SERVING TRAVEL DEMAND WITH AUTONOMOUS VEHICLES IN BARCELONA

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SEPTEMBER 22, 2017
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Literature review

1. Introduction

The world is changing rapidly, and it is expected to experience changes at an increasing speed in the future. There is a worldwide tendency for people to move to densely urbanised areas. By 2050, it is expected that two thirds of the world's population will be living in cities. Among other issues that will arise from this fact, the efficiency of the transportation system is going to be extremely challenging. On the other hand, there are numerous advancements in technology that will lead to new and more efficient means of transportation. One of the most popular is driving automation, which is the feature that is prone to bring the most important changes to the way we move.

The aim of this work has been to analyse how autonomous vehicles (AVs) can affect the transportation system in the city of Barcelona. In the first section, a thorough literature review on autonomous driving is conducted. Thereby the its main features are observed. In the posterior section, we try to mimic how transportation would change due to the irruption of this new technology. To that effect, a series of probable and/or advantageous scenarios are designed, based on previous research, and its effects on Barcelona's network are analysed. Finally, conclusions are drawn from the results.

2. Effects of the automation of driving

In this section, we will have an overlook at the travel implications of autonomous driving yielded from various recent studies across the globe. In many cases, it is not possible to forecast the effects quantitatively. The aim of the present section is to collect all possible outcomes that can arise from this new technology, and from that point on design and assess a few feasible scenarios in which autonomous mobility plays a role.

2.1. Variation of demand

It is truly difficult to make an accurate prediction of how travel demand will variate with the irruption of self-driving technology. However, there are some factors important to note. In the first place, people that are unable to drive a car —such as children, elderly or disabled persons— as well as goods can be transported by an autonomous vehicle. In both cases, the trip by AV could either substitute another trip that was previously performed by mass transit, or be induced by the benefits generated by this means of transportation, which results in a new car trip. Therefore

Higher number of potential users: those unable to drive come into play

It has been pointed out by some recent studies (Fagnant (2015), Lutin (2013), Harper (2015)) that one of the benefits of self-driving vehicles is the possibility to bring car mobility to people that cannot drive. This fraction of the population includes the cohorts too young to drive and those whose physical condition disqualifies them for this purpose, such as people with disabilities or the elderly.

In many cases this inability leads to a total dependence on a third person to complete their daily mobility needs. As for elderly, there is also the possibility that car use is preferable due to comfort concerns, including in-vehicle experience as well as total walking distance from and to the vehicle. As mentioned in Lutin (2013), the quality of life of oldest age groups are highly susceptible to their mobility capabilities. Autonomous cars can bring these persons completely independent and comfortable travel.

Harper (2015) studies the impact of automation of driving in the increase of demand of the main transport mode involved, i.e. the car. Its approach, rather than pretending to be highly accurate, finds an upper bound of the Vehicle Miles Travelled (VMT) increase due to the mode shift from those demographic groups. To achieve this, non-driving young and elder adults are assumed to use the autonomous car as much as nowadays' under 65 years old conventional car drivers. Furthermore, the individuals unable to drive because of their medical conditions will travel by car as much as everyone else. Results indicate that the total travelled distance by autonomous vehicles due to the entry of new demand groups will be no higher than 12.4%. By "total travelled distance" we refer to the sum of every trip distance on the network.

2.2. Capacity increase

The automation of driving brings along the chance to make use of a whole new group of tools to improve traffic efficiency. Autonomous cars present a much higher responsiveness to unexpected events. This allows vehicles to travel at shorter headways while maintaining the same speed and safety levels. They also have the possibility to take into account much more information upon which it can base its decision-making process. As opposed to human drivers, self-driving cars can interact with other vehicles and share information about the desired route, the state and properties of the vehicle (for instance, how fast the car is capable to accelerate and decelerate). The way autonomous vehicles could work emerges from the fact that it counts on this set of data, and that their behaviour is much more reliable and easily predictable to that of a person. In addition, they could be connected to a data centre that provides them with information that is nowadays not available to drivers, i.e. traffic conditions in real time. With the aim of having a picture of these improvements in mind let's see some examples.

Microscopic behaviour example: The way a traffic light queue empties

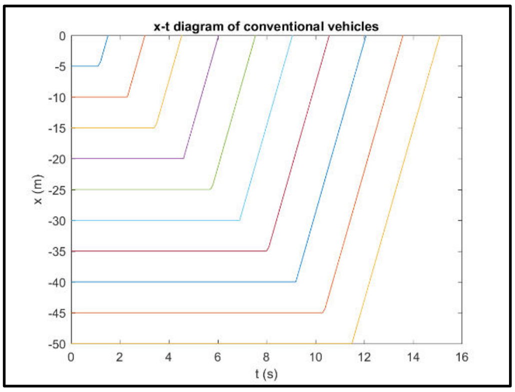

Figure 1: Qualitative representation of the x-t diagram of a traffic light queue emptying nowadays

There is a traffic light in red with, say, ten cars in a constant spacing. Neglecting the acceleration difference between a conventional and an autonomous vehicle, the time it takes to empty the queue is equal to the time needed by the last vehicle to cross the intersection. It writes as follows:

$$t_{queue} = n_{CV} * t_{react,CV} + n_{AV} * t_{react,AV} + \frac{(n_{AV} + n_{CV}) * headway}{v_f}$$

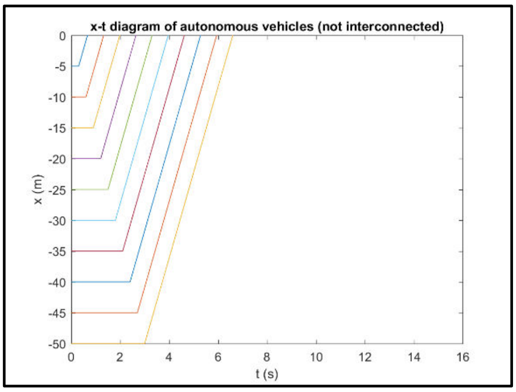

Figure 2: Qualitative representation of an x-t diagram of a traffic light queue emptying made up of AVs

The reaction time of an autonomous vehicle is said to be noticeably lower than that of a human driver. It becomes apparent that the higher the share of autonomous cars, the lower the total time is going to be. This formula is written to account for the current behaviour cars standing in line. That is, each car reacts to the acceleration of the vehicle preceding it. In the case of autonomous driving, the vehicle detects the forward movement of the car in front by sensing an increase of the spacing between both automobiles.

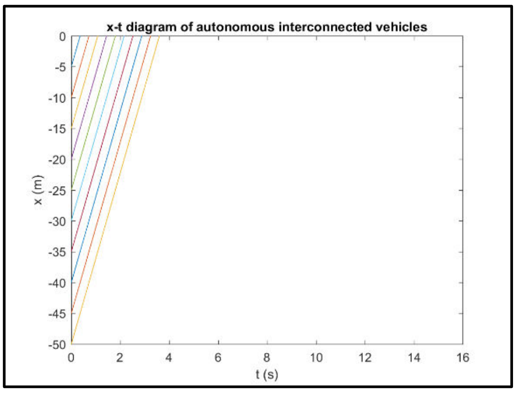

Figure 3: Qualitative representation of an x-t diagram of a traffic light queue emptying made up of interconnected AVs

There is another case that can increase the efficiency of a queue emptying process. The car can be not just reacting to the car in front, but to the whole traffic system. Let a queue be composed entirely by autonomous vehicles, all of them interconnected. Each vehicle is in a good condition, the knowledge of its features allows to determine what trajectory at what speed patterns it is going to carry out its manoeuvre, and shares this information with the other vehicles. In this case, cars can start accelerating not reacting to the car in front, but reacting to the traffic light: all cars start accelerating at the same time at the same acceleration rate, keeping spacing constant. All in all, the way a queue of fully autonomous and interconnected autonomous cars could resemble to the movement of an incompressible fluid through a pipe. In this case:

$$t_{queue} = t_{react,AV} + \frac{n_{AV} * headway}{v_f}$$

Apart from the aforementioned ability of autonomous cars to react faster to whatever happens around them, a substantial part of the possible improvements that come along automation of driving arise from the fact that such robots are thought to be much more reliable than a human driver. If the simultaneous start of movement of a queue of cars is possible is thanks to having the certainty that all vehicles will quickly react to the green light sign. As expressed in Lutin (2013):

> "Autonomous systems do not get drunk. Nor do they get tired, or suffer from distractions like texting while driving."

