), the second approach for calculating service time resulted in a lower total cost.

Scenario 1			**Scenario 1**		
Queue Theory			***Appointments***		
Variable	Value	Unit of measure	Variable	Value	Unit of measure
TT x VTT	46,45	€	TT x VTT	46,45	€
TC	4,06	€	TC	4,06	€
W_s x VST	95,36	€	W_s x VST	53,03	€
SC	0	€	SC	0	€
$\mathbf{C_R}$	**145,86**	**€**	$\mathbf{C_R}$	**103,54**	**€**
$\mathbf{C_A}$	**9.465,21**	**€**	$\mathbf{C_A}$	**9.465,21**	**€**
k	0,01%	-	k	0,01%	-
$\mathbf{C_{tot}}$	**146,81**	**€**	$\mathbf{C_{tot}}$	**104,49**	**€**
p	30%	-	p	30%	-
π_{exp}	**44,04**	**€**	π_{exp}	**31,35**	**€**

Table 46: Scenario 1 comparisons of QT and appointments results

Scenario 2			**Scenario 2**		
Queue Theory			***Appointments***		
Variable	Value	Unit of measure	Variable	Value	Unit of measure
TT x VTT	11,17	€	TT x VTT	11,17	€
TC	2,12	€	TC	2,12	€
W_s x VST	88,57	€	W_s x VST	53,03	€
SC	0	€	SC	0	€
$\mathbf{C_R}$	**101,86**	**€**	$\mathbf{C_R}$	**66,33**	**€**
$\mathbf{C_A}$	**9.465,21**	**€**	$\mathbf{C_A}$	**9.465,21**	**€**
k	0,01%	-	k	0,01%	-
$\mathbf{C_{tot}}$	**102,81**	**€**	$\mathbf{C_{tot}}$	**67,28**	**€**
p	30%	-	p	30%	-
π_{exp}	**30,84**	**€**	π_{exp}	**20,18**	**€**

Table 47: Scenario 2 comparison of QT and appointments results

This finding reinforces the earlier observation that a well-organized and structured safety recall event management leads to a lower cost for the consumer. Therefore, it can be concluded that the model accurately reflects reality in this regard, as owning a vehicle that supports Over-the-air updates becomes increasingly convenient as the complexity of the recall event increases.

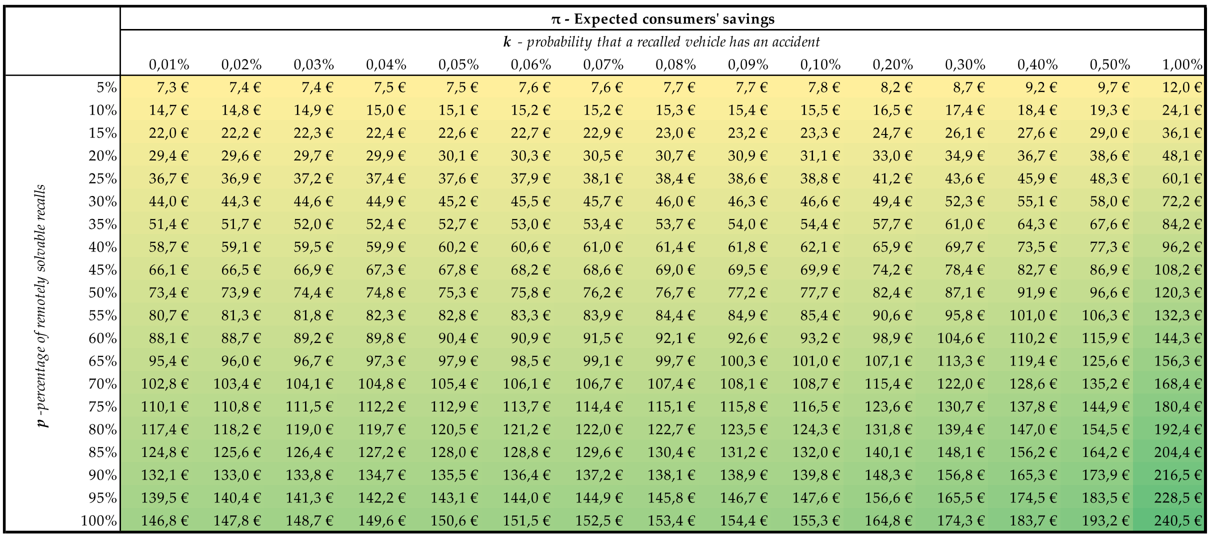
6.4.2. Sensitivity Analysis

Sensitivity Analysis is a tool used in a wide range of fields, to analyse how the different values of a set of independent variables impact a specific dependent variable under certain specific conditions.

For both scenarios, the authors performed a sensitivity analysis on p (the fraction of recalls resolvable Over-the-air, remotely) and k (the fraction of recalled cars then involved in a road accident) in order to understand how different values may influence the final expected saving for the customer owning a vehicle supporting Over-the-air updates.

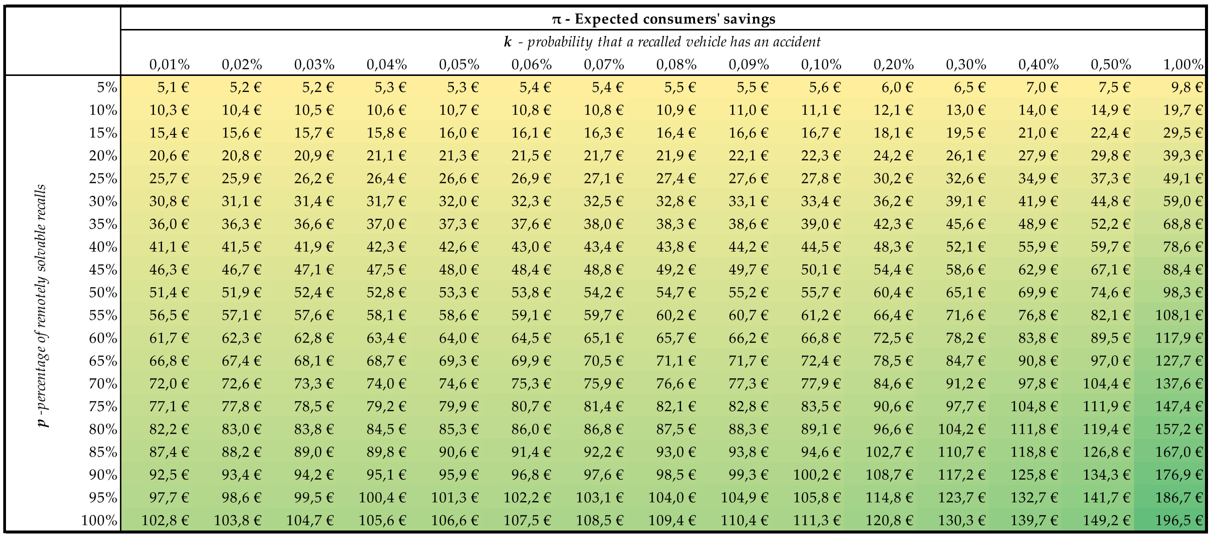
The interviews conducted and the analysis of scientific literature indicated that an increasing number of vehicles will shortly support OTA applications. Additionally, an increasing number of vehicle components will be managed and controlled by ECUs, which will result in a greater number of problems being remotely managed and resolved through simple software updates. Therefore, examining how the cost to the consumer varies as p increases is of paramount importance.

The next two figures (Figure 6.1 and Figure 6.2) point out the sensitivity analysis performed for each of the two scenarios. The authors used conditional formatting with a colour scale (increasing, from yellow to green) in order to stress out the increase of the expected saving for the consumer with a car supporting OTA updates:



		π - Expected consumers' savings														
		k *- probability that a recalled vehicle has an accident*														
		0,01%	0,02%	0,03%	0,04%	0,05%	0,06%	0,07%	0,08%	0,09%	0,10%	0,20%	0,30%	0,40%	0,50%	1,00%
p *-percentage of remotely solvable recalls*	5%	7,3 €	7,4 €	7,4 €	7,5 €	7,5 €	7,6 €	7,6 €	7,7 €	7,7 €	7,8 €	8,2 €	8,7 €	9,2 €	9,7 €	12,0 €
	10%	14,7 €	14,8 €	14,9 €	15,0 €	15,1 €	15,2 €	15,2 €	15,3 €	15,4 €	15,5 €	16,5 €	17,4 €	18,4 €	19,3 €	24,1 €
	15%	22,0 €	22,2 €	22,3 €	22,4 €	22,6 €	22,7 €	22,9 €	23,0 €	23,2 €	23,3 €	24,7 €	26,1 €	27,6 €	29,0 €	36,1 €
	20%	29,4 €	29,6 €	29,7 €	29,9 €	30,1 €	30,3 €	30,5 €	30,7 €	30,9 €	31,1 €	33,0 €	34,9 €	36,7 €	38,6 €	48,1 €
	25%	36,7 €	36,9 €	37,2 €	37,4 €	37,6 €	37,9 €	38,1 €	38,4 €	38,6 €	38,8 €	41,2 €	43,6 €	45,9 €	48,3 €	60,1 €
	30%	44,0 €	44,3 €	44,6 €	44,9 €	45,2 €	45,5 €	45,7 €	46,0 €	46,3 €	46,6 €	49,4 €	52,3 €	55,1 €	58,0 €	72,2 €
	35%	51,4 €	51,7 €	52,0 €	52,4 €	52,7 €	53,0 €	53,4 €	53,7 €	54,0 €	54,4 €	57,7 €	61,0 €	64,3 €	67,6 €	84,2 €
	40%	58,7 €	59,1 €	59,5 €	59,9 €	60,2 €	60,6 €	61,0 €	61,4 €	61,8 €	62,1 €	65,9 €	69,7 €	73,5 €	77,3 €	96,2 €
	45%	66,1 €	66,5 €	66,9 €	67,3 €	67,8 €	68,2 €	68,6 €	69,0 €	69,5 €	69,9 €	74,2 €	78,4 €	82,7 €	86,9 €	108,2 €
	50%	73,4 €	73,9 €	74,4 €	74,8 €	75,3 €	75,8 €	76,2 €	76,7 €	77,2 €	77,7 €	82,4 €	87,1 €	91,9 €	96,6 €	120,3 €
	55%	80,7 €	81,3 €	81,8 €	82,3 €	82,8 €	83,3 €	83,9 €	84,4 €	84,9 €	85,4 €	90,6 €	95,8 €	101,0 €	106,3 €	132,3 €
	60%	88,1 €	88,7 €	89,2 €	89,8 €	90,4 €	90,9 €	91,5 €	92,1 €	92,6 €	93,2 €	98,9 €	104,6 €	110,2 €	115,9 €	144,3 €
	65%	95,4 €	96,0 €	96,7 €	97,3 €	97,9 €	98,5 €	99,1 €	99,7 €	100,3 €	101,0 €	107,1 €	113,3 €	119,4 €	125,6 €	156,3 €
	70%	102,8 €	103,4 €	104,1 €	104,8 €	105,4 €	106,1 €	106,7 €	107,4 €	108,1 €	108,7 €	115,4 €	122,0 €	128,6 €	135,2 €	168,4 €
	75%	110,1 €	110,8 €	111,5 €	112,2 €	112,9 €	113,7 €	114,4 €	115,1 €	115,8 €	116,5 €	123,6 €	130,7 €	137,8 €	144,9 €	180,4 €
	80%	117,4 €	118,2 €	119,0 €	119,7 €	120,5 €	121,2 €	122,0 €	122,7 €	123,5 €	124,3 €	131,8 €	139,4 €	147,0 €	154,5 €	192,4 €
	85%	124,8 €	125,6 €	126,4 €	127,2 €	128,0 €	128,8 €	129,6 €	130,4 €	131,2 €	132,0 €	140,1 €	148,1 €	156,2 €	164,2 €	204,4 €
	90%	132,1 €	133,0 €	133,8 €	134,7 €	135,5 €	136,4 €	137,2 €	138,1 €	138,9 €	139,8 €	148,3 €	156,8 €	165,3 €	173,9 €	216,5 €
	95%	139,5 €	140,4 €	141,3 €	142,2 €	143,1 €	144,0 €	144,9 €	145,8 €	146,7 €	147,6 €	156,6 €	165,5 €	174,5 €	183,5 €	228,5 €
	100%	146,8 €	147,8 €	148,7 €	149,6 €	150,6 €	151,5 €	152,5 €	153,4 €	154,4 €	155,3 €	164,8 €	174,3 €	183,7 €	193,2 €	240,5 €

Figure 6.1: Sensitivity analysis – First scenario expected consumers' savings as k and p change



		π - Expected consumers' savings														
		k *- probability that a recalled vehicle has an accident*														
		0,01%	0,02%	0,03%	0,04%	0,05%	0,06%	0,07%	0,08%	0,09%	0,10%	0,20%	0,30%	0,40%	0,50%	1,00%
p *-percentage of remotely solvable recalls*	5%	5,1 €	5,2 €	5,2 €	5,3 €	5,3 €	5,4 €	5,4 €	5,5 €	5,5 €	5,6 €	6,0 €	6,5 €	7,0 €	7,5 €	9,8 €
	10%	10,3 €	10,4 €	10,5 €	10,6 €	10,7 €	10,8 €	10,8 €	10,9 €	11,0 €	11,1 €	12,1 €	13,0 €	14,0 €	14,9 €	19,7 €
	15%	15,4 €	15,6 €	15,7 €	15,8 €	16,0 €	16,1 €	16,3 €	16,4 €	16,6 €	16,7 €	18,1 €	19,5 €	21,0 €	22,4 €	29,5 €
	20%	20,6 €	20,8 €	20,9 €	21,1 €	21,3 €	21,5 €	21,7 €	21,9 €	22,1 €	22,3 €	24,2 €	26,1 €	27,9 €	29,8 €	39,3 €
	25%	25,7 €	25,9 €	26,2 €	26,4 €	26,6 €	26,9 €	27,1 €	27,4 €	27,6 €	27,8 €	30,2 €	32,6 €	34,9 €	37,3 €	49,1 €
	30%	30,8 €	31,1 €	31,4 €	31,7 €	32,0 €	32,3 €	32,5 €	32,8 €	33,1 €	33,4 €	36,2 €	39,1 €	41,9 €	44,8 €	59,0 €
	35%	36,0 €	36,3 €	36,6 €	37,0 €	37,3 €	37,6 €	38,0 €	38,3 €	38,6 €	39,0 €	42,3 €	45,6 €	48,9 €	52,2 €	68,8 €
	40%	41,1 €	41,5 €	41,9 €	42,3 €	42,6 €	43,0 €	43,4 €	43,8 €	44,2 €	44,5 €	48,3 €	52,1 €	55,9 €	59,7 €	78,6 €
	45%	46,3 €	46,7 €	47,1 €	47,5 €	48,0 €	48,4 €	48,8 €	49,2 €	49,7 €	50,1 €	54,4 €	58,6 €	62,9 €	67,1 €	88,4 €
	50%	51,4 €	51,9 €	52,4 €	52,8 €	53,3 €	53,8 €	54,2 €	54,7 €	55,2 €	55,7 €	60,4 €	65,1 €	69,9 €	74,6 €	98,3 €
	55%	56,5 €	57,1 €	57,6 €	58,1 €	58,6 €	59,1 €	59,7 €	60,2 €	60,7 €	61,2 €	66,4 €	71,6 €	76,8 €	82,1 €	108,1 €
	60%	61,7 €	62,3 €	62,8 €	63,4 €	64,0 €	64,5 €	65,1 €	65,7 €	66,2 €	66,8 €	72,5 €	78,2 €	83,8 €	89,5 €	117,9 €
	65%	66,8 €	67,4 €	68,1 €	68,7 €	69,3 €	69,9 €	70,5 €	71,1 €	71,7 €	72,4 €	78,5 €	84,7 €	90,8 €	97,0 €	127,7 €
	70%	72,0 €	72,6 €	73,3 €	74,0 €	74,6 €	75,3 €	75,9 €	76,6 €	77,3 €	77,9 €	84,6 €	91,2 €	97,8 €	104,4 €	137,6 €
	75%	77,1 €	77,8 €	78,5 €	79,2 €	79,9 €	80,7 €	81,4 €	82,1 €	82,8 €	83,5 €	90,6 €	97,7 €	104,8 €	111,9 €	147,4 €
	80%	82,2 €	83,0 €	83,8 €	84,5 €	85,3 €	86,0 €	86,8 €	87,5 €	88,3 €	89,1 €	96,6 €	104,2 €	111,8 €	119,4 €	157,2 €
	85%	87,4 €	88,2 €	89,0 €	89,8 €	90,6 €	91,4 €	92,2 €	93,0 €	93,8 €	94,6 €	102,7 €	110,7 €	118,8 €	126,8 €	167,0 €
	90%	92,5 €	93,4 €	94,2 €	95,1 €	95,9 €	96,8 €	97,6 €	98,5 €	99,3 €	100,2 €	108,7 €	117,2 €	125,8 €	134,3 €	176,9 €
	95%	97,7 €	98,6 €	99,5 €	100,4 €	101,3 €	102,2 €	103,1 €	104,0 €	104,9 €	105,8 €	114,8 €	123,7 €	132,7 €	141,7 €	186,7 €
	100%	102,8 €	103,8 €	104,7 €	105,6 €	106,6 €	107,5 €	108,5 €	109,4 €	110,4 €	111,3 €	120,8 €	130,3 €	139,7 €	149,2 €	196,5 €

Figure 6.2: Sensitivity analysis – Second scenario expected consumers' savings as k and p change

The results show that increasing values of p and k result in greater savings for consumers in both scenarios. Furthermore, when p equals 100%, meaning that the recall can be solved remotely, the savings are equal to the total cost that consumers with vehicles that do not support remote updates would bear; the savings exceed 100€ in both scenarios. To conduct a comprehensive analysis, the authors varied k from an initial value of 0,01%, equivalent to 1 car per 10.000 crashed vehicles, to a value of 1%, equivalent to 1 car per 100 crashed vehicles, which represents a very high probability of an accident occurring. Although this value is statistically unrealistic, examining extreme cases provides a clearer and more insightful analysis of the results. The sensitivity analyses reveal a notable finding: as k increases from 0,01% to 1%, the savings in the second scenario increase more significantly than in the first scenario (+91% vs. +64%). This is because as the number of recalled vehicles (R) grows, the savings for consumers increase more than proportionally, as will be demonstrated in the analysis of the variation in the number of recalled vehicles (R) in Section 6.4.6. Notably, in the second scenario, the fleet of recalled vehicles is ten times larger than in the first scenario.

