Infrastructure Readiness for Autonomous Vehicles

TREBALL FINAL DE GRAU

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The present report corresponds to the academic final work prepared by the student **Miguel Campillo de Frutos** for finishing his studies in the Civil Engineering Degree which is offered by the Polytechnical University of Catalonia (UPC), in Barcelona, Spain. The elaboration of this paper has been supervised by **Prof. Miquel Estrada Romeu**, Associated Professor at Barcelona School of Civil Engineering (UPC).

The preparation of the present work started in mid-february 2019, when the supervisor suggested the student to conduct a research on the expected apparition and rapid proliferation of Connected and Autonomous Vehicles (CAVs) on urban media, and their connection with the existent road infrastructure but also with the yet-to-be-deployed infrastructure needs.

This project was also raised targeted to make visible the problematics that are hampering the driving tasks of the newer vehicles which have some specific driving functions automatized (the so-called "semi-autonomous vehicles" or cars with lower levels of automation). Detecting and listing the problems that the cars of today must cope with may ease the driving tasks for the "completely-autonomous vehicles" of tomorrow, such vehicles without a human driver which would form part of the future transportation modals and services. These services and the opportunities that would likely imply and bring in to the global society have been gathered and listed throughout the document.

Finally, the supervisor suggested the author of the present work to prepare a case study with the implicit purpose of using a microscopic traffic simulation software. The simulation stage also implied the student to get familiarized with the software that has been used for performing the simulation stage and, moreover, it became an opportunity for enriching the present report and making it being more heterogeneous rather than being a simple paper consisting of a bibliographic review.

A literature review was carried out during the first months of the preparation of the work (namely, during the spring semester of 2019). The redaction of the primitive ideas that were thought to be worth mentioning in the report also started at such semester. By the end of May 2019, Professor Miquel Estrada suggested the student to participate as a research fellow in the elaboration of a project conducted by **CARNET Future Mobility Research Hub** (The centre of mobility research of the Polytechnical University of Catalonia, Volkswagen and Seat) aimed to provide the Barcelona's Metropolitan Transport Authority **(ATM)** a technical assistance oriented to the management of the transition stage towards the implementation of self-driving technologies and their applications. The student agreed to participate and, after preparing the project during the month of June, 2019, the document "*Assistència Tècnica a L'ATM per a la transició cap al vehicle autònom*" was delivered to the Metropolitan Transport Authority.

After having finished his stage as a research fellow, the author conducted the simulations during the summer of 2019, while he was completing the initial report with some information that was also gathered in the document prepared for the Metropolitan Transport Authority. Finally, the present document became completed by the end of September 2019.

Barcelona, September 29^{th}, 2019.

The Author

Miguel Campillo de Frutos

Acknowledgements

The author wants to express his very great thankfulness to Prof. Miquel Estrada Romeu for his guidance and advice on the elaboration of this document, for his willingness to track its drafting, and for providing him the opportunity of participating as an intern in the preparation of the document that was redacted for the Metropolitan Transport Authority. Jointly with this acknowledgement, the author wishes to write some words of thankfulness to CARNET Future Mobility Hub, in special to Prof. Elisa Sayrol for delivering the author a great deal of essential information about wireless interconnetions, and, foremost, to the Executive and Scientific Manager of CARNET Future Mobility Hub, Dr. Laia Pagès, for offering the author to participate in the drafting of the previously mentioned paper, but also for her interest in the object of the paper the author was preparing, which is presented in this document.

Moreover, jointly with the acknowledgement for his supervisor, the author wants to manifest his appreciation to the Transport division of the Department of Civil and Environmental Engineering of the Barcelona School of Civil Engineering. In particular, to Prof. Francesc Robusté, for organizing every year at Barcelona School of Civil Engineering a workshop consisting of a cycle of conferences where *transport* is the common subject. The author wishes to word his appreciation and thankfulness to Prof. Robusté for letting him attend the most important talks given during the academic year 2018/19. Assisting to the conference given by Pere Navarro Olivella, director of *Dirección General de Tráfico*, which was held on March 27^{th}, 2019, has been a milestone in the preparation of this document, because the author realized about the crucial importance of road safety.

Finally, he also wants to recognize his gratitude to his parents, relatives, and best colleagues, in special those which have been constantly encouraging him to do his best in relation with the preparation of this paper, but also to those people who have been expressing their interest in the topic of the document he was preparing. For the author, sharing with his relatives and acquaintances the knowledge he has gained while conducting the research and elaborating this paper has been a key aspect that surely led to improve the quality of the research and the work, but he believes it also fostered him to focus the drafting of the paper from a wider set of standpoints.

Abstract

A great shift on private mobility has started. Newer laws and standards intend to start a change from former petrol cars to electric vehicles. The rapid emergence of newer technologies has made self-driving algorithms become a reality. A broad range of opportunities may arise due to the proliferation of such technologies, but they would only be helpful and would only enhance safety for all the mobility agents if our streets and roads were prepared for the early autonomous vehicles, which are currently becoming more and more marketed.

It would be important to take the biggest profit as possible of these new opportunities seeking to transform current private, selfish mobility towards a more sustainable scenario where the vehicles that compose overall fleet could ride and arrange between them in a more sustainable and altruist way, based on smarter traffic management algorithms, more eco-friendly self-driving mechanisms (which would exactly know the optimal instantaneous speed for reaching a given point with the current traffic conditions and semaphore phases information) but also based on platooning phenomena (which would provide some aerodynamic benefits in terms of energy saving). Otherwise, the new self-driving technologies may also revolutionize current public transport and the importance on society of carsharing and ridesharing services might definitely take-off. These services would need some physic requirements, such as more pick-up and drop-off areas and might even require the construction of currently inexistent and unimaginable interurban road-transport hubs. Storage of vehicles is expected to dramatically change, and the road equipment should prove readable and must not lead vehicles to misunderstandings: Marks and signage must be readable under all lighting and weather conditions and the asphalt layer has to prove well-maintained and their drainage capabilities have to be functional.

Some needs that would likely appear for providing a proper service of self-driving and connected vehicles are deeply analysed in this document. These items would not be separately required, but a given combination of all the listed needs could be required in order to get autonomous driving started and widely deployed. These needs might also be required for solving a given problematic related to mobility and/or urbanism at a given city. Moreover, such combinations of needs must be sufficient for ensuring that any given vehicle is able to both interpret the traffic circumstances and to read the road infrastructure that surrounds it in a biunivocal way. These sets of requirements also have to provide a reliable infrastructure base for all the different steering algorithms that nowadays are being developed. Nevertheless, such algorithms, which are being prepared by different automakers, ought to tend to be uniformized.

The different infrastructure needs for a proper operation of newer, self-driving vehicles, and the most important relations between them are collected, analysed and discussed in the document, which also observes the traffic behaviour using Aimsun.next traffic modelling software on a model which represents an existing urban area. Furthermore, traffic performance if a corridor gets equipped with a reserved lane for self-driving cars is also discussed in the document.

Contents

1 Introduction

Sustainable mobility has become a mandatory matter for cities among the last decades. Cities, which have been developed and structured due to great potential of private vehicles during the previous century, are nowadays preparing and updating their mobility plans seeking a shift to more sustainable, accessible, efficient, eco-friendly, fair and safe modals, in terms of improving citizen's living conditions.

Some changes have started to appear: It is more and more common to observe personal mobility vehicles (e.g. bicycles, electric bicycles, e-scooters, etc.) riding through the streets of our cities. Priority to pedestrian, non-motorized and electrical vehicles is being more and more implemented and improved. City centres, which were plenty of cars until the decades of the 2000's and 2010's, are becoming more and more freed of traffic and private vehicles, less polluted and congested areas, and their streets are being pedestrianised, seeking to recover former kerb-to-kerb area for active mobility.

In addition, municipalities are developing strategies to restrict the entrance of the most polluting vehicles to the city centres, allowing only residents and eco-friendly vehicles to access to the central core. Since the commissioning of the Madrid restricted central area, *Madrid Central*[1] , in November 2018, a study of the Polytechnical University of Madrid conducted in March 2019, has revealed that the emission of polluting particles has been successfully reduced, achieving some benefits involving health concerns. As a result of this strategy, sales of hybrid and electric vehicles have significantly increased after the central almond pacification, with a dramatically higher growth rate in comparison with other Spanish regions[2].

Besides that, an objective being sought by administrations is to improve road safety conditions. The ideal objective is to completely eliminate the number of road crashes and the number of road killed and injured victims. Some steps have been taken and are being taking towards such goal (e.g. The European Union wants to incorporate to all the human-driven vehicles of the European car fleet some devices in order to avoid crashes which might be caused by driver's malpractices, such as a digital breathalyser which blocks the car in case the driver had ingested alcohol before driving). Road safety is a major issue that concerns general public and administrations, and therefore major directives are being developed with the goal of enhancing road safety.

Up to these days, driving has been solely a human task. Vehicles could only be riding through the road network only if a capable, authorized person was controlling the vehicle. Such person, as it is stated in Royal Automobile Club, 2017, has to be capable almost-simultaneously to [1] observe what is happening on the road/street, [2] to analyse each observation, [3] to take decisions from the results of these analysis as rapidly as possible, and [4] to act coherently according to such decisions. The depicted chain is constantly repeated in time. Acting after an observation which deserves being analysed and would require a response (a decision) cannot be immediately performed by a human being. To correctly perform such procedure imply a non-zero reaction time, which might be between 1.5 and 3.0 seconds, depending on the person.

An alternative is expected to be provided: current human drivers would be able to share roads and streets with robot cars, which may even be being steered with zero passengers. As it is deeply analysed in this document, automation applied to mobility would lead to autonomous vehicles, which are expected to generate beneficial but also some negative impacts, and to create some needs for their implementation. Autonomous vehicles are expected to quite instantaneously and continuously depict and model what it is placed on its vicinity ([1]) from sensors, cameras, and wireless information received. To assume the expected behaviour of each depicted being ([2]) and to take a decision ([3]) which leads to act ([4]) according to the forecasted behaviour of

[1] Madrid Central, commisioned in November 2018, is the low-emission zone which includes the historical city centre of the capital of Spain. Only authorised vehicles and cars accessing to parking facilities are allowed to enter inside the perimeter of Madrid Central.

[2] Published in the Newspaper "El País", April 4^{th}, 2019 Edition.

Level	Name	Main goal	Driver's task	Technologies
L0	**No Automation**	Support drivers while driving	Driving	TSR
L1	**Driver Assistance**	Assistance	Driving	LSS, SCS
L2	**Partial Automation**	Assistance	Driving	CAS, TJA
L3	**Conditional Automation**	Self-drive if driver consents to	Being ready for recovering control	AHC
L4	**High Automation**	Self-drive with some limitations	Not expected to participate	AVP
L5	**Full Automation**	Self-drive without limitations	*(The vehicle could even be empty)*	(ASoD)

Table 1: Classification of the different automation levels. OWN ELABORATION FROM KOCKELMAN, 2016 AND ROYAL AUTOMOBILE CLUB, 2017, IN PARALLEL BASED ON THE DEFINITION OF THE SOCIETY OF AUTOMOTIVE ENGINEERS (SAE).

the other participants while adverting them about its own behaviour. This cycle, due to proper technologies, is expected to take much less than 2.0 seconds. Therefore, current reaction time would be considerably reduced hand-in-hand with self-driving technologies. Precision on steering tasks is expected to be significantly enhanced, human error likelihood would be mitigated, and therefore, vehicles would be riding across the road and streets network in a quite safer manner.

Despite a certain lack of infrastructural readiness and regulations, Full-automated vehicles are intended to be marketed in the oncoming decades. For that reason, large expertise is being acquired from semi-automated vehicles, which are currently being marketed and riding across countries. Table 1 shows the classification of the different automation levels. In the whole bibliography, such levels are commonly clustered into two groups: L1 and L2 are formed by a series of ADAS applications (Advanced Driver-Assistance Systems: technologies which aid a driver while performing the driving task, in order to reduce the likelihood of a collision and to make driving more comfortable). Levels L3 and further are considered as the sets of applications which can autonomously perform a driving task: While Level L3 consist of the steering technologies which can temporarily drive a vehicle, levels L4 and L5 are the technologies which have been born for driving autonomoulsy a vehicle at all times. Finally, it is worth mentioning the existence of Connected Vehicles (CV), which are just human-driven vehicles that are in constant wireless communication with the road infrastructure. Connected and Autonomous Vehicles (CAVs), by definition, would be such vehicles both connected to the road infrastructure and capable to perform a given set of driving tasks autonomously.

Automation will require some significant changes to urban and rural infrastructure. Introduction to the market of higher automation-level vehicles goes hand-in-hand with infrastructure adaptation for self-driving (i.e. Road adaptation is necessary to start to develop reliable self-driving car fleets).

Our streets and roads need to be ready for AVs

A series of infrastructure requirements must be identified with the purpose of seeking a huge performance of the automated mechanisms and a huge sensor readability and interconnection. Furthermore, some other needs would appear not as a requirement for CAVs to get started but as a result of automation, especially if a large self-driving fleet were implemented and such vehicles constitute a great percentage of the entire car fleet or they have some kind of impact on public transportation. To list these road amenities is the first objective of this document.

In order to identify these needs, the bibliographic research has been carried out. Although some of them were presented and discussed in the majority of the papers, most of them are fewer general requirements and are deeper scanned as a tangential issue.

These needs can be arranged on the following categories:

- Road marking, signage and signalling
- Parking and Pick-Up and Drop-Off Areas
- Automated Car/Ride-sharing services on Demand.
- Safe Harbour Areas
- Service Stations
- Bridge structures and pavement reinforcement
- (3D) Map Creation
- Traffic Management measures and V2x interconnections
- Junction Management and Intersection prudence
- Lane reduction
- (Further needs)

It is worth commenting that there are no physical borders between the cited categories. Most of them are closely related to some others and their implementation would have better performances if combined with other road requirements than if implemented in an isolated way. Some examples are presented:

- V2x wireless interconnection would provide vehicles the same information as physical road signs and signals currently provide.
- Mapping and V2x wireless interconnections would provide better positioning results than positioning systems based only on road marking reading. Moreover, current Satellite Positioning Systems are expected to be enhanced, seeking to improve their accuracy.
- Current bridge structures may need to be reinforced if automation were widely implemented. Interconnection vehicle-to-vehicle (V2V) would imply smaller headways between cars (and even between heavy goods vehicles) thus, leading to greater densities at highways and main urban access arterials. As a result, current traffic loads per unit of surface could become larger.
- Vehicle interconnection may lead to reduce reaction time at semaphored intersections. In consequence, lane capacity may be increased. If current traffic flow could be rearranged in terms of reducing lanes, a considerable land surface would be saved for developing other kind of urban activities.
- Automated transportation modals based on Carsharing and Ridesharing Systems may imply a reduction of self-owned vehicles.
  - It will have some effects on parking demand, due to lack of necessity of great number of cars to be parked and a switch from current on-street parking surface to platforms where perform a safe boarding in vehicles.
  - Moreover, passenger flow may be rearranged in fewer cars due to occupancy rate increase, closer to optimal values from an efficiency perspective. Therefore, vehicular flow may decrease, and lane reduction strategies could be performed in an easier way.

Although large research has been carried out, uncertainty about the real impacts that connected and autonomous vehicles may create on current traffic, transport systems and urban infrastructure is still wide. Real results will not be obtained before implementing large autonomous fleets on real day-to-day traffic environments at cities. These fleets have not already been implemented not due to a technologic but a liability problem: Policies regarding to self-driving vehicles have not yet been developed in detail.

Nevertheless, not completely automated vehicles but semi-automated ones, which include some technology in order to perform some activities independently -or just to assist or warn the human driver if a problem were detected- are becoming more and more marketized. These technologies, such as Lane Keeping or Traffic Sign Recognition (TSR), deserve a well-maintained infrastructure in order to show stronger performances.

For example: TSR consists of a computer vision camera which is able to read some traffic signs for conveying important sign information to the human driver. This information is displayed in front of driver's eyes. Such system can read well-maintained standard signs. But it may not be able to understand a dirty, unmaintained sign. The problematic is extended due to huge variety of traffic sign geometric parameters (e.g. width of the external red band) or font that can be observed in a trans-national scale.

Another problem related to lack of maintenance is related to Lane Keeping systems. They are also based on computer vision cameras, which also monitor the state of the upcoming road. Computer vision is not as precise as it were desired and therefore a camera can misunderstand a pothole and interpret it like a significant obstacle, actioning the assistance mechanisms and unnecessarily braking the vehicle. If traffic environment were relatively close to congestion, it could also generate a shockwave, in terms of creating an unnecessary significant queue at that section.

In order to ease these non-fully-automated technologies to work properly, maintenance programmes should be revised. Local governments must start to take into account and assess the performance and failures of current semi-autonomous cars for developing strategies related to maintenance in the short-term, and the potential appearance of AV fleets for long-term planning. Moreover, some international conventions about signage, signalling and marking may need to be revised, seeking a world-wide standard. In other words: **we should let cars across the world speak and understand the same universal language**.

Sustainable mobility planning documents may start to consider CAVs in order to stablish actuation guidelines if potential impacts actually occur (e.g. if lane reduction strategies were actually possible, current sidewalks would be broadened, in terms of transforming former private-vehicle land to active-mobility land) which should lead to the common objective of sustainable planning:

Transform cities from congested and polluted areas into more kind, gentlier cities.

2 Scope and objectives

This report is aimed to provide a reliable summary of all the elements that are expected to be useful and/or exploitable for the deployement of connected vehicles, autonomous vehicles, connected and autonomous vehicles and mobility services based on self-driving systems. At the time this document was completed, a small fraction of vehicles with some given autonomous features compose the global vehicular fleet, but it is expected that the commercialization of the early self-driving vehicles will lead to make this share to take off from figures close to zero during the decade of the 2020s. The deployment speed of this kind of vehicles will depend on their actual performance: The more barriers for autonomous driving are detected, the more resources could be devoted to minimize such barriers, and therefore the more properly self-driving and semi-autonomous vehicles would operate, which might lead to a more rapid proliferation of Autonomous Vehicles.

The document itself intends to gather all the present and future requirements and needs (namely: Urban equipment, technologies, devices, traffic management signals and control centres, road maintenance, etc). A literature review has been conducted with the target of collecting all these infrastructural requirements but also for bringing together their most important features. The needs that have been gathered in the document have also been deeply analysed and critically discussed.

Furthermore, some suggestions have been written and some ideas about some infrastructural requirement have been expressed. This is the case, for example, of the paragraphs devoted to the ideal design of the Pick-Up and Drop-Off areas and platforms.

The final purpose is not oriented to suggest administrations that they must deploy rapidly all the infrastructural needs that have been collected in this document. Instead, each of these requirements appears as a tool for solving a given urban problem. Administrations could be targeted to solve a given problem if such problem exists. Therefore, this report has been drafted with the aim of collecting some **guidelines** in relation with the broad deployment of self-driving cars that could eventually be useful for a given administration that is targeted to solve a given problem of a given city.

A secondary but overall and crucial goal of this document is also to extend the general knowledgement about self-driving vehicles and therefore, the report itself tries to beautify the citizenship's perception about cars being driven by a non-human being. The author of the document has checked that a rellevant share of people mistrust in self-driving technologies[3] and therefore, the document intends to clarify that self-driving algorithms could be as safe as human-driven vehicles. But not only as safe as human-driven vehicles: Self-driving technologies have been born with the target of enhancing current road safety.

Another goal of this document is to conduct a basic simulation case based on a model that represents an existing urban area. The model is based on the Barcelona city centre's road network. The model is aimed to forecast the overall behaviour of the road network if it were completely prepared for allowing autonomous vehicles to make use of it, and is also targeted to analyse the pros and contras of deploying central CAV-ONLY lanes at a given corridor, which is one more of the possible physical infrastructure requirements that may fit on our roads for making easier the deployment of self-driving vehicles but has not been deeply discussed in the bibliographic references.

Summing up, this report is presented as an academic work but also as a useful document that compiles the main road requirements for self-driving systems and provides some clues and advice about the paradigm shift on urban mobility linked to the automatization of the driving tasks.

[3]Some days before the trials related to the project INFRAMIX (more information at Page 73), some people started to demonstrate their suspicion about the fact that several trials with self-driving vehicles were going to be performed at a given road stretch that they had to use. Some Twitter users demosntrated their thankfulness to the Twitter accounts that were adverting about the execution of the trials, and they also declared their intention as road users of avoiding using that specific road section while the testings were performed.

3 Methodology

The fourth chapter of this report is focused on expressing ideas about the infrastructural requirements for deploying a reliable and growing fleet of self-driving vehicles.

At that given chapter, several requirements have been analysed and evaluated. For each of the main requirements, it has been depicted a radar chart that assess the most important impacts that the given need could create (impacts in terms of safety, security, time saving, investment, congestion, emissions, energy saving, and fares and taxes).

This evaluation has been mainly prepared with the information and main keys and ideas gathered from the bibliographic review that has been performed in parallel to the drafting of the report and have been written on it. The issues and points that have been exctracted from other papers have been quoted. The bibliography chapter can be found at page 107.

More information about the methodology used for assessing each of these needs and some further explanations about the mark given on each category of impacts for each infrastructural requirement can be found at the Appendix: *Methodology of the valuation criteria used for creating the radar charts that are shown in this document.* (pages 116 to 121). Moreover, page 121 presents a gathering of all the diagrams that are depicted across the whole document.

Moreover, the fifth chapter is focused on presenting and discussing the most important features of the simulation case study, which consists of analysing traffic performance on a given road network. Data have been computed by means of **Aimsun.next traffic simulation software**. Data are also handled at the fifth chapter, where some discussion about these data have been made and some findings have been also written. This chapter is completed with some remarks on further research.

Finally, the most important key aspects are listed and highlighted at the sixth chapter, which is also conformed by the principal overall points and by the conclusions of this work.

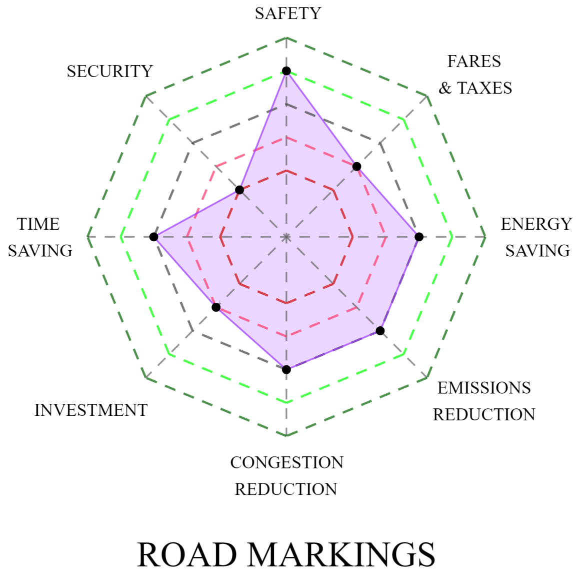


Figure 1: Valuation of road marking needs and potential impacts. OWN ELABORATION.
NOTE: In these diagrams, the most positive aspects of each category are located on the external ring, and the most negative are represented on the inner one. More information is provided in the correspondent appendix (Page 116).

4 Impact analysis of AV

4.1 Road marking, signage and signalling

Although computer vision systems are still slightly inaccurate, road signage and marking are the foundations for self-driving technologies. Their usefulness is enormous, both for human drivers and for automated vehicles. Current marking and signage are the result of over a century of human driving, but automation systems, which firstly have had to adapt to human-scaled rules, are also claiming for introducing a handful of changes on road marking and signage in order to be capable to read roads better without altering human's readability. Due to marking and signage major importance, it is the more documented and broadly discussed need at bibliography.

a) Road Marking

Current marking system consists of physical marks on the road surface, whose main function is to split the road land into several lanes, optimizing the carriageway surface in order to maximize the vehicular flow that a given section can process. Although these marks usually consist of painted lines, some countries (for example, the UK) also use reflectors seeking to reinforce their visibility. Moreover, sign information is sometimes painted on the road surface (e.g. maximum speed, lane destination at diversions, bike-car shared carriageway, entrance to residential areas. . .) for a better transmission of crucial information to human drivers.

Lane Support Systems are being developed for cars and could be divided into two main groups: Lane Departure Systems (whose main task is to warn drivers if a strange lane abandonment is detected to occur) and Lane Keeping Support Systems (which, moreover, assist driver in terms of steering and braking the vehicle if necessary). Both are active[4] systems and are able to distinguish yellow markings from white markings. Both yellow and white colours are the most commonly-used colours for lane marking.

[4]The main objective of an active system is to avoid the event of a crash.

Nevertheless, empirical tests have proved that Lane Support Systems may fail if road readability conditions are not optimal. According to European Road Assessment Programme, 2011, Markings can be misread (or even unread) in case of:

- Old markings, if they were still visible (If they were not completely erased).
- Presence of snow or water on the surface.
- Lane markings with low contrast with respect to the road surface (e.g. concrete surfaces).
- Surface discontinuity due to digging works, which had left their mark in terms of a darker-shade asphalt band. (figure 26, page 53)
- Asphalt cracks and potholes.
- Furthermore, there are some differences between countries in terms of road marking.
  - Several countries (e.g. UK) use a continuous double line for marking sections where it is not allowed to overtake. Some others (e.g. Spain) mark those sections with a continuous but single line at single carriageway interurban roads.
  - Coloured lines or surfaces are becoming more and more used.
    * Blue, green and orange lines are being more commonly-used for on-street parking regulation.
    * Some cities (e.g. Barcelona, Spain) use red surfaces for marking the entrance to 30kph zones and road intersections with bike lanes. (Figure 2)
    * At some Spanish secondary roads, green lines parallel to the external continuous mark are also used for indicating road sections where speed may be being controlled from helicopters. According to the *Dirección General de Tráfico*[5] Newsletter (Dirección General de Tráfico, 2016), this measure belongs to a pilot test which has been carried out after some successful experiences on Dutch and Swedish roads, causing the visual effect of lane narrowing and thus inducing drivers to low their speed. (Figure 3)
    * Some countries, such as the Netherlands, have started to mark with green bands the road stretches where it is allowed to drive at 100kph.

Road markings should be always readable whatever the road, traffic and weather conditions are. National and sub-national marking rules must be contained on a transnational framework, seeking for international standards which could allow for a better road readability. Furthermore, road marking maintenance should be planned in order to avoid excessive marking degradation, which may lead to road misinterprets.

The perfection of marking systems is challenging: According to Public Sector Consultants and Center for Automotive Research, 2017, *"Maintaining and improving road infrastructure could speed up deployment, avoid costlier technologies needed to cope with road imperfections, and increase the reliability of automated vehicles.* [...] *It is unrealistic to expect that all roads will have lane markings in perfect condition all the time. With the goal to produce a self-driving car capable of driving on any road time, automakers are exploring other ways to automate lane keeping, such as positioning with respect to the other vehicles, guard rails, and barriers, with input from several sensors and 3D maps. Improving road markings could be beneficial to encourage early adaptation and accelerate the potential safety benefits of these vehicles, but it is not obligatory in the long run. Communities that want to provide optimal conditions to automated vehicles will need to maintain road markings in good condition on their public roads, potentially increasing road maintenance costs. These improvements would prove useful for human-driven vehicles, cyclists, and pedestrians as well".*

It is suggested that, despite adequately-maintained road marks are useful for current technologies, further innovation should lead to other positioning and lane-keeping methods, which

[5] The Spanish responsible organ for road transportation.

Figure 2: Example of a street in Barcelona where information about 30kph zone has been marked with a red-coloured surface. Notice that on-street parking zone is marked with green colour. OWN ELABORATION.

would be useful at late-transition to CAVs stages. Since then, improving road marking conditions would be optimal for both technology and current road users. As it is claimed for signage and signalization at the mentioned paper *"Pedestrians, cyclists and human-driven vehicles will still need signs and signals [and road markings], so removing them is not a viable option at present"*.

The previous paragraph could be synthetized as follows: The more readability due to proper maintenance, the less investment in automated driving technologies, and the more usefulness for human participants. Therefore, it is quite important for these technologies to keep roads in good condition, looking for a proper performance for vehicles with low automation levels. And, for sure, road markings, jointly with traffic signs and signals would still be necessary for a long time.

3-D Mapping technologies (as it is mentioned at the correspondent section) and V2x connections will lead to more efficient positioning systems within the carriageway area, with respect to other vehicles and the carriageway boundary lines. These technologies would be useful not for semi-Autonomous Vehicles but for future vehicles with higher automation levels (L3 – L4 – L5).

Finally, and related to road asphalt, it is worth commenting that it is still unknown whether or not computer vision cameras would be able to **correctly detect and accurately quantify the presence of water on the road surface**. If such presence were not as well detected as desired, self-driving vehicles would proceed like they do under normal circumstances. Therefore, **dangerous skidding phenomena such as *aquaplaning* would occur.**

A good on-surface water detection system would be compulsory to form part of self-driving cars and fully-automated vehicles if a proper performance level under whatever meteorological conditions were sought. Nevertheless, it is suggested at Royal Automobile Club, 2017 that better designs of the road surface which could ease surface drainage jointly with a proper maintenance level were key measures which would allow self-driving cars to roam in a more efficient, simpler way, and such cars would work properly in order to perform the required manoeuvres. Obviously, the more efficient the road surface in terms of water drainage is, the more investment in order to build and maintain the superficial asphalt layer would be needed.

Figure 3: Spanish sign which indicates that green marks on asphalt mean that a speed control may be being carried out.

REVISTA DGT. AVAILABLE AT:
http://revista.dgt.es/es/noticias/nacional/2016/11NOVIEMBRE/1114franjas-verdes-tramos-de-carretera-invive-palencia-y-leon.shtml#.XMGPC5hKg2w
Dirección General de Tráfico, 2016

Figure 4: Example of a street in Valladolid (Spain) whose former road markings have not been completely erased. Notice that the two lanes have been broadened by terms of eliminating the former on-street parking space, which was placed at the leftmost side of the road. The set of road markings formed by the former (on-street parking and former road edge) and the newer lines (real road edge) could become a barrier for Lane Support Systems.
own elaboration.

Furthermore, the street represented in the figure seems not to be quite adequately maintained and its surface presents several discontinuities caused by cutting works and cracks, which could also become a barrier for these optical systems whose main function is lane recognition.

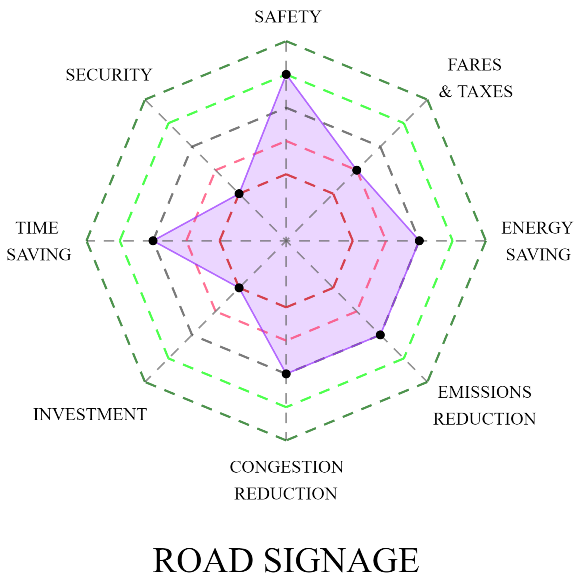


Figure 5: Valuation of road signage needs and potential impacts. OWN ELABORATION.

b) Road Signage and Signalling
The main mission of road signage is to inform and warn about the road legislation applied to a given road stretch, and to warn about the potential risks and conditions that current human drivers may have to cope with, adding further information in terms of giving some advice for dealing with that given road segment. Although some differences can be found between them, the majority of those signs respond to a worldwide standard convention (UNECE Vienna Convention, 1949. Revised in 1968). Nevertheless, signs with words written on their geometry are more likely to present variations among countries. The most telling example is the "STOP" sign, which it can be found written as "PARE" or "ALTO" at some Latin-American countries, or even "СТОП" at some countries where the Cyrillic alphabet is extended, like Russia. Although the characteristic octagonal-shape of this traffic sign is internationally well-known, not all the countries around the world use "STOP" signs with an octagonal shape.

Indication signs are also useful for human drivers in terms of guiding them across the road network, in order to ease to orientate themselves, and facilitate them to check whether they have chosen the desired road or not. This type of signage is especially useful for occasional drivers, who are driving for first time throughout a given road segment, or are just taking an unusual path, which is not part of their day-to-day journey. Typically, those signs present huge variations among geographic zones (Figure 6), even among nearby cities at the same country. Nowadays, such indicators signs are being more and more ignored by occasional road users due to the proliferation of newer GPS/GNSS navigators and other digital map platforms such as Google Maps, which are expected to make such signage completely unnecessary. **Former orientation panels would become old-timer, vintage decorative urban elements rather than useful signage.**

Global Navigation Satellite Systems (GNSS), based on Global Positioning System (GPS) or similar SatNav systems, had become quite popular during the last decades, due to their usefulness for giving some advice in terms of guiding drivers throughout foreign atmospheres, not only in terms of computing faster routes and giving instructions about the decisions to take at diversions, but moreover provide crucial information in terms of advising through which lane it is better to drive in order to ease immediate future manoeuvres.

Traffic Sign Recognition (TSR) Systems, like Lane Support Systems do, are becoming more and more extended on vehicles. Nowadays, their main objective of these technologies (based on

Figure 6: Indication signage variations between some European countries: Portugal (top-left), Spain (top-right), France (bottom-left) and Italy (bottom-right). Notice that each sign corresponds to a junction where E-80 European route meets other major European routes. GOOGLE MAPS.

computer vision cameras, mainly located at the reverse sides of rear mirrors) is to provide human drivers some relevant information that it worth being highlighted. Relevant signage indications (e.g. current maximum speed limit) are displayed at the car's dashboard, while drivers could also be warned if current road regulations are being, consciously or not, disobeyed (e.g. vehicle's speed is clearly over the road limit). Moreover, traffic signs lecture and interpretation carried out by TSR systems is also valuable for full-automated vehicles, which can be guided throughout the road network combining both traffic sign and navigation systems information. Further technologies, such as V2X would lead to transmit sign information not through an optical but wireless pathway, and 3-D Mapping could lead to servers which provide road regulation information depending on vehicle's current position, time and traffic environment.

Similarly, as it is mentioned for road marking, a good readability of traffic signs, especially those which provide not secondary details[6] but vital information for all participants[7] is needed and must be guaranteed whatever the luminance and visibility conditions are. Seeking for highly readable, clear signs, signage must be maintained in proper conditions and vandalism related to traffic signs (e.g. pasting stickers on road signs) must be more controlled in order to avoid signage misreads. Some examples of signs which could be misread by TSR system due to vandalism and unproper maintenance are exposed in Figure 7.

Moreover, international standards would be compulsory in order to homogenize and harmonize the trans-national road network. If the goal is to ease the recognition task which the system performs, an important measure which may help to reach this goal would be to implement an international road signage catalogue: A STOP sign should have exactly the same shape, size, geometry, font, font size, colour, and other secondary details wherever it would be placed. A traffic sign which allows cars to turn left but does not allow to turn right at a given intersection in UK, should be exactly identical to the traffic sign located at an intersection with similar characteristics whether in France, in the USA, in Ecuador or in China. Therefore, the global signage catalogue

[6] Traffic signs whose information is important for a tiny portion of drivers and would likely be ignored by some other road participants, such as parking regulation signs or signage which contain rules for heavy vehicles.

[7] In a complementary way, traffic signs which provide information that all participants must understand and consider, such as maximum speed limit or warning signs.

Figure 7: Dirty, unmaintained, hidden and vandalised traffic signage in Barcelona, which may be misread by some TSR systems. OWN ELABORATION.

would consist of some centenars of traffic signs instead of consisting of several thousands of them, as it happens nowadays.

Indication signage would be superfluous for self-driving cars and full-automated vehicles, which would be steered taking into account information provided by navigators rather than information scanned from indicators. Nevertheless, this signage would be crucial at roads that would permit a mixed vehicular flow (CAVs and conventional cars) because human drivers and other road users would still need such information.

Finally, according to Royal Automobile Club, 2017, a proper, enhanced urban lighting system would prove completely necessary in order to ease the readability of marks, signs and signages. Such items should be completely identified and clearly interpreted both day and night. For that reason, in the cited document it is suggested that lighting systems at cities might be improved in terms of reducing the length between light bulbs.