Friedrich (2015) research studies, as its title reveals, the effect on transportation engineering features of moving to a fully autonomous vehicles environment from a general, theoretical point of view. For a city, it distinguishes between the effects on a link and on an intersection. The latter is found to be more restrictive in terms of how much the flow capacity of the network increases. A microscopic study of autonomous cars of an intersection results in a 40% increase of the capacity on the streets of the city.

Macroscopic behaviour: stationary flow on a highway

Let's now observe a section of a motorway. The irruption of automation of driving allows a more predictable, consistent, and secure behaviour of vehicles. Intercommunication between them facilitates well in advance preventive driving. All this can lead to significantly shorter headways between vehicles at high velocities, especially at free flow conditions. Vehicles are said to be able to keep free speed even at high densities, which would increase traffic flow as well. Diagrams would therefore change as follows:

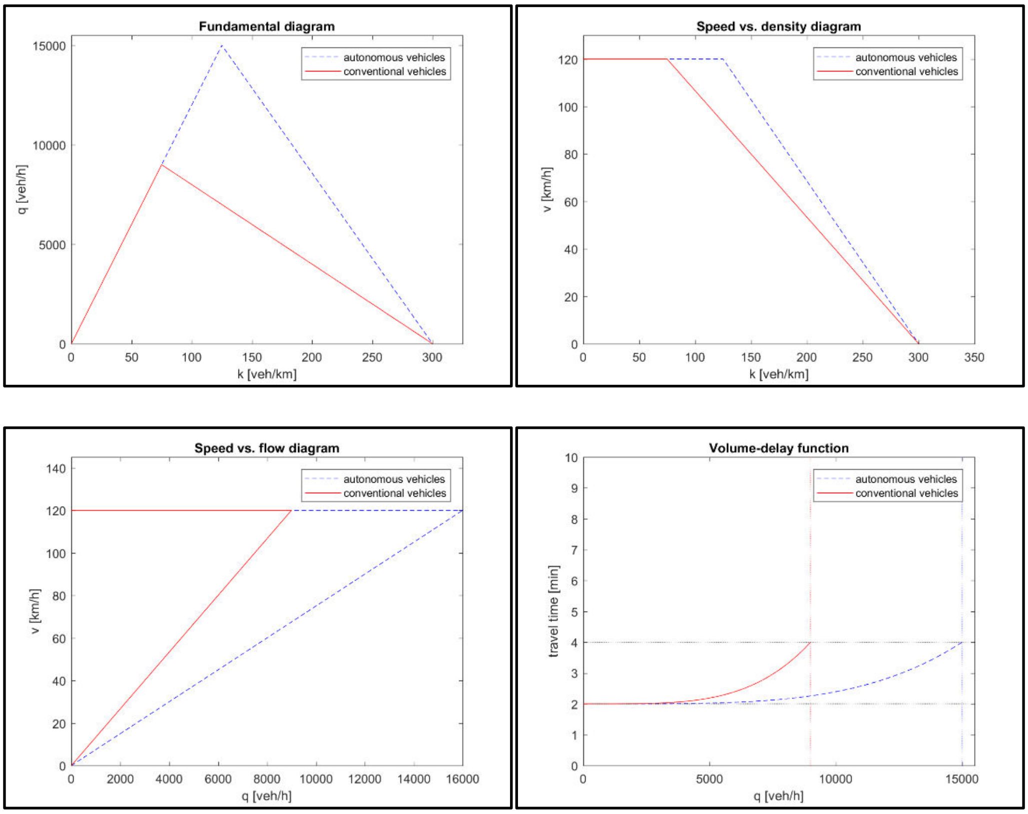

Figure 4: Qualitative representation of the predicted effect of AVs on traffic.

Friedrich also analyses in the aforementioned research paper the outcome of cars becoming autonomous for the highway case. The rise in capacity turns out to be twice as much as in the previously seen urban network case. This is owing to being able to increase mean velocity while maintaining high densities, as it can be seen in the figures above. Formally:

$$v_{highway} \approx 2 * v_{city}$$

$$k_{highway} \approx k_{city}$$

$$q_i = v_i * k_i, i = highway, city$$

$$\Rightarrow \quad q_{highway} \approx q_{city}$$

2.3. Comfort and its implications on mean velocity

As we have mentioned before, all autonomous automobiles' users will be entirely formed by passengers. As such, a wide range of activities will potentially be carried out inside the vehicle, and travel time could become more productive. To this end vehicle distribution could be redesigned and vehicle driving behaviour can be affected.

Nowadays, car designs are centred on the driver's comfort, as it is the only indispensable person and they often travel alone. Modifying the distribution of the car cabin and adapting it towards a more productivity-oriented space will rise up the agenda of car manufacturers.

Additionally, the higher variety of activities and possibilities that can take place inside the car will require high comfort standards. This is primarily affected by the driving behaviour. As Le Vine (2015) points out,

> "(…) car passengers start experiencing discomfort at lower rates of acceleration than car drivers; it is therefore plausible that occupants of an autonomously-operating vehicle may wish to instruct their vehicle to manoeuvre in a way that provides them greater ride comfort than if the vehicle-control algorithm simply mimicked human-driving-operation."

Figure 5: Autonomous vehicles are set to lead the next jump in transportation comfort

This study finds necessary the investigation of how traffic would be affected from the fact that passengers demanded a smoother driving behaviour than that of a human driver in order to be able to perform a broader range of activities while inside an autonomous car. It considers the possibility that feasible levels of accepted riding experience will be similar to those of public transportation. Series of scenarios resulting from the combination of different conditions of longitudinal and lateral acceleration and deceleration constraints, traffic light timing modifications and interaction with conventional vehicles are carried out. As far as my piece of work is concerned, it is interesting to note the decrease of an intersection capacity of 4% and 18% for acceleration and deceleration patterns similar to light rail transit (LRT) and high-speed rail (HSR) with respect to nowadays usual human driving style. The associated time delays for these capacity drops are 4% and 36% respectively.

From this aftermath it is to foresee a probable trade-off between high ride comfort (with an associated high travel time productivity) and high mean speed. While being beyond the scope of the present investigation, it is also worth noting the fact that a certain agreement on driving patterns will be needed.

Let's try to picture somebody that nowadays needs 20 minutes time to get to work with his/her privately-owned non-autonomous car, a trip that would require 25 minutes under the aforesaid acceleration upper bounds. If this user gets on a self-driving car 35 minutes before he needs to get to his office and he would like to prepare the upcoming meeting, he would probably prefer a highly smooth ride to work under more enjoyable conditions, maybe even more smoothly than a train's. As the behaviour of a vehicle directly affect the other users on the network, a prudent combination of limits should be set, now that we have the chance to code the driving standards of future cars instead of being up to each customer.