6.4.3. Cost composition

The authors conducted a comprehensive analysis and comparison of the components that constitute the total cost of a safety recall event, focusing on the factors that have the greatest impact. Given that the cost associated with a potential accident remains constant across both scenarios and has a negligible effect on the overall cost calculation due to the low likelihood of occurrence, the most significant cost element is found to be the expenses related to the recall operations (C_R). The analysis of the 1st scenario, depicted in Figure 6.3, reveals that the largest cost component is attributed to Service Time and its translation into monetary terms through the Value of Service Time. This component surpasses the multiplication of Travel Time and Value of Travel Time by more than two-fold, due to the considerable discrepancy between the 5,93 hours of Service Time and the 1,30 hours of Travel Time (in the 1st scenario).

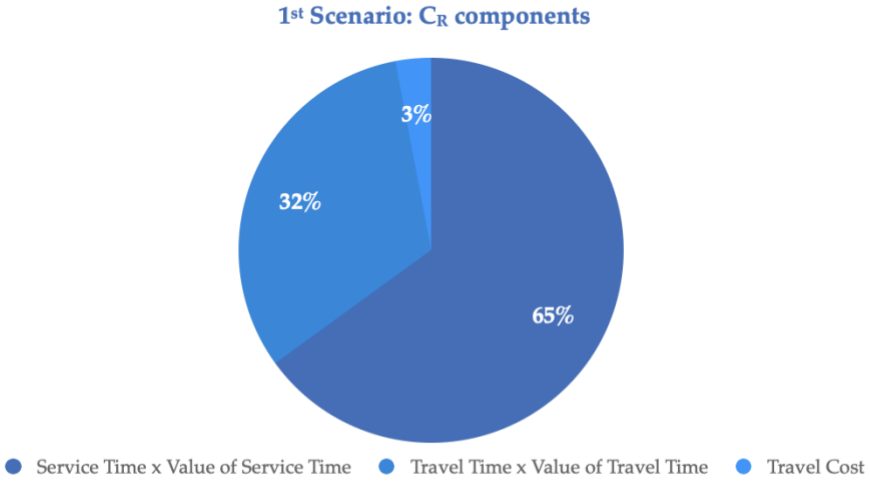


Figure 6.3: First scenario - C_R components

Moreover, it is noteworthy that the VST magnitude assigned to Service Time is lower than that assigned to VTT, with VST equal to €16,07, and VTT ranging from €32,14/h to €36,64/h for subway and car travel, respectively. The reason for this disparity can be attributed to the methods used to calculate the VST and VTT. The VST is determined by dividing the average yearly net salary of the average customer by the yearly working hours, whereas the VTT is derived from the definition of the VoL and the VTAT, which are established based on scientific literature. The VTAT takes into account not only the opportunity cost of work activities but also the value of leisure activities. Consequently, there is a noticeable difference between these two conversion factors utilized to convert time into economic terms. This differentiation is rationalized by the fact that during travel time, the vehicle owner is unable to engage in both work and leisure activities, while the authors' assumption is that only work activities cannot be carried out during service time. The second scenario (Figure 6.4) displays a comparable structure to the first, with Service Time being the most dominant component at 87%, while the Travel Time component is nearly three times less than in the initial scenario (11% versus 32%). Specifically, Travel Time amounts to 0,37 hours in the second scenario. The greater coverage of the territory (which extension is the same in both scenarios) offered by the larger player's dealer network in the second scenario results in a smaller average distance between customers and dealerships. This average distance (d) is indeed 1.00 km in the second scenario compared to 3,96 km in the first scenario.

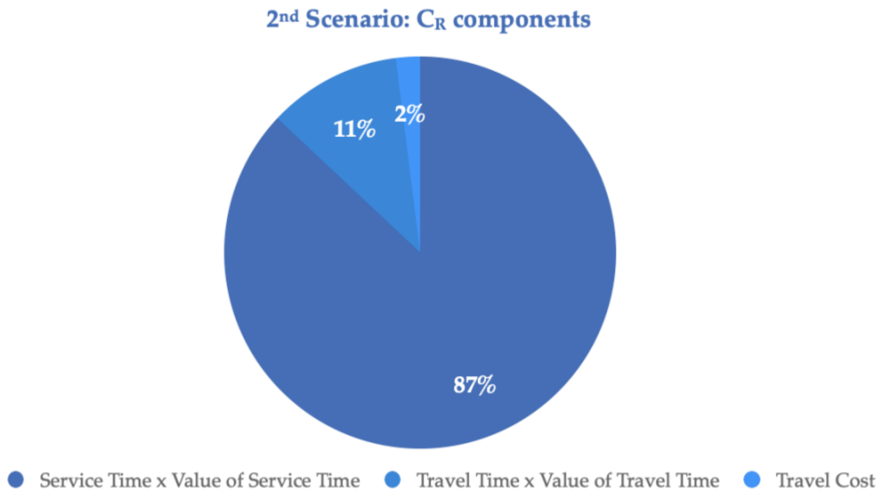


Figure 6.4: Second scenario - C_R components

Regarding the breakdown of the costs linked to a potential accident (Figure 6.5), it is notable that they remain constant across both scenarios. The primary contributor to these costs is the expense associated with car repair, which accounts for 86% of the total. Additionally, although to a much lesser extent, the cost related to the loss of productivity resulting from potential inactivity following an accident represents 13% of the total. The other components (health care, breakdown assistance, and insurance costs) have a negligible impact on the overall cost.

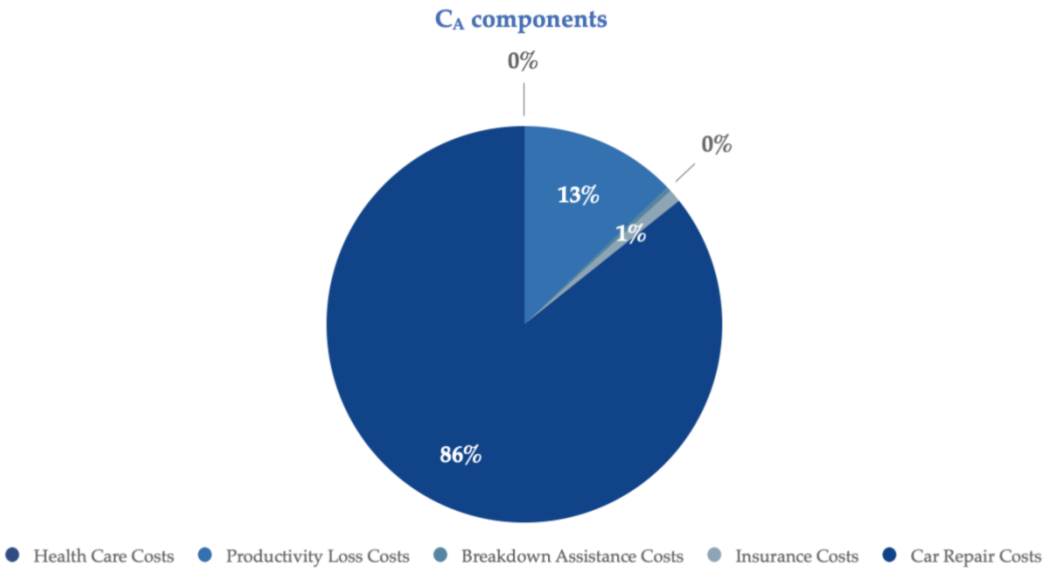


Figure 6.5: C_A components

6.4.4. Update Time variation

The authors also analyzed how the value of C_R varies when the update time (UT) varies. In practice, the duration of recall operations may differ depending on the complexity of the software issue requiring updates. The authors compared C_R results when service time was calculated using Queue Theory versus the second approximation method that assumes no waiting time for consumers, with service time equal to the update time (“appointments case”). Results depicted in the Figures 6.6 and 6.7 clearly point out that C_R increases reasonably as UT increases.