Furthermore, traffic signals, which can be clearly identified during the night and on cloudy, grey days, could become misread or even unread by TSR systems in strong sunny days. Greater illuminances are the weak point of computer vision cameras, but also weak, poor illuminances, as is stated in the previous paragraph, may lead to readability problems of the traffic signs. To keep a balanced illuminance level under all meteorological conditions may become an expensive task. **Therefore, an alternative could be provided in order to correctly convey the information of the intersection in a biunivocal way.**

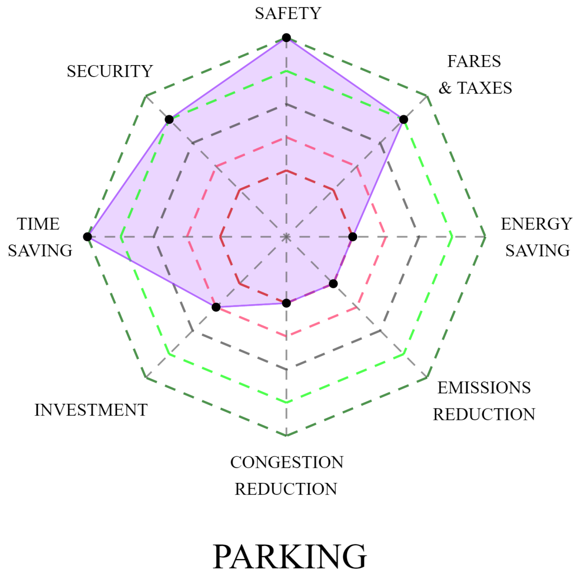


Figure 8: Valuation of Parking needs and potential impacts. OWN ELABORATION.

4.2 Parking and Pick-Up and Drop-Off Areas

Cities foster parked cars everywhere: Most streets are prepared for on-street parking, whether regulated or not. Newer buildings are equipped with garage facilities. Municipal and private car parks offer several spaces (spots) where leave an own car parked while performing other activities (namely work, leisure, shopping, sports, etc) near main foci of interest of the city: commercial areas, business districts, sports and shopping centres, and even metro, tramway and suburban rail stations.

Cars can be catalogued as “underused valuable items”. According to International Transport Forum, 2015, Private vehicles are used more than 10% of the day (2 hours and 24 minutes) in some rare cases. Even cars that are used for more than one hour are quite exceptional. In other words: Their main function is just to provide mobility to their owners, but they remain parked and unused most of the time. For that reason, land area destined to parking facilities is dramatically large inside cities.

Currently, private vehicles have to be used for a door-to-door service: Human drivers can only get-off their cars if it has been already parked, and there is no second option: Until these days, a private vehicle can only be used for dropping-off a passenger if at least one person (capable and authorized to drive) remains in the vehicle and steer it to a parking destination. Traditionally, dropping-off operations are most likely to occur at some hubs like schools, hospitals, airports and train stations: Places significantly away from homes which are mandatory landmarks of a journey and/or places where people unable for driving need to displace there.

Autonomy means “Self-governance”, and that implies, for the first time in history, cars would be able to drive in a lonely manner, without a driver. Thus, humans would be able to not play the role of a driver anymore: They would be just another passenger and could be dropped-off before ordering their own vehicle to drive and look for a parking place alone. Furthermore, autonomy is expected to enable every person to ride alone in a vehicle, with independence of their own capabilities, age, licence, and medical conditions, and providing them a fundamental mobility service: A 16 year old, young person will be able to convey his/her old grandparent to the doctor or to make a long trip on holiday by car with his/her disabled/injured best friend.

Parking
To park a car within a given gap could not be an easy task. Depending on the vehicle and the referred gap dimensions, a finite number of manoeuvres have to be performed to successfully complete the parking mission without hitting and/or damaging closer vehicles. Land involved at the parking operation is much bigger than the gap area: The number of manoeuvres will depend on the driver's expertise and, consequently, those operations will need a little greater area taking into account likelihood of human error. Moreover, our parking spot will need direct access to the roadside, in order to ease the car's exit whenever the owner desire to use his/her car in order to displace to another point.

Some technologies have appeared seeking to assist human drivers while parking. According to Kockelman, 2016, vehicles with lower automation levels are capable to steer the vehicle, fitting it at the parking spot. These technologies are quite useful and can reduce the probability of human error, performing more precise manoeuvres. Nevertheless, these systems require the driver to select the gap where he/she desires to park the vehicle. Further technologies, for example, Automated Valet Parking (AVP) system, are available for fully automated vehicles (L4 – L5) and are able to drive the car with no occupants from a drop-off platform at the parking entrance, look for a spot where park the car, and get parked.

More accuracy on parking manoeuvres will imply spot land reduction, but the total area being covered by the vehicle during the approaching manoeuvres is also expected to be reduced. In line with the document Catapult Transportation Systems, 2017, cars are expected to fit closer one to each other, reducing up to 20% the current gap width and gap length. AVP systems would potentially revolutionize the current idea of parking amenities: Automated Vehicles are capable to drive and park without a driver, therefore, no room for opening doors and allowing drivers to get off is needed: **If these technologies reach higher and higher penetration rates, cars would park in more efficient ways**, and car park current capacity could be therefore multiplied by a factor which runs between two and three.

The magnificence of this multiplying factor comes from the ability of self-driving cars to lock each other and let them go out when summoned. Connected and autonomous vehicles would be capable to park and re-park if needed, being continuously rearranging between them. Reduction of direct exit space for each parking spot would be beneficial in terms of land saving and more land could be used for parking area due to higher accuracy of parking operations. Thus, current lane land would be significantly reduced. Cars would be more packaged between them not only in parallel but in both dimensions. (Figure 9)

Car park demand is also an interesting point that deserves being remarked. The more parking capacity due to fully autonomous systems, the fewer vehicles will compose the entire fleet. Drop of demand would be caused by the promotion of automated car/ride-sharing transportation, and due to governmental ecologist measures to encourage passengers to reach more occupancy in private vehicles, optimizing the needed energy for performing all displacements while emissions are reduced.

Infrastructural issues linked to car parks would likely perform significant changes. On the one hand, private owned vehicles would be able to self-park and would be commanded to park at cheaper but further parks[8], thus generating more empty Vehicle Miles Travelled (VMT) and likely powering congestion, fuel waste, and emissions[9]. On the other hand, despite parking capacity would increase, car park demand is expected to decrease, leading for a smooth conversion of current car park buildings to other urban equipment: From logistic hubs, supermarkets, or sports and cultural centres up to corportative offices and headquarters or even residential flats. Furthermore, a shift from car storage to bicycle and electric scooter storage would be possible: Current on-street parking would also be reduced, and its land recovered for enlarging sidewalks,

[8] Private parks would start to appear at surrounding cities, where land prices are sensibly lower.

[9] Depending on the greatness of impact on VMT per car that parking issues would cause, emissions may actually rise or decrease. It is still early to predict whether emission rates would increase or descend.

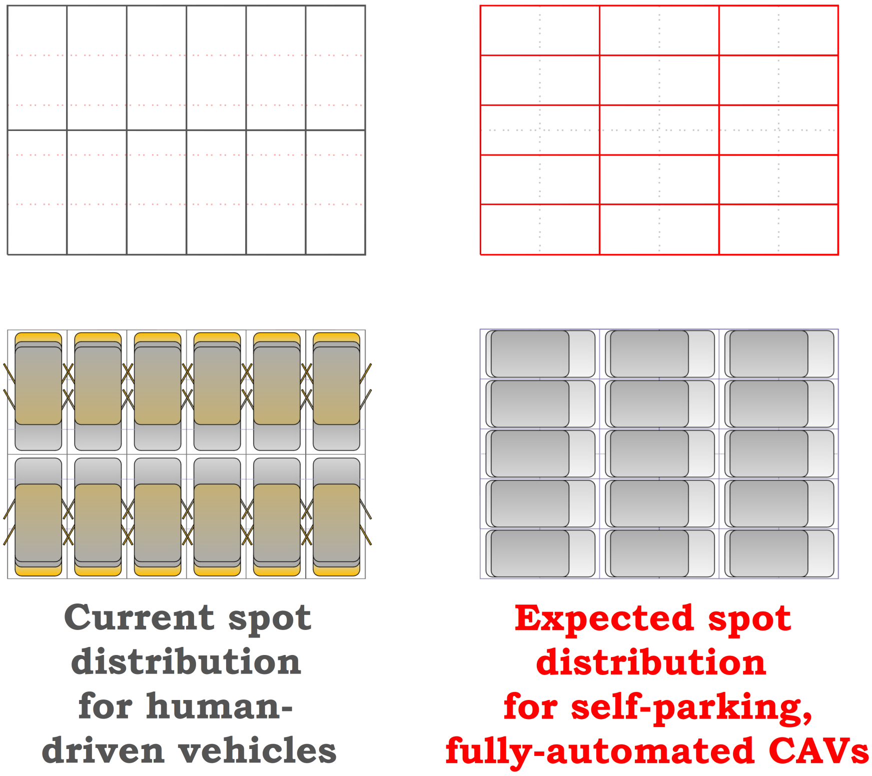


Figure 9: Comparison between a current car park generic spot distribution and an expected distribution for a given land. Notice that it would be produced a shift from a $2 \times n$. distribution to a $m \times p$ array, where $m \geq 2$ and $(m \times p) \geq (2 \times n)$.
OWN ELABORATION.

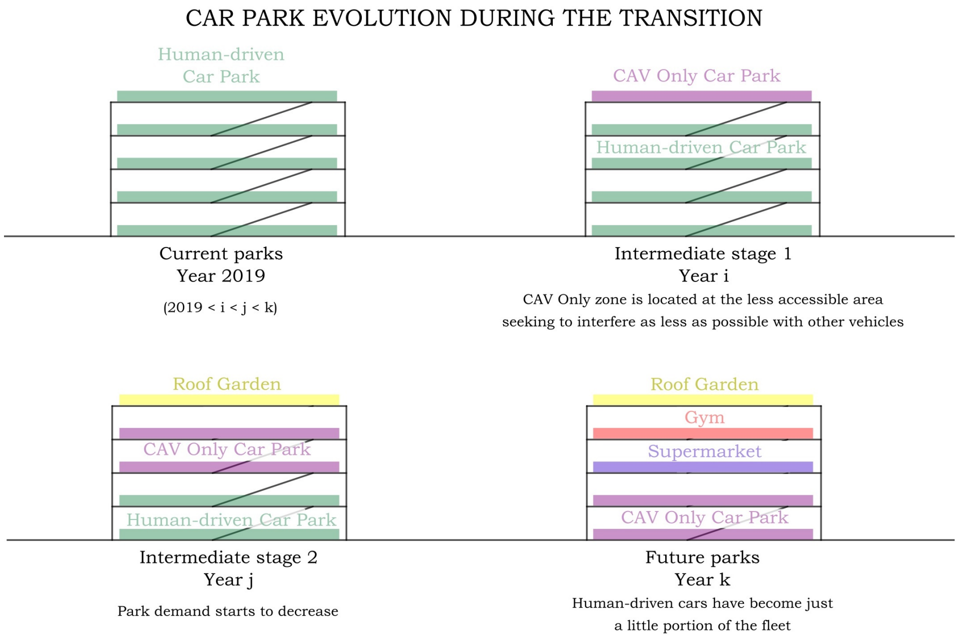


Figure 10: Cross section of the likely evolution stages of a given car-park building. OWN ELABORATION.

improve bike lanes network, and provide pick-up, drop-off and goods distribution platforms. CAVs would likely lead a new urban landscape.

Nevertheless, the main gain that autonomous vehicles will provide in terms of parking is to save parking time. Nowadays, looking for a spot where get parked is a mandatory stage at each displacement, that may actually occupy even more than one third of the vehicle travel time. Being dropped-off and commanding the owned vehicle to park itself would be clearly beneficial for passengers, which would reduce not only searching for parking time but also time for displace from their parked car to their final destination, saving a handful of minutes or even more, which being applied to day-to-day commuting displacements, would lead to important overall time saved.

To deal with the transition from 100% human driven vehicles to great automation rates is expected to be challenging, and to guarantee good performances of Automated Valet Parking systems for the immediate future would ease further developments. Catapult Transportation Systems, 2017 suggests governments to create a guidance document containing recommendations and optimal generic designs for autonomous car storage systems, which would lead to better self-valet parking performances.

Such document is intended to be prepared within the framework of some trial tests conducted at several car parks: A closed zone of the park must be designated as a test area and trials should be performed with real autonomous cars that are wanted to get parked at that precise garage. Nevertheless, the market penetration of vehicles with the required technology is still low, and the presented initiative may take a long time to be satisfied. Therefore, lack of trial tests would imply to delay the development of these technologies, and consequently, the stalled situation could actually lead to an endless loop.

Beyond steering manoeuvres and car storage, future car parks would need to be equipped and prepared not only for Connected and Autonomous Vehicles, but moreover for electric ones. Private cars could be recharged while being parked, which could be a huge positive aspect due to its usefulness and time saving.

Car parks for electric vehicles must be equipped with electric chargers. It has been commented that CAVs are expected to be continuously displacing through the car park area, because they will have to let other CAVs to both park and go. For that reason, a car park which would host electric CAVs would require wireless chargers, in order to ease the mentioned manoeuvres. For that reason, **an equipment based on electromagnetic induction would be quite useful for these parking facilities**.

Finally, it is worth demonstrating that car parks deserve a clear signage and marking in order to improve the efficiency of such systems, in a similar manner as it is mentioned for general road marking and signage. 3D Mapping would help CAVs to steer throughout the garage. Moreover, as no human participation would be needed, facilities for them would not be necessary. Car parks would be able to switch-off their lighting (therefore, electricity would be saved). Lifts, bathrooms and even other secondary amenities such as radio music for customers would become completely unnecessary and superflous. Nevertheless, a **pedestrian access** should be guaranteed for **maintenance assistance** in case of any system failure.

Pick-Up and Drop-Off Areas

Taxi service has been always considered as a door-to-door public transportation service: The unique door-to-door service. Nowadays, a Taxi customer can access a taxi vehicle both moving to a Taxi Stop or ordering, by means of hand gestures, the driver of an empty taxi to stop[10] and pick-up him/her. Most drop-offs but also pick-ups carried on by taxis usually take place *ad-hoc*. In other words: Taxi drivers convey their customers to their destination and drop them there by stopping

[10] Newer technologies enabled customers to request and schedule a taxi at the desired place.

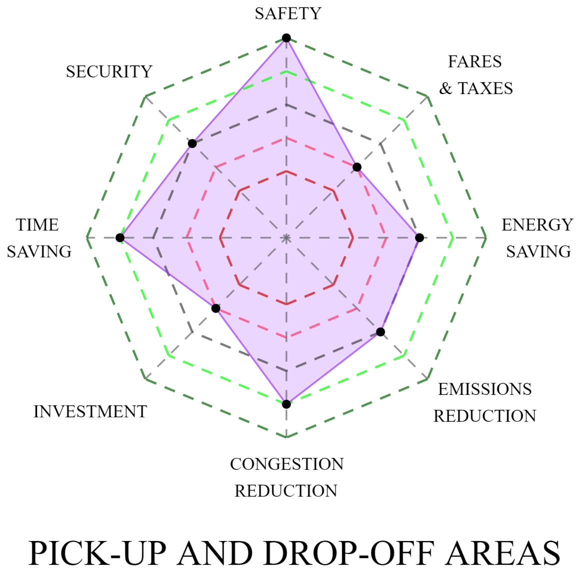


Figure 11: Valuation of PU-DO platforms needs and potential impacts. OWN ELABORATION.

the vehicle on a safe place of an external lane, which depending on the street typology may affect, disrupt or block current traffic flow.

In the twenty-first century, some ridesharing companies have appeared and are being more and more expanded around the world. Those companies provide ridesharing services with a human driver, therefore competing with taxi drivers for a similar clientele. Such services, which are expected to be converted to automated services seeking to save on labour costs, are increasing the demand of dropping-off ride interruption, and thus, safer places for performing pick-up and drop-off actions are being more and more demanded. Moreover, the demand of such places would likely increase if automation started to be applied.

Currently, pick-up and drop-off bays are mainly located at airports and stations, nodes which also have large Taxi stops and are well-connected by public transit: Highly-demanded hubs where most inter-city travellers should make an inter-modal transfer, and some of them would need someone to pick-up him/her or be dropped-off. As the automated ridesharing services are being improved, those platforms would be needed at various strategical points of a given city: On-street parking zones would likely be unhurriedly converted to pick-up and drop-off platforms. Firstly, those facilities would appear at other highly-demanded points, such as shopping centres, schools or hospitals. Later, as parking demand would decrease, such bays could start to appear homogeneously distributed among most streets of the city.

Some of the possible ubications for such infrastructures are listed:

- **Business Districts**: a peak on worker's arrival would happen everyday between 8 and 9 AM. If a dramatic shift from private vehicle to ridesharing systems is produced, parking demand would decrease but dropping-off demand would sensibly increase, which may imply traffic flow disruptions if main streets were not prepared for dropping-off operations and bays were not implemented.
- **Schools**: Currently, traffic flow at narrow main streets in the surrounding area of a given school is notoriously affected twice a workday: some minutes before the lessons start and some minutes after lessons have finished. This is caused by parents which give their children a lift to school by own car, who have to drop them off by stopping the vehicle at the carriageway and blocking their current lane. Automated services would not lead to a substantive change

of such situation but will enable children, who are not allowed to drive, to be self-conveyed by car to school without the need of a licensed driver. Independently from autonomous driving, schools would need pick-up and drop-off bays, which would lead to fewer significative disruptions of the vehicular flow. Furthermore, encouraging children to share automated vehicles for being carried to school would lead to less car demand, and thus, less car density near schools.

- **Shopping Centres**: a high flow of customers entering and leaving the building would be produced every weekend all the afternoon and evening. Major shopping centres currently have large parking areas, which would be transformed to other services. A possibility could be installing such platforms inside the current car park. This measure would help to protect customers from adverse meteorological conditions (rain, snow, hot sun, chilly days. . .) but would also help to less-interfere with traffic flow in the surrounding streets.
- **Cinemas, Theatres and Sport Centres**: a gigantic peak of people flow would be produced depending on scheduled activities. Some stadiums currently have large parking facilities at the surrounding area, which are commonly underused unless an important event is being hold at the stadium. Important music concerts or football finals are activities that concentrate up to tens of thousands of fans which would require ridesharing services once the event has finished. To manage the most optimal access to vehicles for all them would be a challenging topic due to large number of assistants.

Furthermore, public transport systems are expected to be complemented by car/ride-sharing automated services. Although in American Public Transportation Association, 2016 it is demonstrated that Shared Automated on Demand services will not compete with public transport for the same public but it will compete with automobile displacers, these services are also expected to reinforce current public transportation systems, as it is claimed in Catapult Transportation Systems, 2017. Public Transport would be improved in terms of providing "*the last mile leg of the journey*". In other words: Conveying commuters from the transport stop (Train station or bus stop) to their own homes or offices would be more and more common. Such vehicles would offer an unmatched service "*penetrating narrower residential streets or into the heart of business parks*". These services may be quite useful for dense and quite populous suburban cities, where vehicles would be able to give commuters a lift from and to suburban rail stations. Therefore, pick-up and drop-off platforms should also appear close to main public transport stops.

Beyond being safe and secure, an **optimal design for these platforms and bays should be obtained** with a double goal:

[A] to disrupt and interfere as less as possible with the main traffic flow, and
[B] to provide a fast, comfortable and safe access for public to the vehicles that want to pick-up.

The easier the pick-up and drop-off operations were (for example, providing a proper access either at the left and right sides of the vehicle), the faster the events would occur and the more capacity the access platforms would process. Some ideas about the optimization of such platforms' capacity are slightly analysed as follows:

Design of Pick-Up and Drop-Off areas
Currently, Pick-up and drop-off bays that are placed at airports, rail stations and similar hubs are generally placed occupying an external lane on the right side of the road land at the continental Europe countries and other states where traffic drives on the right. In other words: Pick up and drop off areas are most commonly placed *at the so-called "starboard" side of the vehicle* (if a comparison between driving and maritime navigation is made).

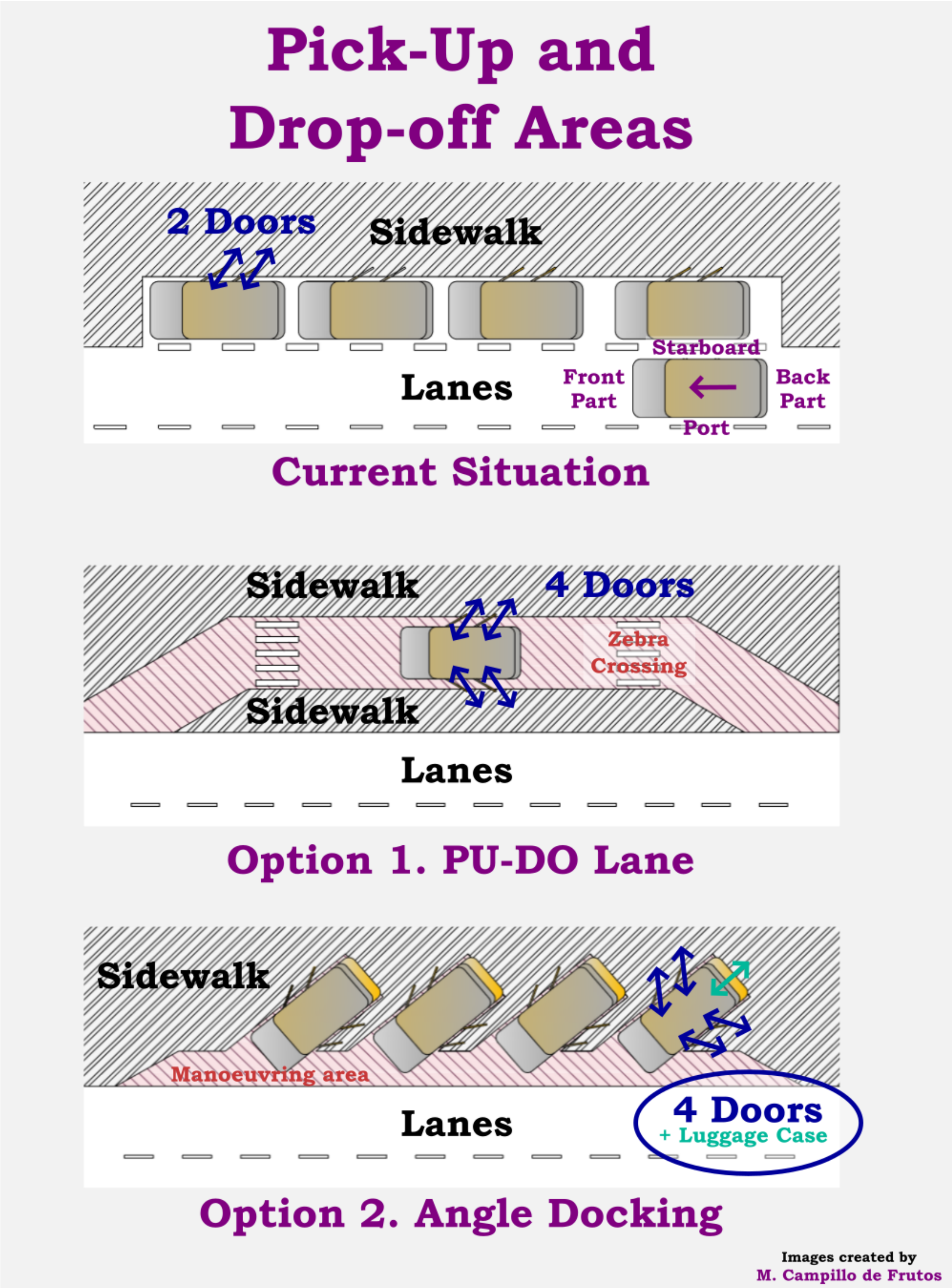


Figure 12: Plan-view of the considered design options for a proper functionality of PU-DO areas. OWN ELABORATION.

Otherwise, in Ireland, the UK, Japan, Australia, South-Africa and other countries where left-hand traffic keeps in force, such areas are commonly ubicated at the left side of the street, *at the "port" side.*

The reason of such phenomena is given by the position of the driver's seat of conventional vehicles.

- At left-hand traffic regions, driver's seat corresponds to the frontal starboard seat.
- Otherwise, at right-hand traffic countries, the frontal port seat is occupied by the driver.

Until these days, vehicles had to be driven by a person. The main objective of Pick-up and drop-off platforms is to pick up and/or drop off passengers, but drivers use to remain seated on his/her seat (they are not going to be dropped-off at a given platform: They will need to move the car to another spot in order to get parked). Passengers who are not driving may use any door of the car except the driver's one. Thus, since car's doors are symmetrical, passengers would get picked up and dropped off in a simpler and faster way if they use the doors placed at the contrary side from the driver's side.

Self-driving cars would not require a driver. Former driver's seat will be one more passenger seat, like the others. Although traffic drives on one of the two sides of the road, vehicles would be completely symmetrical from an operative point of view. Therefore, it will not be worth giving priority to one of the two sides of the vehicle: Passengers displacing at every seat deserve an optimal accessibility in terms of safety. The objective, therefore, would be to prioritise not one side but both sides of the vehicle in a balanced way.

Two options are presented in order to be discussed. These options are depicted in plan-view in figure 12.

Option number one consists of a slight transversal displacement of the current pick-up and drop-off lane. The objective is to provide the proper vehicle-sidewalk accessibility in terms of disposing a slice of sidewalk at the internal side of the road and the conventional sidewalk at the external one. A road low-speed lane through the former sidewalk land is created.

The main requirements of such pick-up and drop-off lane should be to bear a pacified traffic flow (i.e. only vehicles which are going to drop-off or to pick-up a passenger should be allowed to use such lanes, in the same way as it is currently regulated that only such cars whose final destination is a pedestrian street are allowed to ride through such kind of streets). Therefore, the maximum allowed speed should be quite low (not more than 5 or 10 kph) and at least one safe pedestrian crossing from the slice of sidewalk to the main sidewalk should be provided (e.g. a zebra crossing) in order to allow passengers which are dropped off at such sidewalk to access to the main sidewalk in a safe, adequate way.

This option would allow to access conventional five or seven-passenger vehicles by any of the four doors of a common vehicle in balanced conditions (in the current situation, only the two doors at the external side of the road can be used guaranteeing a minimum level of safety). Nevertheless, the commented infrastructural requirements may constrain the capacity of the pick-up and drop-off lane for some determined cases.

Seeking an optimal capacity, **option number two** comes from the current design of angle parking lots, is based on CAVs huge accuracy and efficiency and could be an option that it would worth being consider if vehicles were capable to autonomously park in a fast and precise way. If such capabilities were successfully developed and if they became a reality, **option number two would be quite efficient in terms of dwell time**, but might be the worst option taking into account not dwell time but manoeuvring time.

As in the case of angle parking lots, vehicles would have to enter and get parked in a quite temporary manner within a prepared angle parking spot. Thus, the importance of manoeuvring in a fast way is enormous in order to achieve huge efficiency rates.

Such pick-up and drop-off angle spots must be prepared with proper sidewalk accesses (docks) at both “port” and “starboard” sides of the car. Such platforms would resemble current docks at bus stations, but a huge distinction would differentiate bus docks and PU-DO angle spots: The author of this document finds that it would be better for CAVs to get parked in the spot entering not forwards but **backwards**. Several arguments for supporting this idea are presented:

- Connected and autonomous vehicles would be capable to get steered backwards in a much more precise way as human-driven vehicles.
- The design of current inter-city bus docks at bus stations is optimal because the main door of such buses is placed in the frontal part of the vehicle, and the secondary one is located at mid-body of the bus. Otherwise, current conventional cars have their doors closer to the back part of the vehicle. Moreover, doors of conventional cars, which consist of hinged doors, can only be opened forcing passengers to displace to the rear part of the vehicle instead of to the front end. Thus, it would be logical to provide the safer access from the rear zone of the vehicle instead of from the front side.
- Moreover, current vehicles **have their luggage case at the rear part of the vehicle**. It would be quite useful, especially at airports and train stations, if passengers were capable to gather and drop their large-volume belongings (e.g. suitcases, bags, boxes. . .) accessing the luggage compartment from a safe platform rather than from an asphalt surface where other vehicles are being manoeuvring. Thus, the interaction between pedestrians and vehicles at such platforms would be mitigated: **Pedestrians and passengers would be kept away from the road land all the time**.

Such dock distribution might show higher capacity rates rather than the other ones due to the large sidewalk surface available surrounding the vehicles. If such “berthing” (approaching and parking) manoeuvres were rapidly and comfortably performed, the maximum number of cars using a platform with a given number of spots could be large. Furthermore, the mean dwell time of vehicles that use such platforms would be reduced from current dwell time, especially in the case of such pick-up and drop-off operations that imply the uncomfortable accomodation of passengers at the most inaccessible seats from the external sidewalk of the road.

Each pick-up and drop-off area should be dimensioned in order to adequately process the expected flow of customer’s peak.

NOTE: The comments expressed in the previous paragraphs about the optimal design of pick-up and drop-off areas focus mainly on customer’s comfort and safety. The objective of the previous subsection is to gather some notes in order to provide a safe and accessible autonomous car service, beyond considering a reduction or optimization of the time that a given car must spend for accessing a given PU-DO platform from the main road section. Manoeuvring time has not been taken into consideration for the redaction of such comments.

Can you imagine yourself being picked-up at your home's entrance by an automated taxi and dropped off at your office building every day? How would you feel if, instead of being stressed as a consequence of your driving task, you could be relaxed, reading that day's newspaper edition during your commute? Did you know that this service would be much more cheaper than current taxis, because of the lack of necessity of paying the taxi driver's income? Would you be willing to share a typical size vehicle with some strangers?

4.3 Automated Car/Ride-sharing services on demand

Mobility based on private owned vehicles is currently depicted by a large piece of the modal share pie chart of any big or medium city. Although its significant inefficiency[11], private vehicles are quite popular for urban mobility due to their route and schedule flexibility, higher operational speed than public transport, and also their utility in order to perform long and medium distance trips. Despite public transportation is being more and more promoted and keeps growing, and in spite of measures applied in order to discourage displacing by private vehicles, private mobility is still quite important.

Due to its large proportion, mobility by private car causes main traffic congestion in cities. Vehicles are quite often occupied by only one passenger, and are occupying a substantial land of the kerb-to-kerb surface. Peak-hour mobility demand is therefore quite related with peak-hour congestion and traffic jams, which lead to more fuel waste, more pollution, higher travel times and negative affections to urban public transportation, not to mention out-of-pocket costs and parking challenges. Seeking to definitely mitigate these induced problems, some strategies such as ridesharing or encouraging population to reach higher car occupancies have been arising.

Early private ridesharing generally consisted of shared vehicles by neighbouring workmates on the route to the workplace (most commonly), and acquaintances or even stranger hitch-hikers, which occasionally asked for being conveyed to an optimal location. Day-to-day ridesharing trips had to be planned and scheduled, and odd ridesharing trips surged in a spontaneous way. More recently, companies specialized on ridesharing services have emerged and ridesharing has been largely promoted. a medium-large penetration rates of these services could lead to some beneficial effects, such as allowing cars to reach higher occupancy rates, reducing the maximum number of vehicles riding through a city during peak-hour episodes, saving fuel and money due to unified displacements, reducing congestion, and thus, reducing pollution and travel time. **In essence: to share low and medium capacity vehicles would lead to a more sustainable mobility**.

Newer ridesharing concept, which is based on mobile applications and newest technologies, consist of human-driven vehicles, whose driver offer available seats of their car for carrying anyone else between two points of a planned route in exchange for an income. Users have to pay a fee to use these services.

Some studies have been carried on, seeking to find the optimal receipt for ridesharing systems. According to International Transport Forum, 2015, scenarios from shared taxi services (Zachariah et al, Santi et al)[12] to automated ridesharing services (Fagnant and Kockelman) have been investigated and studied. Vast research summarized at International Transport Forum, 2015, shows that automated ridesharing services would be able to provide the current mobility offer with fewer resources:

Automated vehicles will not need a human driver, so therefore vehicles could operate continuously, without breaks for drivers (which need to rest), and operational costs would be significantly reduced, because driver's wages would not be needed

[11] Vehicles, which weight at least 1000kg, are commonly used for individual displacements. Total weight being displaced per trip could be up to twenty times higher than the self-weight of the driver.

[12] Such references are a subset of the bibliography of International Transport Forum, 2015.

to be paid anymore. Nevertheless, human resources for other tasks, such as fleet controlling, would be needed.

It is expected that if these services were implemented, and if they were quite popular, reaching a high modal share rate, the commented benefits would be attained. In other words: If people started to change their habits, and a general conversion from owned private vehicles to ridesharing systems were produced, a more sustainable door-to-door mobility would become a reality.

Furthermore, in International Transport Forum, 2015 some conclusions related to an autonomous car-sharing service and an autonomous ride-sharing service applied for a case study, focused on the city of Lisbon, Portugal, are presented. The demonstrated results are quite interesting due to the diversity among the studied scenarios.

Lisbon, a medium-sized European capital city, shows a quite car-centred inner-city mobility, complemented with an underground rail network, a large tramway network[13], and public buses. Case study analyses the introduction of automated services both considering and not the presence of a high capacity public transport network (namely metro, light rail and BRT services), which provides interesting information not only for Lisbon but for similar cities such as Valencia, Spain, which currently has a large metro system, or Turin, Italy, whose unique metro line performs a slightly tangential service, leaving aside the city centre.

Moreover, Lisbon shows a quite high car density during peak-hours ($60\frac{veh}{km}$) and a high occupancy of the parking capacity (78%). Although the cited problematic and despite the city possess a large suburban rail network, almost three out of five commutes within the metropolitan area are performed by own private car.

The case study contemplates introducing both car and ride sharing systems. Although ridesharing system is expected to cause major beneficial impacts, carsharing scheme, consisting on small capacity vehicles (with capacity for just one or two passengers), would not perform impacts as large as ridesharing, or would cause more harmful prejudicial ones. In other words, efficiency of pooling most common sized vehicles (vehicles which can carry four or five passengers) is quantified and expressed as the expected effects. Some of these impacts are listed:

- Both systems would reduce dramatically the number of vehicles that compose the fleet of a city. This reduction could even be a bit higher for the ridesharing scenario rather than for carsharing. Carsharing could reduce by a factor of 8 the current number of vehicles, but the car reduction factor for ridesharing could even be 10. Larger vehicular reductions are expected after the mid-transition (more than 50% of penetration rate).
- In a supplementary way, parking occupation would decrease for both cases, experimenting more dramatic descents after reaching the 50% of penetration. Parked cars are expected to be reduced by a factor of 10 if automated carsharing services are implemented, while considering ridesharing this factor could reach 12.
- Consistently, Automated vehicles will not remain parked 23 hours a day anymore: Idle time (% or hours) is expected to be severally reduced, since vehicles would only need to stop for charging and maintenance labours. From current mean inactive time, the vehicles which compose these fleets are expected to remain inactive 8 hours per day (carsharing) and even 6 hours per day (ridesharing).
- Both cases would improve high-capacity public transportation share.

Nevertheless, some prejudicial effects would also be produced.

[13] Lisbon old-timer trams are well-known around the globe and their services are quite focused on tourism. Nevertheless, such network is complemented with modern trams, which play out in a quite useful urban transport network through Lisbon's topography (Lisbon is so-called "The city of the seven hills").

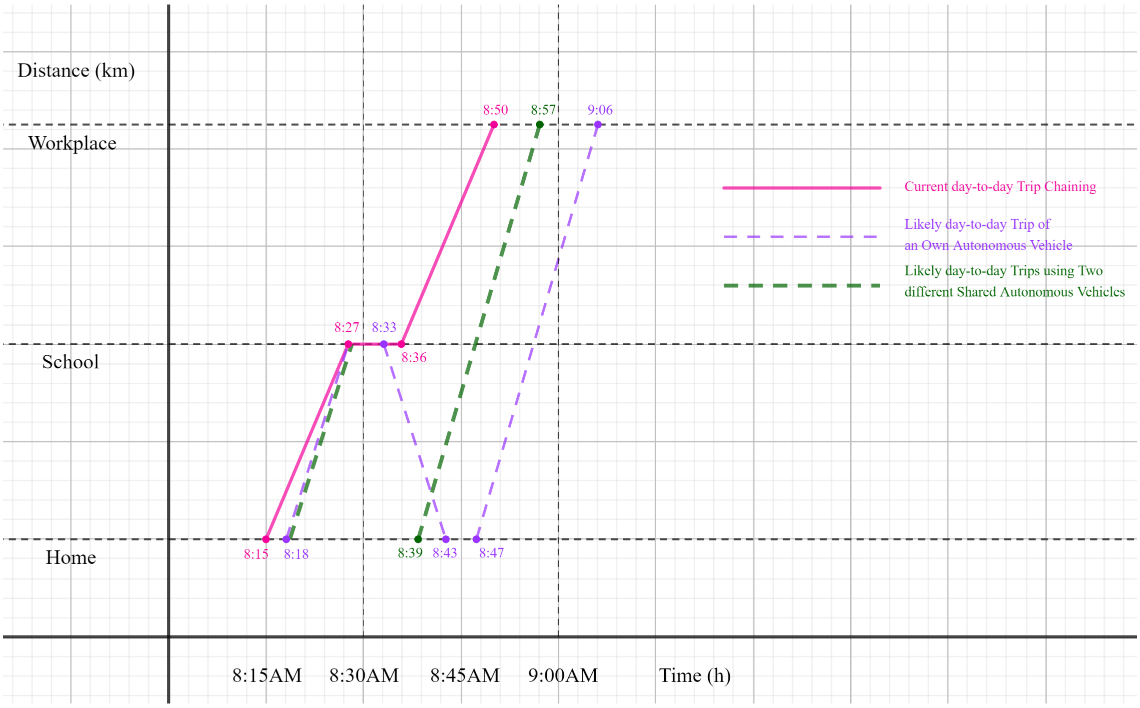


Figure 13: Trip chaining would be quite affected due to automation, which would lead to scenarios where vehicles are expected to travel much more kilometres than nowadays. OWN ELABORATION.