2.4. Lower costs

Let's define a utility function of travelling by car for a generic user, similarly to what can be seen at Ortuzar (2011):

$$V_{mode} = \beta_{mode} + f(time) + f(€) + f(others)$$

In 2013 the first pieces of research on how costs would vary when autonomous vehicles step in were conducted. All of the most prominent studies —from Columbia University, University of Texas at Austin, Victoria Transport Policy Institute, Argonne National Laboratory and the Boston Consulting Group, among others— investigating robotic cars have found operating costs will drop. A recent report carried out at ETH Zürich on this matter has pursued the most accurate approach so far. From its own words, the report aims at performing "a transparent and comprehensive bottom-up calculation of the respective cost structures of fully autonomous (...) vehicles", and it certainly does so. It analyses not just the automation of driving, but also the effects of cars using electric energy instead of petroleum products, as well as different operational models such as carsharing and ridesharing schemes. For the purpose of this work, Bösch (2017) will be used to obtain certain values for it is recent and the time investment on deriving cost structures for the specific case of Barcelona would by no means assure us a more accurate prediction.

For the automobile, a feasible utility function could be:

$$V_{mode} = \beta_{mode} + \beta_{IVTT} * IVTT + \beta_{ACCESS} * t_{ACCESS} + \beta_{€} * € + \beta_{PARK} * €_{PARK}$$

Results show that the operational costs (i.e. fixed and variable out-of-pocket costs) remain about the same when a single person uses an autonomous car instead of driving a vehicle himself. The costs are directly related to the price the user has to pay, so, this factor would not be improved. However, an important advantage needs to be taken into account: the person is no longer a driver, but a passenger, and thus he can make use of this time to eat, work, sleep. This is, the in-vehicle travel time productivity increases significantly, which is a positive outcome for the user. In the utility function, the factors that have a negative impact on the user's satisfaction have associated a negative coefficient. Then, in the case of autonomous driving, β_{IVTT} is found to still be negative with a smaller absolute value.

2.5. Empty rides

Besides allowing users to travel without driving, the main reason automation of cars is said to reshape transportation is that they can operate while being empty. In the current situation, where most vehicles are privately owned, cars could drive themselves from and to parking facilities. Users would then have to walk less and their total travel time could be significantly reduced. In Figures (…) two different travel times have been computed for the same trip, varying upon the means of transportation used —a conventional vs. an autonomous vehicle.

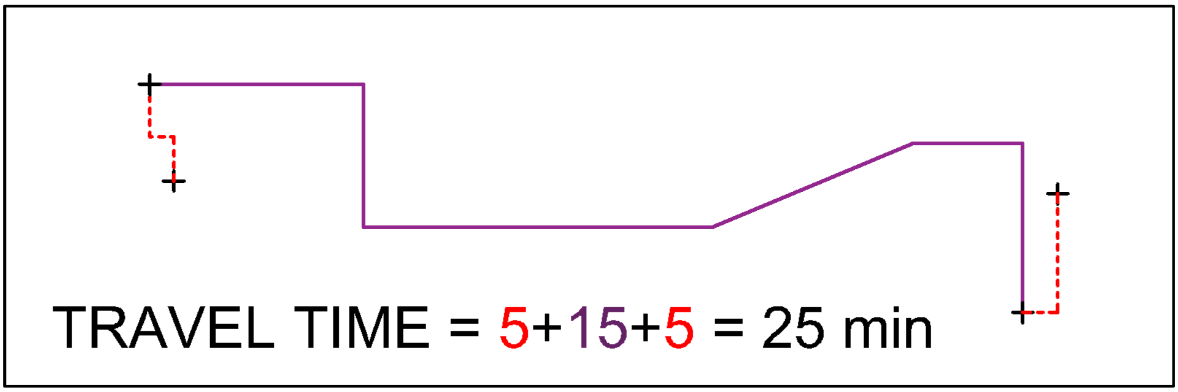

Figure 6: Conventional vehicles often require on foot access from and to car's parking locations (in red)

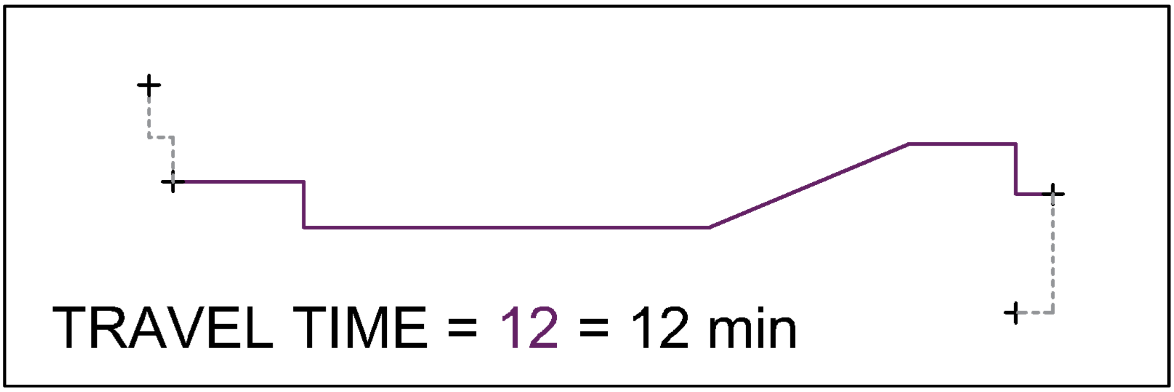

Figure 7: Autonomous vehicles can perform empty rides (in grey), such as for pick-up and self-parking purposes

Carsharing schemes would definitely obtain major benefits from this feature. This will be discussed later in this report.

2.6. Safety

In the US, 5.5 million car accidents took place in 2008, 93% of which had a human mistake as the main reason for the incident (Fagnant (2015)). This statistic shows great evidence of the effect of automation of cars on driving safety, as the amount of crashes concerning robot car error would be reportedly low.

Figure 8: Autonomous vehicles promise to drive down the number of accidents on the streets

There is something worth noting in relation to liability. If an accident due to driving malpractice happens, it would be —unless the car has not been taken to a prescriptive inspection—, as stated in Marchant (2012):

> "Autonomous vehicles will increase the safety of vehicle travel by reducing vehicle collisions. Ironically, autonomous vehicles are likely to increase the liability exposure of vehicle manufacturers. Autonomous vehicles will shift the responsibility for avoiding accidents from the driver to the vehicle manufacturer. Although the autonomous vehicle is expected to result in a net decrease in the number of accidents, it will create new modes of failure that will be attributed to the vehicle."

2.7. Effect on urbanism

The field of urbanism is likely to be affected by the automation of automobiles in the long run. Self-driving vehicles are predicted to be able to operate more accurately and without the aid of explicit, visual traffic signs.

On the one hand, and as a consequence of what has been pointed out in section (2.5), distance between the origin of a trip for the user and for the vehicle —because of parking needs— will be much less costly. As a consequence, the fact that the autonomous car self-parks right next to the actual person's

Figure 9: The space reserved to parking and driving could be greatly reduced with the emergence of autonomous vehicles

destination instead of at a parking three blocks away will not make a big difference from the user's point of view, as opposed to nowadays. So, on-street parking and its heavy urban space usage could vanish thanks to the ability of autonomous cars to drive by themselves, as stated in OECD (2015). Additionally, the higher accuracy of robots than humans while driving can facilitate a certain reduction of the driving space reserved for a given lane.

This allows for extra lanes and additional capacity while maintaining the original road width. Alternatively, the reduction of the necessary space for a given road capacity can be used to increase other land uses such as pavement for pedestrians. OECD (2015) estimations show a 20% of a street section would be freed up.

On the other hand, autonomous cars could, instead of reacting to visible stimuli, react to data exchanged in real time with infrastructure intelligence centres, that have the potential to broadcast a much broader range of data than traffic lights and conventional signs. In this case, the latter will no longer be essential. The disappearance of traffic lights and signs —those oriented to the regulation of traffic functioning— will free up additional space on the streets and lights, and streetlights could be reduced to the ones set aside for lighting (as opposed to signalling) purposes.

At a regional scale, recent studies have indicated that automation of cars will make car travel cheaper. Meyer (2016) analyses changes in accessibilities arising from self-driving vehicles at different levels of adoption in the country of Switzerland.