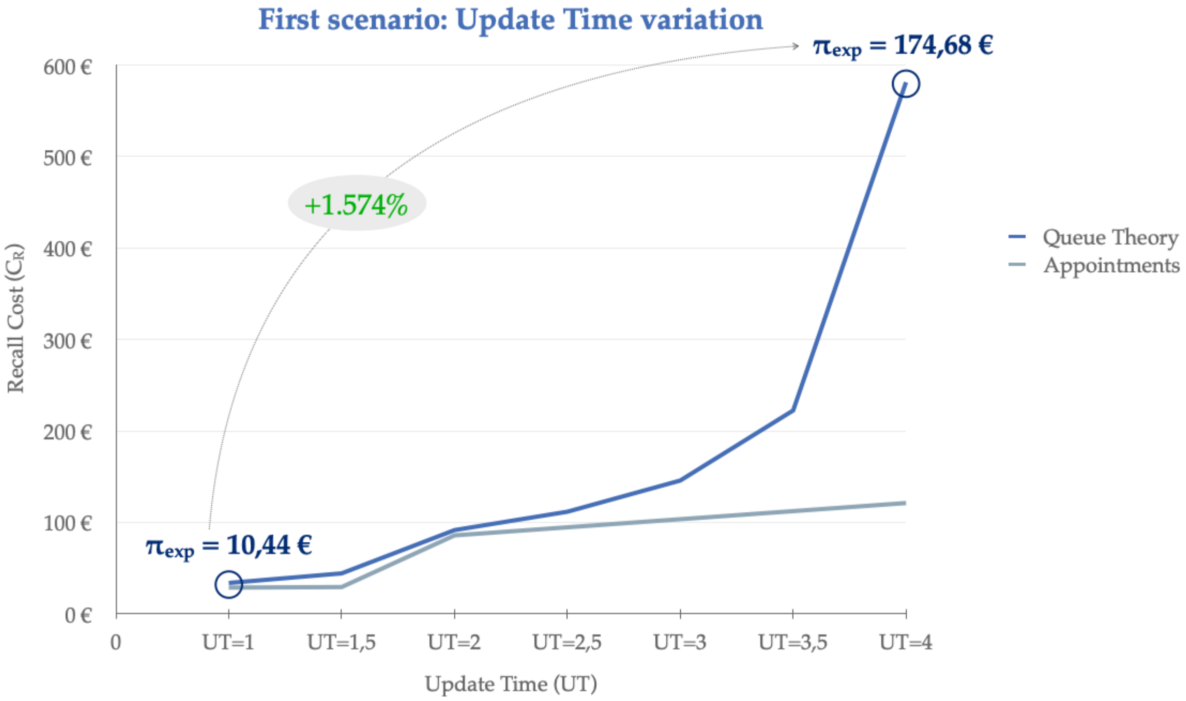


Figure 6.6: Trends in the C_R function in the first scenario as the UT changes (QT vs appointments)

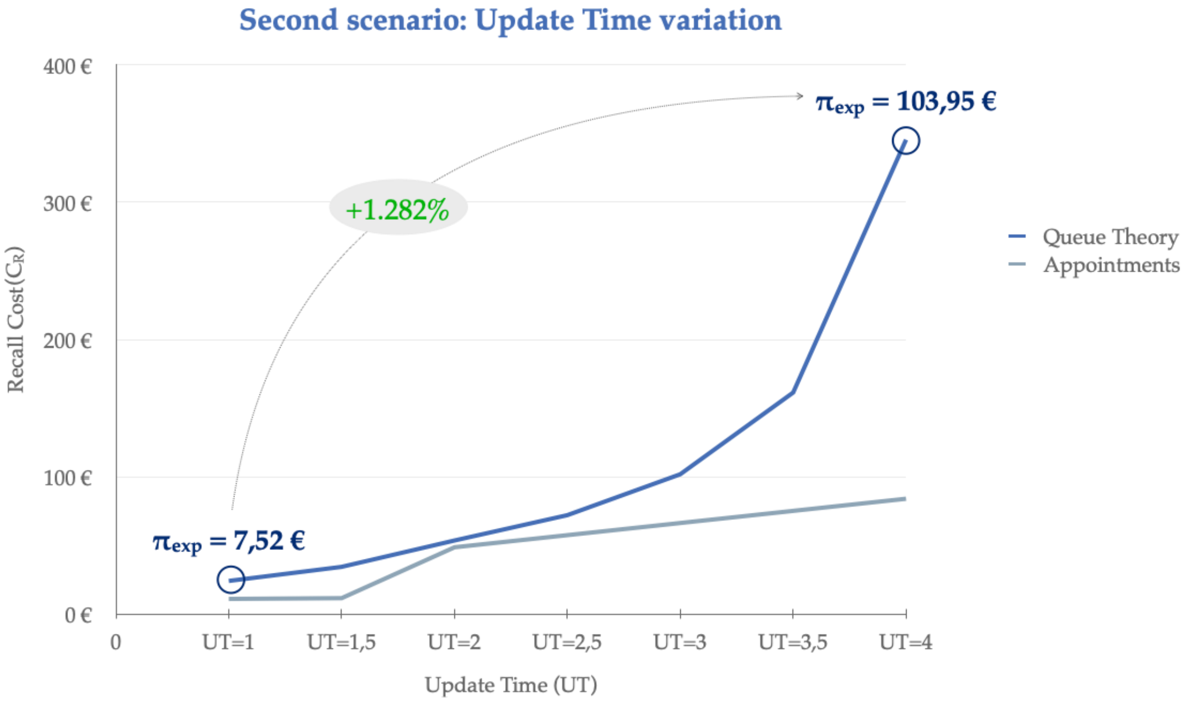


Figure 6.7: Trends in the C_R *function in the second scenario as the UT changes (QT vs appointments)*

In both scenarios, C_R varies depending on how the service time is calculated. When service time is based on appointments, the cost increases (almost[1]) linearly, while when it is calculated using Queue Theory, the cost increases more than proportionally as the update time increases. This means that owning a vehicle that supports OTA updates becomes increasingly convenient as the update time increases. The graph demonstrates this by showing how, in the first scenario, the expected savings increase from €10,44 to €174,68 when the update time is 4 hours. These results obtained using Queue Theory provide a more accurate representation of reality. In fact, as the update time increases, there is a greater likelihood of issues arising in the system, such as bottlenecks that slow down the traversal time, which has been supported by interviews with companies in the industry.

Moreover, upon comparing the graphs of the first and second scenarios, it is evident that the π_{exp} variation is more significant in the former case when UT changes from 1 to 4, as compared to the latter (+1.574% vs. +1.282%). This can be attributed to the fact that in the first scenario, the smaller player has a relatively less extensive and effective

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[1] Both graphs display a slight increase in the cost of recall operations in the case of appointments. This occurs as the service time increases from 1,5 hours to 2 hours, causing a change in the customer journey. Until 1,5 hours, the vehicle owner waits for the update in the vicinity of the dealership. However, from 2 hours onwards, the authors assume that the driver returns home and then returns to pick up the car once the update is completed, resulting in a cost jump.

dealer network, resulting in a higher R/D ratio than in the second scenario. It is reasonable to conclude that a change in UT would result in a more significant rise in C_R and therefore, an increase in the growth of π_{exp} in the first scenario.

6.4.5. Servers number variation

The authors also examined how the consumer savings results vary when the number of servers at the dealership, denoted as c, changes. Interviews conducted during the study revealed that an average-sized dealership typically has two servers, given the onerousness of the computers (diagnostics) that are required for updating vehicles. However, some larger dealerships may have up to four servers at their largest locations. Therefore, the authors found it relevant to investigate how changes in c impact C_R and consumer savings. As depicted in Figures 6.8 and 6.9, both scenarios display a similar trend. As the number of servers c available for the dealership increases, it becomes clear that the C_R decreases at a faster rate than linear, which in turn results in a decrease in the π_{exp}.