- Vehicle Miles Travelled (VMT) per vehicle would increase in both cases. Fortunately, it is expected that VMT increment would not be quite large for ridesharing if high-capacity public transport were available, and it would decrease after a peak among the transition. However, the same would not be said for carsharing, whose VMT increase would be quite important, and it is expected to remain constant after the mid-transition.

- Both cases would decrease active mobility (pedestrians and bicyclists) share due to its comfort and attractiveness. This effect could lead to a major health problem, because customers would seize more and more the mobility benefits of automated cars, but these benefits, however, would lead to a decrease of their physical activity, according to both Fagnant and Kockelman, 2015 and as it is deduced from the results shown for the case study based in the city of Lisbon published in International Transport Forum, 2015. This is largely discussed at the section called "Further Needs" of the present document.

VMT per vehicle is a telling parameter which is still unexpected whether it will rise or decrease due to self-driving. It can be deduced from the preceding paragraphs that if ridesharing strategies are developed, it would noticeably increase the number of kilometres travelled by a car, due to fleet reduction and active time increase, but would overall VMT increase or decrease? Depending on automation effects and their weighting system, total VMT could rise or could descend.

On the one hand, a reduction of trip chaining would be possible if self-driving vehicles enabled nondrivers and objects to be self-conveyed by a car. A generic and well-known example is shown at the space-time diagram shown in Figure 13: Currently, a large percentage of parents give their children a lift to school by own car seizing their own journey to their workplace (pink solid line), optimizing therefore the distance travelled by the vehicle. If self-driving technologies were applied to current self-owned cars, it would be possible for parents to route their children to school by car and summon their vehicle to return home some minutes later for being picked-up to the workplace (violet dashed line). Therefore, although the distance travelled by the car would raise[14], a parent could spend former unproductive time at home, for example, undertaking home tasks. Furthermore, if a proper Shared Automated demand-responsive car service were available (green broad-dashed line), a similar scenario would be possible, but second users would not have to wait for the comeback of the owned vehicle from completing its first mission. Shared cars would be summoned when necessary, and therefore, every individual trip would be planned to attend individual schedules, seeking for an optimal arrival time.

At both scenarios, overall VMT would experiment a growth, which would also increase if a big number of cars started to perform major day-to-day rides without any occupant, completely empty. This could be caused, for example, by remote car parks locations or by a sensible increase in home delivering services demand, within a vast collection of factors.

DISCLAIMER: The example shown in the referred figure has been prepared in a theoretical manner. The main goal is to show how self-driving technologies could change commuting patterns. Timing showed in the figure does not respond to any specific model. It just responds to some overall theoretical concepts which can be summed up from the whole document (e.g. Self-driving technologies would lead to faster journeys and higher average speed in terms of computing faster routes and wreaking a decrease in number of cars riding at peak hours, reducing therefore traffic congestion. According to Frost and Sullivan, 2018, travel time could be reduced up to 27% due to the vehicle's knowledge about the traffic status).

Fortunately, automation could lead even to a reduction from current overall VMT: On the other hand, self-driving technologies, according to American Public Transportation Association, 2016 and Public Sector Consultants and Center for Automotive Research, 2017 would improve current transportation systems, in terms of conveying the residents of a certain neighbourhood to their closer metro or rail station. Pay-per-use services[15] would likely discourage potential users to ride if a certain displacement could be easily performed walking, and jointly with the induced reduction of searching for parking time and car ownership, an overall decrease of total VMT could be possible.

Traditional, newer and yet-to-be-born transport companies could specialize in ridesharing services, providing a vehicular fleet capable to satisfy any need of urban displacement. Carsharing services might be more and more demand-responsive: Higher capacity vehicles would be used during peak-hour episodes in order to increase carpooling efficiency and would substitute or complement medium-capacity vehicles which operate during out-of-peak intervals and may need to be recharged, maintained or just parked, waiting for a scheduled customer. Moreover, if generic ridesharing demand were analysed, some predetermined ridesharing routes throughout main urban arterials would be useful, in terms of providing a similar transportation system as public transport currently does, but passengers would be able to alter the route if needed and to avoid some unnecessary stops, therefore obtaining a faster, more sustainable and much more efficient mobility service.

Furthermore, companies which would operate automated ridesharing services could both own the vehicles of their fleet, or take profit from unused private-owned cars, whose owners could decide to enable it to serve general public when not needed, receiving a certain income in return. This idea is suggested in Catapult Transportation Systems, 2017, where the potential service is compared with current prosperous house-sharing services in terms of increasing the availability of accommodation and personal mobility. In Catapult Transportation Systems, 2017, in addition, it is demonstrated that the idea was included at the masterplan in force of a well-known electric car developer.

[14] It is worth mentioning that travel time is expected to be reduced due to automation and its reduction impact on traffic congestion.

[15] Although maintaining an own car is not a quite affordable task, currently it could seem that using an own car for a short displacement is a costless activity. Actually, it is not truth, but seems to be free because out-of-pocket expenses are null. Nevertheless, if a person had to pay a few cents for travelling just a mile at their own car, it is likely that him/her would refuse to perform a senseless car journey.

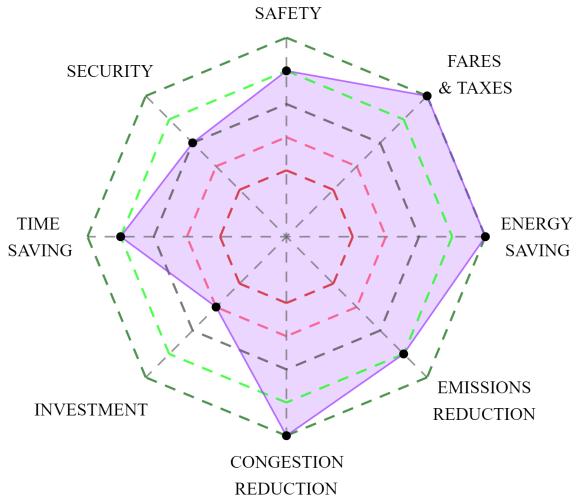


Figure 14: Valuation of Automated Sharing services on Demand needs and potential impacts.
OWN ELABORATION.

Both public and private ridesharing services deserve being highly accessible. Platforms and bays for picking-up and dropping-off passengers must be implemented homogeneously over the city map, in order to provide a proper accessibility to these services for all participants and all inhabitants. Moreover, control centres are compulsory in order to manage a proper performance of the transportation system. Finally, jobs related to these companies would shift from current drivers to fleet managers and vehicle's maintenance crews.

In order to finish with this section, it is worth commenting the **importance of vehicle sharing on suburban mobility**. Mainly, it is important to consider the existence and functionality of **High-Occupancy Vehicle Lanes.**

On working days, a significant share of vehicular flow in an urban region consists of commuters which have to displace to the principal, central town because they live in a suburban town. Such kind of mobility has a significant impact on major arterial streets and access highways, which could even become overcrowded, causing congestion episodes during peak hours. Such congestion is typically produced by the fact that most commuters use to commute alone: Occupancy of their cars is just one person.

As a strategy to reduce the great number of cars on such roads during peak hours, High-Occupancy Vehicle (HOV) Lanes have been disposed and built on major access highways. Such lanes may only be used by working, operative buses and private vehicles whose occupancy is greater than or equal to two passengers. The objective of the commented measure is to split the vehicular flow into two groups: Cars and buses with greater occupancy rates would be able to ride faster through free, uncongested lanes while drivers commuting alone must share the saturated lanes and to cope with traffic jams will be their most likely outcome. The commented splitting seeks, as a final objective, to encourage carpooling and discourage private vehicles with just one occupant.

More and more cities and populous metropolitan areas are building and designing new HOV lanes. If the commented impacts on vehicular occupancies caused by carsharing and ridesharing platforms and services based on autonomous driving finally occurred, current HOV lanes would prove unnecessary, inefficient or inadequate. If a great share of the vehicular flow consisted on vehicles with two or more passengers, and if most of these cars intended to ride through the HOV lanes, **a reversal phenomenon would appear:** pooled cars would saturate HOV lanes while normal lanes would prove empty.

Such possible phenomenon may be analysed and tracked in order to estimate whether HOV lanes will still prove useful (attending to current regulation) or not. Strategies to split once more the vehicular flow in a weighted manner would be optimal in order to achieve the best possible Level of Service on the highway during peak-hour episodes.

Depending on the evolution of the traffic flow on highway stretches with HOV lanes, some strategies such as swapping lane's object or increasing the number of HOV lanes while reducing normal lanes should be considered if an actuation were needed.

Last, but not least, is worth considering the possibility of including some "CAV-ONLY" lanes (lanes and/or road stretches where only the Connected and Autonomous Vehicles would have the right of way). Operating current HOV lanes as CAV-ONLY lanes is an option which could lead to a better traffic distribution at least at early stages, boosting therefore autonomous ridesharing services and fostering people to replace their former human-driven cars with AVs or move to these autonomous mobility services.

Further notes about these CAV-ONLY lanes are expressed in this report, in relation with the microscopic simulation chapter.

4.4 Safe Harbour Areas

When riding, all kind of vehicles and their passengers deserve be provided of any kind of backing where rely on in case of emergency. Such backing system should consist, as a minimum, of a safe place where stop the vehicle as soon as the incidence is detected.

Nowadays, it is possible to stop and detain a vehicle for an emergency at the external side of almost each street in urban areas, in a similar way as taxis do for dropping-off their customers. In rural environments, main roads, where median speed is sensibly higher than in urban areas, are equipped with hard shoulders along its whole length (otherwise, these roads could also be equipped with periodic refuge areas). The objective of such shoulders and refuges, as their name suggest, is to provide a safe and secure place where detaining the vehicle immediately after a trouble (such as a mechanical malfunction, a lane disruption or any health concern of a passenger) has been detected. Most refugees have been traditionally equipped with an emergency phone, in order to allow passengers to report a mechanical/health problem and call for an ambulance/technical support, and in case of hard shoulders, such phones were periodically distributed along the roadside. Interval between refuges (and phones, when the road is equipped with a hard shoulder) varies generally between 1 and 2.5 km (being rarely larger).

It is stated in Catapult Transportation Systems, 2017 that such areas would be longer useful if automated driving were introduced. Semi-automated vehicles (L2 – L3), which would be able to fully-automated drive through highways, would require a driver to regain control of the vehicle. Nevertheless, such driver would not be able to carefully resume the driving task (e.g. him/her was sleeping and has just been awakened or is suffering a malaise). **In any case, any self-driving car must stop in a given lane of the road**:[16] **It will need to stop in a lay-by surface**. A place where the vehicle would be able to stop and wait for the driver readiness would be provided.

Moreover, fully-automated vehicles would also rely on such infrastructures, especially in case of mechanical malfunction or serious illness of a passenger. In such cases, the car should be able to carefully drive to a safe area and stop if a misfunction were detected or a problem were reported by a passenger, asking therefore the car to stop.

For such reasons, according to Catapult Transportation Systems, 2017, it is fundamental that the companies that prepare digital road maps for navigation systems have accurately mapped all the highway and conventional road stretches which possess a hard shoulder, and the exact position and geometry of each refuge area, in order to ease and make possible any emergency stop which would be needed. **The main point of this section is that the main need is not the creation of newer refuge areas but the precise marking, positioning and definition on maps of the existing refuge bays and shoulders.**

Such areas would need to be hundred percent safe. For that reason, a crash barrier would be mandatory to be installed on the roadside, in order to allow passengers to be refuged behind them from other vehicles. Passengers should exit their cars always on the external side of the road, in order to avoid any kind of interaction with the oncoming vehicles. For that reason, refuges should be prepared for easing the exit from the car on the optimal side.

Finally, it is important to mention that some other road facilities oriented to give drivers and passengers some kind of safety support, such as runaway ramps[17] must also be perfectly mapped and their exact ubication has to be perfectly broadcasted to the vehicles that are riding on the road. **In case a safe braking manoeuvre were required, the more precise the manoeuvre were, the safer the stopping would be**. Therefore, the positioning task of the vehicles with respect to such safe areas **needs to be as precise as it would be possible, especially at such stretches where heavy vehicles may be riding at very high speeds** due to outstanding

[16] Published in BBC News, September 11^{st}, 2019.

[17] Lanes paved with some kind of gravel and soil, which are placed at descending steep slopes for enabling heavy goods vehicles to brake and completely stop in a safe way in case a mechanical problem involving the braking mechanisms happened and/or were detected. In most cases, consist of an external lane with an ascendent, climbing gradient. Figure 16

Figure 15: The precise marking, positioning and definition on digital maps* of the existing refuge bays and shoulders would be a quite important requirement in order to ease vehicles to safely, carefully stop in any case it were required. GOOGLE MAPS / OWN ELABORATION.

Figure 16: Some examples of runaway ramps and the road sign that informs about the existence of a runaway ramp. Note that such sign may also show some format variations between countries. GOOGLE MAPS.

(*) (Further comments about such digital maps are expressed in further sections of this report).

circumstances. (e.g. Steep downward gradients). In other words, vehicles which are driving with a great linear momentum may need to completely stop in the safest way as possible.

4.5 Service stations

The main role of a service station nowadays is to provide some kind of support to human drivers and passengers on roads, in order to save travel time (if located near main roads and highways, vehicles do not have to displace far from the main road looking for that type of services). For that reason, major service stations are currently located near highways and are quite accessible from the main road, seeking to minimize the access time to the station.
Some of the common facilities that a service station offer can be listed:

- Fuel supplying pumps.
- Resting areas.
- Toilet facilities.
- Grocery store and newsstand.
- Restaurant.
- Children's playground.

* Traditionally, were also equipped with public telephones, which have been more and more underused due to proliferation of mobile phones.

In some cases, a service station is just a little extension of a surrounding city, an approximation of the city centre to the highway users who are passing by: Service stations hold some restaurants and shops where typical local dishes and products are offered. A small supermarket, coffee shops and even a low-cost hotel may be part of the service station facilities.

To re-fill the fuel deposit is a compulsory and frequent activity. The more a vehicle is used, the more frequent the refuelling task is. Up to nowadays, fuel has mainly consisted of hydrocarbon petrol products (gasoline and diesel). All the same, it is expected that this type of fuel will be moderately substituted by electricity.

Current petrol pumps are quite efficient: A large car autonomy, sufficient for travelling from Madrid to Barcelona (600 km), can be re-achieved in no more than five minutes. Nevertheless, current electric chargers are not efficient enough. Although it is expected that electric car batteries will achieve more efficiency rates, current chargers can supply an autonomy between 100 and 200 km after a certain charge time (about half an hour) which is clearly longer than re-fuelling time. Therefore, electric vehicles are becoming popular not for long-distance travels but for urban day-to-day displacements.

Petrol supply areas are currently dimensioned in order to process a certain demand. Tank re-filling waiting time is quite low, due to rapidity of the supply system. Since governments are encouraging population to use more eco-friendly, sustainable electric vehicles and prohibiting petrol cars to perform some activities, namely entering city centres or highly-polluted areas, the presence of electric cars will continuously increase on roads. The number of electric cars over the total summation of all vehicles is also expected to monotonically increase and gasoline and diesel cars would likely dissapear[18]. Therefore, **the fewer petrol cars form the vehicular fleet, the fewer petrol pumps would be needed. And the more electric cars riding through the road networks, the more chargers would be necessary.**

Consequently, considering current efficiency rates of electric chargers, and current fuel stations land occupancy, it is easy to imagine that capacity of supplying stations will decrease considerably.

[18] In some cases, a deadline for the petrol cars abolition has been established.

If it were desired to process the current demand not for diesel and gasoline vehicles but for electric cars, land area destined to vehicles being charged must be much greater. The future charging stations have to be dimensioned attending future vehicular demand and charging times, which may lead to greater land occupancies.

Substantially high charging times may also affect passenger's timing, especially for long-distance travellers. Road users would have to spend a while at the service station, waiting until the charging process is finished. Therefore, an entertainment program could be offered by the service station operator, in order to divert the eager travellers, or some other activities that can amuse bored riders. Moreover, when possible, positioning service station closer to actual town/city centres, when possible, would become a strategy which may impact positively on municipality's tourism: A cultural and commercial offer is provided to passing-by travellers, which must spend at least half an hour at the city.

It is important to remark that **major impacts on service stations would be mainly caused by electric vehicles rather than by self-driving technologies**. Nevertheless, automation would help to explore paths yet to be navigated: If a passenger leaves its vehicle re-charging alone, and goes for a walk through the surrounding area, he or she might prefer to call-on its car to pick-up him/her when finished instead of walking rearwards.

Also remarkable is the fact that, although current petrol vehicles can only be re-filled at service and petrol stations, chargers for electric vehicles will be largely scattered across the map of a given city. Chargers would be commonly placed in car parks and private garages. Therefore, chargers at service stations are expected to only be useful for those riders which would need an electric support. For example, long-distance travellers which displace by electric car: Such people may need a charger facility among their origin and destination towns. Other riders will not need to use such chargers at service station (e.g. because they would be capable to charge their cars at home). To sum up: **charging demand at service stations will be lower as current re-filling demand**.

Further development.
Looking forward, automated carsharing and ridesharing systems would appear not only to revolutionize mobility in urban areas, but are also expected to reinforce inter-city medium and long-distance mobility. Thus, a new national-scale mobility modal, based on vehicles of different size and capabilities, may share the high-capacity road network with other vehicles. These vehicles would need an interchange point: A kind, comfortable, safe and secure place where interchanges between vehicles could be realised, and where getting-in and leaving vehicle operations could be performed.

These buildings would likely resemble railway stations or even like little airports. They would be new transportation hubs and would need some indispensable services for such infrastructures and have to be dimensioned for the expected demand. These hubs, the closer to arterial, tangential highways and ring roads, the more sense will make. Thus, current service stations located in the surrounding area of big cities would be transformed in order to host some of these "road stations" or "roadports". Deepen into this idea, a fundamental notion that would make road stations possible and successful is to guarantee a proper access to these hubs.

Passengers would need to displace to a road station, and the main idea is to provide several ways for making it possible: Public Transportation systems would need to serve them (like current situation with airports and rail stations). Parking facilities would be needed, in order to provide a better access to those who still own a vehicle and will likely be fewer and fewer people. Thus, areas for picking-up and dropping-off passengers would also be a compulsory need. Road Stations would need to be equipped with pathways for allowing pedestrian and cyclist access. Finally, for sure, Road Stations must be designed for allowing access by urban automated carsharing and ridesharing

Figure 17: Variable message signage panels in Barcelona. Notice that the panel represented at the figure on the left side is not displaying any information and the right panel seems to be misfunctioning beyond being vandalised. OWN ELABORATION.

demand responsive modals: Transfers at the road side of the stations would be possible not only in a highway-highway scale but also in an city-highway dimension.

This new modal potentially would reinforce those interurban relationships which are not well served by railway. It could be useful for those countries which have an excellent road network, but some rail relations are not in proper conditions due to lack of maintenance or timetables are not flexible at all due to railway capabilities. Automated mobility on demand does not require continuous double track: each vehicle can use each lane of each road mostly every minute, each vehicle is able to adapt its itinerary depending on congestion, and road networks are sensibly larger than rail networks so therefore more small towns would be served by such potential services.

Nevertheless, it is worth considering that the described new inter-city modal may create new demand on highways, which likely will have to host greater vehicular flows. Fortunately, as it is commented at the following chapter, headways between CAVs are expected to decrease and therefore road capacity is expected to increase.

This possibility is mentioned and discussed in Catapult Transportation Systems, 2017. It is worth remarking a key idea about the possible new modal which is written at the mentioned report. Such idea is written as follows:

“This essentially reimagines the motorway network as the tracks of a new public transport system, with service stations as the new railway stations”

In other words, it is suggested the possibility of taking profit from the existent road network in order to provide a essential, enhanced transport service to the less-populated areas. This option is a possibility that may mitigate the construction of expensive, unprofitable and hard-to-maintain railway lines. The existing transport infrastructure may be useful for providing a better service of public transport, accessible for everybody. The expansion of the transport infrastructure network (for example, railways) across some given regions may prove unnecessary, which would lead to great monetary savings by the administrations but would also lead to reduce the environmental impact of such infrastructures.

Figure 18: A variable message signage panel in Barcelona which is showing some information about the current traffic state and the expected time that a vehicle will spend on reaching the next highway section. OWN ELABORATION.

4.6 Bridge Structures and Pavement Reinforcement

Automated vehicles and self-driving technologies would be based not only on artificial intelligence resembling and/or emulating human capabilities while driving but also interconnections among cars, whether autonomous or not, which compose the whole vehicular fleet (V2V), and moreover, based on connections between these cars and the road management authority, whose mission is to transmit in real time all the vital information that current road users riding within a certain radius around a traffic malfunction or disruption would deserve to process, in order to enhance the road traffic and mitigate the negative effects caused by a traffic malfunction (V2I).

From the beginnings of the automobile mobility up to nowadays, the interconnection between drivers has been not inexistent but quite bounded and enclosed: Drivers which desire to turn or overpass a certain vehicle use to advert other road participants employing car blinker lights, or even gesticulating with their arms if blinkers were not available. Furthermore, in order to warn about the following drivers if an unexpected braking happens, brake lights are automatically turned on. Finally, it is worth mentioning the importance of car horn, used to advert other drivers the high likelihood of a smash in an acoustic way.

Moreover, the carn horn has been quite useful up to nowadays in order to wake up such scatter-brained drivers at intersections, which are blocking the traffic flow because they think the traffic light is still lighting a red signal. Nevertheless, some furious, mad, angry drivers use to depict and spread their rage on the road in terms of pressing notoriously their trumpets: unfortunately, the depicted events are typical day-to-day deeds which actually do not lead to any positive scenario but may drive unnecessary to a negative one.

Due to the former difficulty to deliver current road information (e.g. non-operative lanes, traffic state and crashes which had just occurred) from one car to each other, authorities used to (and still use to) broadcast information via local radios and variable message signage. Although local radios offer a non-quite detailed information, variable message panels provide human drivers a highly-detailed and updated information about current oncoming road state, weather forecast, lane disruptions, and expected travel time to several nodes. What is more, these panels are used to display advices from the authorities, to manage the road displaying the optimal traffic speed depending on the traffic environment, and to provide some secondary information such as current time.

V2V technologies would be significantly useful to deliver crucial information to both human drivers and self-driving technologies in a quite fast manner. If necessary, vital details will be

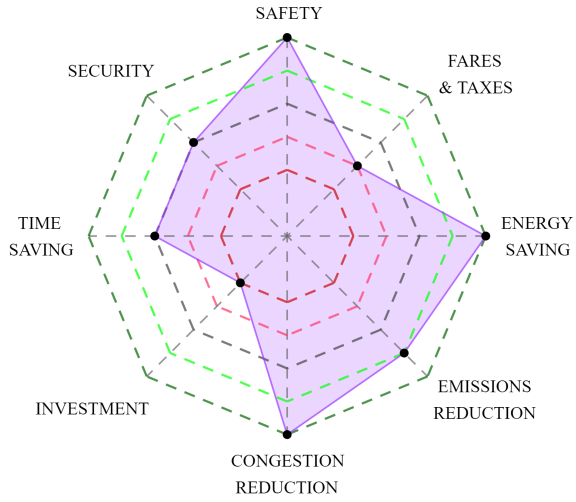


Figure 19: Valuation of structures and pavement reinforcement needs and potential impacts.
OWN ELABORATION.

processed by cars and displayed or voiced to the passengers. Such supplied information could help passengers to improvise an alternative route or plan. Furthermore, some profits would be obtained from such technologies: Cars at fluid and dense roads would be able to coordinate between them, seeking for a more efficient driving in overall terms.

Vehicles on a major road stretch are expected to cooperate in order to reduce current headway between them, leading to platooning phenomena. The strongest aspect of platooning phenomena, if automation let them be largely held, is the beneficial aerodynamic profit that vehicles would experiment, which may be quite useful for heavy vehicles (e.g. trucks) riding long distances throughout transnational highways. It would cause a reduction on emissions and moreover, the energy (petrol, electricity, gas, ...) for achieving a certain vehicular displacement would be noticeably reduced from current situation, due to reduction of wind resistance (windage). **Automation would cause a significant energy saving from long-distance trips on intercity roads**, which would lead to a more sustainable inter-city mobility.

Despite the huge beneficial effects on energy saving, the main problem linked to platooning comes from the need to bear the majored traffic loads. If vehicles started to ride closer to each other, loads per unit of surface would likely increase. Therefore, current bridge structures could become weaker, more fragile structures. Future structures would be designed from the very beginning to resist these traffic live loads. The goal is to find the new optimal design for bridges and some other road structures. Seeking this goal, some structural studies have to be carried on, which would imply a quite significant sum of money. Furthermore, it is expected that the new designs would imply to increase the amount of material needed to support and distribute such overloads.

Major arterial and ring roads, which currently host a huge percentage of heavy vehicles riding within a city[19], would have to be adapted and prepared to cope with the expected traffic live loads. Their bridges would have to be redesigned in order to allow trucks to ride bunched in a safe manner, which would lead to reconstruct most of the current bridges and structures of the global road network. One more time, it is demonstrated that implementing this measure would

[19]Heavy trucks are not allowed to enter the city centre and residential zones at most cities.

be very expensive in spite of its potential benefits: On the one hand, overall economic expenses and investment would be significative. On the other hand, general energy saving is expected to be enormous.

4.7 (3D) Map Creation

Since new technologies have started to change driving habits, more and more roads have been depicted on maps. From former vintage nationwide in printed road maps, a shift was produced to more detailed and comprehensible digital maps, which were available in several digital supports, such as GPS (widely, GNSS) navigator devices, PDA devices, and more recently, tablet computers, PCs and Mobile Phones.

Global Navigation Satellite Systems (GNSS) were designed and deployed initially not for civilian purposes but for military ones among the twentieth century. During the decade of the 1990's, the civilian usage of GNSS systems was enabled. Nowadays, a wide range of GNSS applications are possible: From real-time positioning all the vehicles or aircrafts that a certain transportation company owns and/or manages (logistics applications) up to precisely controlling local displacements in the vicinity of urban excavations and the displacements caused by the action of loads on certain structures (civil engineering applications).

Maybe the most well-known application of GNSS are **on-board navigation systems**, which have become quite popular due to their usefulness. While computing the vehicle's position in a quite precise way, the optimal route for reaching a given destination is computed. Such systems, meanwhile, convey drivers in an acoustic way the instructions of the computed roadmap in terms of assessing the most suitable lanes that they should use for easing further turns and advising when they are approaching to a certain intersection where the driver must leave the current street. The proliferation of these systems had converted former indication signs to not useful signage.

There are different classes of receptors (devices whose position is intended to be computed) depending on their accuracy. The most basic ones are widely commercialised nowadays (e.g. each smartphone possess a GNSS receptor) and although their precision are not so useful (such positioning receptors currently display an area with a few meters of radius where it is most likely that the receptor is located) , up to nowadays such positioning systems had been enough to determine with a low error rate at which road section was riding a given vehicle.

It is worth mentioning briefly that GNSS systems are based on the triangulation of the distance to a certain number, n, of satellites which are orbiting the globe almost permanently and are visible from a certain on-ground spot ($n > 3$). Such distance is precisely computed taking into consideration that each satellite just broadcasts current time information via Hertzian waves. Therefore, a given on-ground positioning device can compute its position [1] considering that the interval between current time and received time information is the wave travel time, [2] computing the distance to a given satellite as a product of such wave travel time by its propagation speed, and [3], triangulating the distance to each visible satellite. The position of each satellite as a function of time is known and can also be precisely computed.

The most famous Global Navigation Satellite System is GPS (Global Positioning System), which was deployed by the U.S. Department of Defense (Pozo-Ruz, 1999) and consists of a series of 24 satellites located in orbits with an average altitude of 20.200 km over the earth's surface[20]. Other GNSS systems are BeiDou (Chinese GNSS) or Glonass, that was developed by the former Union of Soviet Socialist Republics (USSR) and also consist of a constellation formed also by 24 satellites. Nevertheless, Glonass system has not been always operable. Such system has been occasionally restrained due to the lack of maintenance of their satellites during the political transition in the Russian Federation.

[20]Therefore, the radius of each orbit is about 26560 km.

Furthermore, The European Union has been deploying a GNSS project called "Galileo", which was born not for military goals but only as a product to be marketized in order to complement current GNSS systems and to provide a civilian service. Nevertheless, although Galileo System started to be deployed in the late 1990's, has shown a quite slow deployment due to some technical and financial problems. It started to operate in 2016 in a partial manner.

Newer **digital map platforms**, which were able to recognize the current user's location due to positioning systems, not only could provide more information about major and minor junctions and local, secondary roads than paper maps used to provide but moreover were able to compute not so trivial routes in a quite rapid, instantaneous way. In addition, these services were able to provide and deliver information about current traffic status, lane reduction and location of RADAR speed control devices, which had been processed and contrasted from Traffic Management Departments and road users, which had reported some incidents and landmarks, such as the location of dangerous road stretches.

Although some GNSS navigation companies and manufacturers commercialize their products, some public access websites are well-known all over the world due their utility for planning sporadic and rare, unusual journeys. Some of these websites, such as *Google Maps*, are managed by private companies, which moreover have to update their maps while some users are able to report mapping bugs, inaccuracies and missing roads. Other websites, such as *openstreetmap.org* (OSM) are being constantly updated hand-in-hand with anonymous users. OSM, which is actually a free-editable map service that can be edited by anyone, can be subjected to digital vandalism acts in spite of being kept quite up-to-date.

Waze.com is moreover an interesting map platform and GNSS navigation service, which is widely based on the internet community. According to Catapult Transportation Systems, 2017, Waze platform conducts a free-data share programme (called *Waze Connected Cities Programme*) with public agencies, which are able to act rapidly to the briefed problems which were reported by their 65 million monthly users that *waze.com* has got (2017). Moreover, public agencies that are partnered with *waze.com*, deliver major information to the private company, such as information about scheduled road works and inaugurations, current traffic state and other data obtained from roadside sensors. Therefore, the company can use this information for computing routes and travel times for their customers in a more precise and truthful, realistic way.[21]

Roads are constantly changing: Everyday, a finite set of road works is carried out within a given region, and more and more road stretches are being built and opened to general public. To keep these map services constantly updated is not an easy undertaking, especially if road novelties are not publicized. For that reason, GNSS-based navigation companies use to ask their customers to download the latest version of their maps, which may still be a bit obsolescent version or even a premature version that shows some future, unopened road stretches.

Nowadays, despite efforts to keep map services up-to-date, it is still quite common to observe a certain delay between the date a new stretch has been inaugurated and the date it is correctly depicted on a map service. An example is analysed in Figure 20, which actually represents an interesting exercise that can be observed whenever a new road stretch is inaugurated.

A short section of the Spanish major transversal highway A-11, which substituted a conventional road section, was opened on April 10^{th} , 2019. The following day, April 11^{th}, a new map displaying the new stretch was only available at *openstreetmap.org* (both top-right and bottom-right), but not at *Google Maps* (top-left), nor *waze.com* (bottom-left) websites. The updated map containing the opened section was not available at *Google Maps* and *waze.com* for some days. Nevertheless, as it is shown in Figure 21, the new road stretch, when depicted, was

[21] It is worth noting that the name of *Waze.com* platform has been used for naming a phenomenon called "The waze effect". According to Bits and Atoms, 2017, such phenomenon is produced by the dispersion of the overall vehicular flow through all the streets that compose the road network due to the smart platforms for computing routes. Traffic from main, congested arterials can be now diverted to other secondary roads with fluid traffic flow, stressing therefore some streets through residential areas.

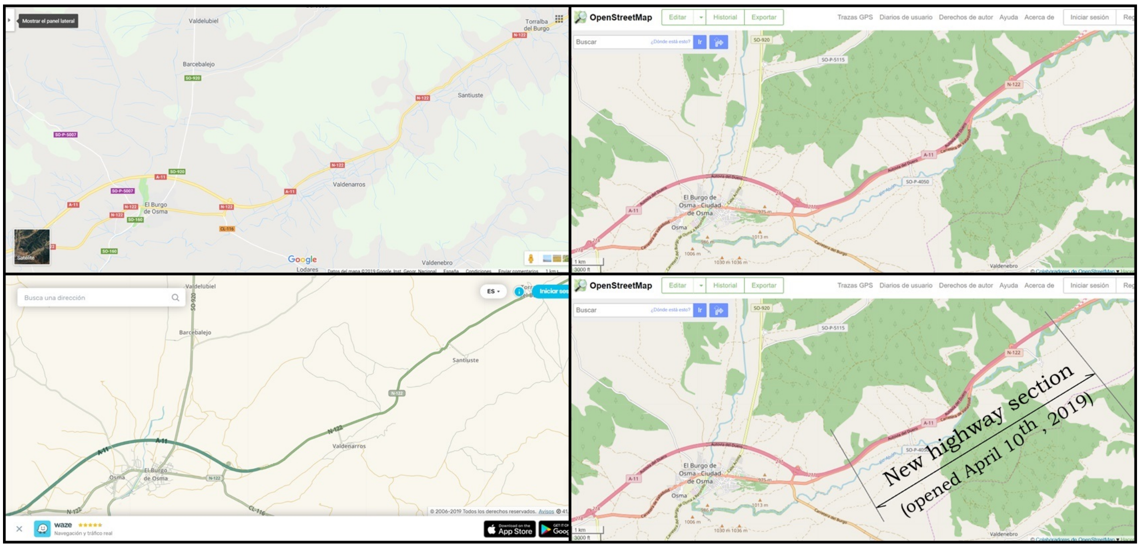


Figure 20: Digital maps are expected to remain updated. Actually, they could be not so up-to-date. OWN ELABORATION FROM WAZE.COM, OPENSTREETMAP.ORG AND GOOGLE MAPS.

wrongly marked not with the correct A-11 road number sign but with the road number badge that corresponded to the former single carriageway road, N-122. Although the new road section is part of a planned major highway, its opening was only advertised at some local newspapers and just a few people were conscious about the new highway stretch had been putted in operation[22].

Likely, these digital maps, which have been a product of several years of enhancement, would be quite useful if were applied to self-driving technologies. Autonomous vehicles would be steered throughout a road land depicted and homologated on a digital map. Drivers will not have to drive their cars supported by navigators anymore: These navigators are expected to deliver the proper information to the steering mechanisms, therefore vehicles would be guided by themselves. Nevertheless, despite some maps are already quite accurate and detailed, further work and improvement would be needed.

- Positioning systems are expected to be more and more precise. Current positioning and navigation systems would be more precise, reaching a precision of just a handful of centimetres instead of current poor, weak accuracies[23]. The more precision in terms of positioning, the better performance for self-driving in terms of lane detection.

  * The precision of GNSS in terms of positioning is expected to be enhanced with newer GNSS projects. Although its slow deployment due to some technical problems, the European GNSS project *Galileo* is partly-operating since 2016. According to Pan, 2017, it is expected that a bigger number of satellite devices (from different projects) being used for geopositioning would be useful in order to improve the accuracy of positioning computations, especially at such points where conventional satellite positioning systems used to misfunction due to the obstruction of visibility[23]. **The more density of satellite devices in the sky, the more satellite devices an on-ground unit will be able to detect, and the more precisely a receptor would be able to compute its position.**

[22]Due to proximity to Spanish both local and national polls, to celebrate an opening ceremony was completely prohibited that days.

[23]It is worth mentioning that current GPS and other satellite positioning systems are not accurate at all in tunnels, narrow streets, underground parking facilites and other spots and stretches where the visibility of the sky is considerably obstructed.

Figure 21: A new road stretch may be erroneously marked at *Google Maps*. GOOGLE MAPS.