Accessibility is formally described as:

$$A_i = \sum_{c_{ij}} X_j * f(c_{ij})$$

That is, the accessibility A_i at a given location i is determined by the combination of the utility function $f(c_{ij})$ of getting from i to j, times the potential benefits X_j offered at location j, for every j.

Thus, accessibility is a way of describing a place's connection quality to other places that represent high opportunities such as work places. The irruption of autonomous vehicles is found to have a positive effect overall, for all scenarios studied in Switzerland. In some cases, where road capacity is assumed to increase marginally, accessibilities do not experience a rise in the main agglomerations of the country. A saturation effect is observed, as autonomous driving generate an increase in demand that cannot be properly fulfilled by the associated road capacity. However, the countryside regions undergo an improvement in accessibilities in all cases. Considering that the benefits that can be obtained at a certain location (at a supermarket, football stadium or working place) doesn't change from the incursion AVs, it can be deducted that utility functions are likely to become higher and therefore car travel cheaper (speaking in monetary terms) in extra-urban areas.

If travelling costs decrease more in the outskirts than at the densely populated areas, living outside the city becomes more attractive than before. This phenomenon can generate urban sprawl of any land use, and especially residential ones.

In the case of a city such as Barcelona, the benefits of living in the outskirts could be especially high. First, because of a decrease of operating costs of the AV with respect to a conventional car, as said. Second, because of the availability of high capacity roads not only to get there, but to drive within as well. The irruption of autonomous mobility is reportedly going to allow a much more efficient use of such roads —American cities, which are characterised by an important urban sprawl and numerous high capacity links connecting residential areas to city centres could definitely benefit from driverless cars. And finally, automation of driving can be an important factor in the pursuit of urbanistic conditions' improvement in the Catalan city. The prioritary objectives to allow Barcelona become a convivial (smart and slow) city include are stated by Turró. The most outstanding ones include transportation reliability and safety; an increase of the public space and a decrease of the number of vehicles on the streets through the servitization of car use (with carsharing models) and encouraging off-street parking; and some externalities such as air quality improvement and noise reduction. All these goals are predicted to be achievable through the irruption of AVs.

On the contrary, some other cities where a large and dense network formed by streets of rarely more than two lanes for each direction will probably struggle to perceive the advantages of autonomous driving. At the same time this new technology emerges, a concentration of the worldwide population in big cities is expected. Some cities such as London need to urgently reshape their transportation plans in the long term to be able to deal with the uprising challenges.

2.8. Potential drawbacks

There are still some aspects that remain uncovered so far, and that will become of high importance for planners.

In the first place, the aforementioned more inviting travel and a higher number of potential users (as seen in (2.1)), as long as a promised capacity increase comes along (see (2.2)), seem to indicate that people will travel more by car when autonomous cars take the streets. UNDESA (2014) expects that two thirds of the global population will be living in urban areas. Spatial development will surely become a key issue in that scenario, and making travel more convenient is set to be of great help to manage space more wisely. However, travel *per se* is not beneficial, as opposed to, for instance, the opportunities offered at the trip's destination. Besides, travelling by car will be advantageous, but could cause a heavy dependence on this mode of transport, because of the convenience of its availability.

In the second place, most of what has been mentioned before works under the hypothesis "what if *all* cars were *fully* autonomous". It is relevant to note that the transition to this scenario is far from taking place. The uprising concerns in this matter brought the prominent University of Texas at Austin's Civil Engineering department to dedicate a report to the challenges of this process.

> "AVs present many opportunities, benefits and challenges, while ushering in behavioral changes that effect how travelers interact with transportation systems. The speed and nature of any transition to a largely AV system are far from guaranteed; they will depend heavily on AV purchase costs, as well as state and federal licensing and liability requirements. Moreover, AVs present some unusual risks, particularly from security and privacy standpoints. Even with a smooth and relatively rapid deployment that addresses security and privacy concerns, a system that optimally exploits AV capabilities requires special research efforts. The following discussion outlines several barriers that AVs face."

In addition, however promising the end situation can be with respect to the current scenario, the transition to that point is reportedly going to present a numerous uncertainties in terms of level of service. The fact that car travel will be open to a much higher amount of people is going to increase the demand. However, most of traffic flow improvements will be visible at 100% penetration rate of AVs.

A critically acclaimed investigation presented at the International Transport Forum studies what would happen when half of cars became autonomous, and the other half remained conventional. Most significant results indicate a decrease in mode share with respect to public transportation, and a (quite alarming) increase in VMT. Furthermore, the dependence on high-capacity transit becomes apparent, because the findings for a situation where conventional and autonomous cars have to cover all transportation needs are discouraging.

3. Fleet effects

Mobility-as-a-Service (MaaS) is becoming more and more popular. It presents numerous advantages with respect to car ownership. In this section, we will first have a look at some relevant definitions in the field of MaaS. Afterwards, the findings from recent pieces of research on the combination of vehicle fleets with autonomous driving, meaning to assess what operational model —current vehicle ownership vs. carsharing— services will be a better option in the case cars become autonomous.

Definitions

Carsharing

It consists of a transportation operational model in which customers can use a car to perform a trip, generally through a subscription system. Once the trip is completed, this vehicle is available to serve a trip for any other user. Depending on the freedom offered by the organization of the service, they can be station-based (sub-divided in those who allow one-way trips and the ones that require the car to be driven back to the original station by the customer) and free-floating —i.e. cars are picked up and parked anywhere.

Ridesharing

Possibility that two or more users share a (fraction of a) trip. This was a common phenomenon among family and friends —automobiles with more occupants than just the driver can be considered to be performing a *shared ride*— until the irruption of companies such as BlaBlaCar. This allows customers to match up with other stranger users that have similar trip timing and route preference and therefore travel together in the same vehicle. Some benefits from this approach includes a reduction of per passenger costs (per vehicle cost remains approximately constant regardless of the number of occupants), of number of vehicles needed (especially advantageous for long trips). As a drawback, travelling with strangers is in some cultures regarded to generate discomfort.

In Mobility-as-a-service, ridesharing services are usually regarded as a feature that can complement carsharing. Instead of referring to the two options as “carsharing allowing vs. not allowing for ridesharing”, from this point on carsharing (or shared fleet) will implicitely represent carsharing systems with a unique user per trip, and ridesharing (or carpooling) will mean that the system allows users to share a ride. In the case of the fleet being made up of autonomous vehicles, carsharing will oftentimes be named “individual taxis”, and ridesharing denoted as “pooled taxis”. The purpose of using this notation is to be in line with that of the pieces of research that will be covered in this section.

Autonomous vehicle fleets vs. privately-owned

One of the key features of autonomous vehicles, as mentioned in (2.5), is the ability to drive without a passenger. When the vehicle serves an only owner, empty rides can be used for pick-up and parking duties as well as for carrying goods. When a fleet of shared vehicles serves a group of customers, numerous advantages come into play. A significant number of recent studies (Burns (2013), Fagnant (2014), Spieser (2014), Spieser (2015), Ciari (2016)) have found that a carsharing-like scheme is a highly efficient operational model to consider when AVs step in.

Recent research shows a great reduction of the number of vehicles to serve travel demand could be accomplished. The widely common private possession of conventional cars results in a high amount of cars per capita with an extremely low productivity, as they spend most of the time parked. In contrast, a fleet of autonomous and shared taxis could consist of a system of vehicles that serve multiple users while a conventional car would serve a trip for its owner and stay parked for the rest of the time. This can result in many less vehicles with a much higher vehicle active time proportion. Furthermore, as the taxi driver and his wage disappears from the equation, automation of driving (as we will see in section ()) cuts down operational costs to a level that positions it as an extremely competitive option. In the following paragraphs, a description of various studies on vehicle fleet sizes needed to serve different requirements (demand sizes and spatial and temporal distributions, at different levels of service) is carried out.