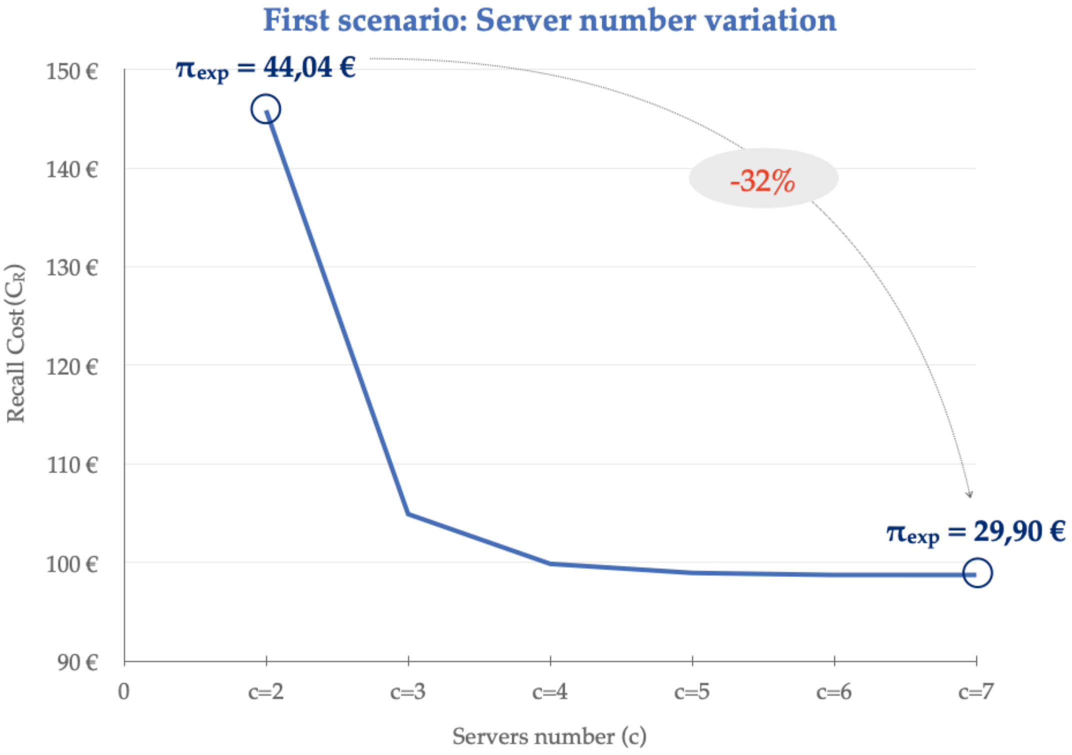

Figure 6.8: Trends in the C_R function in the first scenario as c changes

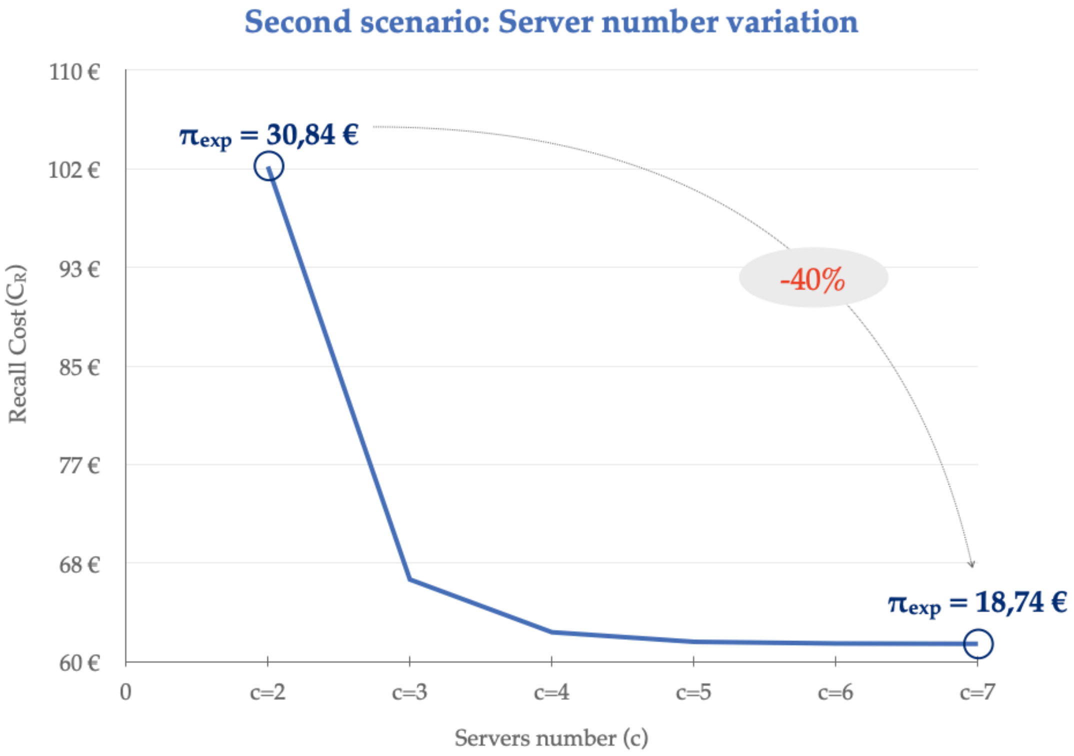

Figure 6.9: Trends in the C_R *function in the second scenario as c changes*

In both scenarios, C_R tends to an asymptotic value, which is a result of the fact that the Service Time, calculated using Queue Theory, tends toward the Update Time as the number of servers, c, increases. Therefore, it becomes increasingly ineffective to add too many servers as it does not significantly improve the C_R. This analysis provides valuable insights for both the manufacturer (OEM) and its dealer network. While investing in more servers may lead to a decrease in the cost to the consumer and their dissatisfaction, investing in too many servers may not be cost-effective, especially considering their onerousness. Being outside the scope of this research, whose aim is to focus on the benefits of the end-consumer, the authors refrained from delving deeply into the analysis of the optimal number of servers to have in each dealership. However, they believe that such an analysis could be interesting and valuable to be conducted in the future from an OEMs' perspective, to determine the optimal and efficient number of diagnostics to have in each dealership taking into account the average number of vehicles recalled in the territory in the past.

6.4.6. Recalled cars number variation

The authors aimed to investigate the impact of the variation in the number of recalled vehicles (R) on the cost of recall operations for the consumer. Due to the larger volumes of vehicles, this analysis was limited to scenario 2, making it more interesting to observe the change in C_R as R varies. Figure 6.10 shows that as R doubles (an increase of 100%), increasing from 10.000 to 20.000 recalled vehicles, the cost of the recall to the consumer grows more than linearly and almost exponentially, with a growth rate close to 300%, three times the growth rate of R, and likewise π_{exp}.

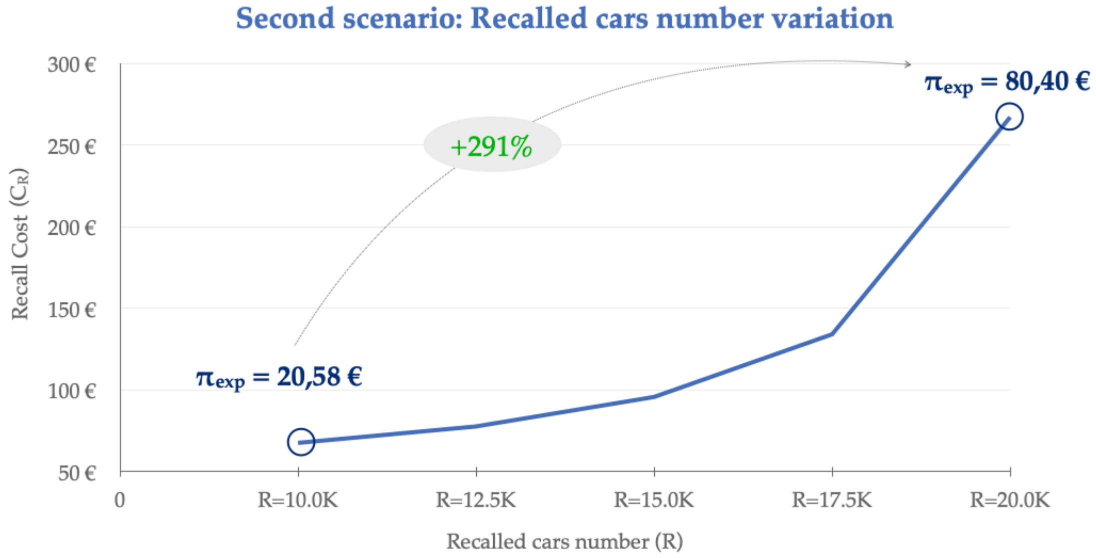

Figure 6.10: Trends in the C_R *function in the second scenario as R changes*

The presented result exhibits the model's capacity to accurately represent real-world scenarios. As the value of R escalates, the cost to the consumer rises sharply due to the accumulation of vehicles requiring updates, leading to longer queues and potential bottlenecks in the OEM's dealership network. Consequently, the outcome unequivocally highlights the substantial convenience of possessing a vehicle equipped with OTA update functionality as the number of recalled vehicles increases.

6.4.7. Final considerations

To summarize, the validation of the model yielded the following significant outcomes:

- With a percentage of remotely resolvable recalls greater than 30%, for a consumer who owns a vehicle equipped with OTA functionality, the potential savings range from 44,0€ to 240,5€ in the first scenario and from 30,8€ to 196,5€ in the second scenario.

- The expenses incurred by the consumer are predominantly generated by the Service Time and the waiting of service completion, which are subsequently converted into monetary terms by the VST.
- As UT increases, π_{exp} experiences a more significant increase in scenario 1. This can be attributed to the first scenario player's relatively less extensive and effective dealer network, resulting in a higher R/D ratio than in the second scenario.
- In scenario 2, as the number of servers c increases, π_{exp}declines at a faster rate.
- With an increase in the number of recalled vehicles (R), π_{exp} experiences a more than proportional increase.