* Moreover, computer vision, LIDAR[24] systems and V2V interconnections, applied to 3-D Mapping, would also prove useful for local positioning. An autonomous vehicle would be able to interpret whether it is located at the left or right lane depending on the distance to kerbs, crash-barriers, buildings and even to other vehicles. Maps should also consider the number of lanes of each street and road land destined to on-street parking, delivery bays, rubbish dumpsters and some other amenities. Local position would be contrasted between the different positioning systems and the result may be improved in terms of redundancy. According to Florinda Boschetti and Suzanne Hoadley, 2018, the unproper accuracy of current positioning systems should be compensated in terms of triangulating the current position of the vehicle from well-mapped existing and yet-to-be-placed landmarks, such as the commented kerbs, crash barriers, or just basic signposts and billboards.

- Information about main signalized intersection cycle time (current and future signal colours lighted at semaphores) worth being available on maps. Therefore, the traffic light information would be quite valuable in terms of computing the current fastest routes not only attending to current traffic but moreover considering whether the vehicle must wait a minute for the green light at a determined intersection or not. **In some cases, a day-to-day displacement may be performed through more than one path, with very slight differences between them.**

  * An insignificant time saving would be produced. Perhaps, in terms of time saving the benefits would not be so significant in comparison with the economical effort that would be required. Maybe, in terms of time saving, is not worth implementing the measure. Fortunately, to know the exact future status of each intersection would be quite beneficial not in terms of time but in terms of emissions reduction. Optimal, faster routes would be computed in terms of consuming the less energy as possible and optimizing braking manoeuvres, therefore reducing PMx particles emissions. Vehicles would know exactly when they must start to brake or the optimal acceleration and deceleration rates which would minimize the energy needed to displace and reaching a given point of 'the chessboard' (the city map) at a certain moment. Upgrading navigation in terms of mapping semaphores would lead to a significant overall **energy wastage reduction**.

- Traffic requirements are very related to local road characteristics. Some basic, straight and safe roads may not have or may have a quite basic signage system, but the more difficulty to

[24]LIDAR (Light Detection and Ranging/Laser Imaging Detection and Ranging) is an optics-based technology that is very useful in the automation field for depicting and modelling all the objects that are surrounding a given vehicle at any moment. Such system is based on the emission, reflexion and reception of laser beams.

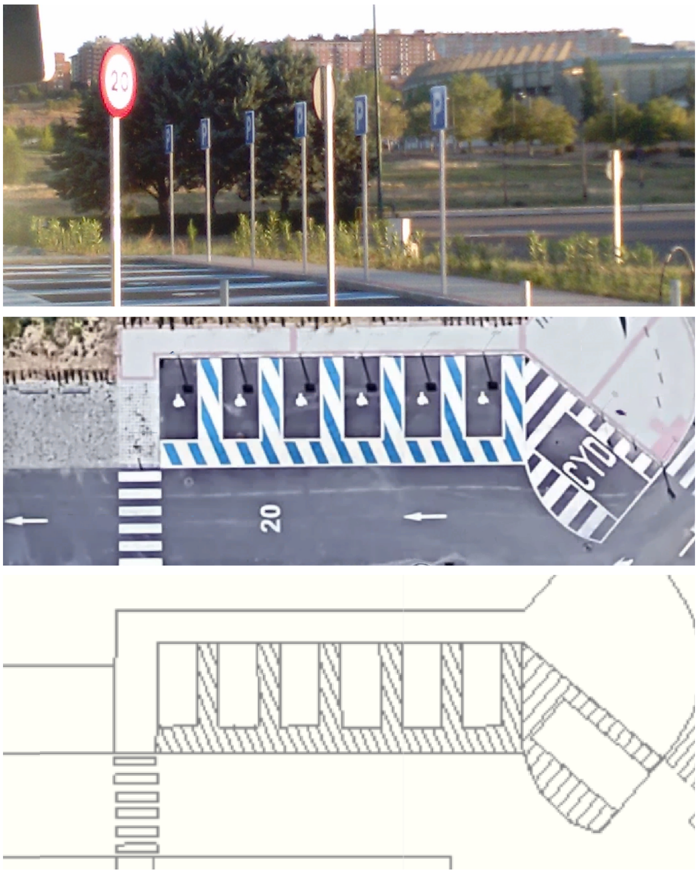


Figure 22: Roads and car parks should be **adequately marked, signposted** and **correctly mapped** for a better operation and management.
OWN ELABORATION / GOOGLE MAPS / GIS APPLICATION OF THE VALLADOLID CITY COUNCIL.

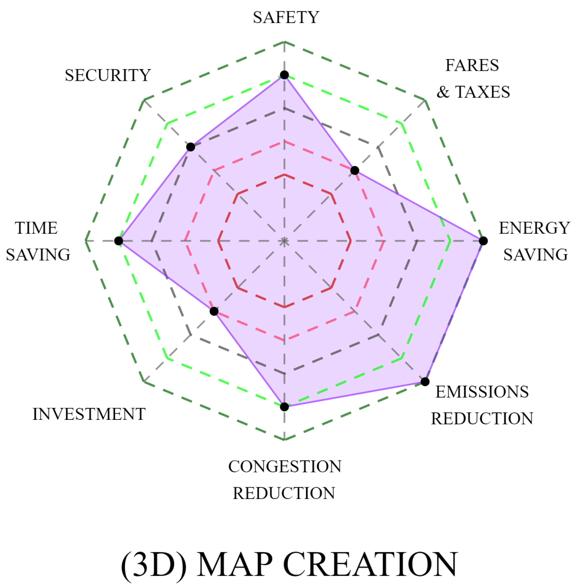


Figure 23: Valuation of Map Creation needs and potential impacts. OWN ELABORATION.

drive through a road stretch, the more complete its signage system is. Roads which consist of a succession of bends and turns, a succession of junctions and intersections and/or hold heavy traffic are much more dangerous than normal roads. The signage system of these roads seeks to depict the risks and scenarios that a certain vehicle may have to cope with in the foreseeable future. Signage system is still quite based on physical, static signs, which are related to a certain road section: the immediately upcoming road section. **If signs are related to a geographical point, it could be worth putting them on the map**. A certain vehicle would be able to know the traffic requirements at a certain road stretch not in terms of reading physical signs or wireless information but interpreting the signage mapped on the route plan, which moreover could be stochastically altered from a traffic management centre instead of consisting of permanent physical signs. This measure, jointly with wireless signage, could lead to the elimination of road signs at some CAV-ONLY road stretches and areas, in a similar manner as they are being removed at more and more railway lines.

* Speed Control Systems (SCS), which are becoming more and more common in vehicles, are systems which adapt the vehicular speed according to the legal limit, whether read from signs through TSR cameras or obtained from I2V wireless communication. According to Nitsche, Mocanu and Reinthaler, 2014, to possess a map containing the legal speed limit[25] with a certain level of precision is a very important step in order to achieve an optimal performance of SCS systems.

To sum up, to map the road network in a more complete way would lead to reduce emissions, to compute faster routes depending on the current traffic and future traffic lights status. Moreover, it would enable to provide a more realistic management of the road infrastructure, depending on the road traffic circumstances, which depend on time.

To achieve the potential benefits that have been mentioned, collaboration between different stakeholders is required, and would need a huge constant effort between them, especially between traffic managers and private companies which provide maps and navigation products. Managers must deliver these companies information about traffic disruptions caused by several agents (e.g. accidents, demonstrations, construction works, objects and stopped vehicles on the carriageway, etc) and some other risks which may deserve to be known, not only by passengers and vehicles but moreover by management and maintenance services, such as missing, dirty and unreadable marks and signs, potholes, and some other secondary problems which may disturb a proper traffic operation.

Therefore, a constant cooperation between management services, mappers and maintenance services is required to be as fast and precise as possible. V2V interconnections should allow to deliver information about observed traffic disruptions in an almost-immediate way. Passengers and road users should also be allowed to report their own observations, which could remain further, beyond car's observations, based on computer vision and sensor detection (e.g. a cracked gantry which supports some traffic lights, that could break up and disrupt the traffic flow, causing therefore serious damages to several cars and/or people). Nevertheless, vandalism related to reporting task should be avoided: Some briefed problems could actually be inexistent and some occurrences could be mischievously reported, seeking a malicious goal.

[25] Some GPS navigators and maps already show the mapped legal speed limit. Nevertheless, since these kind of maps are not quite updated, current speed limits could be altered (Traffic laws may change) and therefore, could not correspond with the former, mapped legal speed limits.

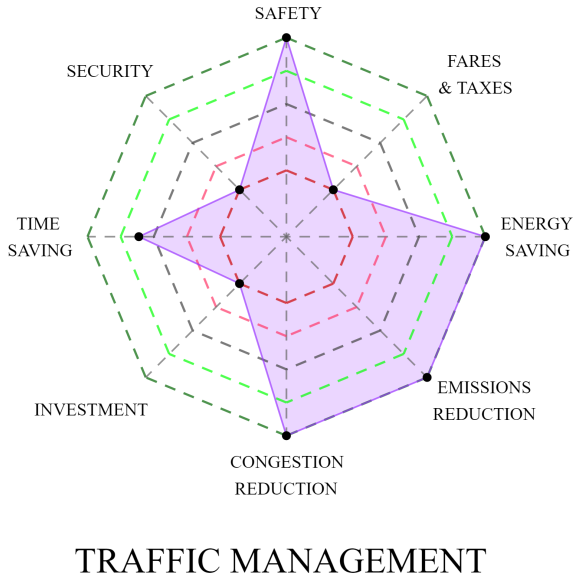


Figure 24: Valuation of traffic management needs and potential impacts.
OWN ELABORATION.

4.8 Traffic Management measures and V2x interconnections

It has been mentioned at the previous section that mapping and V2x technologies may improve road management, in terms of transforming the current stiff signage into a variable one. Roads could be managed in terms of altering its signage, seeking for the optimal road characteristics depending on current traffic, current flow, special events, demonstrations and some other circumstances.

Physical signs would give way to other kind of signage, based on positioning systems and wireless connections. Self-driving cars would be able to interpret the new norms and to steer accurately the vehicle according to such norms, but moreover human-driven vehicles would also ride a road network without physical signs because signage could be displayed on the windscreen, in front of driver's eyes, instead of being placed at the roadside. The only mandatory condition that all the vehicles which could ride those roads, whether autonomous or not, is being Connected Vehicles (CVs). Therefore, such connected cars must be equipped with the appropiate V2x equipment.

The expected benefits of V2I2V (V2I + I2V) connections go beyond managing the road network. In case of a crash, which may imply some seriously injured people, **a crashed car would be able to automatically call for an ambulance** instead of needing an alive and capable person looking for some help. A vehicle would be able to report the crash instantaneously after the accident to guarantee the medical assistance[26]. A crucial time, which may mean a lifeline for some injuried people, would be gained with such system.

Furthermore, a proper Traffic Management system would enable an ambulance being able to reach as fast as possible the exact place where the accident occurred, even riding through a quite congested network: **The road management service could ease the displacement of emergency vehicles**. Connected cars riding through the surrounding streets would know that they must give way to such kind of vehicles and would automatically rearrange between them at

[26] Nowadays, assistance after a crash can only be possible if an external observer has noticed the accident or a damaged passenger is capable to call for help. A crash with no survivors or with seriously injured passengers at a secondary road could had not been observed by an external observer for some hours or even days. Therefore, a vital time would have been wasted and could imply the death of a person.

signalled intersections, seeking the creation of a free lane which could let emergency vehicles to pass through. Such algorithms would be applied not only for ambulances but moreover to police vehicles and firefighter's trucks, improving the efficiency of their crucial, vital missions.

In addition, **An almost-optimal management of the road network would be achieved.** If a major arterial were quite congested in one certain way but some other parallel avenues and secondary axes were clearly far from congestion, managers could mitigate the congestion in terms of:

- Managing the available lanes at the given arterial.
- Diverting some cars to those non-saturated streets in a random manner.

With such stochastic way of traffic management, not only congestion and mean travel time would be reduced but moreover tank-to-wheel emissions would be mitigated (considering current petrol vehicles) and a better service would be offered to all the road users.

The goal is to delegate to vehicles the capability of engaging with the rest of the road participants. In order to achieve this goal, cars would need to be adapted and converted to Connected Vehicles.

Brief notes about V2X technologies.
The present document focuses mainly on the physic infrastructural needs for a proper deployment of autonomous cars in our cities and leaves aside the operational subject. Although such issue is closer to telecommunications engineering rather than to civil engineering, **the current systems** that have reached a certain degree of deployment and **could be useful in order to ease a proper transition to autonomous cars are worth being mentioned.**

It is also worth being mentioned that CAVs would require a quite low latency[27] in order to almost-instantaneously act once an input message has been received. Logically, in terms of road safety, latency should be as low as possible: If such latency were a tenth part of a second, for example, a given vehicle whose current speed were 72 kph (20 metres per second) would travel at least two meters before being capable to recognize a given message and to act consequently with such message. Such two metres could be fundamental in terms of road safety in some determined cases (e.g. the message adverts about the presence of a pedestrian on a pedestrian crossing or the presence of a blocked truck on the road).

Latency should be as low as possible in order to minimize the travelled distance which depends on latency. There are two highly-developed communication systems which could provide a latency close to one millisecond[28] (0.001 s): The first system is based on cellular telecommunications and requires a proper cellular phone coverage. The other one is just based on device-to-device communications but require devices being close to each other, because it is based on short-range communications.

- Cellular network telecommunication technologies are involved in the deployment of the fifth generation of such technology, also known as **5G**[29].
  + Cellular network technology consist of a series of antennas which are placed in a strategical way on the territory. Each antenna provides the proper coverage to a given

[27] Latency, in terms of communications, is the amount of time which elapses since a stimulation has occurred and a response has been generated. The lower the latency were, the more immediate the response is obtained

[28] If the car of the previous example were using a communication system which worked with a latency of one millisecond, the travelled distance due to such latency would have been two centimetres, which actually is a negligible travelled distance while processing the message.

[29] 5G started to commercially operate in Spain in June 2019 (nevertheless, it has been only deployed in the fifteen biggest cities of the country in an initial stage, and the service has been only afforded by one of the major telecommunication companies that operate in Spain).

area around it (known as the "cell"). The average radius of such antennas could be a few kilometres. In consequence, the area being covered by a single antenna could consist of various square kilometres and therefore a certain area could be covered with a not-quite-large number of antennas, which moreover will provide a proper coverage of phone communications to such area.

+ Nevertheless, due to the presence of obstacles, the operative area of each antenna (the area being covered by each cell) in cities is much more reduced than in the countryside.

+ Although the latency of 5G system is expected to be close to one milisecond, by the moment, the early technology which has been tested has shown a latency of about 10ms (this real latency is actually quite higher than the expected latency, which could lead to some problematic situations involving road safety).

- Conversely, a technology called **ITS-G5** (also commercially called WAVE-Wireless Access in Vehicular Environments or DSRC-Dedicated Short Range Communications), which is based on the Wi-Fi standards (IEEE 802.11, ETSI EN 302 663 in the European Union) , is currently being applied for some V2V and V2I applications.

  + ITS-G5 technology is currently much more mature than 5G technology and offers a latency close to the targeted latency of 1ms. Beyond being mature enough and having the required expertise on such system, ITS-G5 offers a safer solution (in terms of road safety) than 5G.

  + Nevertheless, the coverage of each device is quite short: just a few centenars of metres. In consequence, the road network should be equipped with a huge number of devices (Road Side Units, RSUs) in order to adequately process messages coming from vehicles and to broadcast some other crucial information such as the presence of pedestrians on a given zebra crossing or the signal phase and time that remains until the following phase shift of a given semaphore.

  + Furthermore, the volume of data which can be broadcasted using ITS-G5 technology is quite lower than the volume of data that 5G can deliver. According to Frost and Sullivan, 2018 ITS-G5 can only broadcast a maximum data-transfer rate of just 27 Megabits per second, while 5G could be able to broadcast up to 10 Gigabits per second (or even more). In other words: the data-transfer rate of 5G cellular communications could be approximately 370 times higher than the transfer rate of ITS-G5 technology.

NOTE: The similarity on the name of both systems may be confusing. It is important to remark that the name of 5G cellular network technology comes from the fact that it is the fifth generation of cellular network technology, and the name of ITS-G5 is because such technology operates in a nominal frequency channel of 5.9GHz (Super-High Frequency). In any case, 5G should not be confused with G5, and vice-verse

Both technologies will enable the desired V2V, I2V and V2I communications. Due to its capabilities, 5G Cellular Network technology is moreover expected to provide a geofenced, plenty of information digital map[30] of the area the vehicle is riding in an immediate way, and it is expected that a server would be able to be continuously providing the map(s) which most fit with a given journey. Such measure would enable to occupy much less overall memory than if each car stored itself a precise map of the whole road network. An advantage of the 5G cellular network communications is that will be able to provide a large amount of data in a quite short lapse of time.

On the other hand, ITS-G5 is expected to provide a brief, succinct message in a quite efficient manner. Such message is related to the road conditions at the vicinity of a given car at a given moment: A suitable message which could be broadcasted using ITS-G5 technology could be, for example, the presence of a pedestrian at a given zebra crossing.

[30] Due to the large amount of information that such maps will contain, the map files are expected to occupy a large amount of bytes.

A car which were approaching to a given zebra crossing would receive a concise message which includes the reference of such zebra crossing and a basic information claiming whether a pedestrian is on such crossing or not. An algorithm would be continuously asking "Is there any pedestrian roaming on the zebra crossing?" (YES/NO). Such response, as it is further explained on this document, could be obtained from different sensors being placed on the roadside.

It is still unknown whether both systems could collaboratively enable the required communications or, otherwise, one of them will predominate over the other one, leading cars to rely only on one of them. Maybe the technology used for the deployment of autonomous cars will depend on the legislation of each country (or on the European Union standards, in the case of the 27/28 countries that constitute the EU). Assuming that 5G cellular network technology was finally utilized; a proper cell phone coverage would be required: Roads and streets should be equipped with antennas and other devices which could guarantee the required, essential 5G cellular network coverage, which would also enable other 5G applications, such as mobile phone communications.

NOTE: For the reasons mentioned above, these technologies (5G and ITS-G5) are being quite important and are a subset of the technologies that fit perfectly for the deployment of the ideal concept so-called *Internet of Things* (IoT), which is intended to be, in this starting information age, the abstract world created by the data delivered by each cotidian object about their current position and status provided by their main parameters: Unquestionably, **vehicles are nowadays one of the most important cotidian objects for millions of people**.

In case the ITS-G5 technology were finally deployed, a series of hardware devices are required to be scattered, placed and distributed across the road network in order to allow these V2V, V2I and I2V short-range communications. Each device will only operate in order to deliver a discreet amount of data about the current state of the infrastructure (therefore, a large number of devices must be scattered across a given city). As it is stated in Public Sector Consultants and Center for Automotive Research ,2017, such devices need a proper broadband rollout and infrastructure which would enable fast internet connections required for data exchange. To make use of the existing wire and optic-fibre network instead of deploying a new one could be an initiative which would ease to reduce the required investment for the placement of such devices. It would not be necessary to perform new digging works, and therefore no traffic flow would be temporary disrupted. Figure 26.

According to both Public Sector Consultants and Center for Automotive Research, 2017 and National Cooperative Highway Research Program, 2017, it would be compulsory to possess a hardware infrastructure consisting of Road-Side Units (RSU) to materialize a good data exchange performance. RSUs could be able to process data provided by the vehicles.

Furthermore, as it is commented at the section dedicated to junctions and intersections, signalled junctions would perform adequately if they had a device capable to broadcast to CVs the same information as the traffic lights currently display: whether the colour phase of a given intersection is currently green, amber/orange or red, and how much time it remains until the following colour change.

A proper data transmission network is required to deliver all the collected information to a Traffic Control Centre. This facility would be useful in order to process all the received data in an adequate and general way. Data would have to be processed as a whole. Summing up and concluding, new jobs would need to be created on the field of traffic management.

Moreover, cars would have to broadcast to the cars in its vicinity some basic but substantive, vital information, which tells clearly not only the current position of the vehicle but moreover its position in the immediate future. Broadcasted information, called Basic Safety Message (BSM) such as basic vehicle's parallelepiped-shaped geometry (length, width and height), current position, heading, steering angle, speed and both longitudinal and lateral acceleration is quite useful for nearby vehicles in order to compute the exact future position of that car. Such information, which is broadcasted around ten times per second, is expected to be broadcasted

Figure 25: Some road sensors such as license plate recognition cameras (placed in gantries for tolling systems and average speed controlling) or other traffic cameras (for traffic management) are currently being used at major streets and road sections.
GOOGLE MAPS / CARNET, 2019.

Figure 26: When a new infrastructure is disposed through the streets of a city, in most cases the only option is to remove the asphalt and dig, therefore disrupting traffic while the infrastructure is being disposed. OWN ELABORATION.

using DSRC (Dedicated Short-Range Communication[31]) network. Cars would need at least one device (Onboard unit, OBU) capable to both spread and deliver such information and to process adequately received data from other cars and from infrastructure.

There is even the possibility that other road participants, such as bicyclists, electric scooter riders, wheelchair users and even pedestrians also could carry with them a device, comparable with an OBU, in order to provide useful information about the current position of a person to OBUs capable to detect them. Such information, despite not being quite in lane with Personal Data Protection Laws, would be crucial in case of an unlikely (accidental) presence of one on these road participants on the road, forcing oncoming cars to avoid them. Nevertheless, in order to avoid completely the likelihood of run overs, each pedestrian, each bicycle, each wheelchair and whatever vehicle would have to be equipped with such devices, which although the benefits on live savings, would be a not cheap, costly implementation. This scenario is also commented in Public Sector Consultants and Center for Automotive Research, 2017.

Finally, attending to security issues, it is worth considering that the information and generated data delivered and diffused by these mobile devices should be treated in a serious, responsible way. Prevention against hacking would ensure a secure, fair road operation.

In a supplementary way, despite illegal data extraction could be an easy task for some expert hackers or even dissatisfied employees with malicious aims, fortunately, to scuttle an Autonomous Vehicle is not a trivial task. It is claimed in Fagnant and Kockelman, 2015 that it is much more common to hack an informatic system in order to obtain secret information rather than to cause robotic malfunctions. The reason is quite simple: It is much easier to obtain data from a private server rather than producing a malicious program which causes a mechanical malfunction and could lead to an attack with fatal consequences. Nevertheless, although being difficult, there is a non-zero likelihood of suffering a terrible attack, which could be devasting. The problematic exists, and the strategy to avoid every kind of attack would require a considerable dedicated effort.

Moreover, in relation with security, it is also important to remark that a smart management system could also be oriented to mitigate and eliminate the likely damages and negative effects that some driving misbehaviours -but also misleads- which often occur on the road network (e.g. entering a road stretch in opposite direction) could cause to passengers and some other goods being conveyed. An intelligent management of the road network, based on several variable message signal panels, RSUs and sensors controlling whatever happens on in, jointly with basic controlling algorithms and a human staff, could lead to enhance the current security of road passengers in terms of stopping the traffic flow and diverting it to other roads and streets in case of a vehicle driving under some unusual circumstances and making a dangerous use of the road network were detected.

[31] In this case, "short-range" means that the broadcasting coverage radius is approximately one kilometre (1000 m). Each vehicle would be able to receive and process information from all the vehicles which are placed less than one kilometre from itself, and each of those cars would receive its spread information, if no obstacles restrain the signal.

There is a tramway without control descending a steep slope. If you do nothing, it will undoubtedly kill five people that are crossing the street at a given zebra-crossing. If you press a button, you will activate a railroad switch and the five people will live, but the single passenger of the tramway will surely die. What will you do? Will you press such button or not?[32]

This moral question with no logical answer, jointly with some more examples, are quite typical jigsaws for expressing some of the most likely situations that self-driving alghorithms may have to cope with and will have to solve in the safest way.

4.9 Junction Management and Intersection prudence

Some comments about the way to convey information displayed on signals to autonomous cars and about traffic management based on information spread by I2V technologies have been expressed among the several section of the present document. It is worth gathering them and sum up them together:

- Computer vision cameras must read and interpret information displayed on current semaphores in a clear and biunivocal manner.
- Such information would be spread more adequately if a I2V device delivers the information that the traffic light is currently displaying.
- Either as an alternative or as a third way to convey traffic light's current status, information being displayed on traffic lights could also be transmitted to cars by their navigation systems (such information could be reflected on digital maps).
  - Furthermore, attending to these new forms to convey traffic signal's information, a stochastic traffic management system would be possible and more feasible than nowadays, in terms of transforming current signs and signals into more flexible and ubiquitous signalling system.

Nevertheless, to manage the road network requires to focus on a discreet, finite number of road incidences and malfunctions in a general perspective, considering the opportunity to make traffic flow being diverted to other streets in the vicinity. **But the principal matter of the present section is how to manage a given road intersection**: Both local (semaphored or not) road junctions, and road lands that both pedestrians and vehicles must share. **At this second group of intersections, any kind of trampling that could occur should be avoided. It is very important to consider the great pedestrian's vulnerability in order to enhance their safety and protection**.

There is an almost-infinite set of road junctions around the globe. At any given city, most important junctions, which bear large sums of vehicles every day due their strategical ubication, are regulated by traffic lights. On the contrary, minor junctions are commonly underused from the standpoint of road capacity, and most of them do not require any kind of regulation to perform their function in a proper way (such intersections do not require any kind of traffic light in order to provide an optimal level of service).

Finally, most urban semaphored intersections typically possess a zebra crossing for allowing pedestrians and active mobility agents to move transversally from side to side of the road stretch while the vehicular flow is being disrupted by means of a red signal. Pedestrians and bicyclists are informed whether they should move to the other side or not by means of another semaphore (which shows the figure of a pedestrian and/or a bicycle). At non-semaphored zebra crossings, drivers are warned (sufficiently in advance by means of signage) about the presence of a zebra crossing and should stop and let any possible pedestrian to pass through if he/she had demonstrated his/her intention to move to the other side.

[32] Adapted from a news publication in the Newspaper "El País", August 29^{th}, 2019 Edition.

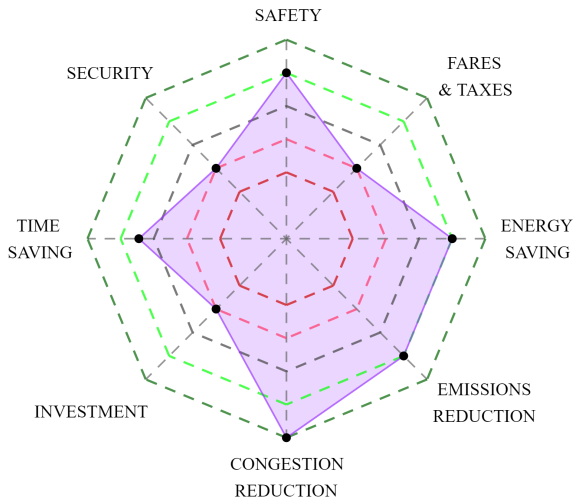


Figure 27: Valuation of signalled intersections needs and potential impacts.
OWN ELABORATION.

It is worth mentioning the existence of "Jaywalking phenomena". Some pedestrians use to move from one side to the other of a street not through their reserved areas (Zebra crossings) but intersecting the lanes of a given street where and/or when drivers do not expect to find any pedestrian roaming on the road. Such uncontrolled crossings could be more or less dangerous and more or less expected depending on the width of the road section and the hierarchical importance of the street. Moreover, the degree of hazardousness also depends on the jaywalker's skills and behaviour: Some jaywalkers only displace to the other side if they had previously checked that no coming vehicle is expecte. Nevertheless, some others do not take the reasonable precautions and could trespass the road stretch even looking at the screen of their mobile smartphones rather than checking what is happening at the kerb-to-kerb surface.

Let's separately analyse each kind of road intersection. The analysis, in line with what it is stated in Catapult Transportation Systems, 2017, is focused on:

- Signalled crossings and junctions
- Zebra crossings
- Uncontrolled crossings
- Yield junctions[33]

Signalled crossings and junctions
Depending on the way(s) used to convey traffic light's current and immediate future status to cars, Connected and Autonomous Vehicles which are stopped at a given semaphored junction could be able to resume their journeys at the exact moment when a traffic light shifts from red to green light. In fact, human reaction time could be almost-completely mitigated. Therefore, the effective green phase time at such junctions could be enhanced and its duration extended closer to real green phase time. This fact putted together with headway reduction would imply a significative growth of the junction capacity.

[33]Contains some other interesting junctions which are quite common, such as highway access lanes and roundabouts.

Although some signal-controlled junctions do only consider the presence of vehicles (e.g. conventional road junctions far away from population centres), most of them are prepared for both vehicles and pedestrians. Active mobility players usually act in a more flexible manner (they use to cross the road if no vehicle is coming even in the case of being unallowed to cross by means of traffic signals) but are also quite vulnerable to suffer a serious accident.

Typical day-to-day performances may start to change. For example: a quite typical behaviour is performed by such pedestrians which start to run through the pedestrian crossing when they have detected that semaphore's phase is immediately going to shift. Some of them often do not reach the opposite sidewalk on the stipulated time, unconsciously ordering cautious drivers to wait a few seconds for them before resuming their journey in a safer way. In fact, this behaviour reduces the effective green phase time and therefore junction capacity is also reduced.

CAVs should consider not only the current and future phase displayed on the signal but also **the presence of obstacles** (human beings and misplaced vehicles) **at the pedestrian crossings before resuming their journeys**. The critical point from a technological standpoint will not be the phase detection but pedestrian's presence recognition.

Some sensing and vision systems (computer vision, lidar and infrared cameras) are able to recognize the presence of a human being or any other obstacle in an easy way. Furthermore, Connected Vehicles, which can precisely recognize other cars, would surely be also able to recognize other road participants, like bicyclists and pedestrians, if they were carrying with them any device capable to broadcast their current position accurately. Such device would be like an On-Board Unit (OBU), for example, their mobile smartphone.

Nevertheless, any single failure of such detection system combined with the presence of any absent-minded pedestrian could cause serious or even fatal consequences. Due to this problematic, some philosophical questions arise: Should people be always carrying with them a device which is continuously broadcasting their current position? Which implications could have the fact that a given person were not carrying with him/her its device? Can we ensure a perfect performance of the conventional sensing systems (lidar, radar and computer vision) in all environments and circumstances?

When it exists a hazard that could imply human lives, it is not worth introducing technologies which are unknown if they will perform correctly or not. It is not worth starting to operate in a risky way. Therefore, the objective must be to reduce the likelihood of human presence at pedestrian crossings while signals are displaying vehicular green phases.

- From the technological point of view, semaphored pedestrian crossings should be programmed in order to display how much time it remains until the following phase shift, and should consider a certain lag (a time gap of x seconds, $x \geq 0$) between pedestrian's shift from green to red light and vehicle's shift from red to green light, in order to provide a slight respite for those pedestrians which have still not finished their crossing task.
- From the sociological perspective, citizens should be discouraged from the current common behaviour. Educational programmes should encourage pedestrians to make a responsible use of such crossings, warning people about the potential risks of moving to the other side when pedestrians do not dispose the required time for crossing in a safe manner before the following phase shift.

Although a citizen's determination to change their minds in terms of road safety would be required, some benefits could be obtained from self-driving applied to signalled intersections beyond an increase of road capacity.

As it is mentioned at the mapping section, wireless communications and smarter navigation systems would lead to compute optimal journeys in terms of energy saving and emission controlling. Instead being constantly braking and accelerating in an abrupt manner, vehicles would be able to accelerate and decelerate slighter (such accelerations and decelerations would be monitored from the navigation system, which would let the steering system know whether the car can reach the following semaphore displaying the green phase or not). Controlled braking manoeuvres present some advantages versus abrupt manoeuvres, such as less PMx emissions and less energy being wasted.

Finally, road capacity would be completely affected from reaction time reduction. It is stated in Kockelman, 2016 that triangular Macro-Fundamental Diagrams progressively change their shape depending on the considered reaction time at signalled intersections. Reducing reaction time would imply reaching the maximum capacity for greater densities, which would imply greater capacities: If a current reaction time (Δt) of 1.5 seconds were considered, maximum capacity would be considered to be close to $2100\frac{veh}{h}$ and would correspond to a density close to $30\frac{veh}{mi}$.

- If a current reaction time of 1.5 seconds were considered, maximum capacity would be close to $2100\frac{veh}{h}$ and would correspond to a density close to $30\frac{veh}{mi}$.
- Considering 1.0 second, such maximum capacity increases to approximately $2900\frac{veh}{h}$, which corresponds to about to $50\frac{veh}{mi}$.
- For lower reaction times (0.5 and 0.25 seconds, respectively), maximum flows are expected to be about $4900\frac{veh}{h}$ and to $7500\frac{veh}{h}$, which correspond to densities close to $80\frac{veh}{mi}$ and to $120\frac{veh}{mi}$, respectively.

It can be seen that a slight reduction of reaction time from current reaction times according to human capabilities[34] would remarkably increase lane capacity. It has to be explained that such MFDs are computed attending to the formula $q = min\{u_f k, (\frac{L-l}{\Delta t})k\}$, where u_f is the free-flow speed ($u_f = 60\frac{mi}{h} = 96.60\frac{km}{h}$), $l = 20ft = 6.1mts$ and L is computed as a function of density, k.

Triangular Macro-Fundamental Diagrams also show a progressive variation if a mixed flow (situations with two different groups of vehicles: Autonomous vehicles and Conventional Vehicles. Each group is assigned a certain value of reaction time) is considered. Variations in a triangular Macro Fundamental Diagram are shown attending to different AV proportion (reaction time of 0.5 seconds) amidst other conventional vehicles (1.0 seconds). If no AVs are considered, the diagram shows the same diagram it has been considered for a reaction time equal to 1.0 seconds. The same situation but for 0.5 seconds occurs if no conventional cars are contemplated. For intermediate shares, the maximum capacity varies progressively in an almost-linear way. Both diagrams are presented in Figure 28.

Finally, it is worth mentioning that traffic lights can be strongly related to an enhanced traffic management for optimizing the network operation, not only in terms of lane capacity but also to enable a quite efficient and optimal management of the road network depending on the traffic atmosphere:

According to Florinda Boschetti and Suzanne Hoadley, 2018, current semaphores are ruled by a quite basic algorithm called "**Fixed-time control**". Basically, current traffic lights are programmed in order to display each phase during an established lapse of time (x seconds, x $\geq$ 0) independently of the traffic atmosphere. A traffic light will display the green or red phase for x seconds whether the street is overcrowded due to peak-hour congestion (e.g. Wednesday, 7:30 AM) or no cars are riding through (e.g. Wednesday, 3:30 AM). Such system does not require any kind of sensors for monitoring the traffic flow: By definition, all the traffic lights are computationally determined to show each phase regularly, and a short but determined cycle is indefinitely repeated from now until the end of the age, which allows to create "green waves" through main corridors and arterials. In sum, no new investment would be required for improving such control system because it is the current one at most cities.

[34] it is stated in Kockelman, 2016 that human reaction time runs between 1.0 and 1.5 seconds.