Fagnant (2014) generates a road network grid on a 10 square-miles area in which demand consists of 3.5% of total motorised trips and has different rate and direction patterns for each time period of the day. AVs operate in a network where most of the travel demand is served by currently operating transport modes and are obliged to interact with them. Shared AVs also make use of different relocation strategies when it does not have a trip assigned right after dropping off a passenger. Thus, waiting times for the next customer will be reduced. Results show the fleet size required is ten times smaller than the one needed to serve the same demand through the classic ownership model. However, empty rides cause an 11% increase in VMT.

It does not consider electrified vehicles, but still emission savings are arise from the shift to carsharing. Pollutant gas emissions is primarily dependent on two factors: first, on the vehicle consumption during service time, which can be assumed to be proportional to the travelled distance or VMT; second, on the amount of times the vehicle's engine turns on after being on standby for a while, also known as "cold start". In the case of shared AVs, the reduction of emissions due to the decrease of cold vehicle starts (their active times are much longer) overcome the increase of gases freed because of the extra VMT observed.

Fagnant goes one step further, and considers a ridesharing scheme on the Austin, Texas, network. While in the previous approach travel patterns were obtained from Austin but included in a synthetic grid, in this case the assessment takes place in the actual Texas road graph. Findings throw some light on ridesharing effects. With respect to carsharing, it is found to drive down both wait and in-vehicle travel time. It is also possible to reduce overall VMT with respect to today if users agree to be flexible in terms of pick up times and route flexibility, which helps generate higher vehicle occupancies and reduce the number of vehicles needed.

Spieser (2014) attempts to size the fleet of a carsharing system to serve the entire transportation demand in the city of Singapore. The analysis is carried out using the actual city's transportation network graph. Substantial reductions in the number of vehicles needed are observed, although they represent 1/3 (as opposed to the 1/10 from Fagnant (2014)) of the current amount of private use cars in the Asian city. Spieser (2015) perform a similar study, to find out the required size of a carsharing fleet to serve New York City's current taxi demand. Findings show that 7 out of 10 vehicles will still be needed to serve the demand. Note that it is understandable that vehicle fleet reductions are not as important in this case, given that a key factor for this decrease comes from a high increase in vehicle utilization, which in the case of taxis is already high. Let's not forget that the difference between conventional taxis and a fleet of shared AVs mainly resides in the automation of driving.

Ciari (2016) shows the effect of serving a proportion of the total demand with a carsharing scheme, for the canton of Zurich (i.e. at a regional scale). A particularity of this piece of research is the use of a state-of-the-art agent-based simulation framework MATSim, which provides with high temporal and spatial resolution. The performance of the system is assessed by means of the creation of scenarios that result from combining different levels of travel demand, fleet sizes and level of service (LOS). As far as my work is concerned, the most useful results generated at Ciari (2016) are the following.

First of all, the correlation between required fleet size and AVs mode share is non-linear, as the number of vehicles needed stabilizes when demand grows. This indicates a more efficient use of vehicles for high demand, and can be interpreted that carsharing is robust enough to scale up from the currently available services.

Secondly, the region-wide demand can be served at a reasonable level of service (here, $10\ min$ waiting time was set) with 1/10 of nowadays' number of conventional vehicles for a 10% mode share for the carsharing service. This finding suggests that autonomous vehicles can be of use while coexisting with currently active transport modes.

4. Effects of the electrification of vehicles

Electric vehicles (EVs) are already stepping in, and are probably going to take up a higher share of the automobile market in the future, just as automation. In order to assess the effects of electrification of cars, it is convenient to analyse at the work by Patrick M. Bösch previously mentioned. Electric cars are found to be cheaper, costing 0.42 to 0.31, in comparison to $0.44 \frac{€}{passenger*km}$ of those equipped with an internal combustion engine, which corresponds to a 6 to 31% decrease in travel cost.

Additionally, they represent major benefits in terms of fuel emissions, as electric automobiles are non-pollutant. Electric engines are significantly quieter than gasoline-driven, and present higher maximum acceleration rates.

Nevertheless, electrification of vehicles does bring along a few drawbacks to consider. First, the widely-known low autonomy of the car and the long charging times. Tesla’s Model S is reportedly able to reach 540 km without recharging, being the highest driving range for an EV to date. Even the fastest supercharging technologies require 30 minutes to recharge 80% of batteries’ capacity. Waiting for how electric car batteries develop in the future, it should be noted that the present autonomy of EVs disqualifies them for long trips. Furthermore, electric charging stations are not yet widely spread.

Figure 10: Tesla's model 3 is the company's most affordable car to date (35 000 US$), with up to 500 km range

Chapter II

Practical study

1. Introduction

This section aims to predict the effect of autonomous vehicles on the transportation network of Barcelona city. The main intention is to foresee how AVs could serve the demand in the city, building upon the theoretical framework presented above. The form of entry (i.e. through which operational model), along with its main features with respect to conventional vehicles are included in a conceptual model.

Sections 2 to 4 show that some operational models seem to prove more benefitial than others in the case where cars can drive by themselves. Carsharing (i.e. autonomous taxis) are found to be highly efficient to serve the demand in densely populated areas, because pickup distances are low. It would basically work the same way taxi fleets do nowadays, but at substantially lower operating costs as the driver's figure disappears.

The present piece of work consists of a framework for assessing how well an autonomous carsharing fleet could serve the taxi demand, plus a fraction of the private transportation demand. First, the data used and its adaption to the autonomous driving case is presented.

Results are assessed in the context of what has been predicted by other researchers in the literature review.

2. Spatial trip distribution: Origin-Destination matrix

An Origin-Destination (OD) matrix contains the trips taking place from and to different areas. Formally, given a set of geographical zones, the element a_{ij} of matrix A is equal to the number of trips from origin zone i to destination zone j. It is worth noting that an O-D matrix is a square, not (necessarily) symmetrical, with $a_{ij} \geq 0, \forall\ i, j$, and diagonal elements (representing in-zone travel) can be different from zero too.

In the context of this work, an O-D matrix $T_{ij,pax}$ representing the distribution of the daily trips taking place among 44 zones belonging to the city of Barcelona is used. In this work, a fraction of the total private transportation demand, plus the total taxi demand is used to assess the autonomous carsharing system's performance.

$$T_{ij,pax} = \beta_{PrT\ demand} * T_{ij,PrT} + T_{ij,taxi}$$

Where β_{PrT} is the fraction of users that shift from conventional car to the proposed carsharing fleet i.e. the penetration rate of the autonomous service.

It does not represent the total travel volume in Barcelona, because trips from and to other places outside the city of Barcelona —such as from towns inside the metropolitan area of Barcelona— also exist. However, as far as this study is concerned only the trips happening inside the city are of interest, given that the carsharing service proposed covers only trips happening within Barcelona.

$T_{ij,PrT}$ is adapted to account for a certain demand increase of the population. As it has been reported during the literature review, the entry of new potential car users with the emergence of automation of driving is expected. Such new groups are predicted to incur in a total vehicle-miles travelled (VMT) increase of up to 12.4%. Therefore, this upper bound is considered to evaluate how well the business would work under the increase of these new groups. This demand increase is generated by assuming that these new user groups carry out a similar type of trips than those of private transportation users, and so adding this increment to the number of passengers travelling on each zone-to-zone relationship.

$\beta_{PrT\ demand}$ takes different values, that generate various scenarios of travel intensity for the system. After some preliminary tests it has been decided to adopt the following set of penetration rates:

$$\beta_{PrT\ demand} \in \{0.05, 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.75, 1\}$$

This choice allows us to properly evaluate the system at the early stages, where usage shares are low. Also, the lack of a high spatial resolution model (presented further down) is believed to explain little about the service performance at high penetration rates, the travel behaviour of which is today highly uncertain.

The O-D matrix has been obtained from EMIT (2007).