The preceding results unambiguously establish and show the cost-effectiveness of possessing a vehicle equipped with OTA functionality in case of a safety recall. As evidenced by the outcomes, the convenience of owning such a vehicle increases in proportion to the magnitude of the recall and the OEM and its dealership network organizational setup. These events, owing to their significance, can give rise to inefficiencies and bottlenecks that severely impact the consumer. Moreover, the cost to the consumer escalates proportionately with the OEM's and its dealer network's limited geographic coverage (which also reflects their market share in Italy) when these exceptional events such as recalls for vehicle safety issues occur.

Nonetheless, it is worth noting that the exceptional nature of this event is gradually diminishing as time progresses, as connected vehicles (whose diffusion is expanding) indeed present hundreds of Electronics Control Units (ECUs) and this is the reason why a Connected Car nowadays contains more than 100 million lines of code for performing several controlling functions. The upsurge in the number of lines of code significantly increases the likelihood of software bugs that can pose serious consequences to the safety of the vehicle and its passengers. Consequently, as software problems arise, an increasing number of original equipment manufacturers (OEMs) are compelled to recall their entire fleet of vehicles to update the ECU software.

In conclusion, it is worth noting that if it is assumed that the cost to the consumer (C_{tot}) is directly proportional to customer dissatisfaction, these findings can serve as a valuable instrument for manufacturers (OEMs) who continually strive to enhance customer satisfaction. By leveraging these results, OEMs can devise and implement effective measures to mitigate the impact of safety recalls on customer satisfaction and minimize the associated costs. By minimizing these costs, OEMs can optimize their business operations, increase customer retention, and attract new customers.

Consequently, OEMs can maintain and strengthen their market position and competitiveness.

6.5. Limitations

In this section, the limitations that emerged during the application of the model are discussed. While implementing the proposed model, certain limitations were encountered that may affect its reproducibility in real-world contexts.

Firstly, it should be noted that the model was applied in Milan, Italy, and thus the numbers used are influenced by its geographic application. However, it should also be mentioned that the authors have only presented one example of an applicable territory, and based on the theoretical framework of the model, it can be applied to other cities or countries as well. Nevertheless, it is certain that the values of savings, if the model were applied to a small village that only relies on a single authorized dealer (where the R/D ratio would increase significantly), would be different and would deviate from the values found by the authors in the two scenarios.

Another significant limitation is the choice of the event for which the savings were calculated: safety recalls. The authors decided to limit the application of the model solely to safety recalls for two main reasons. Firstly, based on the evidence found in literature and through interviews, it emerged that safety recalls are the most relevant ones for OEM and consumers, in terms of the criticality of the event but also in economic terms. Secondly, between the different types of recall (presented in Chapter 3), given their different criticality and importance, some parameters may vary substantially, thus not allowing to analyze and model the different recall types in the same way. For instance, from the interviews emerged clearly that there is a degree of penetration of recall campaigns depending on whether they are for safety or non-safety purposes. For safety recall campaigns, a penetration parameter of approximately 90% was used, as it is plausible given that it concerns the safety of people on board the vehicle and in the surrounding environment. Moreover, the customer journey, presented in Chapter 5, for another type of recall might be different.

Furthermore, it should be emphasized that the model is based on a set of simplifying assumptions, which may not be entirely representative of all circumstances. For example, the definition of the parameter k for both application scenarios. Its value of 0.01% was estimated empirically, aided by consultations with experts from the automotive industry, who advised on a plausible order of magnitude for applying the model. This limitation arises due to the recent and experimental nature of the subject matter, namely, the commercialization and usage of Connected Cars, which has resulted in a dearth of statistical data concerning accidents caused by software malfunctions necessitating a recall. The authors acknowledge that the model, by its nature, includes simplifications necessary to reproduce real-world scenarios and therefore is not capable of considering all the dynamics characterizing reality.

It is also true that in the future, with the diffused use of Connected Cars, more and more studies and statistical analyses will be carried out, with surely studies that will quantify avoidable accidents with OTA technology, thanks to the lower Time To Market required to disseminate updates for the safety of the vehicle and its passengers (including the driver). The authors, therefore, believe that the proposed theoretical model is a valuable robust starting point for further studies. Furthermore, an increase in research on this topic could reasonably convince more OEMs that the installation of OTA functionality on as many Connected Cars as possible may produce considerable savings for the consumer, ensuring the car manufacturer to improve its strategic position and gain long-term monetary and competitive advantages.

Furthermore, when discussing the benefits that consumers derive from owning a vehicle that supports OTA technology and enables remote software issue resolution, it must be acknowledged that the model only considers quantifiable factors in monetary terms, completely disregarding qualitative benefits that would enhance the convenience of OTA support for drivers. This is because customer experience and satisfaction are difficult to quantify and reproduce mathematically to be considered within an analytical model.

Another limitation that has been encountered while developing the model calculations concerns the boundary of the automotive market taken as a reference. The figures the authors used as a reference for the vehicle fleet and scenario definitions refer to automotive brands that do not belong to the luxury category. The latter were excluded from the sample analysis because they have different market dynamics and characteristics. Firstly, their volumes are much lower, which allows the manufacturer to offer a higher level of service in the event of a safety recall, unlike mass-market manufacturers who have to serve thousands of vehicles with a level of service that inevitably cannot be comparable to that of luxury brands.

Nevertheless, the authors acknowledge that these limitations the model was built upon may restrict the generalization of the outcomes. At the same time, the authors believe them to be acceptable, remaining applicable to any of the most important cities with a model validation with similar outcomes, and to any other city in the world with the outcome extendibility that cannot be guaranteed, but that can be adapted and refined in the future for each specific case of application.

7 Conclusions

The presented dissertation had the primary objective of conducting an extensive analysis of the Connected Cars concept and their positive externalities. Aiming to have a comprehensive overview of the topic the authors conducted an extensive literature review over the time horizon 2011-2022. An evident lack of studies investigating the quantification of the economic externalities of convenience services ensured by Connected Cars emerged. In particular, the authors identified no scientific work focused on the quantification of the consumer economic externalities provided by Over-the-air updates. To dive deep into this topic, the authors carried out an additional and more targeted investigation of the topic of Over-the-air updates applied to the automotive industry. This secondary research confirmed the gap previously emerged.

On these grounds, the authors aimed to cover the gap characterizing the scientific literature by creating an analytical model for evaluating the consumer economic benefit of owning a car supporting OTA updates in a safety recall event. The specificity of such recall lies in the relevance that safety recalls have in the real world, with the associated implications for both automakers and consumers.

The model was grounded on the travel and service time the consumer bears when the need to bring the vehicle to the dealership to perform the car's update arises. To obtain a final monetary value, the authors translated the travel and service time in economic terms through the Value of Travel Time and the Value of Service Time. Moreover, the model also considered the cost of an eventual accident caused by the software failure for which the recall was issued. Nevertheless the very limited impact of this latter event on the total cost value, the authors found it appropriate to include this element in the model in order to have a more comprehensive analysis.

The study's findings hold significant relevance and have the potential to create a significant impact due to the novelty of the subject matter and the limited existing scientific literature available on this topic. The model results point out unambiguously the cost-effectiveness of possessing a Connected Car equipped with OTA functionality in case of a safety recall. At the same time, the authors of this dissertation acknowledge that the model's assumptions and hypotheses may limit the generalization of the results. For instance, the decision to solely focus on safety recall events restricts the application of the model to this specific type of recall. Moreover, the model is limited to the case of recalls issued by mass-market manufacturers who serve thousands of clients with a level of service that inevitably cannot be comparable to that of luxury brands which instead, with lower volumes, can provide a higher level of service in the event of a safety recall.

Nevertheless, the authors expect that the model application can be extended in any of the major metropolitan cities in Italy and they expect to achieve comparable validation outcomes. However, it should be noted that the extensive number of input model variables contextualized to the Italian setting may pose a challenge in generalizing the results to foreign countries. Hence, caution must be taken when applying the model to other regions, and it should be considered that the results may not be guaranteed to be transferable across different contexts.

The unique insights gained from the research offer invaluable insights to Original Equipment Manufacturers (OEMs) who wish to investigate how safety recalls impact economically their clients. As this dissertation largely discussed qualitatively, safety recalls significantly affect customer satisfaction and companies' brand image. By delving deeper into this aspect, OEMs may gain valuable insights on how to mitigate the economic impact of such recalls and improve customer satisfaction. Therefore, this study's results are of utmost importance and can prove to be a crucial source of information for OEMs and other stakeholders in the industry.

To conclude, thanks to the analysis and validation performed, it is now possible to answer the Research Questions that were formulated in Chapter 4.

RQ1: What is the actual state-of-the-art about Over-the-air (OTA) updates?