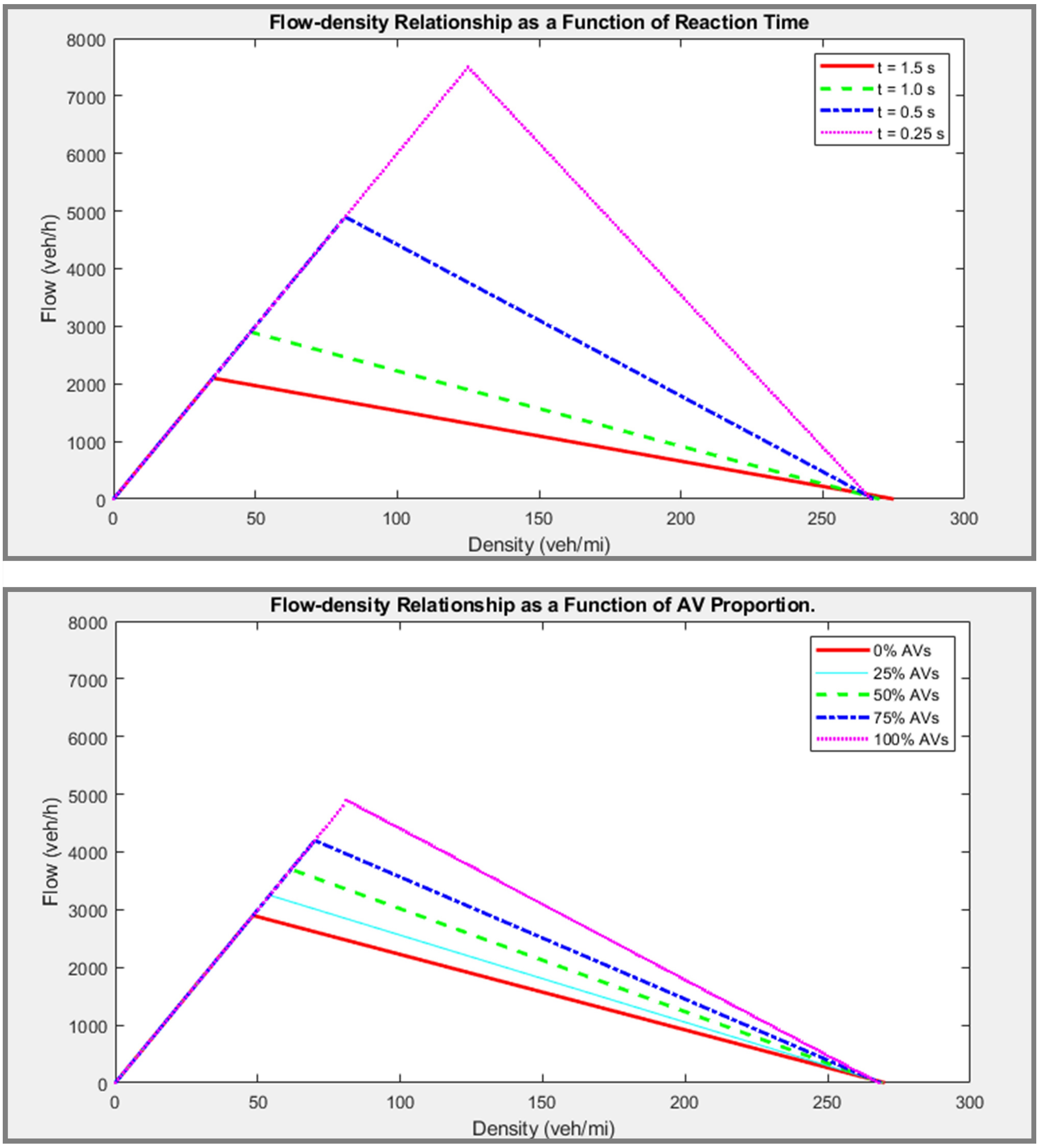


Figure 28: Triangular MFDs attending to reaction time (top) and mixed flow (bottom). ELABORATED FROM Kockelman, 2016

Florinda Boschetti and Suzanne Hoadley, 2018 focuses a bit beyond: three other options (other algorithms) for road management are suggested, but such measures will require more investment. Such three algorithms are presented:

- "**Actuated Control**", which is radically different from current fixed-time control, consists of an algorithm that prioritizes the most demanded streets at intersections, and if no car were waiting for a green light at a certain road stretch, the traffic light for such empty street would not show any green light anymore until a vehicle came from this street. With this algorithm, the main road can be opened for enabling the most-demanded displacements most time, in a similar way as it currently happens at pelican crossings[35]. Although it seems a perfect traffic management system, its main problem is the need of investment: A sensor would have to be placed near the stop line in order to monitor how many cars are waiting for a green light at each line.

- A hybrid algorithm between "Fixed-time control" and "Actuated control" is presented as "**Semi-fixed time control**". It requires the same sensors as the Actuated control algorithm, but such algorithm would be only applied when green fixed-time phases are close to be over. It is mentioned at Florinda Boschetti and Suzanne Hoadley, 2018 that this option provides some advantages in terms of creating and propagating green waves.

- Finally, it is suggested the option of "**Adaptive control**", which consists of an algorithm that seeks to model the vehicular approaches to a given intersection from upstream. Such algorithm seeks to optimize the traffic flow but also maintains the green waves in such manner that enables the most sustainable, eco-friendly and less energy-wasting driving speed between intersections. Nevertheless, this option is the most expensive due to the huge number of sensors that would be needed for its operation.

Such algorithms would become interesting alternatives to "fixed-time control". Unfortunately, the more advantages an algorithm provides, the more sensors and the more investment would be needed.

The strongest point is that from a technological standpoint, an optimal (in terms of number of passengers and freight being transported and in terms of the reduction of average unnecessary stops for all vehicles), sustainable, eco-friendly and adjustable to the border conditions road management would be possible. Such scenario would also be quite expensive but, at least, would be possible.

Zebra crossings

Zebra crossings present a huge difference from signalled crossings: There is no a scheduled time for pedestrians to be allowed to move to the other side. They can do it whenever they want. Pedestrians, instead of waiting for a green phase, only have to approach to the kerbside of the sidewalk at a given zebra crossing and demonstrate to coming drivers their intention to cross through the zebra crossing. A normal behaviour is to demonstrate this by means of trespassing the zebra crossing. Coming vehicles must stop and wait for them until they have left the vehicle's lane. At that precise moment, the vehicle can resume its trip in a safely manner for every participant.

The problematic associated to the interaction between zebra crossings and Autonomous Vehicles has been depicted for signalled pedestrian crossings. There is no the enough experience for claiming whether pedestrian detection systems are safe and precise enough for their implementation with no incidents nor mishaps.

Some alternatives to zebra crossings are provided in the bibliography:

- It is suggested in Public Sector Consultants and Center for Automotive Research, 2017 that footbridges and tunnels over and under major arterials will avoid the road sharing between

[35] Pelican crossings are signalized pedestrian intersections, which are managed on demand. When a certain pedestrian wants to move to the other side, he/she press a button of a control panel and waits for the pedestrian's green light. Due to such characteristics, this kind of crossings are mostly placed in areas where commonly there is a huge road intensity but quite few pedestrians (e.g. residential areas).

pedestrians and vehicles. No interaction between vehicles and active mobility agents would occur.

- The simplest solution provided in Catapult Transportation Systems, 2017 is to upgrade all zebra crossings to signalled crossings. But the problematic just shifts: Instead of facing a zebra crossing, vehicles will have to cope with a signalized intersection. Both kind of intersections are somehow troublesome for self-driving technologies.

Despite a small number of major zebra crossigns could be enhanced to signalled intersections, such solutions are not realistic enough, whether from technical or economic issues. Although being a challenging problem, Autonomous Vehicles are expected to coexist with zebra crossings, and such intersections have to be prepared for them while Connected and Autonomous Vehicles have to consider the existence of these crossings.

Such intersections could be controlled by mast-mounted cameras and infrared sensors (for night vision), which must be constantly monitoring what is happening at a given zebra crossing. Such infrastructure must broadcast to coming connected vehicles in terms of I2V signals whether the intersection is free from pedestrians or not. These cameras and sensors should interpret the current crossing status in a more realistic way than sensors located in vehicles. Jointly with car's information, the presence of a pedestrian would be easier to be detected if there were two ways to detect it than if it were only one.

Such solution is expected to be useful for the early stages, until newer technical innovations were developed. If sensing capabilities were unhurriedly enhanced, sensors would be able to interpret and see the current atmosphere in the vicinity of a certain vehicle in a similar way than a current driver do. Such interpretation could even be unhurriedly performed better and better. A gain in terms of safety would occur if human driving capabilities were replicated but also if the likelihood of human error were mitigated.

Uncontrolled crossings
It has been previously commented that Jaywalking is a common, widespread but dangerous activity, even at minor streets. Jaywalkers could become one of the greatest threats for self-driving technologies. Therefore, to detect such pedestrians is one of the most important challenges that autonomous driving must cope with.

One more time, on-board sensors are not expected to be as precise as human vision and sensing. Mast-mounted cameras must be placed only at zebra crossings, but for sure there will not be cameras nor sensors sensing each road stretch every time, looking whether a jaywalker is trespassing the kerbside or not. One more time, it is worth remarking that on-board units would be able to detect the presence of a hardware device which is broadcasting its current position and could be carried by a jaywalker. Former and newer philosophical questions arise: Would citizens use such devices in a responsible manner?

Jaywalkers are not the only one problem related to uncontrolled crossings: What would happen if a cat, or whatever animal, trespassed the kerbside at a major conventional road in front of a CAV which were only targeted in detecting signals from other units? Such animal would not be carrying an on-board unit: its signal would not be detected, and a fatal crash could occur. Now, lets imagine what could occur if a jaywalker trips while crossing, and his/her mobile phone, which is broadcasting the pedestrian's position, gets two or three metres away as a result of the tripping. Would a coming vehicle, without enough space for braking in a safe manner, avoid the "PEDESTRIAN" (the phone), or maybe would it avoid the "OBSTACLE" (the person)?

Jaywalkers, although they think they are well-controlling the situation, could cause serious problems and accidents to third parties.

An effective objective, according to Catapult Transportation Systems, 2017, could be to make new policies which contemplate jaywalking. Pedestrians who trespass the road land at unallowed

Figure 29: Frontal and back sides of Stop and Yield signs. OWN ELABORATION

Notice that both Stop and Yield signs are the two single traffic signs which could be distinguished from their back side due to their singular shape: an octagon, in the case of the stop sign, and a triangle pointing downwards for the yield sign (all the other triangular-shaped signs consist of a triangle pointing upwards). The reason of the particular shape of such signs is that the information which is provided by these signs is also quite relevant for the vehicles coming from all the road sections which converge at a given intersection.

zones should be fined for their risky, dangerous behaviour. Nevertheless, if educational programmes contemplated jaywalking phenomena and if such programmes were focusing on discouraging such behaviour in terms of informing adequately of the potential risks (it should be informed for getting similar awareness results as it is currently assumed by everyone that roaming on an operative railway or trespassing it could be dangerous), jaywalking would be discouraged and people would perform their side-to-side displacements employing only the official crossings. Moreover, if the average distance between zebra crossings in a given street were diminished, newer official pedestrian crossings would be created and fewer pedestrians would desire to jaywalk. Nevertheless, such solution would imply to increase the number of adapted zebra crossings. In other words: More investment would be needed.

Benefits are expected to result not only in terms of safety but also in terms of security. Newer policies would be useful to fine criminals which were roaming on the roadside with malicious intentions (e.g. disrupting the traffic flow). Nevertheless, the main objective is to fine people who unconsciously could affect the traffic flow.

Yield junctions (and other junctions)

Most non-signalled junctions consist of such intersections that do not require to be managed with the employment of external means in order to operate adequately. Namely, such junctions are expected to work, whether slightly or clearly, under capacity most of the time.

There are two main ways to highlight and regulate these types of intersections: In the first group, the secondary road stretches which converge at a given junction possess a "STOP" sign for vehicles that are riding toward the junction (STOP INTERSECTIONS). At the second one, cars coming from secondary roads will find a "YIELD"[36] sign (YIELD INTERSECTIONS).

[36] Also called "GIVE WAY" sign.

Differences between both groups are quite well-known. Cars which find a “STOP” sign must grind to a halt in a mandatory manner. Therefore, drivers would be able to observe and analyse the situation at the major road before resuming their journey. Otherwise, vehicles which find a “YIELD” sign are not required to stop completely. Drivers may decrease the velocity of their cars if wanted, for observing the environment at the main road. Typical examples of Yield junctions are roundabout and highway accesses.

For human driving, such intersections are designed according to human capacities while driving. Any human driver is able to know the exact moment he/she will be able to cross and/or get incorporated to the main road before reaching the intersection. Therefore, drivers are required to lose momentum in order to analyse the coming traffic flows in a safe way and decide whether they can resume the journey or not.

Self-driving, otherwise, would lead to control secondary intersections in a smarter and more precise way. Nevertheless, since human-driven vehicles have not been completely unallowed to ride through the road network, CAVs and human-driven vehicles will coexist. Therefore, **secondary intersections should remain designed for allowing human participants to take control of and analyse any possible situation**.

V2V and I2V interconnections would ease coming vehicles to understand and assess the current and imminent expected situation at a junction while approaching. OBUs would be able to detect the position and cinematic characteristics of each connected vehicle riding through other roads within a certain radius. Moreover, if such system fails (or cannot work properly due to obstructed wireless signals), information about the current status at the junction could be broadcasted by road-side units (RSUs), considering the information collected from mast-mounted cameras (it is important to consider the possibility of non-connected cars riding through the main road). Therefore, such junctions would be technologically controlled similarly as zebra crossings are expected to be monitored, by means of computer vision and infrared cameras.

The main objective from the traffic regulation’s standpoint would be to create and establish a precise hierarchy in terms of right-of way at each non-signalized junction and intersection adapted to self-driving. Depending on coming traffic flows and on the defined hierarchy, CAVs will wait, if needed, and be steered towards their desired lane in a quite safe manner. Moreover, vehicle-to-vehicle interconnection would make riding cars being steered in order to ease the incorporation of other vehicles to the main road (e.g at a highway access) if needed and if it were possible (e.g. occupying a free internal lane instead of blocking/difficulting the access of any other vehicle if riding through the external one).

4.10 Lane reduction

If the previous sections were merged and summed up, it would be demonstrated that several changes on private motored mobility are expected to occur.

Firstly, new automated vehicles are expected to increase current road capacity. Human reaction time at some semaphored intersections would be even completely eliminated. Moreover, cars are expected to drive closer to each other. As a result of automation, a given vehicle would be able to follow the previous vehicle with a lower headway, due to likelihood of human error reduction caused by vehicular interconnection. A given intersection would be capable to process a greater vehicular flow than it currently can process.

Moreover, existing car/ride-sharing services, which are expected to be enormously improved due to automation, would likely become tremendously popular due to their flexibility (greater than current public transport and almost equal than private vehicles) and their expected low fares. A huge shift from private transportation to car/ride-sharing services, which moreover would symbiotically enhance public transport, is expected to occur. Considering both road capacity increase and these carpooling strategies, road passenger's capacity would be enormously increased. Nevertheless, despite passenger's capacity is expected to be increased, day-to-day passenger's flow would not necessarily increase, because commute demand is not expected to suffer dramatic changes. Consequently, it is likely that as a result of services based on carpooling, it would be noticed a decrease on the number of vehicles riding through a city at peak hours. **Therefore, a given mobility demand would be satisfied using fewer resources**[37], and if fewer vehicles were needed, current roads, which would increase their capacity, would process fewer and fewer cars. **Streets which are optimally dimensioned for human driving would likely become overdimensioned for automated driving.**

Finally, a shift from few efficient, private mobility by car to more sustainable, individual vehicles (Such as electric bikes or electric scooters) is also expected to occur. It is expected that urban day-to-day commutes will be more and more commonly performed using such vehicles. In contrast, inefficient private mobility will become rarer.

These changes would not appear within the first month after fully-automated cars (L5) started to be marketed. For sure, the mentioned events would start to be observed in an unhurried manner, while self-driving technologies would be more and more popularised.

Furthermore, it is worth commenting that during the two first decades of the 21^{st} Century, private mobility in urban areas has been ingeniously, smoothly combated by local administrations, seeking to both promote public transport and more eco-friendly, sustainable modals (e.g. bicycles) and reduce the presence of private, not-so-sustainable vehicles. While strategies to discourage the use of private cars in terms of reducing its usefulness, Public transport has been improved.

Some strategies carried on at a large number of cities around the globe to discourage the use of private cars are listed:

- Creation of Bus Lanes, which can only be used by Taxis and buses, at large avenues.
- Creation of Bike Lanes at major arterials and secondary streets.
- Sidewalks broadening.
- Introduction of a congestion charge for private vehicle users which use to drive through the city centre and congested areas.
- Prohibition to heavy goods and/or most polluting vehicles to enter to urban areas.
- (...)

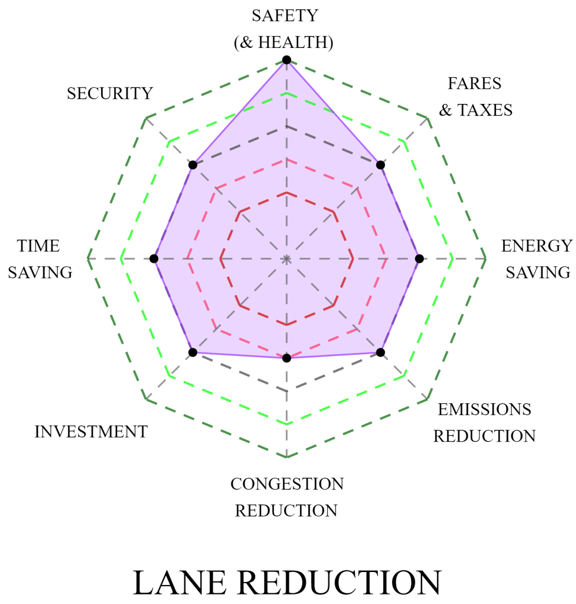


Figure 30: Valuation of lane reduction needs and potential impacts.
OWN ELABORATION.

Strategies which consist of creating lanes with a special purpose (Bus and bike lanes) imply the reduction of conventional lanes. Consequently, the capacity of the road is considerably reduced.

Hand in hand with the expected shift on urban mobility, streets would likely be re-dimensioned, seeking a new optimal land distribution. Strategies related to lane reduction would be implemented, due to the passenger's flow rearrangement. Urban actuations, which would not require enormous investment sums, would seek to both power carpooling services, public transport and eco-friendly personal mobility vehicles and would lead to almost-definitely knock out private mobility, based on petrol vehicles. Consequently, a huge decrease on emission rates is expected.

Some of these urban actuations, which would follow up the guidelines of the former strategies previously commented, are proposed:

- Enlarge the bike lane network, accessing every neighbourhood.
- Broaden bike lanes, in order to both increase their capacity and to allow electric scooters to ride through the bike lane networks.
- Duplicate bus lanes, seeking an increase on public transport capacity.
- Create Pick-Up and Drop-Off areas and Bus Stops.
- Broaden sidewalks and create more green zones (e.g. Creating new gardens at former road lane surface).
- Pedestrianize minor streets.
- (...)

To plan ahead such actuations would be crucial. It is still unknown when it would be possible to implement the mentioned measures, but the most important question here is not when but whether such measures will be within the boundary conditions which would lead them to be implemented.

[37] If fewer vehicles were mobilised every day, it would be produced a fuel and energy saving. This scenario would lead to pollute less.

It is excepted that a scenario with fewer vehicles would be possible and highly probable, and such high likelihood should be somehow reflected on planning documents. CAVs should start to appear on them, in order to clarify what it would be possible to execute if the expected scenario is finally achieved.

If self-driving cars were considered to start to be marketed in the immediate future and the expected impacts were clearly observed after self-driving cars constitute a huge share of the fleet, former planned road expansions, which were born in order to increase road capacity, would have to be rethought (and would likely never become a reality).

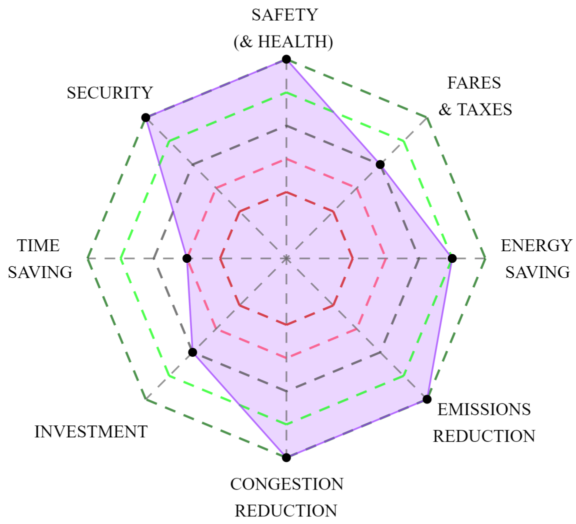
Furthermore, Microscopic modelling softwares could become useful tools in order to plan ahead such interventions and observe and analyse their most likely impacts, which may be produced on such streets to be redimensioned but also on adjacent streets and parallel corridors. Microscopic modelling softwares may anticipate the different problematics and may prove helpful for developing smart management strategies that may lead to a stochastic road management, jointly with a redistribution of the right-of-way of the different lanes at the studied streets (e.g. creating newer "CAV-ONLY" lanes).

Lane width

Furthermore, a certain band of the former kerb-to-kerb land would be possible to be redeveloped, even if no lane reduction were done. Automation is expected to lead to a quite accurate, precise conduction. Human error on driving would be notoriously mitigated and therefore cars would start to drive with high precision within the lanes, which are nowadays sensibly broader than the general car width in order to minimize the likelihood of lateral hits with any other cars or obstacles. The higher precision on automated driving could lead to two different scenarios:

1. Broader vehicles, with more capacity and volume than conventional ones.
2. Narrower lanes. Lane width closer to conventional cars width.

The second scenario referrers to the mentioned land repurpose without affecting neither road capacity nor number of lanes. Nevertheless, it is important to consider an extensive and segregated public transport lane network before implementing lane narrowing: Conventional buses are wider than conventional cars.



ENCOURAGING ACTIVE MOBILITY

Figure 31: Valuation of strategies for encouraging active mobility needs and potential impacts. OWN ELABORATION.

Have you ever been told that if you walk less, your body weight is more likely to rise? Did you know that obesity is one of the most common diseases in the most developed countries and might lead to major health issues? Would you be willing to practise more sport and commute more by walk if you noticed that your lifestyle became more and more sedentary because of your abusive use of your own CAV?

4.11 Further Needs

Automated driving is expected to provide a vast array of advantages. Most of them have been listed throughout the previous section of this document. Some other are given as a result of the listed ones.

For example: Nowadays, depending on the road environment, to drive a car could become a tough, stressing task. A driver must spend all his/her journey putting his/her five senses on the road, which could lead to episodes of fatigue, frustration, annoyance and rage, especially if traffic flow is not as fluid as expected. Such episodes could moreover produce a negative scenario, such as a road accident or a verbal or even physical fight with other drivers.

Automation applied to urban mobility is expected to mitigate the mentioned effects. Former drivers, which do not have to drive anymore for commuting displacements, would not have to be continuously paying attention to what is happening on the road: A transfer of this competence from drivers to vehicles would be produced. Therefore, commuters would not be annoyed by another driver's behaviour anymore. People who formerly used from/to wearily drive to work, would be able to rest while being conveyed from/to their workplace, and would be released from driving task, leading to a more relaxed mobility: Instead of printing their rage on the road with the help of the car horn, former drivers would be able to spend a while reading a book, watching a video, eating a snack or even sleeping while being given a lift by a self-driving car.

A gain in comfort would be unquestionably produced if automation worked as expected. More and more former drivers would start to commute and displace by autonomous vehicles, whether shared or not. Other commuters, which were not capable to drive a car, would be able to be carried to any desired place. Those who did not possess the most adequate financial conditions in order to own a car, could access to sharing services and commute by car instead of public transport, bicycle or by walk. And, maybe, those who used to displace by walk due to shorter journey length, would start to commute more and more by car, due to its irrefutable comfort.

A problematic appears: People would walk less and displace more by car. Since physical activity is enormously important for both mental and corporal health, a decrease on walking and cycling shares would create more healthy concerns, such as a growth of the obesity index.

This problematic is only explicitly commented in Fagnant and Kockelman, 2015, although is quite smoothly treated: It is suggested that although the positive impacts on travel-behaviour such as providing a crucial mobility for the disabled and both junior and aged people, automation may imply other problematics, such as a potential increase of the oil dependence or the increase of obesity rates due to the potential reduction of walk distances.

Furthermore, the case study based on the city of Lisbon, presented in International Transport Forum, 2015, shows that current walking and cycling shares would be dramatically reduced (in more than half of the baseline) if private vehicles disappeared and were substituted by both carsharing or ridesharing services.

In order to avoid a snowball effect related to potential obesity and health concerns produced by automation, health departments should cooperate and discuss with mobility departments and transport authorities from the very beginning. The goal should be to both discourage performing very short journeys by car and encourage people to displace more often by walk, in order to power and prioritise active mobility rather than motored one, when possible. This measure would potentially imply that people would practise more physical activity but moreover would reduce total VMT, which can be summed up in lower congestion, and even lower emissions, especially if the deployment of the electric vehicle were not so rapid as expected and therefore, automated and petrol vehicles must coexist for a certain (not necessarily short) time. It is remarkable that pollution imply other health-related issues, such as the creation of malignant neoplasms at both respiratory and excretory systems, which may lead to premature death. Further information about this could be found in Torres, 2018.

Fortunately, active mobility is currently being powered by local governments (active mobility only makes sense on an urban scale) and previous commented actuations such as broadening sidewalks or creating and enhancing bike lanes, are actuations which worth being implemented for encouraging active mobility. Nevertheless, if the obesity problematic appeared, health departments should consider some other strategies such as **encouraging people to practise more sport**. Jointly with municipalities (urbanism and sports departments), more sports grounds could be constructed, which could become a good development of the recovered kerb-to-kerb land for creating new pedestrianised streets and areas.

Vehicles will also be transformed due to automation. Seeking to improve passenger's comfort, cars will be equipped with ergonomic, folding seats which may allow them to comfortably rest while travelling. Moreover, infotainment devices will be enhanced with the goal of providing a pleasant and individualized entertainment offer, in a similar way as current airlines offer at long-distance travels.

Furthermore, such infotainment devices could make billboards become obsolete, old-fashioned urban elements; in the same way as it has been mentioned for current orientation panels. Advertisements will not appear anymore on the roadside but will start to appear on electronic screens and displays on cars (Gunasekaran, 2019). There is the possibility that ads will be tailored for each passenger attending to their historical preferences, and for example some tailored banners of a certain shoe store website will appear on displays while riding through the vicinity of the given shoe store. Later, while riding through the street where a formerly visited cinema, the schedule of the following films to-be-shown at that given cinema could be depicted on vehicle's screens.

Impacts on the different zones of cities.
A very important topic that deserves being expressed in this report is the likely impact of AVs on urbanism. Depending on whether autonomous cars would be mostly used in a shared or individual way, their impacts on the different areas of a given city could be notably different, as it is depicted at Bits and Atoms, 2017. The predominant way of usage of autonomous cars, which may be very different even between nearby cities at the same country[38], may determine, for example, the parking needs at a given zone (if AVsharing systems were generally used, more PU-DO platforms would be needed, and otherwise, if private AVs were extendedly utilized, fewer PU-DO areas and more parking facilities close to high-demanded hubs will be required).

Such impacts are presented from the areas with lower price of land (countryside) to the most exclusive, higher priced zones:

+ In the **countryside**, where automotive automation presents an opportunity for automated farming and other automated tasks in the primary sector, some other problems arise:
    - **AVsharing** would present the opportunity of enhancing current rural tourism. The countryside could become more accessible from cities, which therefore could contribute to endanger natural, unspoiled and almost-unspoiled natural environments and ecosystems.
    - **Private-owned autonomous all-terrains** may also ease the access to such natural areas which currently are almost-inaccessible by human-driven all-terrains. Recreational activity could impact negatively on such natural environments.
+ **Country towns** and population nucleus far from main cities may also be positively or negatively affected by vehicular automation:
    - **AVsharing**, which would be based on ridesharing and carsharing services that would serve the main urban regions may become inaccessible to some municipalities which are not included within the metropolitan area or, namely, some municipalities are left aside by the companies which operate such services. Therefore, housing opportunities as such villages could become reduced and the population of these nucleus could experiment a notorious decrease.
    - **Private-owned AVs** could lead to the proliferation of "CAV-ONLY" lanes at interurban roads. It is expressed in Bits and Atoms, 2017 that such fact could become an opportunity for car owners to shift their current human-driven vehicles to CAVs.
    - Nevertheless, automation present some other positive opportunities to rural towns, such as the enhanced accessibility to such areas of typical urban activities, such as shopping (the commercialized products could be easily delivered to exurban areas) or other recreational activities and services, for example, *Bookmobile vehicles*, which typically provide public library services for the inhabitants of the less-populated towns.
+ **Suburban areas** may experiment very different impacts depending on the different AV exploitation ways:
    - **AVsharing** may lead to the improvement of city-to-suburb and suburb-to-suburb public transport[39] (e.g. the proliferation of automated BRTs and Trams). Notorious urban developments in the vicinity of main arterials and corridors are furthermore expected to occur.
    - **Private-owned AVs** may lead to the so-called "Waze Effect"[21, *page* 44], caused by smart navigation systems which may imply the diversion of an important share of traffic flow to secondary, residential streets from main arterials. Moreover, the diminished logistics costs would imply the proliferation of small and medium shops and businesses based on proximity, closeness to their customers.

[38] it could also be differences on the way of usage of AVs even between the different neighbourhoods of the same city! (e.g. if the differences between average incomes of each neighbourhood tended to be enormous. It is assumed that private-owned AVs will require a much greater investement, from a microeconomic standpoint, than AVsharing).

[39] Further comments on urban public transit are expressed at the following section of this report.

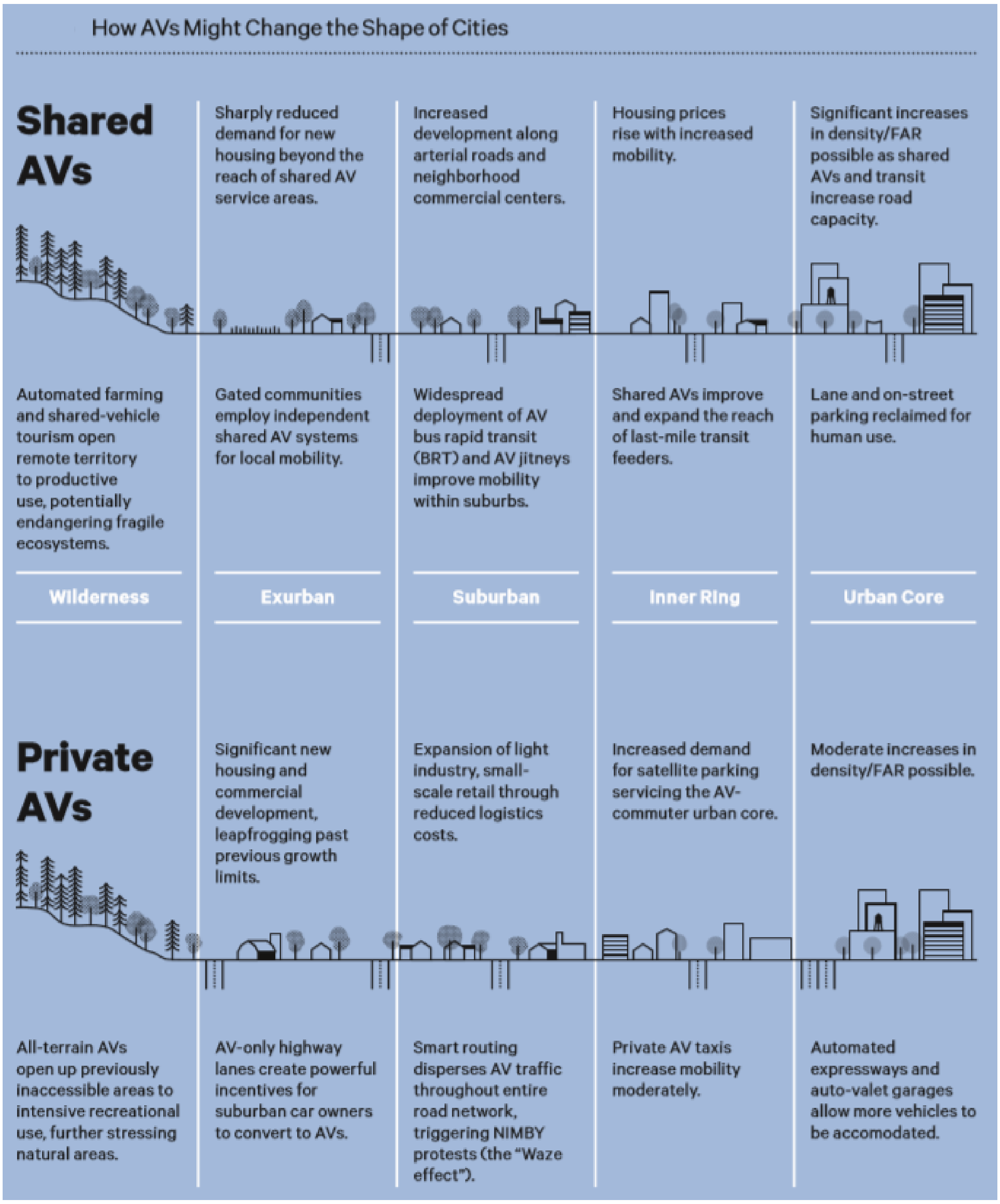


Figure 32: Likely impacts of self-driving technologies and products on urbanism, as it is presented at bits and atoms, 2017

+ The **different neighbourhoods of the main city** would have to cope daily with great amounts of AVs:

    - **AVsharing** could become a very useful transportation system. As it has been demonstrated across this paper, car/ride-sharing services could severely enhance urban mobility and therefore, if urban trips were easier, the housing prices at some well-served neighbourhoods might notoriously ascend.
    - **Private-owned AVs** may increase the demand of parking. There is the possibility of creating satellite parkings at lower-priced lands, which would imply the creation of "zero-occupancy" journeys, therefore increasing Vehicle Miles Travelled and energy wasting for steering such empty vehicles.

+ Finally, the **city centres** should be prepared for the starting apparition of AVs:

    - **AVsharing**, jointly with **autonomous public transport** would optimize the passenger's flow. Occupancies of vehicles could become greater than nowadays, and therefore, current demands could be satisfied with lower numbers of vehicles. Thus, the possibility of recovering current road land for other urban uses appears.
    - **Private-owned AVs** would not modify the current occupancy rates but may increase the passenger's demand. Thus, the number of cars riding through the streets could increase, and cities should be prepared for such possible fact. The creation of reserved lanes for Autonomous Vehicles could optimize the traffic flow, and furthermore, an optimal parking system should be created in order to provide a proper service to newer and frequent parking users, but also to mitigate the "zero-occupancy" journeys, which may lead to worsen the overall level of service of the road network.

- To conclude and sum up, it is worth mentioning that each city in the world could become an isolated case, and therefore each city deserves being studied and analysed in order to know whether their citizens use mainly private-owned AVs or AVsharing services. Such way of utilization may show notorious differences even on an intra-city scale. Depending on the studied behaviour, a city should be prepared for their expected impacts, but also such impacts should be monitored in order to observe possible variations and their possible secondary impacts, that could evolve with time to major problems.

- Moreover, it should be considered that automation could contribute to the final stages of rural depopulation, making current inhabitants of the exurban areas to move to main cities due to the non-connexion to AVsharing systems, the lack of other opportunities at rural villages and the automation of primary sector tasks. **Administrations which seek to cope with rural depopulation should consider the risks that automotive automation could make greater**.

Test areas and corridors.
Some countries have started to develop and enable road stretches and closed circuits with the aim of providing a reliable infrastructure basis where CAV tests and trials can be performed, and furthermore, where new CAV systems and products can be developed while observing and analysing their behaviour and operation. As a whole, the set of such test areas is focused on forming a representative subset of the overall road network: There are highway stretches, single carriageway road stretches and urban streets. These areas may be clustered into two groups: Closed and open circuits.

* **Closed circuits** may only be used by such vehicles which are intended to be monitored and analysed.

* **Open circuits** are such road segments (a subset of the overall road network which are being used daily by a finite number of vehicles) which are adapted in order to conduct researches and studies of AV in real traffic environments.

It is very important to remark that closed circuits are especially conceived for conducting trials which may not affect any other road participant and will not interact with real traffic conditions. Otherwise, open circuits are intended to observe the interaction of the CAV vehicles and products with day-to-day traffic circumstances: Vehicles being tested are mixed with human driven cars.

Such trial zones are being conceived as public-private partnerships (PPP) which are generally participated by governmental administrations, centres of research [universities] and telecommunications and automotive companies. The main idea is that every participant may make use of such test areas.

Further beyond testing the newer products, test areas present some other objectives, which are listed as follows.

* Enhancing **5G** technology and taking profit of such technology in order to **improve road safety**.
* Enhancing **ITS-G5** communications seeking to develop an **optimal road management depending on current traffic status** for both connected and non-connected vehicles.
* Conducting **platooned trucks tests** and **automatic lane changing tests** at mixed-traffic conditions.
* Providing **stronger regulatory frameworks**.
* Standardization of **cybersecurity systems**.
* Standardization of self-driving algorithms at a **trans-national scale**.

NOTE: The presented objectives are expressed in Carnet, 2019 in a similar way as they have been written in the present document. Nevertheless, the listed objectives are gathered at Carnet, 2019 from Bundesministerium für Verkehr und digitale Infrastruktur, 2015, C-ITS Corridor, 2015 and European Commission and Digital Single Market, 2018.

Some corridors and test closed circuits have already been enabled and commissioned. For example, in France[40], a 12-kilometer closed circuit which represent different road categories has been adapted for AV trials. Furthermore, the European Commission European Commission and Digital Single Market, 2018 intends to create cross-border highway corridors between nearby cities from different countries where CV and AV trials may be carried out: It has been mentioned in pages 14 and 20 of the present report that there could be some shallow differences between countries in terms of road marking (width, length, colour, etc) and signage (font, colour, shapes) and the objective is to check whether the driving systems are able to recognize the traffic signage and road markings coping with such cross-border variations or not, leading to making feasible transnational CAV trips.