3. Temporal trip distribution: from daily to hourly scale

The share of trips taking place at the different times of the day for the city of Barcelona are visible in the Enquesta de Mobilitat En dia Feiner (EMEF (2016)). The report shows different travel statistics observed in the metropolitan area of Barcelona.

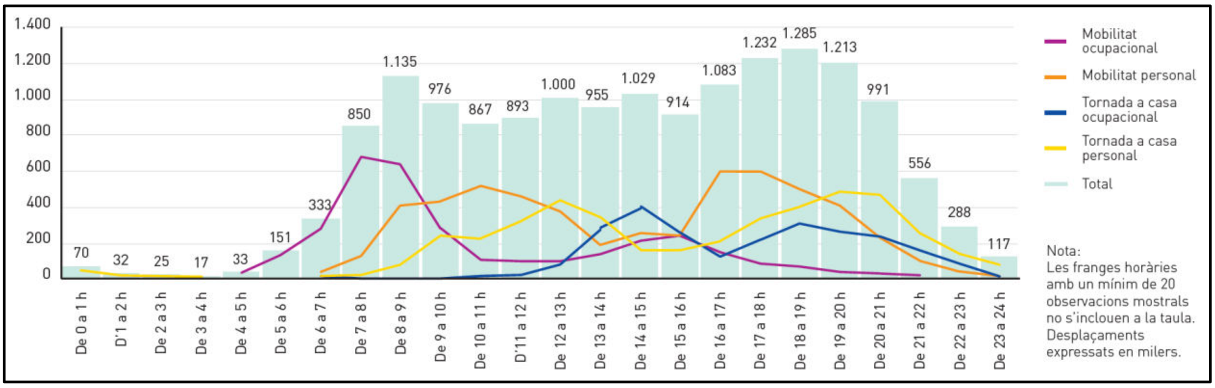

Figure 11: Temporal distribution of trips in the metropolitan area of Barcelona

In the figure above, the total number of displacements per hour are shown in light green (in $1000 * pax$). This temporal split will be used to distribute the trips from the daily O-D matrix into the different hours of the day, keeping the same proportions as provided in EMEF (2016).

This approach is based on the assumption that the spatial trip distribution of the original O-D matrix holds for every hour of the day. This is usually not true, because there are certain travel patterns that predominate during a specific time of the day. For instance, in the morning peak hour most of the trips have work places and schools as destinations (purple line in the Figure).

For a large metropolitan area such as Barcelona's, these commuting trips can be observed from residential areas (in and outside the city) towards the working places inside the city. The way back home follows a similar pattern but in the opposite direction. While this behaviour holds true for the whole metropolitan area, the trips happening within the city seem to have a less noticeable distribution. This is, people go to work or to educational centres during the first morning, but the spatial distribution of working places and schools is not as heterogeneous as at the regional scale. This can be seen in the pictures below.

Figure 12: a) housing (left) and education (right) land uses, in % over zone total

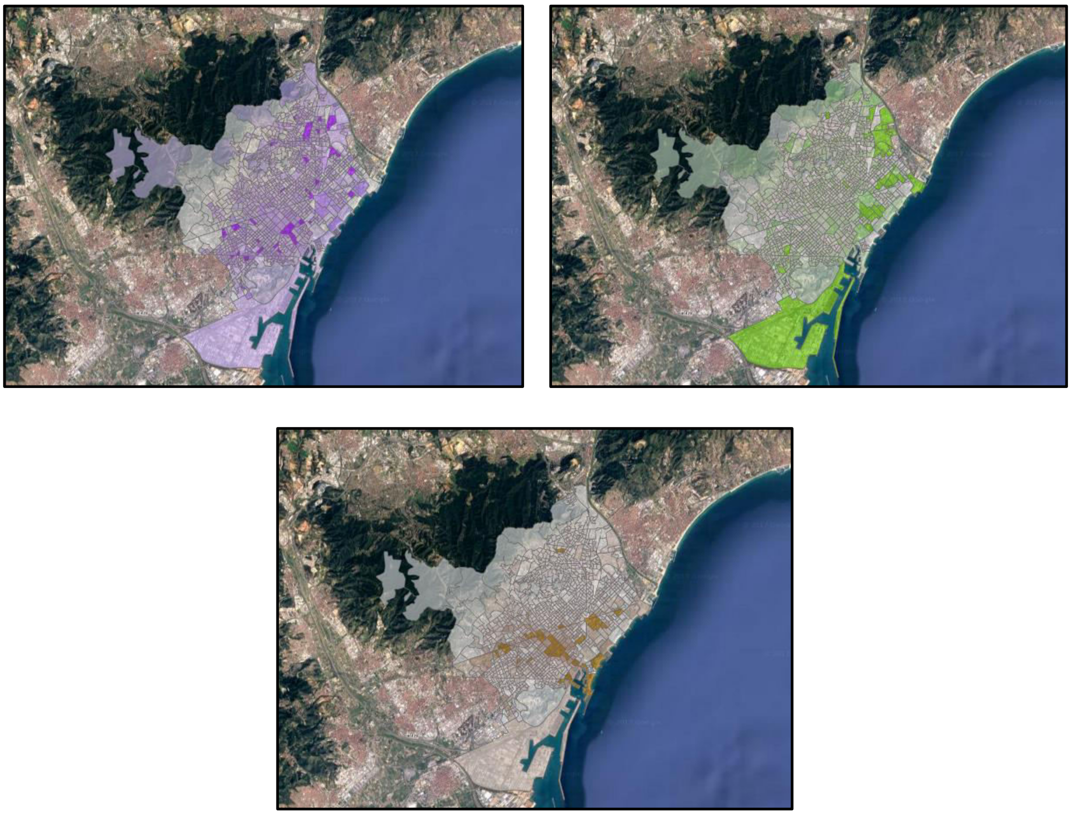

Figure 13: commercial (top left), industrial (top right) and offices (bottom) land uses, in % over zone total

These land uses are all different from one another, and there is not an evident concentration of them in the city centre. Therefore, it has been drawn from this observations that keeping the same spatial distribution of trips for all times of the day is not a too strong assumption, given the absence of hourly resolution O-D matrices for the city of Barcelona.

4. Area, distance, travel time and speed on the Barcelona network

For the same 44 zones of the O-D matrix, the area A_j of each one of them is provided. As far as travel distances and times is concerned, they can be calculated. Coordinates for a centric position inside each zone are available. These 44 points can be used as inputs for a Google API that delivers distance d_{ij} and travel times t_{ij} for different origins as destinations —similar to what can be obtained by introducing coordinates or names of two places on Google Maps, but for numerous instances at a time—. The obtained distance d_{ij} and time t_{ij} matrices have zeros on the diagonal, which is not realistic. To avoid this, the mean travel distance is drawn from the expected distance between two randomly chosen points inside an area.

Time calculations from the google API tool are based on today's conventional car driving behaviour. There are some recent studies, as seen in the first chapter of the present report, that seem to indicate that the irruption of autonomous driving will affect travel times.

On the one hand, urban capacity increases are expected to rise by 40%. The higher the capacity, the higher velocities are at for a given amount of cars on the streets. Thus, congestion is probably going to be greatly reduced thanks to the automation of driving. To account for this fact, velocities are assumed to increase to levels of those trips taking place at off-peak times, such as at night. In an aforementioned paper (Bösch (2017)), private car velocities are obtained for the different times of the day. The percentual increase of night speeds with respect to the average speed presented in this piece of research is taken into account.

On the other hand, there is a possible intersection capacity at the intersections due to higher comfort requirements by autonomous cars' passengers. As seen, acceleration limitations in this respect would lead to a -4% variation in junctions. The same paper computes the associated time delays, being a 4% of the original travel times. However, it has been found difficult to extend this time delay from one intersection to a whole city trip. It heavily depends on the amount of intersections the vehicle goes across during the trip, whether the traffic lights are on green or not, the cycle times, and so on. Provided that this information is unavailable, it has been decided not to include this fact in the mean velocity calculation of the driverless cars of the fleet.