The scientific literature on OTA updates for Connected Cars is still limited to qualitative works that discuss the main benefits these technologies bring to OEMs and consumers. For the former, OTA updates allow solving remotely several recall operations otherwise physically performed with a consequent significant cost. At the same time, OEMs can exploit OTA updates to generate new revenue streams throughout a car's life cycle by enabling the sale of premium over-the-air upgrades. Beyond generating revenues, these services provide companies with recurring customer interactions that may increase brand loyalty. The scientific literature points out that for consumers, too, the benefits are manifold. OTA updates indeed provide a safer car, always up to date with the latest and safest software. The ability to remotely perform car updates reduces maintenance costs and, at the same time, vehicle obsolescence. Last but not least, OTA updates allow for avoiding inconvenient and annoying situations as eventual recalls can be solved remotely and in a short time, producing a considerable saving of time and money for the consumer.

RQ2: How can benefits generated by a safety recall be quantified?

Through the design of an analytical economic model and its application, the authors demonstrated unambiguously the convenience of owning a car supporting OTA updates in case of a safety recall. Two distinct simulations were conducted, both replicating a safety recall scenario in the province of Milan. In both simulations, the expected total recall cost for the consumer (without a car supporting OTA updates) is over 100 €. In particular, when a safety recall can be solved remotely, the expected saving generated by OTA updates varies from a minimum of 102,8 € to a maximum of 240,5 €. Moreover, the model results highlighted the increasing convenience of possessing a car supporting OTA updates as the number of recalled vehicles increases. Indeed, as the number of recalled cars rises from 10.000 to 20.000 the consumer cost of the recall, and, in turn, the expected saving generated by OTA updates, grow almost exponentially, with a growth rate close to 300%.

Finally, the achieved results ensure a solid foundation for the further promising development of Over-the-air updates in the automotive industry. After demonstrating the convenience that OTA updates in safety recall events produce for consumers from an economic point of view, it would be worth extending the cost-benefit analysis to other recall types beyond safety ones. OTA updates have also a significant impact on customer satisfaction, maintenance costs, and vehicle obsolescence over the entire lifespan of the car. Therefore, conducting a cost-benefit analysis of these aspects could provide valuable insights into the vast potential of OTA updates from a consumer perspective. By exploring these areas, the automotive industry may uncover ways to leverage even more the benefits of this technology.

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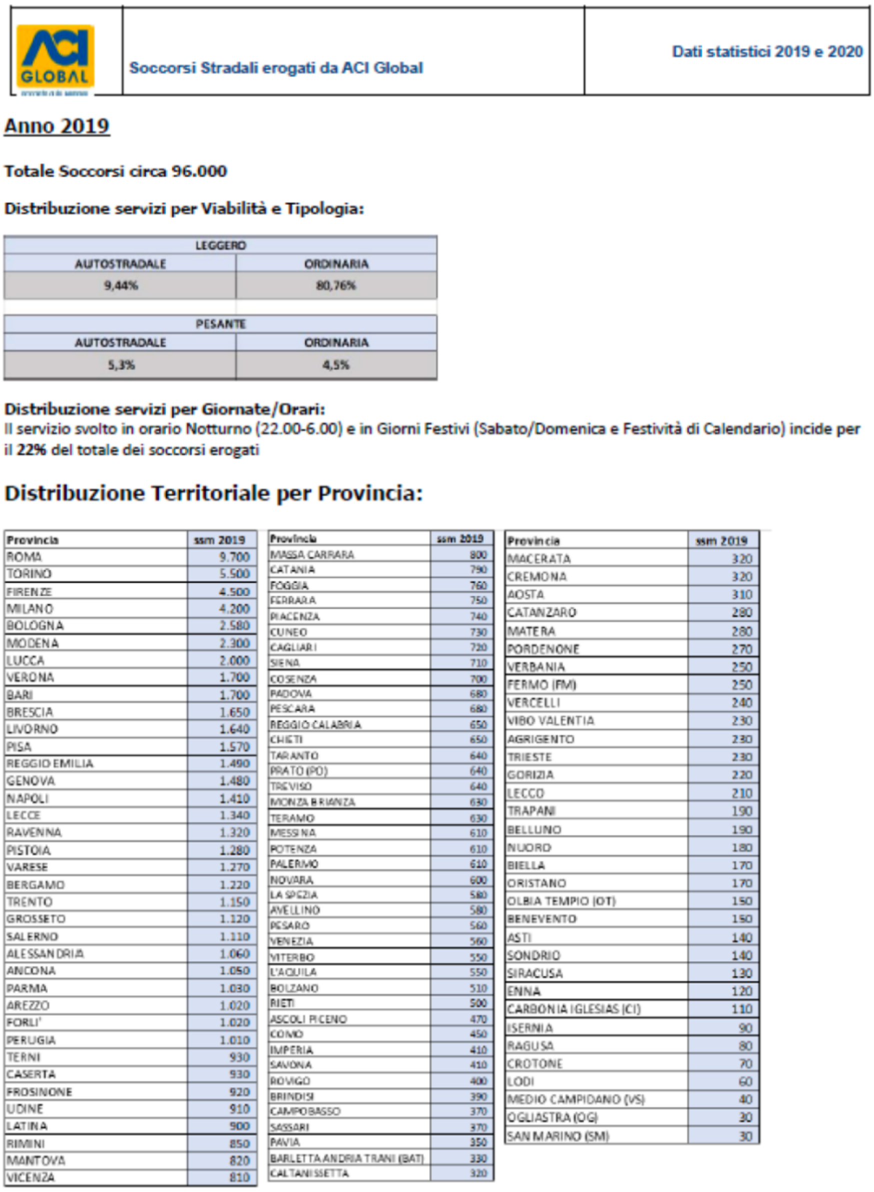
A Appendix

Scenario 2		
Variable	Value	Unit of measure
R	15.000	cars
D	125	dealerships
UT	3	hours
c	2	servers
pr	90%	-
T	30	days
WH	8	h/day
λ	0,45	cars/h
μ	0,33	cars/h
ϱ	1,35	-
Ws = ST	5,51	h/car
A	1.575	Km^2
S	12,6	Km^2
r	2,0	Km
d	1,0	Km
s_{bike}	16,9	Km/h
s_{walk}	5,16	Km/h
T_{subway}	0,133	h
$T_{r1} = T_{o2}$	0,129	h
s_{car}	18	Km/h
T_{o1}	0,056	h
T_{r2}	0,056	h
TT_{car}	0,111	h
TT_{bike}	0,039	h
TT_{subway}	0,089	h
TT_{walk}	0,129	h
TT (case 2)	0,369	h
$VoL_{distance\text{-}income}$ (business)	27,30	€/h
$VoL_{distance\text{-}income}$ (non-business)	17,93	€/h
% of dealership trips in business hours	100%	-
% of dealership trips in business hours	0%	-
VoL	27,30	€/h
$VTAT_{bike}$	-3,03	€/h
$VTAT_{car}$	-4,23	€/h
$VTAT_{subway}$	0,27	€/h
$VTAT_{walk}$	-4,13	€/h
VTT_{bike}	30,33	€/h
VTT_{car}	31,53	€/h
VTT_{subway}	27,03	€/h
VTT_{walk}	31,43	€/h
$TT_{bike} * VTT_{bike}$	1,20	€
$TT_{car} * VTT_{car}$	3,51	€
$TT_{subway} * VTT_{subway}$	2,40	€
$TT_{walk} * VTT_{walk}$	4,07	€
TT * VTT (case 2)	11,17	€

Scenario 2		
Variable	Value	Unit of measure
c_{bike}	0,2	€/min
Conversion	60	min/h
TC_{bike}	0,71	€
TC_{subway}	2,2	€
TC_{walk}	0	€
TC_{car_fuel}	0,091	€/Km
TC_{car}	0,36	€
TC (case 2)	2,12	€
VST	16,07	€/h
W_s * VST	88,56	€
C_R	**101,86**	**€**
C_H	1,88	€
C_{PL}	1.211,97	€
C_{BA}	34,97	€
C_{REP}	8.115,49	€
C_{Ins}	100,9	€
C_A	**9.465,21**	**€**
p	30%	-
k	0,01%	-
π	**30,84**	**€**

B Appendix

The authors obtained from ACI data about breakdown assistance intervention in 2019. It includes the number of interventions per different days and hours.