One example of the mentioned corridors is the Porto-Vigo corridor, which will join Porto (Portugal) and Vigo (Spain) between them and has been started to be developed in 2018. Moreover, in Germany, some highway [*Autobahn*] stretches are being used as testing corridors,break such as the "Cooperative ITS Corridor" (C-ITS Corridor, 2015), which actually consists of a major European corridor that gets through three EU countries and joins the cities of Rotterdam (The Netherlands), Frankfurt (Germany) and Vienna (Austria), based on the Autobahn A3 route. At the C-ITS Corridor some trials on lane management and its notification via ITS-G5 technology are being carried out. Some information about the object of the C-ITS Corridor project is shown in Figure 33.

Moreover, some other testings have already been performed in some road stretches that were closed and managed just for allowing the completion of these testings. Some of these test have

[40] Published in the newspaper "La Vanguardia", June 23rd, 2019 Edition.

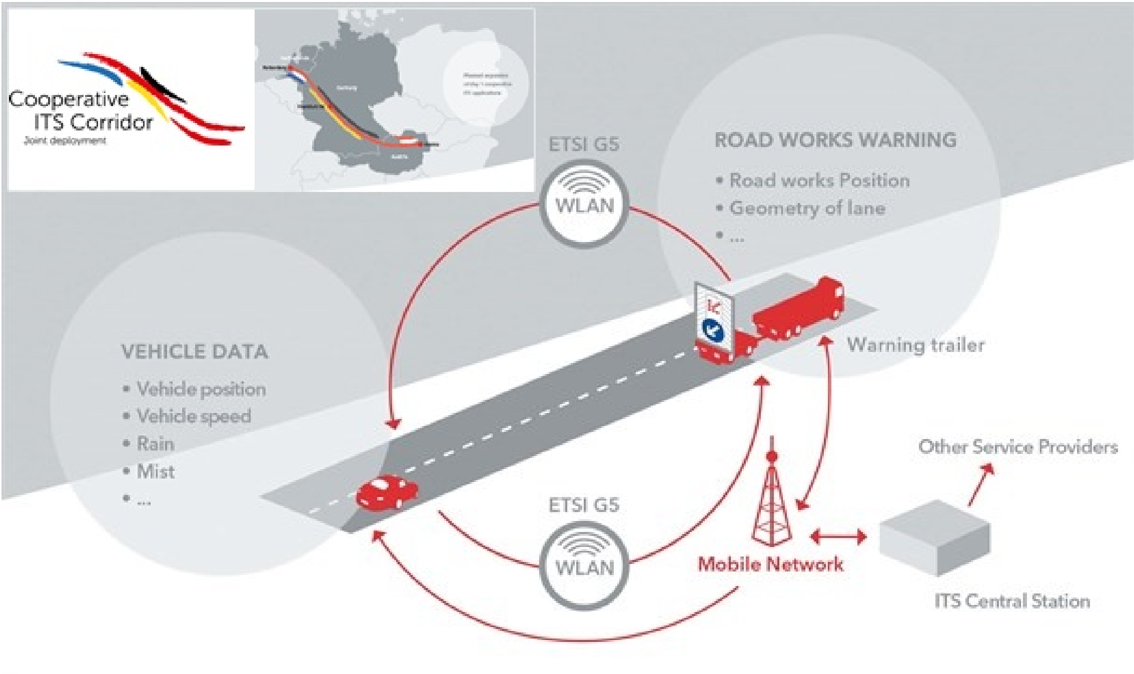


Figure 33: Information about data transmission at the *Cooperative-ITS Corridor* Project. C-ITS CORRIDOR, 2015

Figure 34: Newer traffic signs in Girona, Spain that inform about the existence of a CAV-ONLY lane destined to the performance of the testings related to project INFRAMIX. TWITTER (@punsix)

been performed in relation with the project called AutoCITS (AutoCITS, 2016), which consisted of a series of testings carried out in France, Spain and Portugal. This project was aimed to test some connected vehicles, autonomous vehicles and connected and autonomous vehicles in different weather conditions, as well as to check the behaviour of the vehicles in relation with some different traffic warnings. The test were performed in some given highway stretches in the surroundings of Paris and Lisbon, and at the HOV lane of the spanish A-6 highway, where 10km of such lane were adapted with 15 **ETSI ITS G5** RSUs . Some universities, such as the Polytechnical University of Madrid and the University of Coimbra participated in the project, which moreover checked the behaviour of some autonomous shuttles in the city of Lisbon. The testings were performed between november, 2016 and march, 2019.

In addition, some tests were performed[41] in relation with the project INFRAMIX (Road Infrastucture ready for mixed vehicles traffic flows) were carried on in Catalonia in September, 2019, between the 12^{th} and 15^{th}. These trials were performed on the external lane of a stretch with a lenght of twenty kilometres at the AP-7 toll highway near the city of Girona. The main target of this project is also to try and enhance the G5 system for V2X communications.

The testings were performed with several vehicles, which were conveying a person who had to be ready and prepared for regaining the control of the vehicle in case the self-driving systems failed. The preparation of these experiments required, jointly with the installation of some G5 antennas along the road stretch, the reservation of such external lane for the testings (i.e. it was temporary designed as a CAV-ONLY lane) and it implied the creation of new traffic signs, which were created only for conveying to human-drivers the information about the existence of a lane which can only be used by autonomous vehicles. Some images of the newer signs are presented in Figure 34.

[41]Published in the newspapers "La Vanguardia", September, 9^{th}, 2019 and "Expansión", September 10^{th}, 2019 Editions.

4.12 Some notes about Public Transport.

Focusing a bit beyond, it is also worth discussing the possible impacts that automation may cause on public transport systems.

During the two first decades of the twenty-first century, some cities have adapted or are planning to adapt their aged metro network for automation, seeking for a better operation in terms of capacity increase and faster journeys. In such cases, the metro companies have to prepare their own infrastructure for their own trains, and no other participant can make use of such improved infrastructure.

Automation would be easier for buses. Logically, if roads were prepared for the correct operation of private CAVs, the same infrastructure, by definition, would moreover be prepared for AV Buses. If a given city were prepared for an unhurried automation of the private vehicles' fleet, a given public transport company would be able to automate its operative vehicles (namely, buses) and its investment could only be focused on adapting vehicles and purchase new ones for automation, and benefits may come from a more efficient operation (safer and faster journeys), raise of the number of journeys and improved schedules (more vehicles could compose the fleet) and a reduction of operative costs (no drivers would be needed for driving the buses and thus, their wages have not been to be paid. According to Bits and Atoms, 2017, the annual average wage of a bus driver in the USA in 2015 amounted to $ 39,410) . Although road will be prepared for automation, other requirements arise.

For example, the design of buses could change. BRT (Bus Rapid Transit) systems appeared as an alternative to modern trams, which imply high expenses in terms of infrastructure. Buses for such services offer higher capacities than conventional buses (in other words, these buses could be considered as the intermediate-size vehicles between buses and trams) and therefore are being implanted in more and more cities due their potential of increase capacity with low investment required for their implementation and management, which could imply a reduction of the **out-of-pocket fares** of such systems.

In terms of doors distribution, such buses could start to look like modern trams on a new stage: For example, since such vehicles would be driverless, no room for the driver would be needed, and thus, buses could become completely symmetrical. Such vehicles could be equipped with doors for customers at both "port" and "starboard" sides of the vehicle. Such measure could be interesting, for example, in terms of considering the possibility of placing a bus stop at the left side of a street coming from upstream (considering any right-hand traffic country), just before an intersection where the bus must turn left.

Bus operators would also be able to manage their routes on demand, depending on current traffic or even depending on the customer's requests via applications for mobile phones. Therefore, the current physical borders that exist between ridesharing systems and public transport systems could be blurred or even vanished: Shared vehicles and all sized buses on-demand would coexist on our streets.

Bus companies can update and improve their fleets, seeking for a more sustainable operation in terms of reducing the energy wastage, emissions and optimizing travel times. Connected buses could help to mitigate "Bus-bunching phenomena", and thus, offer an improved service for the bus routes where such phenomena are most likely to appear (buses serving a given route would be constantly knowing the distance and timing with the previous and the next buses, and therefore, the vehicles operating such route would be able to offer the service in a faster way and keep the average headway and/or spacing with the previous and next buses). Average capacity of buses may be increased, and wages would be centred only in management and maintenance crews, so therefore the number of vehicles which compose the fleet would be possible to be increased from the current situation, leading to reduced headways between vehicles.

It is stated in Carnet, 2019 that automated public transportation is expected to show a singular change: As soon as the automation and electrification of the public transportation services become a reality and the number of vehicles is no longer linked to the number of human resources for operating the fleet, a change in the overall fleet composition and therefore some significant changes in the route network design would be possible.

Mid-sized buses are expected to become the most suitable vehicles for providing proper public transportation services (a given demand, q, which nowadays is transported with a given conventional bus route with headway h_c and capacity of their buses C_c would be conveyed with an automated bus route, whose headway h_a must be lower than current h_c because the capacity of such buses, C_a is expected to be also lower than C_c). The requirement for satisfying such objective is to operate the given line with the most suitable number of vehicles, n, which depends on the bus line headway: (Zhang, Jenelius and Badia, 2019)

$$h_i = \frac{\gamma C_i}{q} \quad \mathbf{(1)} \qquad\qquad n_i = \frac{t_{rnd}}{h_i} \quad \mathbf{(2)}$$

γ being the mean occupancy rate and t_{rnd} the round-trip travel time of the given bus line.

Such mid-sized vehicles could be operated and managed in a smarter way than current buses. There's the possibility of coupling them: each mid-sized bus could be considered as a coach of a train, which could autonomously join, or split a given set of coaches. Each self-driving vehicle may drive close to other buses, forming a longer bus unit as a whole, which serve a given corridor that hosts a notable demand taking therefore profit of the aerodynamic benefits which platooned driving is expected to offer, and later such buses may automatically split from such unit in direction to the different final stops in the suburban areas. Current networks could be re-adapted in order to form Public Transport networks based on branched routes.

This new vehicular design for public transport may change the operational costs structure of the transportation companies, and will require, in case it were deployed, to adapt current public transport stops in order to allow a bus train to occupy the whole bus stop without trespassing any other land area. Each stop must be designed to enable a safe stop for a bus train formed by n coaches, being n the number of branches of a given corridor (the maximum number of destinations that a bus train which stops at a given platform could reach).

Automated Shuttles

Another topic involving collective transport could be related to Automated Shuttles. Currently, shuttles are services that link two or more high-demanded hubs, such as airport terminals, between them and/or with another strategic point. The schedule/headway of such services is commonly fixed, and the headway is quite low due to its huge demand at the foci. Other examples are shuttles that join a high demanded airport terminal or main train station located on the outskirts with the city centre.

Shuttles are currently served with two kinds of vehicles. Most common ones are operated with conventional buses, which are operated by a driver. For example, both shuttles that link the two terminals of Barcelona El Prat Airport with the city centre or the shuttle which links both terminals between them. Other shuttles such as people movers, are already automated, but the technology used and the required dedicated infrastructure is quite expensive. Therefore, such kind of shuttles are most typical for quite short distances but the demand of displacement between both hubs is enormously huge. The most typical and clairvoyant example are such shuttles whose unique function is linking a Satellite Terminal of an airport with the main one (e.g. the shuttles which links the main buildings of the Terminal T2 of the Munich Josef Strauss Airport and Terminal T4 of the Madrid Barajas Adolfo Suarez Airport with their respective satellite terminal buildings).

Figure 35: Automated minibus that links Rivium Business Park with Kralingse Zoom Metro Station in Rotterdam, The Netherlands. Notice that the dedicated lane for such service is the lane made out of concrete, and the intersection with conventional traffic lanes is controlled with level crossing barriers. GOOGLE MAPS.

Automated Buses could substitute or become a low-cost alternative for such conventional buses and people movers. Shuttles being served by conventional buses could be managed with automated ones if the road infrastructure, which may be shared with other vehicles, were prepared. Otherwise, newer people movers would not be necessary but other kind of vehicles, which may be cheaper due to the large extension of automotive industry, may replace the need of a people mover but may circulate throughout a dedicated infrastructure (for example, a tunnel under the runways and aircraft's platform).

Some trials have been done. According to Catapult Transportation Systems, 2017 and other consulted bibliography, a service consisting of automated PODs[42] connects a car park with the Terminal T5 of the London Heathrow Airport. Furthermore, an automated service consisting of small buses joins a business district in Rotterdam, The Netherlands, with a nearby metro station.

Such services ride throughout exclusive lanes, and there is no interaction with other vehicles: PODs and minibuses are just programmed to link the given stations through the given lane but are not expected to share its platform with human-driven buses. In fact, surprisingly, intersections with conventional lanes in Rotterdam are controlled with level crossing barriers, so it is assumed that any vehicle should interfere with such system because the likelihood of cars-automated buses interaction is mitigated with such barriers. This is shown in Figure 35.

Pre-determined routes

Finally, it is worth mentioning that the automatization of a Public Transport service could be an easy task, especially if compared with automating private vehicles or on-demand services. Bus lines possess the peculiarity that their routes are predetermined. All the buses that operate a given bus line use to ride throughout the same streets unless some special traffic management measures had been implemented. For that reason, it would be possible to configure the bus self-driving

[42] A POD is a small vehicle with quite low capacity: Just for one or two passengers.

Figure 36: Semi-autonomous trolleybus that links Castellon Harbour (Grao) with Jaume I University Campus (UJI) in Castellon, Spain. Notice that the dedicated lane for such service is equipped with two parallel sets of markings which create a fictitious track which is being observed by a computer-vision camera placed over the info panel of the trolleybus. OWN ELABORATION.

algorithms for making them follow a given usual path. This path could be abstract (for example, could be well-marked on a digital map platform) or could even be physically marked on the road surface.

In this connection, it is important to highlight the case of the semi-autonomous trolleybus service which operates in the city of Castellon, Spain, since 2008. The service was created as a shuttle which connected the city centre (Ribalta Park) with the Campus of the Jaume I University (UJI) and has been later extended towards the city harbour passing through the city centre. This service rely on dedicated platforms. Most stretches of the dedicated platform have two parallel road markings which are followed by a computer-vision camera on the public transport vehicles. This camera creates a non-physical track that the vehicle must follow. Nevertheless, despite this service is intended to be self-driven and the infrastructure is prepared for it, such services have been always operated by human drivers. All these features can be seen at Figure 36.

Trolleybuses in Castellon are able to follow a given path which is marked on the road surface, in the same manner as trams follow the steel tracks which are disposed on the road for them. Nevertheless, the difference between such trolleybuses and trams is that these trolleybuses do not have to mandatory follow the track if the operator does not want to. It offers the priceless advantage that vehicles could be removed from the dedicated infrastructure in case of need or emergence. Furthermore, the trolleybus system in Castellon is formed by vehicles equipped with batteries, and can be driven without contacting hundred percent of the time the fixed electricity wires. The mentioned system, which is based on the principles of the system called ART (Autonomous Rail Transit) that is being developed in some chinese cities (Newman, 2018), offer a public transport service which is much more flexible than conventional trams, which implies that the overall transportation network could operate in a more reliable way.

Nevertheless, it is also important to mention that making buses follow a given path leads to make their wheels be constantly abrading the same asphalt surface. Meanwhile, most of the lane surface does not show any abrasion because no wheels could touch them. It can be seen at Figure 36 that the wheels of the vehicles are causing the erosion of some bands of the asphalt superficial layer: Such bands present approximately the width of the wheels of the trolleybuses. Therefore, it can be deduced that making heavy vehicles being kept centered on a certain lane would create the need of increasing the resources for asphalt maintenance.

The future of Public Transport is still an unknown. Thus, some pilot projects seeking the most optimal options for the autonomous public transport vehicle have been deployed and some other services are being adapted with newer technologies that assist the drivers in the driving functions. For the companies, the principal objective is **reducing as much as possible the operational costs** that providing their services to citizenship imply, but moreover, with the goal of taking care of the planet, the second but not least objective is **reducing the amount of energy needed** for providing the basic mobility services.

4.13 Foresight of socio-economic impacts.

The proliferation of self-driving vehicles is expected to cause a great, visible economic impact in the macroeconomic scale of countries. But, due to the great number of vehicles that compose the vehicular fleet of a given country (for example, in the United States of America, the number of vehicles that compose the fleet is estimated to be around 125 million vehicles[43]), this impact would be caused by adding the overall impacts in a microeconomic scale.

Until these days, car ownership has been following a model that has not been strongly modified. Historically, the requirement of a licensed driver for its driving, and the model that insurance companies have been following, based on linking a certain vehicle to a certain driver, jointly with some other implicit advantages like the availability of using the vehicle immediately after taking the decision of displacing by car, have led to consider cars as a necessary good for families. At the most developed countries, almost all families have purchased and keeps maintaining, at least, one car. In fact, one of the most important socio-economic indicators that is used for representing the development level of a given country or region is a rate that measures the number of vehicles by each 1,000 inhabitants.

The emergence of newer technologies and applications for mobile devices is currently shifting personal mobility. In some cases, due to the newer, more efficient and eco-friendly ways of displacing by means of sharing a vehicle, is causing that more and more young commuters are losing their interest in getting licensed for driving: More and more young people are postponing taking lessons at driving schools since they reach the minimum age for being allowed to get a driving license.

This situation is only being produced only by the proliferation of the so-called *Information and Communication Technologies* (ICTs), which allow day-to-day commuters to know exactly at what time will a given bus halt at a given bus stop before leaving home or while going shopping at a given department store. If the possibilities of displacement that self-driving technologies would offer (e.g. automated ridesharing services or automated public transport systems) were considered together with the existent new ways of commuting that ICTs are offering, the potential shift on mobility and car ownership from the current situation could be enormous and a great share of people from every age bracket and gender will not want to drive a car anymore.

In this connection, at Fagnant and Kockelman, 2015 are given some figures that seek to provide an order of magnitude of the overall savings that the deployment of Autonomous Vehicles would imply in the USA, but also provide the overall savings divided by the number of autonomous vehicles. In other words, the saving per each single AV.

Firstly, it is worth mentioning that three different percentages of AV market penetration are considered: 10%, 50% and 90%. Moreover, it is expected that each step towards the complete automatization of the fleet is assumed to reduce the overall number of vehicles: While the number of AVs operating in the USA is assumed to be around 12 million for the 10% AV penetration case, it is expected to be 45.1 million and 65.1 million for the 50% and 90% AV penetration cases. Note that these figures do not follow any kind of linear progression.[43b]

In other words, the assumed total number of vehicles (Both AVs and human-driven cars) is assumed to be 120 million at the early introduction of AVs, while is assumed to be around 72.3 million at the last introduction stage. Therefore, Fagnant and Kockelman, 2015 considers that the automation of the fleet would reduce the number of vehicles riding through the U.S. road network approximately by 40%.

[43] [43b] This figure could not have been reliably contrasted. Nevertheless, 125 million vehicles is an approximate figure being extrapolated from the fleet data for the several AV market share scenarios drafted in Fagnant and Kockelman, 2015, when it is assumed a national fleet composed of 120 million vehicles when the AV penetration share would be 10%, 90 million vehicles for the mid-transition towards autonomous driving (50%) and 72.33 million vehicles for an AV market share of 90%.

% AV market shares	10%	50%	90%
	(per year)	(per year)	(per year)
Economic crash cost savings per AV [A]	$ 430	$ 770	$ 960
Comprehensive crash cost savings per AV [B]	$ 1,390	$ 2,480	$ 3,100
Congestion benefits (Savings per AV) [C]	$ 1,320	$ 590	$ 550
Parking savings per AV [D]	$ 250	$ 250	$ 250
Overall economic cost savings per AV (A+C+D)	$ 2,000	$ 1,610	$ 1,760
Overall comprehensive cost savings per AV (B+C+D)	$ 2,960	$ 3,320	$ 3,900
Economic crash cost savings	$ 5.5 Billion	$ 48.8 Billion	$ 109.7 Billion
Comprehensive crash cost savings	$ 17.7 Billion	$ 158.1 Billion	$ 355.4 Billion
Overall economic cost savings	$ 25.5 Billion	$ 102.2 Billion	$ 201.4 Billion
Overall comprehensive cost savings	$ 37.7 Billion	$ 211.5 Billion	$ 447.1 Billion

Table 2: Foresight of socio-economic impacts of autonomous vehicles in the USA.

OWN ELABORATION FROM FAGNANT AND KOCKELMAN, 2015.

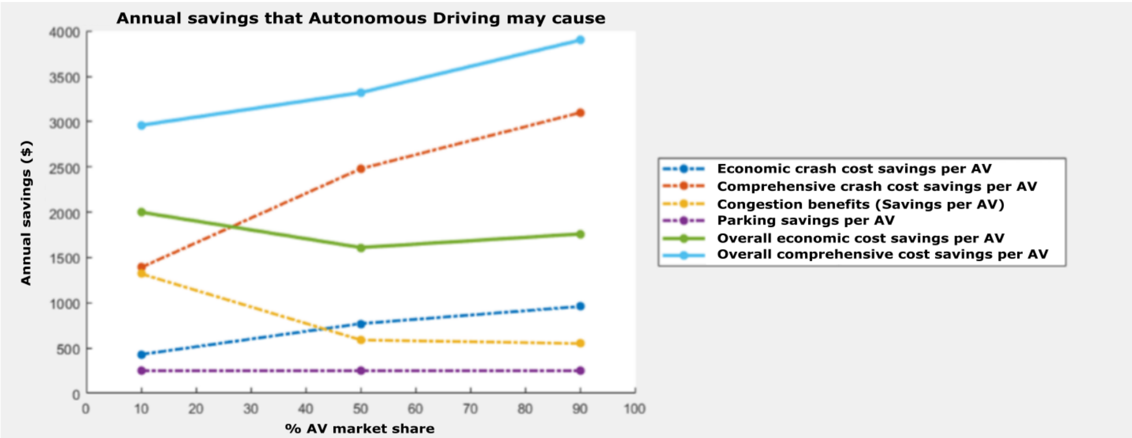


Figure 37: Graphic that represents the information delivered in Table 2.
ELABORATED FROM FAGNANT AND KOCKELMAN, 2015. TRANSLATED FROM CARNET, 2019

Table 2 shows the foreseen annual savings that AVs could produce in the USA as they are published in Fagnant and Kockelman, 2015. Depending on the market share, AVs could generate such economic cost-savings up to $ 2,000 per vehicle and year at early stages, that would descend to $ 1,760 per AV with a 90% AV market share and would have a minimum peak at mid-transition. Moreover, AVs could generate annual comprehensive cost-savings between $ 2,960 and $ 3,900. It is important to remark that these comprehensive savings are expected to become greater as the AV market share keeps growing.

Finally, it is worth remarking that the overall economic savings that AVs are assumed to run between $ 25.5 Billion (10% penetration share) and $ 201.4 Billion (90%) per year. Otherwise, the overall comprehensive savings would be much larger: they are assumed to grow from $ 37.7 annual Billion (10% market share) up to $ 447.1 Billion (90%).

Among this report, it has been expressed some of the most technical aspects which, after solving the most challenging barriers, would lead to convert Autonomous Driving technologies in the base for new modals, which are expected to be safer and more eco-friendly. The transition towards a world of mobility based on self-driving systems is quite important from an engineering standpoint, but the importance of Autonomous Vehicles is much greater when talking about economics: The fact that AVs would reduce the number of crashes, jointly with parking savings and congestion benefits may imply every year almost half trillion comprehensive dollars (only) in the USA.

% AV market shares	10%	50%	90%
	(per year)	(per year)	(per year)
Overall economic cost savings in the USA	$ 25.5 Billion	$ 102.2 Billion	$ 201.4 Billion
Overall comprehensive cost savings in the USA	$ 37.7 Billion	$ 211.5 Billion	$ 447.1 Billion
Overall economic cost savings in Spain	$ 4.92 Billion	$ 19.70 Billion	$ 38.83 Billion
Overall comprehensive cost savings in Spain	$ 7.27 Billion	$ 40.78 Billion	$ 86.20 Billion
Overall economic cost savings in Catalonia	$ 0.71 Billion	$ 2.86 Billion	$ 5.64 Billion
Overall comprehensive cost savings in Catalonia	$ 1.06 Billion	$ 5.92 Billion	$ 12.52 Billion
Overall economic cost savings in all the world	$ 245 Billion	$ 981 Billion	$ 1,933 Billion
Overall comprehensive cost savings in all the world	$ 362 Billion	$ 2,030 Billion	$ 4,292 Billion

Table 3: Foresight of overall socio-economic impacts of autonomous vehicles in the USA, Spain, Catalonia and all around the globe.

OWN ELABORATION FROM THE DATA PUBLISHED AT FAGNANT AND KOCKELMAN, 2015.

With the figures which are presented in Table 2, and in order to approximate the expected savings that autonomous driving may imply if it were deployed in Spain, a simple cross-multiplication could be done.

DISCLAIMER: Obviously, the costs presented in the following paragraphs will be expressed in american dollars, continuing with the methodology used by Fagnant and Kockelman, 2015 and considering the same values of expected annual savings per AV that are considered in that paper. The objective is to provide an approximation of the likely savings that Autonomous Driving would imply. This methodology will be used instead of considering different market prices for Spain and for the United States of America. (In reality, Spain and the USA are quite different in terms of microeconomics: For example, the Average annual wage in the USA represents a value which is almost twice the Spanish value of the Average annual wage).

For computing this approximation, it will be only used the total number of the sedans[44] that are registered in Spain (about 24 million sedans) and in the four provinces that compose Catalonia (about 3.5 million sedans)[45]. Thus, the total savings would be approximated by terms of the following cross-multiplication:

$$\frac{Total\ number\ of\ vehicles\ in\ the\ USA}{Total\ number\ of\ vehicles\ in\ country\ x} = \frac{Expected\ savings\ caused\ by\ autonomous\ driving\ in\ the\ USA}{\textbf{Expected savings caused by autonomous driving in country x}}$$

where both numerators and the left denominator are known. The single unknown to be computed (Expected savings caused by autonomous driving in country x) is located downstairs at the right side of the equation. This unknown has been marked in bold letters and in magenta colour.

Table 3 presents the computed overall expected savings that AVs may cause in Spain and Catalonia for the same considered market shares.

Finally, in order to provide a slight approximation to the overall economic and comprehensive savings that AVs could imply in a world-scale. Nevertheless, to know the total number of vehicles in all the world is much more difficult than knowing the same figure for just one country. Therefore, it has been assumed the approximate figure of 1.2 billion (1,200 million) cars as the total number of vehicles that are currently composing the world-scale fleet. In other words, it is assumed a number of vehicles that represents a bit less than ten times the number of vehicles of the USA, which is one of the most developed countries that represents almost the 5% of the world's population. The expected savings are presented in Table 3 and claim that the overall economic cost savings

[44] For this exercise, it has been considered the number of sedans instead of the total number of vehicles in order to provide a minimum benchmark that could represent the expected savings.

[45] These data have been extracted from Dirección General de Tráfico, 2019.

in all the world could reach, if autonomous driving were widely-deployed, an amount of almost two trillion american dollars per year, while the comprehensive annual cost savings could largely overpass the barrier of four trillion dollars.

It is important to finally note that in the case considered at Fagnant and Kockelman, 2015 it is implicity said that the more AV market share were reached, the greatest economic and comprehensive savings were produced. Those savings could speed a bit up during the final stages of the transition (i.e. at the transition stage that corresponds to proceed from a 50% of penetration share up to a 90% of market share).

Figure 38: Cartographic basis of Barcelona's *Eixample*
.

5 Simulation of traffic performance on a given road network.

Seeking to supplement a basic case study to this report, and in order to anticipate and quantify some of the expected benefits that automation may provide in terms of lane capacity, network capacity, and in the overall traffic behaviour, a microscopic simulation has been carried out.

All the simulations have been computed using Aimsun.next traffic modelling software.

5.1 Urban area description

The case study is based on the cartographic basis of Barcelona's *Eixample*[46]. This cartographic basis is shown in figure 38.

The model based on the cartographic basis of Barcelona's *Eixample* was developed in 2011 and therefore it responds to the Barcelona's road network layout of 2011. Moreover, simulated bus lines correspond to the TMB (*Transports Metropolitans de Barcelona*, the public company which operates the urban public transport in Barcelona) bus network in 2011. Such bus network has been almost completely modified and updated among the decade of the 2010's and new reserved bus lanes have been marked and deployed at most streets, consequently reducing the number of lanes for private vehicles. Some other streets have been modified in terms of number of lanes (e.g. Diagonal Avenue, between Macià Square and Cinc d'Oros Square) and some other have been pedestrianised (e.g. surrounding streets of Sagrada Familia Temple and Sant Antoni's Market).

Nevertheless, it is important to note that, although the cartographic basis it not quite updated, **the computations have been performed based on the real cartographic layer**

[46]Barcelona's *Eixample* consists of the neighborhoods of the city which surround the historical city centre and were developed and built during the nineteenth century. Barcelona's *Eixample*, as a whole, forms a large grid plan zone, consisting mostly of orthogonal streets.

of a city which has been adapted for newer mobility trends after the model was built. Anyway, the results are intended to be representative for any medium/big-sized city like Barcelona.

The model is quite heterogeneous and includes several road classes: From local streets where the maximum allowed speed is quite low (20 kph) up to highway stretches, with the highest maximum allowed speed in the model (110 kph).

The model's layout of Barcelona's *Eixample* has approximately 136km of road sections. The total lane length is about 365km, distributed among 1558 sections. Moreovoer, the model possess 692 intersections and 210 centroids.

Demand data that has been considered for this simulation exercise have been extracted from Estrada et al. 2012.

5.2 Procedure

Assumptions

- No trucks are allowed to ride through the considered study area (currently, trucks are not allowed to enter inside the area delimited by Barcelona's ring road. Any section of the model corresponds to a street located outside such area).
- Although it is expected (and it has been demonstrated in the report) that buses and vehicles that operate public transportation services could be automated, for this simulation case the public transportation vehicles will remain considered as human-driven vehicles.
- Autonomous Vehicles are assumed to use the same OD (Origin-Destination) matrices that were set for current human-driven cars. Although it has been explained that AVs would lead to the opportunity to create newer Car/Ride-sharing services, which would create the need of PU-DO areas at some streets for allowing express stops of the vehicles operating such services, and otherwise, AVs would be able to park by themselves (thus creating new "Zero-occupancy" travels, which are inexistent these days), it would be assumed that the overall behaviour in terms of travel behaviour will remain unmodified.
- Reaction time of Autonomous Vehicles is assumed to be $t_{AV} = 0.3$ sec, and corresponds to the assumed general reaction time, the reaction time when the vehicle is stopped, and the reaction time at a semaphored intersection. Such reaction time $t_{AV} = t = 0.3$ sec is equal to the considered simulation step.
- Otherwise, for both conventional cars and buses, it is assumed that the general reaction time is assumed to be $t_{conv} = 0.6$ sec. The reaction time when the vehicle is stopped is considered to be $t_{conv\ p} = 1.2$ sec. and the reaction time when the vehicle is waiting for the green light at a semaphored intersection is assumed to be $t_{conv\ s} = 1.5$ sec.
- No vehicle platooning is considered (Nevertheless, some simulations have shown some similarities to vehicle platooning with AVs at some main corridors, such as Aragó Street). Sensibility parametre of vehicles has been altered and is assumed to be 1 for human-driven vehicles and 0 for AVs.
- The overall amount of vehicles is not altered. In reality, the proliferation of ridesharing services would lead to reduce, in a still unknown percentage, the number of vehicles that are needed to convey a given demand.
- The stochastical route election is computed attending to a Logit model. The cycle of the model is assumed to be $t_{logit} = 180$ sec. $= 3$ min.
- A warm-up period of 30' between 7:30 and 8:00 has been considered. The demand data used for this warm-up period has been assumed to be the same that has been used for computing the overall simulation task for each simulation stage.

- It is important to remark from the very beginning this simulation only considers the performance of human-driven vehicles and autonomous vehicles in different sharers on the current road network. Seeking to obtain more reliable and unbiased results, no times at semaphored intersections have been changed from current values[47].

Some other assumptions have been adapted from Kokelman, 2016.

- All vehicles are assumed to travel at the same speed. The vehicle speed behaviour model is assumed to be the same for both human-driven vehicles and AVs. Self-driving algorithms would compute vehicle's most suitable speed attending to the future phase changes of traffic lights. Nevertheless, for the simulation, it is assumed that AVs will behave as human-driven vehicles in terms of speed behaviour models, accelerating up to the most suitable speed according to the speed-density diagram ($v_{veh} = f(k_{section})$).
- The car-following behaviour is considered to be identical for all the Autonomous Vehicles considered. In reality, different automakers will develop different self-driving algorithms. Thus, a car made out by the company A may probably be steered by a self-driving algorithm which takes into account a car-following model quite different than car-following models of vehicles manufactured by companies B, C and D, which may probably be also different between them.[48]

Barriers

The model has shown several barriers in order to perform more accurate simulations. For instance, the dimension of the model's layout, based on the geographic reality of one of the biggest and most dense cities in Europe, could be a little bit oversized for a microsimulation model.

Such fact may have led to perform, in general, a bit imprecise overall computation due to the large number of vehicles to be computed. The computer that has been used for the computation task took about 0.5 hours on average for performing the computations that correspond to each sub-scenario considered with a simulation step $t = t_{AV} = 0.3$ sec. In ideal conditions, it would have been optimal to do the required computations considering a lower reaction time (e.g. 0.1 sec.) which actually is closer to real latencies. Nevertheless, to perform the required computations attending to a simulation step of 0.1 seconds would have taken a quite longer overall computation time.

The existence of **parallel auxiliar service lanes** in the model has been another barrier for the modelling task. In some cases, some simulated vehicles intended to use such lanes for city-crossing displacements[49], which in fact led to reduce vehicles at the main lanes of the main avenues but they overcrowded or completely collapse such auxiliar service lanes. The collapse of these lanes, in some cases, implied the complete collapse of a certain road network region of the model's layout.

The partial collapse of the road network might have slightly or even sensibly altered the results of the behaviour of the overall urban road network that is represented in the model.

[47] Smart intersection management is expected to enhance the overall traffic flow.

[48] In reality, the overall behaviour of the road network may actually depend on the AV share (AV penetration rate) but it may also depend on the share of autonomous vehicles manufactured by each company. Therefore, the real overall behaviour of the road network among the transition will almost surely show a different case study for each city around the globe: the share of vehicles made out by each automaker over the automobile fleet of a given city actually depends on the socioeconomical circumstances of such city (e.g. if the average cost of vehicles built by A were significantly higher than the average cost of cars manufactured by B, the percentage of vehicles which compose the fleet of a given city that have been made out by B would probably be higher in cities with low Gross Domestic Product (GDP), rather than in cities located in prosperous regions.) and may be affected by the presence of a car factory on its metropolitan area and/or a nearby region (e.g. if a given city possess a car factory of the company A, the share of vehicles built by A that compose its vehicular fleet may probably be higher than the same share for a city at the same country which has car factories of companies C and D, but does not possess a factory of company A). Administrations, therefore, might have to redact newer laws and standards for these self-driving algorithms. Such standards **ought to uniformize** the behaviour of self-driving cars, seeking a more uniform overall driving.

[49] Such lanes are commonly used just for performing turning manoeuvres from the main avenue to secondary streets or accessing to parking facilities, jointly with a growing use of them as PU-DO areas.

Scenarios
Taking profit from the different possibilities that the traffic microsimulator Aimsun.next offers, two different scenarios have been considered.

Scenario A corresponds to deploying the technological infrastructure for allowing self-driving vehicles to ride throughout **all** the streets of the road network.[50] Nevertheless, any street has been modified in terms of number of lanes from the current situation.

Scenario B presents the same characteristics as it has been written for scenario A but moreover the implementation of a double CAV-ONLY lane at the central stretch of Aragó Street, which is one of the principal arterials of the city, is considered. Such CAV-ONLY lanes are considered to occupy the two central lanes of the corridor (Currently, the section of the street consists of six lanes: i.e. The CAV-ONLY lanes would occupy lanes 3 and 4 of the road section), in order to allow human drivers to adequately perform all the possible and desired turnings.

The double CAV-ONLY lane has about 1.50 kilometres length and is deployed between Passeig de Sant Joan Avenue and Aribau Street, which are two of the main arterials of Barcelona, and it also intersects and can take some traffic flow from and discharge some flow to some other main arterials, such as Pau Claris Street, Passeig de Gràcia Avenue, and Balmes Street. Figures 39 and 40 show the characteristics of these considered CAV-ONLY lanes.