The speed matrix v_{ij} is thus generated as follows:

$$v_{ij} = \begin{cases} \dfrac{d_{ij}}{t_{ij}} * \beta_{speed}, & for\ i \neq j \\ \dfrac{\sum_i \sum_{j \neq i} \frac{d_{ij}}{t_{ij}}}{(n-1)^2} * \beta_{speed}, & for\ i = j \end{cases}$$

, where β_{speed} is the estimated velocity increase from the congestion avoidance. The velocity obtained from Google tools are assumed to be derived from a standard traffic situation. In a first approximation, average speed for a fully autonomous is assumed to increase to a value that characterises a fluid traffic flow i.e. night time traffic.

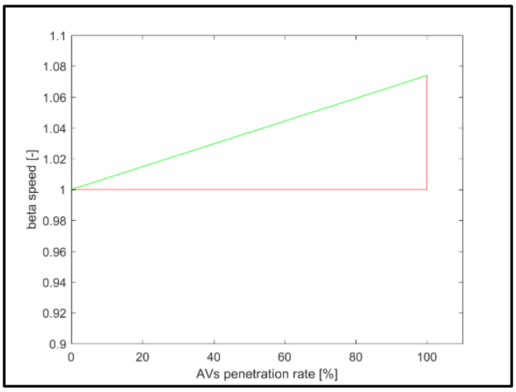

Figure 14: Upper (green) and lower (red) bounds of β_{speed}

The increase in mean travel velocity is predicted, however, for a 100% autonomous vehicles case, i.e. when no conventional cars interact with the emerging automobiles. It is therefore uncertain, how these improvements are going to be visible at intermediate penetration rates. To solve this, two bounding scenarios have been developed: a pessimistic, lower bound impact case, in which velocity improvements are only visible when the total AVs penetration has happened; and an optimistic case, where speed improvements are proportional to the penetration ratios.

β_{speed} maximum value is found to be 1.0740 (see Matlab code for more details). Once accounted for this velocity increase, time matrix is recomputed to be in line with speed values.

$$t_{ij} = \frac{d_{ij}}{v_{ij}}$$

5. Fleet maintenance

Before going down the calculation procedure for the required fleet, it is important to describe a suitable way for the operation of such vehicles. Besides servicing customers, AV cars need to visit parking stations for charging, cleaning or just parking.

In the first place, parking is required for those times of the day where the travel demand is low. The fleet, as we will see, is designed to serve the peak hour requirements effectively, and so out of these times there is an excess of vehicles that do not serve any trips. During the night, when travel demand drops the majority of cars go back to a station. Those parking stations that currently offer a daytime temporal rent of a parking space are a potential solution for these AV to stay overnight. Therefore, it is proposed that the operator can make use of these facilities at a reasonable price. In this work it is proposed that such stations are used.

During daytime these parking places are predicted to be subject to its current purpose, which is offer a parking service to the currently predominant car owners. Thus, it has been necessary to find an alternative location to place new facilities for maintenance and parking purposes. To do so, some suitable zones have been selected following the following criteria: building price per square metre needs to be low, and the mean speed from and to these locations has to be reasonably high, i.e. it has to be well with the rest of areas of the city.

Price per zone is assessed by means of the building price in €/m^2 in Barcelona as for 2016:

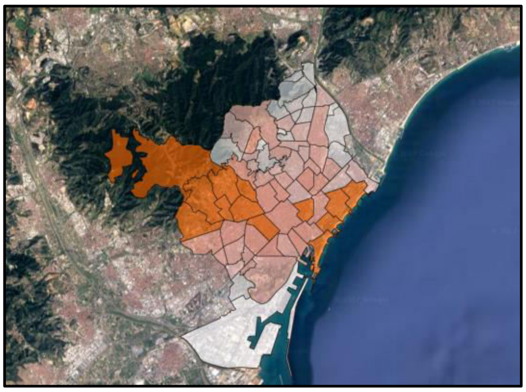

Figure 15: building price distribution, in €/m^2

Regarding connectivity, mean travel speeds were found larger for regions close to the Rondes. Following these two principles, five zones were selected for the placement of maintenance stations during the day: two at the north of the city (Carmel and El Turó de la Peira districts), two at the northeast (El Bon Pastor and La Prosperitat districts) and one at the southwest end of the settlement. They correspond to the zones 28, 34, 39, 35 and 13 of the O-D matrix.

Cleaning operations are assumed to be required once a month, being in line with the study from which unitary costs have been obtained (Bösch (2016)). Exceptionally, vehicles are also cleaned when a car gets dirty because of a passenger malpractice or incident. The new facilities described in the paragraph above are most suitable for these purpose, as current parking stations in Barcelona are not prepared for it and are used for exclusive parking duties during the day. Furthermore, cleaning frequencies are thought to be low enough so that five parking stations can cope with this cleaning demand.

Charging activities, as opposed to cleaning, requires to be done often, i.e. at least twice a day. Luckily, it is not required that the entire carsharing fleet is operating throughout the day, but workload decreases slightly around noon and much more heavily between 9 pm and 7 am.

During the night, as stated above, most of the vehicles stay in the city inner city parking facilities. As for daytime charging, where demand is substantially higher, there are some specific times with slightly lower traffic. It can be proved that the sum of the redundant fraction of the fleet during off-peak times such as 10-12h, 13-14h and 15-16h represents more than the entire fleet size. This means, that if the unnecessary vehicles self-drive to parking stations to recharge, and this is repeated done by turns for each vehicle, all of them can have access charging twice a day. Given the irruption of supercharging technology and the likely advancements in charging speed with respect to already available rates (see literature review), one hour is taken as sufficient for a vehicle to go to a station, charge up its batteries and travel back to serving customers.

If those vehicles recharging in the first round during daytime are also the first ones to go back to a station after 9 pm, and taking into consideration that the mean speed of AVs during their active time is around 30km/h, a fleet of 300 km range electric cars would be able to operate following this scheme. Given the current ranges for electric cars, and the expected improvement of battery efficiency and capacity by the time autonomous mobility services are available, the required range seems to be an achievable target for affordable autonomous vehicles.

6. Fleet optimization

The fleet optimization has been based on the theoretical approach defined in Daganzo (2010). The minimum taxi fleet to serve a certain demand is:

$$m = \frac{A}{(2vt_w)^2} + \lambda A(t_w + \frac{l}{v})$$

Where A is the region's area, v the mean velocity, l the expected service trip length, and t_w the customer's waiting time. Making use of the available data presented in the previous sections, all coefficients present at the formula to determine the minimum fleet.

$$A = \sum_j A_j\,;\; v = \frac{\sum_i \sum_j v_{ij} * T_{ij}}{\sum_i \sum_j T_{ij,pax}};\; \lambda = \frac{\sum_i \sum_j T_{ij,pax}}{\#\, zones};\; v = \frac{\sum_i \sum_j D_{ij} * T_{ij,pax}}{\sum_i \sum_j T_{ij,pax}}$$

And t_w is a decision variable highly correlated with level of service, as explained later in this report. Therefore, the minimum fleet for Barcelona is obtained.

Once the fleet size m is determined, these cars are distributed in the different zones according to the O-D matrix values. Initially, the taxis available at each zone will be proportional to the share of trips starting in that area. This is:

$$fleet_j = \frac{\sum_i T_{ij}}{\sum_i \sum_j T_{ij}} * m * 1.01$$

7. Vehicle rebalance

After the vehicles are assigned to each zone and the trips take place, cars' spatial distribution changes. Vehicles need to relocate to pick up passengers in the different zones. Considering that the demand generation rate throughout a given hour is constant, the optimal fleet for each zone is constant through that period of time as well. Thus, after serving the first trip, vehicles need to relocate so that the number of cars at each zone j equals the previously derived $fleet_j$.