Soccorsi Stradali erogati da ACI Global

Dati statistici 2019 e 2020

Anno 2019

Totale Soccorsi circa 96.000

Distribuzione servizi per Viabilità e Tipologia:

LEGGERO	
AUTOSTRADALE	ORDINARIA
9,44%	80,76%

PESANTE	
AUTOSTRADALE	ORDINARIA
5,3%	4,5%

Distribuzione servizi per Giornate/Orari:

Il servizio svolto in orario Notturno (22.00-6.00) e in Giorni Festivi (Sabato/Domenica e Festività di Calendario) incide per il **22%** del totale dei soccorsi erogati

Distribuzione Territoriale per Provincia:

Provincia	ssm 2019
ROMA	9.700
TORINO	5.500
FIRENZE	4.500
MILANO	4.200
BOLOGNA	2.580
MODENA	2.300
LUCCA	2.000
VERONA	1.700
BARI	1.700
BRESCIA	1.650
LIVORNO	1.640
PISA	1.570
REGGIO EMILIA	1.490
GENOVA	1.480
NAPOLI	1.410
LECCE	1.340
RAVENNA	1.320
PISTOIA	1.280
VARESE	1.270
BERGAMO	1.220
TRENTO	1.150
GROSSETO	1.120
SALERNO	1.110
ALESSANDRIA	1.060
ANCONA	1.050
PARMA	1.030
AREZZO	1.020
FORLI'	1.020
PERUGIA	1.010
TERNI	930
CASERTA	930
FROSINONE	920
UDINE	910
LATINA	900
RIMINI	850
MANTOVA	820
VICENZA	810

Provincia	ssm 2019
MASSA CARRARA	800
CATANIA	790
FOGGIA	760
FERRARA	750
PIACENZA	740
CUNEO	730
CAGLIARI	720
SIENA	710
COSENZA	700
PADOVA	680
PESCARA	680
REGGIO CALABRIA	650
CHIETI	650
TARANTO	640
PRATO (PO)	640
TREVISO	640
MONZA BRIANZA	630
TERAMO	630
MESSINA	610
POTENZA	610
PALERMO	610
NOVARA	600
LA SPEZIA	580
AVELLINO	580
PESARO	560
VENEZIA	560
VITERBO	550
L'AQUILA	550
BOLZANO	510
RIETI	500
ASCOLI PICENO	470
COMO	450
IMPERIA	410
SAVONA	410
ROVIGO	400
BRINDISI	390
CAMPOBASSO	370
SASSARI	370
PAVIA	350
BARLETTA ANDRIA TRANI (BAT)	330
CALTANISSETTA	320

Provincia	ssm 2019
MACERATA	320
CREMONA	320
AOSTA	310
CATANZARO	280
MATERA	280
PORDENONE	270
VERBANIA	250
FERMO (FM)	250
VERCELLI	240
VIBO VALENTIA	230
AGRIGENTO	230
TRIESTE	230
GORIZIA	220
LECCO	210
TRAPANI	190
BELLUNO	190
NUORO	180
BIELLA	170
ORISTANO	170
OLBIA TEMPIO (OT)	150
BENEVENTO	150
ASTI	140
SONDRIO	140
SIRACUSA	130
ENNA	120
CARBONIA IGLESIAS (CI)	110
ISERNIA	90
RAGUSA	80
CROTONE	70
LODI	60
MEDIO CAMPIDANO (VS)	40
OGLIASTRA (OG)	30
SAN MARINO (SM)	30

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Variable	**Description**	**SI unit**
C	Total cost	€
C_R	Recall operations cost	€
C_A	Cost of an accident	€
k	Probability that a recalled vehicle undergoes an accident	-
p	Percentage of remotely solvable recalls	-
π	Expected gain	€
TT	Travel Time	h
$VTT_{vehicle}$	Value of Travel Time	€/h
$VTAT_{vehicle}$	Value of Time Assigned to Travel	€/h
$TC_{vehicle}$	Travel Cost	€
ST	Service Time	h
VST	Value of Service Time	€/h
SC	Service Cost	€
T_{o1}	Time to get to the dealership from home with driver's own car	h
T_{r1}	Time to return back home from the dealership (alternative mean of transport)	h
T_{o2}	Time to return back to the dealership from home with an alternative mean of transfer	h
T_{r2}	Time to return back home after picking up the vehicle to the dealership	h

d	Average distance home-dealership	Km
s	Average speed in the home-dealership route	Km/h
A_j	Area of municipality j	Km^2
D_{k_j}	Number of authorized dealerships for the OEM *k* in the municipality *j*	dealership
S_{k_j}	Area covered by an authorized dealership for the OEM *k* in the municipality *j*	Km^2/dealership
r_{k_j}	Radius of S_{k_j} area	Km
d_{k_j}	Average distance consumer-dealership (k) in the municipality j	Km
δ_{time}	Marginal utility of time	U/h
δ_{money}	Marginal cost per unit of money	U/€
$W_{distance_i}$	Weight of travel distance compared to the income in the computation of VoL_{ij}	-
W_{income_j}	Weight of income compared to travel distance in the computation of VoL_{ij}	-
$VoL_{distance_i}$	Absolute Value of Leisure related to the distance range i	€/h
VoL_{income_j}	Absolute Value of Leisure related to the income range j	€/h
p_{ij}	Coefficient defining the ratio between $VoL_{distance_i}$ and VoL_{income_j}	-
TC_{car}	Car travel cost	€
TC_{car_fuel}	Travel cost component for fuel consumption	€/Km
$\%\ Concentration_{fuel}$	Percentage concentration of differently fueled vehicles	-
$Consumption_{fuel}$	Fuel consumption	$\frac{l/KWh/kg}{Km}$

$Price_{fuel}$	Price per fuel type	$\frac{€}{l/KWh/kg}$
λ	Arrival rate	car/h
μ	Service rate	car/h
n	Number of customers in the system	cars
L_q	Average number of customers waiting in the queue	-
L_s	Average number of customers waiting in the system	-
W_s	Average system throughput time	h
ρ	Traffic intensity of the system	-
c	Number of servers at the dealerships	servers
UT	Update tiem	h/car
R	Number of recalled cars	car
pr	Average penetration rate of a safety recall campaign	-
D	Number of dealerships	dealership
WH	Daily working hours of the dealership	h/day
T	Number of days within which the update must be performed	day
YNS_j	Yearly Net Salary in the geographical area j	€/year
YWH_j	Yearly Working Hours in the geographical area j	h/year
I	Number of vehicles involved in car accidents	car
C_H	Health Care cost	€
m	Percentage of accidents in which the driver of the guilty vehicle is injured	-
i	Percentage of consumers with policy add-on "driver's injury coverage"	-

c_h	Average individual cost for medical expenses following the injury	€
$C_{h_{slight\ injury}}$	Average social expenses for a slight injured person involved in a car crash	€
$C_{h_{severe\ injury}}$	Average social expenses for a severe injured person involved in a car crash	€
$C_{h_{total}}$	Total society cost for the total number of injured persons	€
C_{PL}	Productivity Loss cost due to the involvement in a car accident	€
t_{hosp}	Average hospital stay time	h
VT_j	Value of time in the geographical area *j*	€/h
YNS_j	Yearly Net Salary in the geographical area j	€/y
YWH_j	Yearly Working Hours in the geographical area j	h/y
C_{BA}	Cost of a breakdown assistance intervention following an accident	€
p_{BA_WD}	Base price of breakdown assistance intervention on working days	€
ba_{wd}	Percentage of breakdown assistance interventions on working days	-
p_{BA_NH}	Base price of breakdown assistance intervention on night/holidays	€
ba_{nh}	Percentage of breakdown assistance interventions on night/holidays	-
ba	Percentage of accidents that required breakdown assistance intervention	-
BA_j	Total number of BA interventions in geographical area j per year	-
A_j	Total number of accidents in geographical area j per year	-
C_{Rep}	Costs related to car repair activities	€
sh	Average service hours required for car repair	h

c_{ser_j}	Average dealership hourly service cost in the geographical area j	€/h
c_{comp_i}	Cost of the i-th car's component to be substituted	€
N	Number of components to be substituted	-
$kasko$	% of vehicles with kasko insurance in the geographical area j	-
C_{Ins}	Insurance cost related to the premium increase following a road accident	€
c_{ins_j}	Average car insurance premium in the geographical area j	€
$\Delta_{premium\_j}$	Average % increase of car insurance premium after a car accident in the geographical area j	-

Acronyms

ADAS: Advanced Driver Assistance Systems

ACC: Adaptive Cruise Control

AI: Artificial Intelligence

AV: Automated Vehicles

BA: Breakdown Assistance

B2C: Business To Consumer

CAN: Controller Area Network

CAVs: Connected and Automated Vehicles

CC: Connected Cars

ConFAVs: Connected Fully Autonomous Vehicles

CV: Connected Vehicles

ECU: Electronic Control Unit

ER: Emergency Room

EU: European Union

EV: Electric Vehicles

FIFO: First In, First Out

FQ: Functional Question

HCA: Human Capital Approach

IoT: Internet of Things

IoV: Internet of Vehicles

IVI: In-Vehicle Infotainment

LIN: Local Interconnect Network

MPR: Market Penetration Rate

NHTSA: National Highway Traffic Safety Administration

OEMs: Original Equipment Manufacturers

OTA: Over-the-air

QT: Queue Theory

RQ: Research Question

SAE: Society of Automotive Engineers

ST: Service Time

TTM: Time To Market

UBI: Usage Based Insurance

UT: Update Time

VANETs: Vehicle Ad-hoc Networks

VoL: Value of Leisure

VTAT: Value of Time Assigned to Travel

VST: Value of Service Time

VTT: Value of Travel Time