In the **Impact analysis of AV** section it has been slightly mentioned the likely apparition and deployment of CAV-ONLY lanes. It is important to note that there is the possibility that some reserved lanes at major corridors could be deployed in order to ease the steering manoeuvres and communication tasks to CAVs, providing them a reserved space where it is not expected to find any non-connected vehicle. This simulation stage is also aimed to check the behaviour of a given corridor where a double CAV-ONLY lane is deployed.

AV Share and Demand
For each scenario, A and B, it has been computed the trip of each vehicle that had been defined in the initial OD matrix for different values of CAV market share (0%, 25%, 50%, 75% and 100%). The initial OD matrix has been multiplied by different factors (1.00, 1.25, 1.50, 1.75 and 2.00) in order to simulate different cases consisting of great demands.

Measurements
The most important traffic variables and parameters of the overall road network represented in the model have been computed for each case (each pair of % AV market share and multiplying factor of the initial OD matrix). These variables are, for example, the overall density and traffic flow, number of completed trips, number of vehicles present in the road network. The overall number of completed trips and the overall number of vehicles present in the road network have been obtained for each period of ten minutes (1/6 h) in order to obtain the diagram that relates both variables and is presented in Figure 47.

Furthermore, for all the 25 cases of both scenarios which correspond to each pair formed by one out of the five percentages of AV market penetration considered and one out of the five multiplying factors of the initial OD matrix, the local values of traffic flow ($\frac{veh}{h}$) and density ($\frac{veh}{km}$) have been computed for each period of ten minutes (1/6 h) at the eight stretches of Aragó Street between Passeig de Sant Joan Avenue and Balmes Street. The results of these measurements are presented in the fundamental diagrams shown in Figures 41, 42, 43, 44 and 45.

[50] Actually, it may happen that for the early stages of self-driving technologies, only a given subset of streets of the overall road network of cities would be prepared for CAVs and, therefore, the remaining streets would still be only available for human-driven cars. This situation could last until a given smallish percentage of CAV market share.

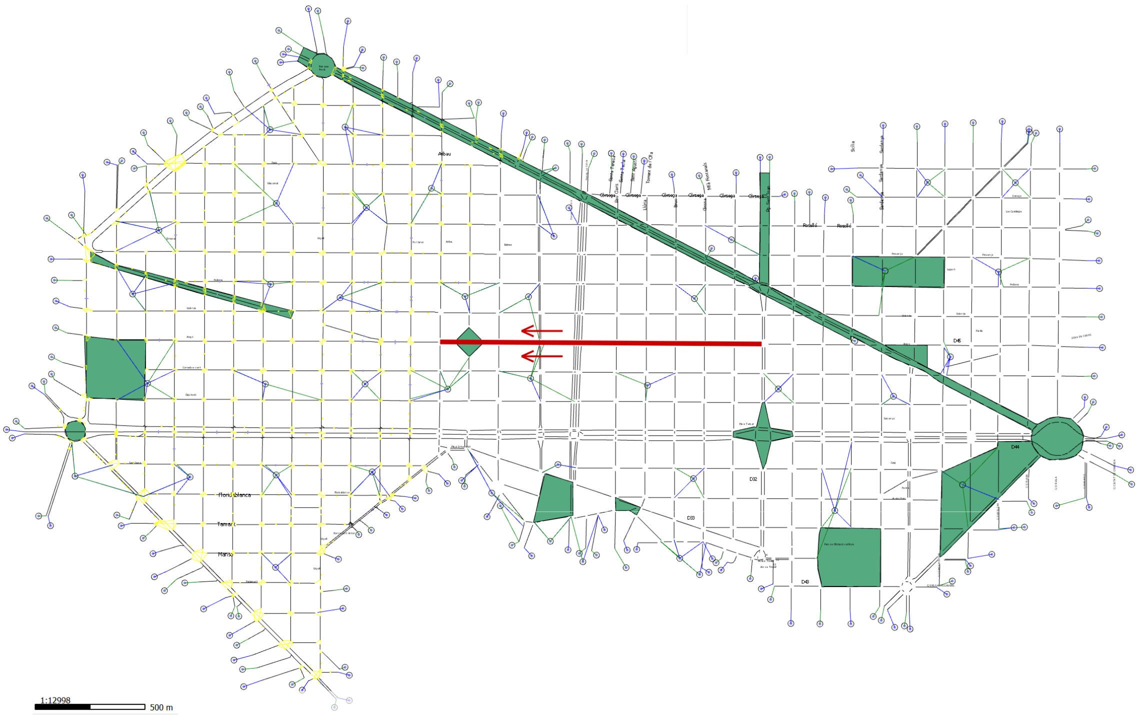


Figure 39: Placement of the double CAV-ONLY lane over the Barcelona's cartographic layer.

Figure 40: Rendering of the double CAV-ONLY lane considered for Scenario B. Lanes in yellow are destined to mixed traffic flow, but the central lanes (violet) are reserved as CAV-ONLY lanes. OWN ELABORATION.

5.3 Results

CAV-ONLY lanes at Aragó Street

Figures 41, 42, 43, 44 and 45 show the fundamental diagrams that have been obtained after simulating the 25 cases of each scenario. The results have been depicted in ten different diagrams: The results obtained for all the five different cases that represent the same AV market share for the same scenario have been plotted in the same diagram. Therefore, the diagrams have been elaborated attending to different demand values.

The diagrams show the computed relation between density (k_i $[\frac{veh}{km}]$) and traffic flow (q_i $[\frac{veh}{h}]$) at each lane for each period of 10 minutes at the eight sections of Aragó Street between Passeig de Sant Joan Avenue and Balmes Street. Only the results of the four central lanes of the infrastructure have been represented on such diagrams (Lanes 2, 3, 4 and 5, being lane 1 the leftmost lane in the traffic flow direction, and lane 6 the rightmost). The most external lanes have not been taken into consideration because a great share of the vehicles that use such lanes use them for performing some kind of turnings towards other streets, which may alter the ideal results.

Each point of the diagram represents a computed relation between density and traffic flow. Seeking to provide a clearer representation of the computed values, the dots that represent the values of the central lanes (Llanes 3 and 4, i.e. the lanes whose conversion to CAV-ONLY lanes is intended to be studied) are coloured in violet, therefore following the colour criterion used in Figure 40. Otherwise, the results for lanes 2 and 5 have been depicted in yellow. Moreover, in order to distinguish the results for each lane, the results of the leftmost lanes (i.e. Lanes 2 and 3) are depicted in a shade darker than the rightmost lanes (Lanes 4 and 5).

Let the **present-day situation** (0% AV market share) be the first case considered in terms of AV penetration. The computed results for the traffic flow and car density for scenario A are represented in Figure 41 Left and show a traffic situation that could even be obtained with real traffic data from present time (year 2019), because this is the single case of the ten diagrams that represent the up-to-nowadays circumstances. It is worth mentioning that the obtained results are substantially gathered at the left region of the diagram, which represent the zone where the values show that the road section operates under capacity, even for high-demand values.[51]. Nevertheless, some dots represent that the street could reach congestion. In this case, the maximum lane capacity is about $1400\frac{veh}{h}$ and corresponds to a density of about $k_0 = 40\frac{veh}{km}$. 88.1% of the computed densities correspond to a value lower than this obtained k_0 (88.1% of k_i values fulfil that $k_i < k_0$).

Also for this penetration case plenty of human-driven cars, it should be appreciated that scenario B makes no sense at all. Two CAV-ONLY lanes are considered to be deployed for a demand scenario that considers zero CAVs. The situation could be easily compared with a given corridor whose number of lanes is reduced for creating a newer bus lane, but any Public Transport line was planned to use such corridor. Obviously, the corridor's overall capacity would be reduced (it is worth noting that the number of available lanes would be reduced from 6 to 4) and it would cause more situations closer to jam density (about $k_J = 200\frac{veh}{km}$). This case is depicted in Figure 41 Right.

Dots which represent lanes 2 and 5 are scattered for all values of density between 0 and 200 $\frac{veh}{km}$, but the number of dots for values of density between k_o (about $75\frac{veh}{km}$) and 200 $\frac{veh}{km}$ is sensibly larger than for scenario A. Otherwise, dots which represent the central lanes are aligned at a straight line which shows a quite low traffic flow for all densities. It is plausible that such dots mean that some human-driven vehicles use the CAV-ONLY lanes even being unauthorised for using them, for example, in order to change from lane 2 to lane 5. 92.3% of the computed k_i values correspond to $k_i < k_0 = 75\frac{veh}{km}$, but only 83.4% of values remain under $k = 40$, which is k_0 for the equivalent case for scenario A. This means that Scenario B for hundred percent of human-driven cars lead to greater densities than Scenario A. Computed lane capacity is about $1700\frac{veh}{h}$.

[51] Aragó Street currently holds quite large figures of traffic flow everyday.

The second case considered with regard to AV share is **25% AV market share**.

For this AV share, scenario A does not show significant changes from the present-day situation for the same scenario. The fundamental diagram correspondent to this case is depicted in Figure 42 Left and also shows a k_0 value close to 40 $\frac{veh}{km}$ (42). It corresponds to a lane capacity close to $1600\frac{veh}{h}$. 88.8% of the computed values lie under this value of k_0.

The case correspondent to scenario B starts to make sense when it exists a certain nonzero percentage of AV penetration. Lane capacity is still about $1700\frac{veh}{h}$. To provide a feasible value of k_0 is a bit hard task because there are dots close to this capacity between $k = 57\frac{veh}{km}$ and $k = 92\frac{veh}{km}$. Let $k = 75\frac{veh}{km}$ be the value of k_0: 90.7% of the obtained values lie under this value of k_0 (90.7% of k_i values fulfil that $k_i < k_0$). It can be deduced that from the previous case considered for scenario B, the share of data that remain under k_0 ($75\frac{veh}{km}$ for both cases) has decreased. In other words, the overall traffic circumstances got a bit worse because more results represent a situation over the optimal lane density. The mentioned case is represented in Figure 42 Right.

The third case considered is half transition **(50%AV market share)**.

Figure 43 Left shows the computed values for this case at scenario A. This diagram resulted surprising for the author: Computed lane capacity not only shows a higher value than previous cases (it slightly overpasses the figure of $1800\frac{veh}{h}$, which corresponds to a k_0 value of about $44\frac{veh}{km}$), but also shows that 95.5% of computed values are gathered under this value of the optimal lane density. For a scenario that consist of one out of two cars being autonomous, **it is deduced that mixed flow could enhance traffic**.

Otherwise, mid-transition case for scenario B shows that, despite traffic flow is split into two groups, the fact of providing such two groups a certain land for riding throughout a given corridor reduces overall lane capacity (1350 $\frac{veh}{h}$ for the human-driven lanes and 1450 $\frac{veh}{h}$ for the central CAV-ONLY lanes). Computed optimal densities are 30 $\frac{veh}{km}$ at CAV lanes and 42 $\frac{veh}{km}$ at lanes for human-driven vehicles.

Figure 43 Right shows the fundamental diagram correspondent to this case, where it can be seen a perceptible scattering of results for greater densities: 91.25% of results for human-driven lanes lie under the optimal density, **but only a 69.0% of the computed density-traffic flow relationships at the CAV-ONLY lanes do not overpass the mentioned optimal density for the central lanes**. Moreover, the diagram also shows a great deal of dots close to traffic jam situations (k_J has been obtained close to 195 $\frac{veh}{km}$ for lanes 2 and 5 and about 210 $\frac{veh}{km}$ for lanes 3 and 4). It is worth mentioning that only 1.04% of results at lanes 2 and 5 overpass the line marked by $k = 160\frac{veh}{km}$, but this figure climbs up to 5.00% for the CAV-ONLY lanes.

It has been deduced that providing reserved lanes to each type of vehicle at a given scenario that considers a mixed fleet (50% of CAVs and 50% of human-driven vehicles) may not be the most optimal solution. Autonomous Vehicles riding through the central reserved lanes may need to perform turnings and therefore they would need to change towards the most external lanes. Human-driven vehicles could also need to displace from one side to the other side of the street in order to continue with their journey (For example, a given human-driven vehicle travelling downwards through Pau Claris Street which needs to turn right to Aragó Street could later need to turn left for continuing downwards through Balmes Street. The optimal response is that the driver keeps steering his/her car throughout the leftmost lanes of Aragó Street, but occasional drivers may turn from the secondary street to a lane placed at the rightmost side of the central lanes and then such driver would need to move his/her vehicle to the other side, therefore trespassing the CAV-ONLY lanes and occasionally disrupting the CAVs flow). Fortunately, a mixed use of the whole street land would mitigate the disturbing effects of such misleads and drivers would have enough

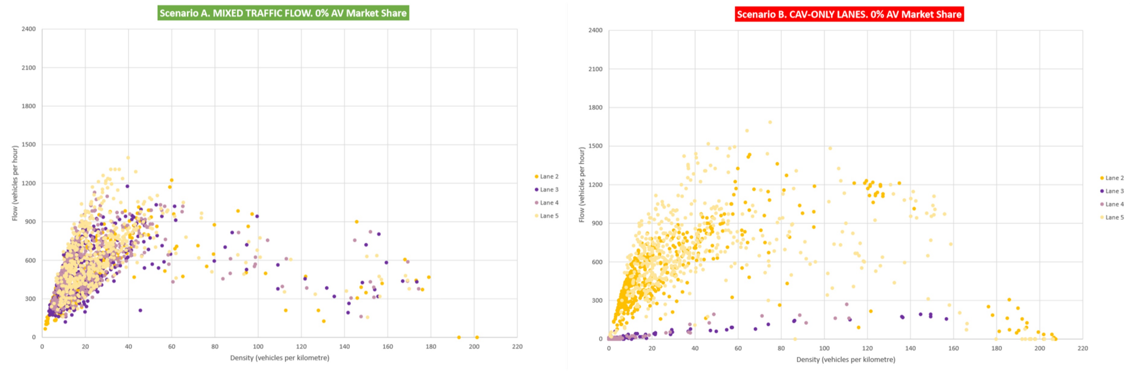


Figure 41: Fundamental Diagrams for scenarios A and B with an AV market share of 0%

Figure 42: Fundamental Diagrams for scenarios A and B with an AV market share of 25%

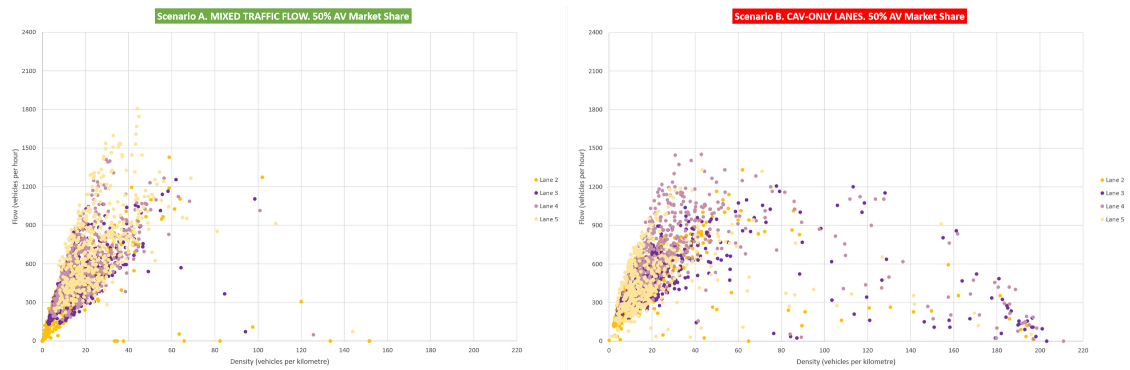


Figure 43: Fundamental Diagrams for scenarios A and B with an AV market share of 50%

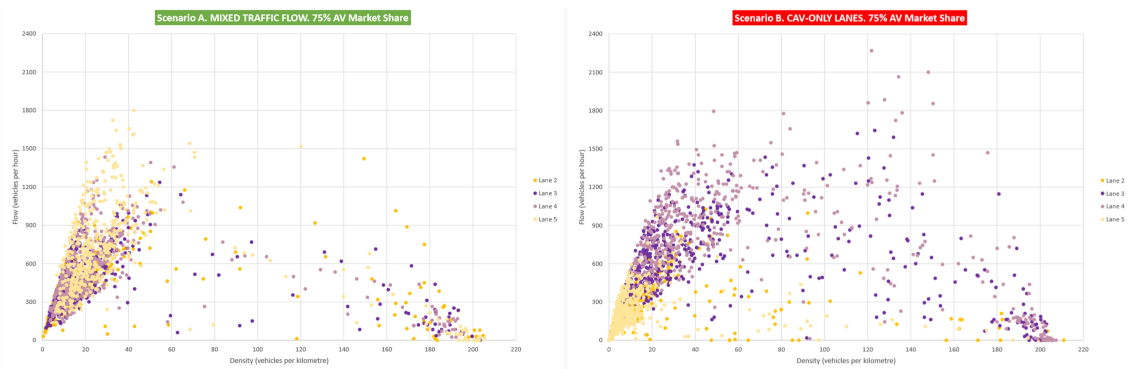


Figure 44: Fundamental Diagrams for scenarios A and B with an AV market share of 75%

Figure 45: Fundamental Diagrams for scenarios A and B with an AV market share of 100%

room for correcting their trajectories: Exactly in the same manner as such misleads are corrected nowadays.[52]

Looking into the far future, there is the possibility that CAVs, self-driving cars could constitute a great share of the overall vehicular fleet. A scenario where three out of four cars **(75% AV market share)** are self-driving vehicles has been considered and the results are presented in Figure 44.

The Left diagram shows the computed results for scenario A. In this mixed-flow scenario, the obtained lane capacity is 1800 $\frac{veh}{h}$, which corresponds to a density of $k_0 = 42\ \frac{veh}{km}$. 86.9% of computed results correspond to a lane density under this value of k_0, but also a remarkably high share of results (6.35%) correspond to lane densities over 160 vehicles per kilometre ($k_i > 160\frac{veh}{h}$), quite near to traffic jam situations. Moreover, 0.84% of computed values correspond to lane densities over 200 $\frac{veh}{km}$.

Otherwise, Figure 44 Right shows the obtained data for scenario B at the considered penetration share. The results surprisingly show that, despite lanes for human-driven vehicles do not show great capacities (1050 $\frac{veh}{h}$ for $k_0 = 44\frac{veh}{km}$), the central CAV-ONLY lanes show greater lane capacities for densities close to normal values of optimal lane densities (1800 $\frac{veh}{h}$ for k_0 close to 50 $\frac{veh}{km}$) but also even greater capacities (over 2250 $\frac{veh}{h}$) for quite larger lane densities (about 120 $\frac{veh}{km}$). The diagram also shows a large amount of dots representing densities k_i over this value of 120 $\frac{veh}{km}$ (3.44% at lanes 2 and 5 and 20.21% at the central lanes) and even over 160 $\frac{veh}{km}$ (2.81% for human-driving lanes and 13.12% for self-driving lanes). Finally, for both cases, k_J density results close to 210 $\frac{veh}{km}$.

The fact of the number of human-driven vehicles being lower and lower enhances self-driving lanes. Some benefits like the increment of capacity mentioned in Page 58 could be profited due to the reduction of obstacles (non-autonomous vehicles) and therefore, the central lanes could work as reliable corridors for self-driving cars. Nevertheless, it is worth remarking that this would occur only for greater penetration rates (namely, this has been observed for an AV penetration of 75%).

Finally, it is analysed what would occur if all the current human-driven vehicles were transformed to Autonomous Vehicles. **(100% AV market share)**.

[52]It is important to mention that reserved lanes fit better for public transport rather than for private vehicles. Although the vehicles destined to public transport represent a quite low share of the overall fleet, the main purpose of bus lanes is to provide buses a reserved track for making faster displacements, in terms of allowing buses to rapidly displace through the network without being disrupted by other vehicles. These lanes have been deployed in most cities around the globe for enhancing public transport systems and discouraging private mobility. The objective of bus lanes is not splitting the vehicular flow into two groups but removing private vehicles from defined bus trajectories while encouraging citizens to use public transport systems.

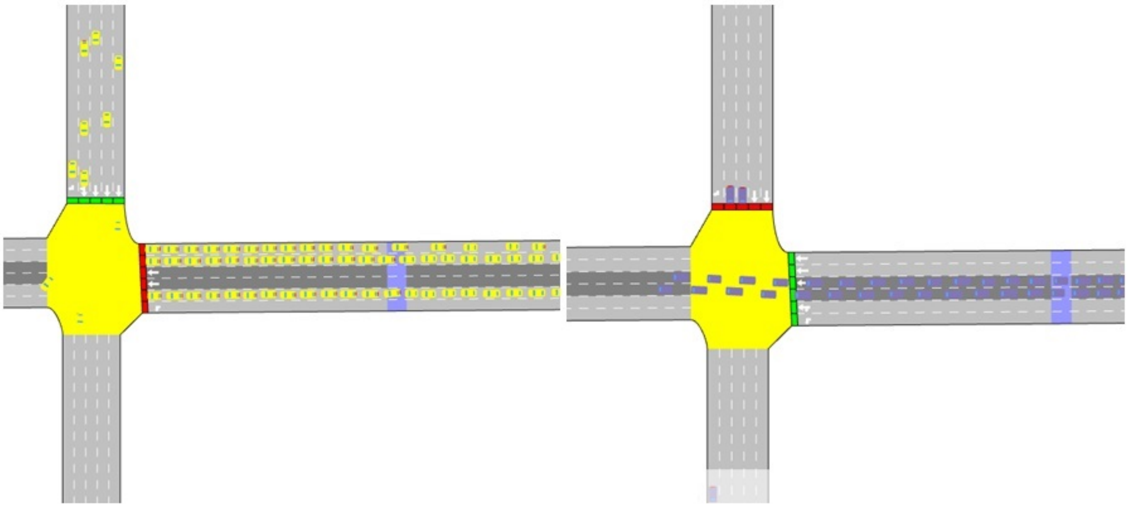


Figure 46: Screenshots of the simulation stage for Scenario B and cases with 0% AV market share (left) and 100% AV market share (right).

Note that both images show all the vehicles riding through Aragó Street being steered throug a given subset of lanes. Mainly, human-driven vehicles avoid using the central lanes, and AVs tend to use the central lanes. Therefore, the infrastructural solution proposed for scenario B (dedicated CAV-ONLY lane) makes no sense for a non-mixed fleet.

In the same way as it occurred for the case with 0% AV penetration rate, scenario B does not makes any sense for a vehicular fleet which is completely formed by self-driving cars. Nevertheless, this case has been studied and their results have been observed. In this case, **It occurs that AVs driving through Aragó Street prefer to use the central lanes and do only use the remaining lanes with the target of performing turnings**. The obtained results are presented in Figure 45 Right.

The two central lanes also show great lane capacities (2100 $\frac{veh}{h}$) for great densities (105 $\frac{veh}{km}$) but also present a great deal of data (9.17%) correspondent to densities higher than 160 $\frac{veh}{km}$, close to traffic jam conditions. 82.2% of the computed values lie below 105 $\frac{veh}{km}$. k_J is obtained between 205 and 210 $\frac{veh}{km}$.

With respect to lanes 2 and 5, the traffic flow through such lanes is not negligible due to the number of vehicles that intend to perform a turning (the cars are allowed to ride through lanes 2 and 5, but their preference is to use CAV-ONLY lanes). This flow reaches its maximum about $q = 1100\frac{veh}{h}$ for 95 $\frac{veh}{km}$. 96.1% of the obtained values correspond to densities lower than 95 $\frac{veh}{km}$.

It is important to remark that in all the previous cases for scenario B, the results offered for lanes 2 and 5 may also include a given small share of AVs instead of consisting only of human-driven vehicles.

Finally, Figure 45 Left shows the results for the computed data for this case consisting of a whole private fleet made out of AVs, and for scenario A (mixed-traffic flow conditions). The results show a quite large capacity (2050 $\frac{veh}{h}$) for an optimal density of $k_0 = 40\frac{veh}{km}$. 83.1% of the computed results correspond to densities below this value of k_0. Nevertheless, 7.86% of values correspond to densities over 160 $\frac{veh}{km}$, close to traffic jam conditions.

Table 4 presents in more detail the obtained values of maximum lane flow that have been computed at each of the four central lanes of Aragó Street for each case of AV market share that have been considered for both scenarios. It can be noticed that the difference between the highest and the lowest values for each case are sensibly lower for Scenario A, except in the case of 50%

% Scenario	%AV market share	Lane 2	Lane 3	Lane 4	Lane 5	Max. difference
A	0%	1224	1176	1128	1398	270
A	25%	1362	1380	1374	1584	222
A	50%	1428	1254	1410	1806	552
A	75%	1422	1236	1434	1800	564
A	100%	1470	1530	2052	2010	582
B	0%	1434	192	270	1686	1494
B	25%	1362	600	900	1716	1116
B	50%	1332	1206	1452	1332	246
B	75%	1026	1644	2268	966	1302
B	100%	1116	1998	2124	888	1236

Table 4: Maximum lane flow computed at each lane for each case of AV market share and Scenario considered. OWN ELABORATION.

AV market share, which is lower for Scenario B. Notice also that for Scenario B, generally, the difference of maximum lane flow between the central lanes and lanes 2 and 5 is typically a great value. All the values in Table 4 are expressed in terms of $\frac{veh}{h}$.

Overall network performance
In order to slightly analyse the performance of the overall road network, a small comparative has been made between the number of completed trips and the total number of vehicles which are present in the road network within a given period of time. Computed data has been extracted for each period of ten minutes. These data have been only extracted for the cases which consider 0% and 100% of AV market share for observing the most important differences between two opposite scenarios. Moreover, it is important to remark that for this relationship only scenario A has been considered. Further research could be based on observing the evolution of this relationship for different percentages of AV market penetration.

Figure 47 shows the relationship between these computed values.

The yellow dots show the results that have been obtained for the case that considers **every vehicle being human-driven vehicles**. No AVs are still assumed to ride through the road network. In fact, these dots could even represent an actual set of data being measured in real traffic conditions. Lighter dots represent the values that have been computed for higher values of the multiplying factor of the initial OD matrix. The lighter the yellow dot is, the greater the multiplying factor that has been considered is.

These yellow dots are arranged in the diagram following a parabolic trend line. Such parabola has been computed and is $\mathbf{e = -4 * 10^{-5} n^2 + 1.1916n + 3239}$, where e is the number of completed trips, and n is the number of vehicles inside the network. This parabola is shown in Figure 48 Left. The computed value of $R-squared$ for this case is equal to $R^2 = 0.8783$, which actually means that in spite of the results could get a bit closer to the parabolic line, the parabola fits ok between the computed data.

Our parabola reaches its maximum value for $n = 14895$ veh, which corresponds to $e = 12113$ veh. If we observe our data set, the maximum value of e ($e^* = 12271$ veh) is reached for a value of $n^* = 11928$ veh. The theoretical maximum of e for this parabola is close to the maximum value that has been computed, but it is assumed to be obtained for a value of n much higher than n^*.

Otherwise, the violet dots show the results for the case considering **the whole fleet being formed by AVs**. No human-driven vehicles are now assumed to be riding through the network. One more time, the lighter dots represent the values that have been obtained for greater values of the initial OD matrix multiplying factor. The lighter violet dots represent the values computed

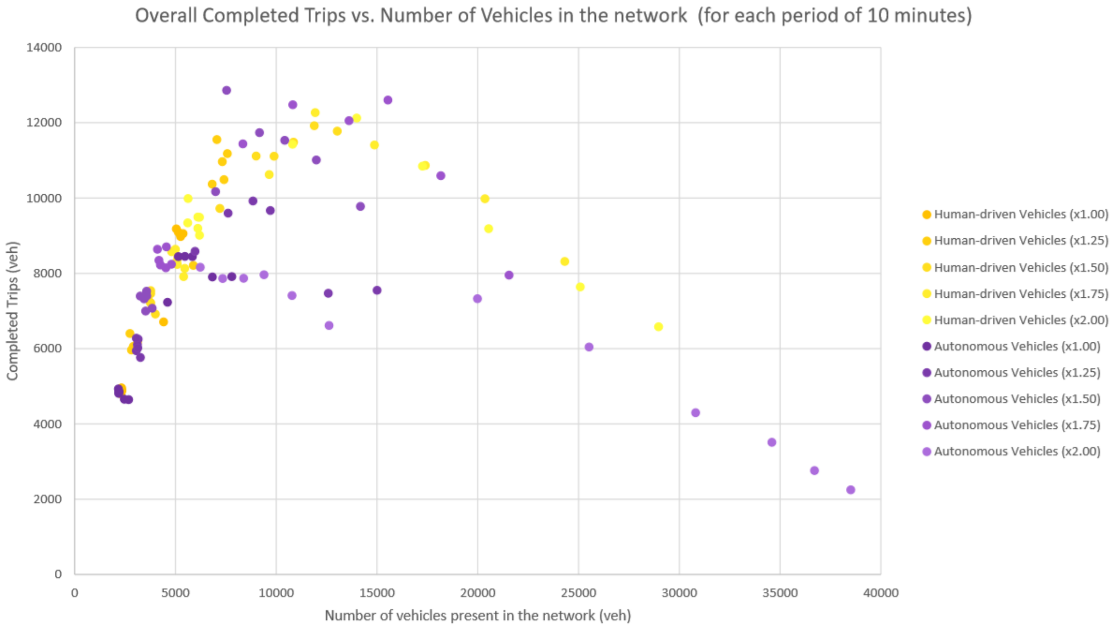


Figure 47: Diagram which relates the number of completed trips and the number of vehicles in the road network.

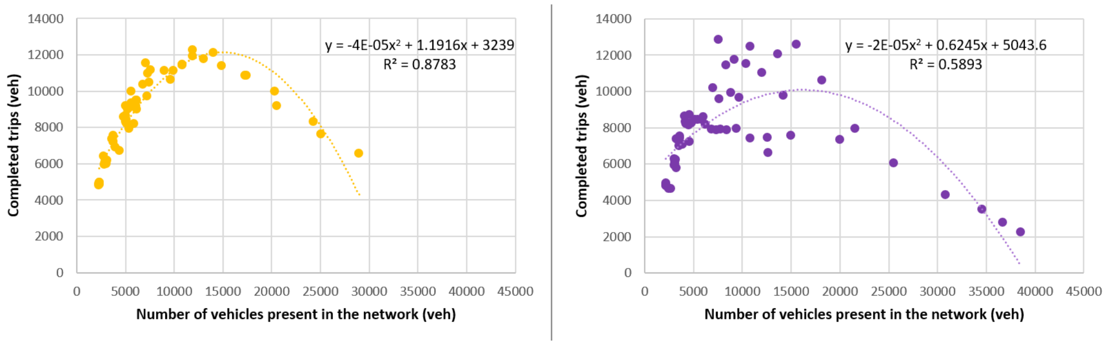


Figure 48: Same diagram as in the upper figure, but the results for both demand cases have been split. The left figure shows the results for 0% AV market share, and the right figure represents the results for 100% AV market share.

for a multiplying factor closer to 2.00 and the darker dots represent such values for multiplying factors close to 1.00.

In this case, which can also be observed in Figure 48 Right, the dots get much more scattered. Although the maximum numbers of completed trips reach higher values than e^* computed for human-driven vehicles, a branch of this parabola below its vertex has been obtained. This leads to obtain a general parabolic line much more flat than the previous one. This parabola of AVs data set is $\mathbf{e = -2 * 10^{-5}n^2 + 0.6245n + 5044}$, and the $R-squared$ value is now $R^2 = 0.5893$. Lower values of R^2 mean this **greater dispersion**.

Observing the data set, it can be seen that the maximum value of completed trips, e^*_{AV} is equal to 12861 veh, and is obtained for $n^*_{AV} = 7535\ veh$. Nevertheless, the parabolic line reaches its maximum value of e at $e = 9919\ veh$, which is reached for $n = 15612\ veh$. Data dispersion leads to an incongruency between the computed data and the modelized data. **With the computed data set for a fleet 100% formed by AVs, it is not reliable nor feasible to approximate the data set to a parabolic line** due to the great scattering that the data set shows.

5.4 Findings

CAV-ONLY lanes at Aragó Street
The results that have been obtained for all the cases related to scenario A show that for mixed vehicular fleets (i.e. fleets formed by both autonomous and human-driven vehicles) a corridor that allows mixed flow fits perfectly for the purpose of increasing lane capacities (maximum lane flow) and reducing congestion. It is remarkable that for the considered case of 50% AV market penetration, the diagram shows 95.5% of data under the considered value for the optimal density. This scenario is also suitable and appropiate for the cases that consider a vehicular fleet formed only by Autonomous Vehicles or only by Human-driven Vehicles. Moreover, the more percentage of AV market share have been considered, the higher the lane capacity results have been obtained.

Otherwise, scenario B makes only sense for the cases that consider a mixed vehicular fleet. This scenario considers segregating the road surface and therefore, a partitioned fleet will be needed for the intended target of enhancing traffic. The diagrams show great vehicular flows at the lanes destined to CAVs but only for great market shares of autonomous vehicles (75% AV market penetration). CAV-ONLY lanes allow having high traffic flows for high values of density. Nevertheless, the highest traffic flow values that have been obtained at the remaining lanes are lower than the lane capacities computed for the correspondent cases at scenario A.

The difference between the highest and lowest values obtained for the maximum lane flow computed at each lane for each scenario and each percentage of AV market penetration considered are dramatically higher at the cases that correspond to scenario B rather than to scenario A. Nevertheless, this is not true for the case that considers 50% of vehicles being autonomous. On the other hand, for this case the average maximum lane flow is higher for scenario A than for scenario B.

Summing it up, this simulation stage is concluded saying that mixed flow conditions at a given corridor with topological characteristics like Aragó Street offer some advantages on traffic behaviour than creating segregated CAV-ONLY lanes at the corridor. Some of these advantages are listed as follows:

+ Lower amount of computed data close to congestion situation.
+ Great amount of computed data that correspond to density values, k_i, lower than k_0, the optimal density that allows a maximum lane flow.
+ Higher overall traffic flow at the four central lanes.
+ Lower differences between computed vehicular flow at the different lanes.

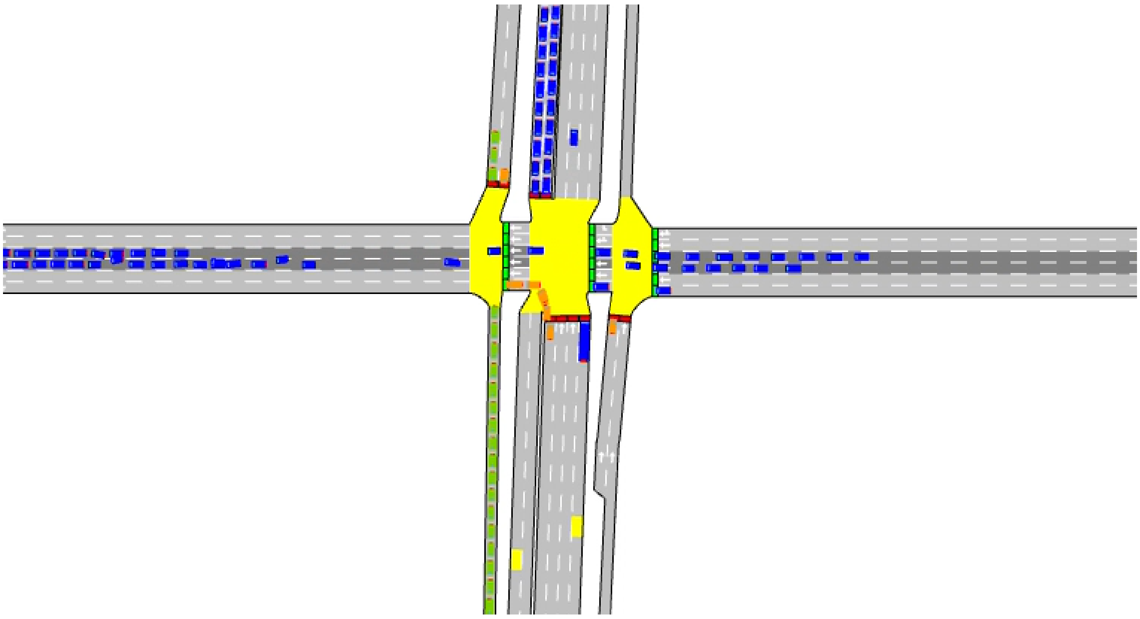


Figure 49: Examples of the simulation stages when cars used to collapse the network by means of riding through the auxiliar parallel lanes.
Note that some cars that intented to turn left from Aragó Street (the horizontal street) to the auxiliar lane of Passeig de Gràcia Avenue (the vertical street) were blocking the vehicles that were riding through Passeig de Gràcia Avenue and such others that intended to turn from Passeig de Gràcia Avenue to Aragó Street.

+ The likelihood of human error related to the positioning of a given human-driven vehicle at the CAV-ONLY lane is mitigated, which impede the accidental hampering of the central lanes.

+ Cars would be allowed to perform lane changings from the rightmost lanes to the leftmost ones (and also from these lanes to the rightmost ones) in order to easily perform further turning manoeuvres. Otherwise, cars in scenario B have to decide whether they will ride throughout the rightmost or the leftmost lanes before entering the corridor depending on their following turning.

Although the creation of CAV-ONLY lanes could be useful for the early deployment of fully-autonomous vehicles, for sizeable percentages of AV market share a scenario based on mixed traffic flow would be the most suitable option.

Overall network performance
The presented results show a slight barrier, which consist of the data set size. Computed data for this analysis could have not been enough for reaching a proper finding. Moreover, the computed data for the case that considers the whole fleet being formed by Autonomous Vehicles presents a great scattering but also a branch line where some dots represent the computed relationship between computed trips and vehicles in the network for values of the number of completed trips much lower than the expected ones. This case could not have been reliably approximated to a trend line.

An hypothesis of the creation of this branch line could be related to the enormous size of the model. The model that has been used represents an important part of the road network of Barcelona, and could be a bit oversized for the purpose of analysing the overall traffic behaviour. Otherwise, another hypothesis of this scattered result might be the fact that some cars preferred to use the auxiliar parallel lanes rather than the main lanes of some avenues (mainly, Diagonal Avenue, Passeig de Gràcia Avenue and Gran Via de les Corts Catalanes Street) as it is shown in Figure 49. This fact may have led to reach values of completed trips lower than the expected ones.

Nevertheless, despite the existance of the branch of dots under the parabolic line in the diagram, it can be also observed that several violet dots (AVs) correspond to values of e (number of completed trips) which are higher than the maximum value of e for the yellow dots set (Human-driven vehicles). Despite the great scattering of these violet dots corresponding to the computed data for self-driving vehicles, there is the possibility that a vehicular fleet partially or fully consisting of AVs could enhance the current figures of completed trips. Nevertheless, **the data set is not so great nor feasible for reaching any conclusion nor formulating any finding about this possibility**.

For this reason, **further research could be focused to deeply analyse this traffic performance in much more detail**, for a greater number of cases and for different % AV shares.

5.5 Further research

Some discussion about other issues that may be worth simulating and being observed in further research stages is made and presented as follows:

Overall network performance

+ Simulating the overall traffic behaviour using a model based on the street network of a middle-sized city (e.g. Valladolid, Spain: about 300,000 inhabitants and about half million in the metropolitan region) instead of considering a model based on a big city like Barcelona (about 1.8 million inhabitants and almost 4 million in the metropolitan area). It would make computations being faster and easier and they could even be more precise.

+ Obtaining more complete diagrams for the relationship between the number of completed trips (e) and the number of vehicles present in the network (n). Obtaining them for different values of % AV market share.

CAV-Only Lanes

+ Simulating the behaviour of the road network at a given subset of the model (e.g. a given corridor) will make computations that involve other road stretches unnecessary. It would also make computations simpler, in special for analysing the traffic behaviour of a given corridor equipped with CAV-ONLY lanes.

+ Considering the existence of a given integer number (k corridors, $k > 1$) of corridors equipped with CAV-ONLY lanes, in order to provide the city a reliable network of CAV-ONLY lanes covering the most important corridors of the network.

+ Considering the existence of at least one CAV-ONLY lane at all the streets. Considering also a different number of lanes reserved for CAVs depending on the kerb-to-kerb width or street hierarchy.

+ Considering the existence of CAV-ONLY **streets** and corridors.

Other issues

+ Setting the origin/destination centroids at parking facilities but also at the planned ubications of pick-up and drop-off areas. Setting as variable parameters the capacity of such platforms and the expected dwell time in order to obtain a sensibility analysis of the behaviour of the overall network attending to the different values of such parameters. Therefore, if the simulation were adjusted attending to newer and more sustainable ways of use of vehicles, the obtained results could look closer to reality.

+ To conclude, utilizing microscopic simulation software would be helpful and advisable for anticipating the likely impacts of urban strategies based on lane reduction. Such strategies had better be computed considering the road section whose number of lanes is intended to be reduced and the parallel corridors and other secondary streets whose capacity may be affected by the implementation of a given actuation. In special, local corporations and some other administrations being liable and owning the given roads where it is intended to actuate must consider the microscopic simulation software as a tool for evaluating whether a planned actuation will be positive or negative attending to their plans, previsions and expectations.

6 Conclusions

A great shift related to urban and inter-city mobility is happening (and it has already started). From a former, not so ancient scenario which mainly consisted of gasoline-powered private vehicles with quite low occupancy rates,[53] **despite some barriers would have to be overpassed, a transition towards a more efficient mobility based on vehicle sharing and more eco-friendly, renewable energy sources is no longer an utopia**.

Some decades ago, world's population had started to realize about the real effects and the hazardous environmental threats of former own car-centred mobility, which has been reigning over a large proportion of the 20^{th} century. Therefore, in order to mitigate such effects and risks, administrations have had to revise and adapt their standards and legislation. Moreover, some strategies to encourage population to take care of the planet have been developed, seeking a faster and more efficient boost to the commented shift, such as banning gasoline and diesel cars sales from a certain date and lowering out-of-pocket trip fares of public transport for frequent travellers.

Nevertheless, the change is not just being powered by the stiff regulation framework but the proliferation of both new technologies and other opportunities as a whole. Newer ways of communicating between people such as social networks and texting apps, which have become widespread due to their enormous efficiency, have led to a more sustainable utilisation of private vehicles. Such applications have allowed drivers who own a personal vehicle to better organize their displacements: They can now give a lift some other passengers which desire being conveyed through a similar path. There is no need of a second private vehicle to perform such journey for the second passenger.

Such sharing initiative is being more and more commonly performed, which implies a significant energy saving. To satisfy a finite number of displacements requires much less energy if passengers are arranged among several cars than if every single passenger drives its own vehicle.

Recently, carsharing and ridesharing systems, which are quite based on mobile phone applications and have been strongly powered by them, have arisen. Ridesharing services, in a special way, have the potential to pool their operative vehicles. Such companies can optimize their requested displacement needs in terms of arranging their customers into their operative cars. Therefore, greater vehicle occupancies, a bit closer to vehicular capacity, are achieved. Otherwise, it is expected that the vehicles which operate public transport services (namely, buses) will reduce their current size and their maximum capacity will be reduced. Average vehicular occupancies, for both cars and buses, would therefore slightly converge towards an optimal vehicular occupancy: **Average occupancy of cars will tend to rise towards the average car capacity while the maximum capacity of buses will tend to decrease.**

Electric engines and motors are expected to substitute internal combustion engines from cars, which caused a very large, immeasurable amount of emissions. But such motors have not only appeared for being applied to newer cars but also have allowed the proliferation of newer modes, such as electric bicycles and scooters. Newer modes for urban commuters, whose apparition has led to eliminate private vehicles in some cases. A significant shift from private cars to such personal mobility vehicles could occur in the near future. Nevertheless, as it is depicted in Bits and Atoms, 2017, the mentioned shift will be quite related to a likely, expected dramatic drop of lithium-ion batteries cost.

Finally, the application of such newer technologies to the automotive field is allowing the proliferation of the primitive autonomous vehicles. Although the majority of them are still semi-autonomous vehicles, cars and vehicles with no driver or even with zero occupancy are expected to start riding through roads and streets. **And our cities must be prepared for this phenomenon**: Current infrastructures must be updated for allowing the best performance of coming self-driving systems.

[53] Such scenario used to imply enormous wastage of fuel, energy and other resources.

a. Road markings and signage must be always in proper maintenance conditions and always readable with independence of the lightning and weather conditions.

b. Information written and displayed on signage and signals must be conveyed to cars in a biunivocal way. Crucial information should be expressed in the same universal language.

c. Car parks could be adapted for self-parking systems, which would imply a better optimization of the car park land.

d. Such car parks could be equipped with electric chargers, for allowing self-driving car owners to recharge the batteries of their cars. If these chargers were based in electromagnetic induction, self-driving connected vehicles could be continuously rearranging between them in an easier way.

e. On-street parking facilities could become unnecessary.

f. Streets must be equipped with Pick-Up and Drop-Off areas. Significative locations such as major hubs and urban equipment (e.g. Hospitals or Schools.) deserve such platforms in a special way.

g. These platforms must be 100% accessible, in order to provide a suitable access for all citizens to ridesharing services.

h. Ridesharing companies must possess control centres and other facilities from where both manage and maintain their fleets.

i. Major roads must be equipped with safe harbour areas where it would be possible to stop and exit the vehicle in case of medical/mechanical emergency.

j. Service stations could become major transportation hubs and transfer nodes.

k. Road infrastructure must be prepared in order to support and bear higher traffic overloads caused by heavy goods vehicles platoons.

l. Digital maps, which are quite useful for navigation tasks, must be accurately and continuously kept up to date. Roads and streets must be mapped in a quite precise way.

m. If digital maps were as up to date and precise as desired, traffic management could be performed throughout such platforms. Moreover, infrastructure information could be instantaneously spread.

n. Car parks, Pick-Up and Drop-Off platforms and safe harbour areas should be correctly mapped and depicted on digital platforms.

o. Hardware devices, in order to allow V2X communications must be placed across the road and streets network. Such devices must rely on an adequate telecommunications infrastructure for enabling faster internet connections. A proper development of 5G mobile telecommunications would be required due to its great utility for self-driving.

p. Road sensors for modelling the current traffic flow would allow to implement road management algorithms for optimizing the overall passenger + goods flow.

q. Zebra crossings most demanded by pedestrians could be upgraded to signalized crossings for a better operation. Other zebra crossings should be equipped with sensors and mast-mounted cameras which must monitor the presence of pedestrians at the pedestrian crossing.

r. Jaywalking should be strongly discouraged. More official crossings could lead to a strong mitigation of such phenomena. Educational programmes should encourage people from early ages to use the official pedestrian crossings in the most responsible manner. Citizens should be conscious about the potential harms that a pedestrian which is unexpectedly roaming on the road can suffer, even considering the existence of hundreds of sensors and apparatus whose unique function is recognizing the presence of obstacles. In other words: the best way to avoid any accident involving a misplaced pedestrian and a misfunction of such sensors is to avoid any uncontrolled trespassing on the road.

Figure 50: Newer and future mobility modes are challenged to respect and take care of the environment as much as possible. OWN ELABORATION.

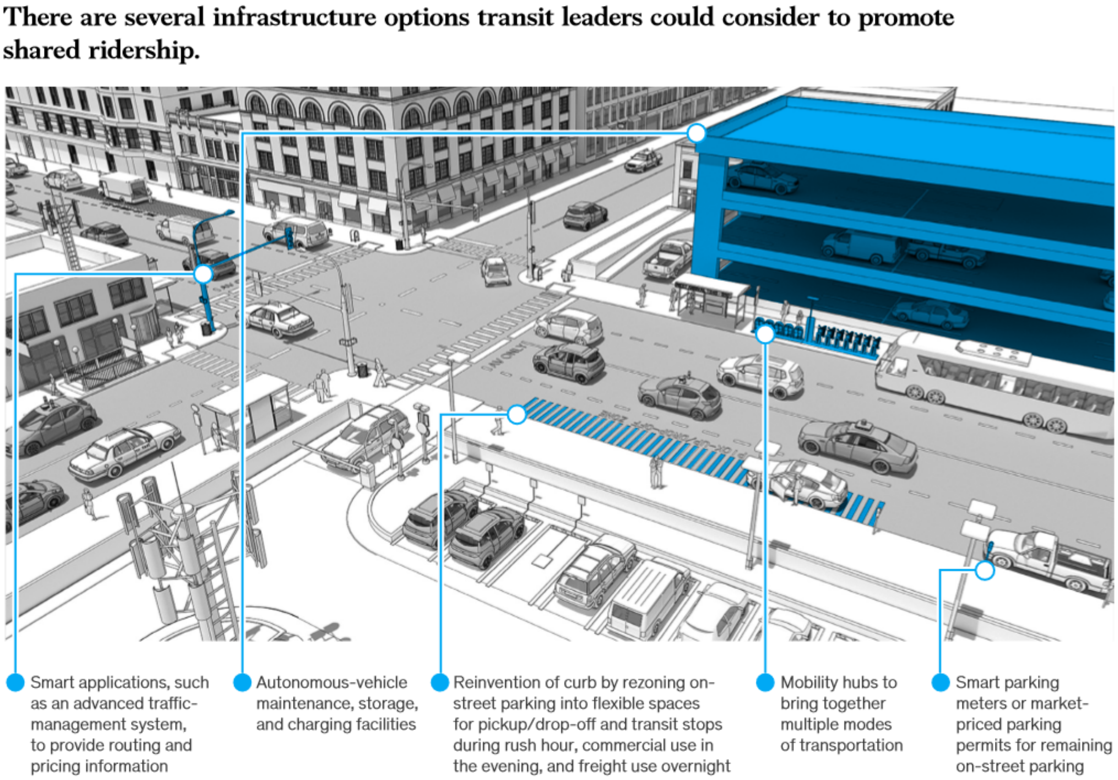


Figure 51: An overview of some of the infrastructure requirements that will be needed for self-driving technologies represented in the vicinity of an urban intersection. MCKINSEY & COMPANY.

This figure has been published by Tyler Duvall et al. at the publication *A new look at autonomous-vehicle infrastructure* (McKinsey & Company. May, 2019) and is available at https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/a-new-look-at-autonomous-vehicle-infrastructure. It is worth noting that some interesting ideas for the deployment of some of the commented needs, such as the stochastic, flexible management of the area destined to PU-DO areas depending on time and/or demand, or the creation of AV-ONLY lanes, are depicted.

s. Clear, unambiguous hierarchies should be stablished for traffic management at non-signalled intersections and junctions. Autonomous and Connected vehicles riding through roads that converge at a non-signalled intersection should negotiate beforehand between them for achieving their respective targets in a safe and efficient manner.

t. The future impacts of automation in socioeconomics are still unknown and several scenarios could still be considered. A similar matter pursues urbanism issues: depending on the citizens' use patterns of automated vehicles, the overall traffic flow will be strongly or slightly altered. On the one hand, streets would be able to process higher peak intensities (i.e. road capacity would increase), thus, a possible increase on vehicular demand would not be troublesome. On the other hand, if people used shared car systems in a more generalized way, the overall number of vehicles needed for satisfying all the displacements would be quite lower. Therefore, current streets would become over-dimensioned for automated vehicles and municipalities could engage strategies for recovering underused, former overcrowded lanes for non-motorized participants.

u. Such recovered lanes could be useful in order to encourage active mobility: New bike lanes and enlarged sidewalks would seek to make pedestrian and bicyclist mobility safer, more pleasant and attractive for citizens. With such measure, the likely raise of physical inactivity rates that automation may imply could be attempted to be mitigated in order to fight sedentism and avoid all the health concerns that may cause.

v. Microscopic modelling would help to plan efficient lane reduction programmes. Several scenarios of car demand, vehicular type share and road surface distribution and right-of-way could be considered and modelled for planning and studying the possible positive and negative impacts of the planned measures on the vicinity of the studied streets.

w. The lack of necessity of a licensed driver for each vehicle presents an opportunity for Public Transport to noticeably revolutionize the design of the Public Transport networks in cities and moreover to evolve the shape and size of the vehicles of the fleets. The companies that operate Public Transport services will be able to increase the number of vehicles of their fleets. A better service may be performed by such companies if they were able to satisfy a given demand with a lower average headway between vehicles.

Automation presents a set of benefits and opportunities that may dramatically change our way of mobility. Gains in terms of safety, comfort, equal accessibility and time saving may become the greatest positive impacts that automation may imply. Furthermore, new job opportunities may appear in the field of the automotive industry and fleet management and maintenance, and an opportunity for mitigating current misbehaviours related to driving activities would appear (Figure 52). Nevertheless, such other threats such as potential diminished active mobility, potential congestion increase due to "zero occupancy" vehicles, potential cybersecurity threats and the potential increase of unemployment rates due to the unnecessity of licensed drivers at the transportation tasks are some expected likely potential problems that should be kept in mind in order to foreseen strategies for mitigating them.

A continuous management of the transition stage must be performed by different level administrations, partnered with transport operators and multidisciplinary departments. The main objective of such management must be **to plan ahead the strategies to develop** after assessing both local and global impacts and their time-dependent evolution (taking into account their correlation with some other strategies, standards and measures). Such strategies must intend to **leverage the most important positive impacts while mitigating or extinguishing the most harmful, negative ones.**

If automation became a successful reality, it would not only involve major changes on urban mobility **but also on the urban landscapes.** Summing up all the points that have been mentioned, it can be thought than street furnitures (traffic lights, street lamps, garbage containers, etc.) will be equipped with a great number of electronic items (namely, sensors and antennas) that may ease the self-steering tasks for Connected and Autonomous Vehicles. Soon, the growing demand of shared autonomous vehicles and the descending number of human-driven cars would make possible to recall former on-street parking spots as old-fashioned, obsolete urban facilities because they would likely be replaced by PU-DO zones and enlarged sidewalks. Current stiff signage may become subtituted by a flexible one, which may be managed attending to current demand and traffic status, current meteorological conditions and many other data.

The image depicted in Figure 51 represents the likely future landscape of any city. it gives an idea of some of the expected new items and facilities that will be introduced in our cities in the following decades of the twenty-first century. It can bee seen that some of these facilities are orientated to a multimodal mobility (e.g. the bikesharing station next to the bus stop and the car park building), whose demand keeps growing due to new technologies and the simplicity of accessing it due to newer smartphone applications.

Moreover, in the figure there are sketched some other interesting ideas that have not been discussed among the present report. This is the case, for example, of the flexible, active conversion of pick-up and drop-off areas to bus stops and other road applications depending on the necessities of any given time period of the week. Such flexible areas have to be signaged and mapped with great precision and its position and current target must be broadcasted to vehicles with the help of beacons. Furthermore, the creation of an AV-ONLY lane is contemplated

Figure 52: Automation would appear as an opportunity for reducing the number of drivers which make a not-so-responsible use of the road network. The image shows a parked vehicle which is blocking the road access to a on-street garbage dumpster while is slightly trespassing the poorly-marked lane. TWITTER (@PoliciaVLL).

and sketched in the figure. Finally, it is mentioned that on-street parking may live on if a pricing strategy were deployed.

A huge, enormous number of combinations between all the mentioned services and facilities would be possible to get deployed, according to the local requirements of the citizenship of a given city and/or region.

Thus, a **given combination of infrastructural requirements** (namely: markings, sensors, beacons, chargers, parking facilities, pick-up and drop-off platforms, "road stations", bus stops, etc.) or even a small number of possible combinations of such requirements **could be deployed** with the target of satisfying the mentioned local requirements and making possible the best level of service of such services, with may be comfortable, accessible, secure, safe, fair and efficient. In other words: **an autonomous and sustainable overall mobility service** would be possible if cities were adapted for it, but it **will also require the citizenship's willingness to adapt to new technologies** and their newer opportunities, seeking a rearrangement of the current demand from current weak vehicular occupancies into a smaller number of vehicles which could be better exploitated, **implying therefore a significant reduction on the overall amount of energy** being used for satisfying the overall set of displacements.

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List of Abbreviations

* **AHC** ..... Automated Highway Cruising
* **ART** .... Autonomous Rail Transit
* **ASoD** .. Automated Services on Demand
* **AV** .... Autonomous Vehicle
* **AVP** .... Automated Valet Parking
* **BSM** .... Basic Safety Message
* **BRT** .... Bus Rapid Transit
* **CAS** .... Collision Avoidance System
* **CAV** Connected and Autonomous Vehicle
* **CV** .... Connected Vehicle
* **DGT** ...... *Dirección General de Tráfico*
* **DSRC** .... Dedicated Short-range Communication
* **EU** .... European Union
* **GDP** .... Gross Domestic Product
* **GNSS** ...... Global Navigation Satellite System
* **GPS** .... Global Positioning System
* **HOV** .... High-Occupancy Vehicle
* **ICTs** .. Information and Communication Technology
* **IoT** .... Internet of Things
* **ITS** ... Intelligent Transportation System
* **I2V** .... Infrastructure-to-Vehicle
* **LIDAR** ... Light Detection and Ranging
* **LSS** .... Lane Support System
* **L0** .... Level of Automation number zero
* **L1** ..... Level of Automation number one
* **L2** .... Level of Automation number two
* **L3** ... Level of Automation number three
* **L4** .... Level of Automation number four
* **L5** ..... Level of Automation number five
* **MFD** ..... Macro Fundamental Diagram
* **OBU** .... On Board Unit
* **OSM** .... *OpenStreetMap*
* **PDA** .... Personal Digital Assistant
* **PPP** .... Public-Private Partnership
* **PMx** .. [Suspended] Particulated Matter
* **PU-DO** .... Pick Up and Drop Off
* **RADAR** . Radio Detection and Ranging
* **RSU** .... Road Side Unit
* **SCS** .... Speed Control System
* **TJA** .... Traffic Jam Assist
* **TMB** ...... Transports Metropolitans de Barcelona
* **TSR** .... Traffic Sign Recognition
* **UK** .... United Kingdom
* **UNECE** ..... United Nations Economic Commission for Europe
* **USA** .... United States of America
* **VMT** .... Vehicle Miles Traveled
* **V2I** .... Vehicle-to-Infrastructure
* **V2V** .... Vehicle-to-Vehicle
* **V2x** .... Vehicle-to-Everything
* **WAVE** .... Wireless Access in Vehicular Environments
* **3D** .... Three-dimensional
* **5G** 5^{th}-generation mobile communications

List of Figures

Appendix

Methodology of the valuation criteria used for creating the radar charts that are shown in this document.

A spider chart has been plotted for each main infrastructural need. Such chart displays eight different categories, which are the eight concepts where self-driving technologies are expected to cause a relative impact. These categories or concepts are the following ones:

A. Safety

B. Security

C. Time saving

D. Investment

E. Congestion

F. Emissions

G. Energy saving

H. Fares and taxes

Such spider charts consist of five levels. The most external one corresponds to the most positive aspects of each category (Great improvement in terms of safety and security, great saving in terms of time and investment, great reduction of congestion, emissions and energy wastage, and lower fares and taxes for customers). Otherwise, the most internal ring shows the most negative aspects of these categories (Great decline in terms of safety and security, great spending in terms of time and investment, great expansion of congestion, emissions and energy wastage, and higher fares and taxes for customers). The intermediate (third) ring represents the situation for current human-driven vehicle's mobility.

In other words: The more external a spot is, the more benefits are expected for the category that such spot represents. Otherwise, the more internal it was, the more harm would be expected.

Attending to the concepts that are expressed and developed in the whole text, a valuation has been carried out in order to express the potential impacts of self-driving in a more visual manner. Seeking to avoid subjectivity, such valuations are discussed as follows:

Road marking

The main target of such need is to provide a safer driving in terms of reducing and mitigating the likelihood of human error. Vehicles will be able to drive by their own, and there is the possibility of basing their steering manoeuvres on current markings.

Such markings would have to be clearly readable. A proper level of maintenance is required in order to make the lecture task easier to vehicles. Therefore, a greater investment would be required, and thus, taxes and congestion fees may arise.

The main problematic may come if self-driving mechanisms and algorithms of AVs were only relying on road markings: A criminal with malicious targets would be able to hijack a self-driving vehicle only utilizing the following equipment: a brush and two paint buckets, the first one for obscuring the official marks, and the other one for creating false marks. Thus, it is quite important to make cars to obtain road information from at least two different ways and merge such information in order to verify them.

No notable savings in terms of energy and time, nor significant reduction of emissions and congestion will come from a delicate maintenance of the road markings.

Road signage

Mostly the same that has been explained for road marking could be said for road signage. Programmes that seek a better maintenance of signage will be needed in order to make signs readable hundred per cent of the time, in any traffic, weather and illumination environment.

Implementing a new, universal signage convention will imply to change a significant part of the current signs that are placed around the globe. Therefore, if such measure were implemented, it will imply a huge, enormous need of investment for changing almost the whole share of signs at most countries, which also implies the need of creating newer fees and taxes and rising current ones. Administrations should have to search for other sources of income: from a sociological point of view, nobody wants his/her taxes to be raised.

One more time, such measures are targeted to achieve a safer driving. Efforts should be centred in guaranteeing that road information is correctly and in a biunivocal way conveyed to cars rather than in changing all the world's road signage. A balance between such measures should be reached.

Furthermore, some security problems could arise if classic, physical signs were rigged, handled by criminals. The meaning of a given sign could be completely changed just if someone pastes a sticker that shows the geometry of another official sign over the mentioned sign (e.g. if vehicles were only relying on physical signs, and if someone replaced a "NO ENTRY" sign with another one that shows "ONE DIRECTION" at the end of a single-lane street, a car chaos and even an accident could occur: a street stretch where cars are allowed to enter from both sides will be operative, and each entering car will face other oncoming vehicles). Therefore, physical signs are quite useful for human participants (most of them are common travellers and know streets beforehand) but may become a problem for connected cars which base their knowledge on images being recorded *ad-hoc* instead of basing it on previous experiences.

Signalling

The main difference between both road marking and signage and traffic signals comes from the potential for change their phase. Despite official marks and signs are physical items and cannot be periodically altered several times per hour, signals are useful for managing the road network because their capability of disrupting and re-establish the traffic flow in a quite instantaneous manner.

The main benefits of automated driving related to traffic signals are the potential of increasing road capacity and a safer driving and active mobility. Such capacity increase will imply congestion reduction and a little time being saved at each semaphored intersection, which could imply a significant, but not-so-noticeable time being saved in overall terms. Perception of time saved would be low because vehicles will still have to stop at semaphored intersections.

Emissions and energy wastage could be seriously reduced from signals, but more especially related to traffic management (coordination between vehicles and semaphores) rather than related to vehicles being stopped at intersections. Such benefits are considered in "(3D) Mapping" and "Traffic management" sections.

Some security problems could appear but mainly related to hacking attacks, which are much more difficult than painting white lines or pasting stickers. Nevertheless, the problematic should be considered as a potential threat.

Finally, it is worth mentioning that automation may require not a better maintenance of current semaphores but the creation of new ones at the most problematic zebra crossings. Investment and taxes should be centred in the creation of these new semaphored intersections.

Parking

Citizen's security is expected to be enhanced because they will not have to roam through dark underground car parks. Furthermore, citizens will experiment a significant improvement in terms of safety, since no drivers are required to gather their cars: Vehicles will be able to drive to their owners' current position when summoned, and no people could be accidentally hit by a vehicle at a car park. A clear time saving is expected to be achieved (drivers will not have to park their cars and will not be wasting time performing parking manoeuvres). Moreover, according to Catapult Transportation Systems, 2017, British drivers spend an average of 6.45 minutes while searching for a parking spot. **Thus, a significant time would be saved from the lack of necessity of wasting time searching for a spot where get parked.** Investment on parking facilities will not differ significantly from current sums, but it may show a slight increase: Maintenance of car parks would also be mandatory, car parks would perform a faster deterioration if capacity were increased, and future car parks will have to be equipped with chargers in order to allow future electric AVs and electric human-driven cars.

Congestion and emissions could be seriously improved if parking facilities for Self-driving vehicles were placed in surrounding cities and areas with lower land prices. Such situation would also imply a significant wastage in terms of energy. Finally, as a positive point, **fares of car parks could experiment a decrease due to park's higher capacity** (from an economic standpoint, if average car park occupancy increased, companies which manage such car parks could regain operational costs and achieve the targeted economic profit by deploying lower fares per vehicle).

Pick-Up and Drop-Off areas

To be picked-up and dropped-off by a vehicle that parks in an automated manner will help to save a huge length of time in overall terms, which is currently wasted while searching for a spot where get parked.

No significant changes related to security, emissions and energy wastage are expected, but congestion may be reduced: The creation of Pick-Up and Drop-Off bays is a need that seeks to avoid the detention of vehicles on operating lanes.

The most important impact will be the benefits in terms of safety: People which want to join a vehicle will not have to trespass the road land, will not disrupt other lanes and will not be in danger of being strucked by coming vehicles.

A certain amount of money will be necessary in order to build newer PU-DO areas and adapt current on-street parking land to PU-DO bays. The more complexity on the design of such areas, the more municipal investment will be required. Therefore, municipal taxes may arise: Taxes are a revenue system that will help to transform the city.

Automated Car/Ride-sharing services on demand

The mentioned self-driving services are not expected to be more secure than current Car/Ride-sharing services (nowadays, a professional driver acts as the ruler of the vehicle. Self-driving vehicles that will operate such services would not carry with them any driver or ruler). Thus, security applied to mobility must become a main issue that town halls and other administrations should catalogue as preferential (e.g. Strategies seeking a fair mobility from a gender standpoint should be stablished). A gain in terms of safety will be provided to both customers and pedestrians.

Customers will notice a reduction of average travel time and parking time will be eliminated for commuters. Nevertheless, depending on the case time would be saved or not: On the one hand, no time will be wasted due to searching for parking, but on the other hand, cars would also have to perform manoeuvres to access the pick-up and drop-off bays. Furthermore, focusing on ridesharing services, a given customer may notice some stops for letting other passengers being picked-up or dropped-off but, for such customer, the mentioned stops may be superfluous and may lead to time wastage. Therefore, stops at PU-DO areas should be as shorter as possible.

Carpooling would lead to a significant reduction in terms of congestion and fuel/energy wastage. Moreover, a great reduction of tank-to-wheel emissions will occur but PMx particles emission will not experiment a huge decrease because vehicles which offer such services will be almost-continuously braking and manoeuvring for picking-up and dropping-off customers (such particles are commonly emitted as a result of performing braking manoeuvres). Finally, although the required investment on equipment for companies which will operate these services is expected to increase (such companies will have to compose and manage a great vehicular fleet), according to International Transport Forum, 2015 (L.D. Burns, W.C. Jordon, B.A. Scarborough (2013), "Transforming personal mobility", Columbia University, 2013), out-of-pocket cost of such services for customers will be quite lower as the fares of current public transport and current Car/Ride-sharing systems, because no driver will be required for each single car, and no incomes will have to be paid.

Bridge Structures

Although no significant changes in terms of driving security and travel time are expected to occur, V2x interconnections will provide a quite safer driving. Huge benefits are expected to be achieved in terms of congestion reduction and energy saving due to cars capability of arranging between them and aerodynamical effects of driving near to each other. Benefits in terms of emissions reduction are also expected to be achieved but PMx particles emission will not experiment notorious changes from current situation. The most harmful impact will be the growth of the required investment for implementing such measure, which would increase current road capacity. Thus, toll pricings may probably increase in order to earn back the required investment.

Map creation

A notorious investment would be required for developing and improving newer digital map platforms. The more accuracy on real landmarks to be depicted on such maps desired, the more economic effort would be necessary. Therefore, such great investment should be balanced, and it may lead to navigation companies to increase the sale prices of their products, which will be applied for self-driving technologies.

Despite no gains in terms of security are expected, safety will be enhanced (more precise driving, less drivers making an irresponsible use of the road network, etc.) and travel time would be reduced (navigators will compute faster routes, which will depend on current traffic, and will be capable to know the traffic light phase when the vehicle is expected to reach such semaphored intersection). Congestion is expected to show a slight decrease due to car platooning and a huge reduction in terms of energy wastage and emissions could be reached, because navigators would provide the necessary information to steering systems for driving in the most sustainable that it were possible.

Traffic Management and intersections

The assessment of the traffic management needs and impacts shows the most double-poled chart of the whole document, and it is worth discussing largely such fact.

On the one hand, the management of a road network that will be used by CAVs and connected vehicles will offer a series of huge benefits such as safety, congestion reduction, emission reduction and energy saving. A smarter road operation would be achieved if lanes and streets were managed on demand, making vehicles to be diverted from main arterials to secondary streets that allow the penetration of vehicles towards the urban core during morning rush hour and permit the exit of such vehicles towards suburban areas.[54] Such smart management, if implemented, would imply an enormous mitigation of congestion. And if traffic jams were mitigated, a significant saving in terms of energy and a reduction of emissions would be achieved jointly with a more efficient steering between signalized intersections.

A safer driving would be possible because humans will rely on self-driving technologies, which would seek for a reduction of road accidents, the reduction of the overall costs related to social care of the accident victims and health concerns that are caused by environmental pollution, and furthermore, a reduction of congestion and traffic jams would also imply a safer driving because road rage would be significantly mitigated: If nobody joined a traffic jam on his/her path, nobody would become angry due his/her powerlessness against the delaying of his/her journey, and will not print his/her feelings on the road by means of the car horn.

On the other hand, such desirable scenario will misfortunately not be priceless. Administrations should have to invest a great sum of money in order to install all the required infrastructure to the whole road network (obviously, a smart management of the road network only makes sense if a large portion of the road network is adapted). Expenses will come from all the amount of sensors and cameras that should be placed across the cities, from the zebra crossings that may need to be enhanced to signalized crossings, from the control centres that will be needed in order to manage the network, from all the incomes for all the controllers that must be paid and from the development of 5G mobile telecommunication or ITS-G5 technologies and further technological equipment and digital platforms which have still not been developed.

Moreover, a proper defence against cyber-attack events should be guaranteed. Any security breach related to traffic control could be quite harmful. Authorities and Police should guarantee a certain cyber-security level in order to avoid such attacks. Investment should be also destined to prepare, train, increase and maintain the staff that will cope with possible cyber-attacks.

[54]Nevertheless, it may imply some other secondary but negative points such as crowding the secondary road network, which may be formed by minor roads and streets which run through residential areas.

All the mentioned expenses will have to be funded by administrations. Some of them may need to strongly increase their taxes, and that will be a huge problem for all the administrations. Any government that implements a tax raising, will have to cope with several sociological problems such as demonstrations and loose of votes at polls.

Private-Public partnerships may become extremely useful and attractive for administrations in terms of funding all the commented requirements.

Lane reduction

Such measure is not expected to generate benefits nor problems related to security, time saving, emissions, energy wastage and taxes: In fact, such measure is currently being applied at some cities not as a requirement of automated driving but as a strategy that seeks to mitigate and discourage private mobility. Municipalities are being implementing it independently from self-driving technologies by means of investing the money being earned with current taxes.

Furthermore, to carry out such works imply a certain monetary sum, but it also would imply much less road surface to be maintained. On the one hand, roads should be maintained in a more delicately manner for a better working of steering systems. On the other hand, road land could be sensibly reduced. Moreover, pedestrianized areas do not require a maintenance programme as pompous as vehicles require.

Nevertheless, to reduce the number of lanes may imply a slight increase of the congestion, especially at the early stages of the implementations. It could even happen that a lane reduction carried out at a given street will not show the expected results. **Microscopic modelling would be helpful in order to prepare an efficient lane reduction programme**.

Finally, the greatest benefits that this measure could provide may be expressed in terms of safety, but more especially in terms of pedestrian's safety: Pedestrians and commuters who usually displace to their work on foot will be authorized to roam on more and more surface portion of the streets. Active mobility would be powered, and physical activity would be encouraged. Therefore, targeted benefits in terms of health would be also achieved.

Encouraging active mobility

This need may appear from a health-related problematic and could come from both an increase of the obesity indexes but also from health issues concerning an excessive pollution (especially, if electric engines and other more sustainable motors than petrol ones were not as efficient in terms of emissions reduction as expected). The target is to offer a gentle, safe and secure on foot and bike-centred mobility.

To encourage peoples to commute on foot when possible will have significant impacts on mobility: Less cars will be used, and therefore, a reduction of congestion, emission and energy used will be possible. Travel times will increase, especially for commutes that imply a walking distance between two and four kilometres.

No taxes nor fees will appear: To roam on streets has always been a free activity. The required investment for municipalities consists of such amenities and facilities that will help to beautify pedestrian areas and provide sport areas, but also strategies to enlarge sidewalks and create newer bike lanes and enlarge their networks. The advantage point here is that most sidewalks and bike lanes are already built. Furthermore, as it has been commented at the previous section, to enlarge them will improve pedestrian's safety and the perception of security could be significantly improved if mast-mounted police cameras were placed and distributed across the city[55]. If the perception of security were higher, more citizens would be willing to commute by walk, especially during the nights or walking through dark, unpleasant pedestrian underpasses.

[55] Nevertheless, mast-mounted security cameras may cause a bias in terms of security perception by citinzenship: Areas which are constantly controlled by videocameras may be catalogued by citizens as *areas that are constantly controlled by security cameras because such areas are places where some crimes or misbehaviours occur with a certain frequence.*

Last Figure: Summary of all the radar charts represented in the report