Rather than making each car return to its original zone, the rebalance is carried out by bringing taxis from areas with an excess of vehicles to other nearby places with a lack of vehicles. This operation is performed thanks to an algorithm that can be seen in the attached Matlab code. The output of this process is an O-D matrix $T_{ij,rebalance}$ containing the number of trips performed for rebalance purposes. These trips are added to the original passengers matrix:

$$T_{ij} = T_{ij,pax} + T_{ij,rebalance}$$

8. The system: operational, user and total costs

The aim of this work is to determine its decision variables so that the optimal functioning of the carsharing system is ensured. Formally, this is achieved by minimizing the system's cost function:

$$€ = €_{op} + €_{user}, where \begin{cases} €_{op} = m(t_w) * v * €_{km} \\ €_{user} = \lambda A * \left(2.1 * t_w + \frac{l}{v}\right) * €_{time} \end{cases}$$

Where 2.1 is a factor indicating how much more costly it is for the user to wait for a taxi with respect to in-vehicle travel time.

On the determination of the optimal operation of the system, many factors come into play. In the first place, the fleet requirements increase if customer waiting times are to be reduced. This phenomenon holds up to a certain point, where increasing the waiting time also results in higher fleet sizes, as it can be seen in Daganzo (2016). Obtained results yield a similar behaviour in the case of Barcelona.

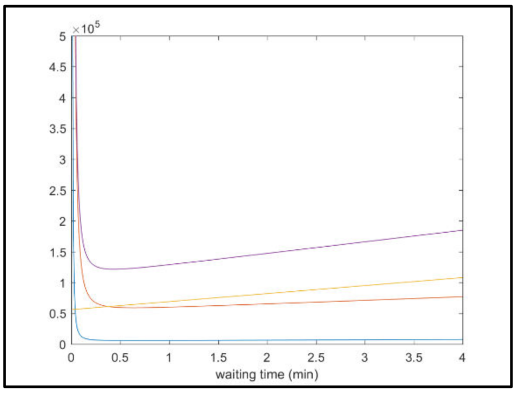

Figure 16: example of minimum required fleet (blue), operating costs (red), user costs (yellow) and total system cost (purple), as a function of the waiting time. The optimal values are obtained from the waiting time that minimizes the total cost function.

In the second place, the mean velocity variates depending on the trips that take place at every hour. The effect of cars going from and to the parking facilities and staying motionless for some time modifies the mean hourly speeds and thus decreases the operating costs during these hours. However, for a given hour the mean speed is not sensible to the variation of waiting times, as we will see later.

On the one hand, from the user perspective, the cost associated to the carsharing service is only dependent on waiting times, as the rest of coefficients do not depend on the waiting time, which is our decision variable. Given the way the user costs are defined, the dependence is linear.

On the other hand, as far as the operating costs is concerned, there is a dependence on other factors as well. It shows a linear dependence on both the cost per kilometre and the mean speed of the vehicles. In a first approximation, the mean speed v had been computed as the mean of all zone-to-zone speeds, weighted by the respective traffic volumes. Now, the real mean speed can be computed as:

$$v = \frac{\sum_i \sum_j v_{ij} * T_{ij}}{\sum_i \sum_j T_{ij}}$$

This is, the speed is computed from the average velocity for each i to j trips, weighted by the share of total trips corresponding to the i to j relationship, which already accounts for both passenger and relocation displacements. Given that travel demand is assumed to be invariant, and the relocation strategy optimal, the mean speed is also assumed invariant. The cost per vehicle-kilometre is obtained from previous research, based on what is predicted for the autonomous carsharing scenario, and is kept as constant throughout the different scenarios.

Operating costs show a linear dependence on the total vehicle fleet, which shows the above shown variation with waiting time (Figure 4). All in all, operating costs variation with waiting time is the same as that of vehicle fleet, multiplied by a constant value resulting from accounting for the mean speed and the unitary cost.

9. Results

In the present section, results from the multiple scenarios are presented. First, all the previously stated interesting features to analyse are summarised:

- Travel demand includes all taxi demand, plus a percentage of private car transportation demand: $\{5, 10, 15, 20, 30, 40, 50, 75, 100\}$. This corresponds to nine (9) different cases.
- Demand is divided between different times of the day (hourly) to evaluate the required fleets at every time. It is analysed between 7 am and 9 pm, which results in fourteen (14) different cases.
- Travel speed, as a function of the penetration rate, has been bounded by a maximum and minimum variation case (see section 5.3), which yields two (2) different cases.

In total, the number of scenarios to be analysed is $9 * 14 * 2 = 252$. For the sake of practicality, only the results that lead to interesting findings are analysed below.

To start with, the optimal waiting times, fleet, operating costs, user costs and total costs are obtained for different usage rates.

Waiting time and user costs

Waiting times are observed to decrease from around one minute for low demands down to less than 30 seconds when the system covers all private transportation demand. So from a user perspective, the higher the carsharing adoption is, the less the customer will have to wait to be picked up by an AV. It is also important to note that it is highly sensible to demand variations for low demands. For rates of up to 30%, demand increases yield notable decreases in travel time for the user. As for the sensibility of waiting times to a mean velocity increment, it is nearly neglectable. This is probably due to the short distances idle AV vehicles need to drive to reach a passenger, and therefore changes in absolute waiting times are residual.

When observing the user costs per trip, these differences are more notable. Let's recall how total user costs have been defined:

$$€_{user} = \lambda A * \left(2.1 * t_w + \frac{l}{v}\right) * €_{time}$$

And the unitary (i.e. per passenger) user cost becomes:

$$\frac{€_{user}}{\lambda A} = \left(2.1 * t_w + \frac{l}{v}\right) * €_{time}$$

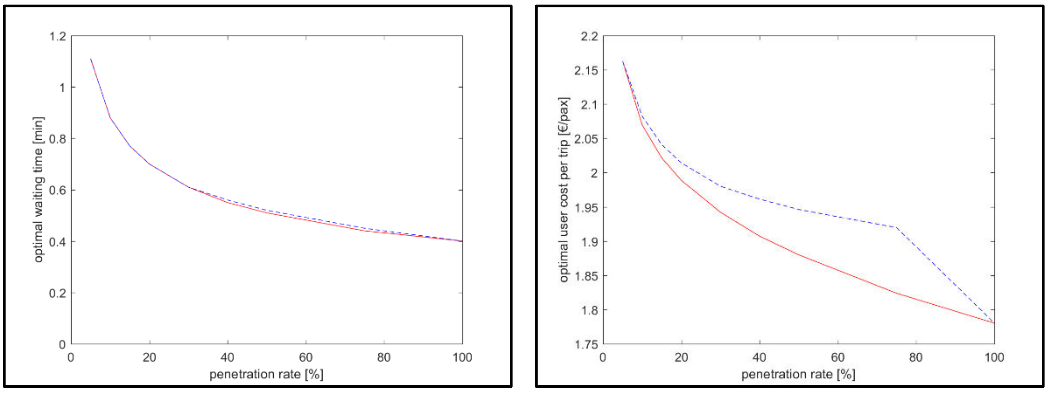

Figure 17: Optimal waiting time (left) and user cost per trip (right) as a function of the carsharing penetration rate

Waiting times play a role in this definition, so it is not surprising that unitary customer costs' variation with the increase of demand is similar to that of pick up times. The second component of the service time for the user, which is the in-vehicle travel time, depends on the distance of the trip (which, for a given trip between two zones is assumed invariant) and the mean speed. The difference between user costs for the two speed scenarios considered are understandable, because travel distances are long, and a speed increase affects heavily the value of this cost. Hence, shorter total service (waiting, plus in-vehicle travel) time reduce the cost per user by up to a 5%.

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<u>*Optimal fleet*</u>

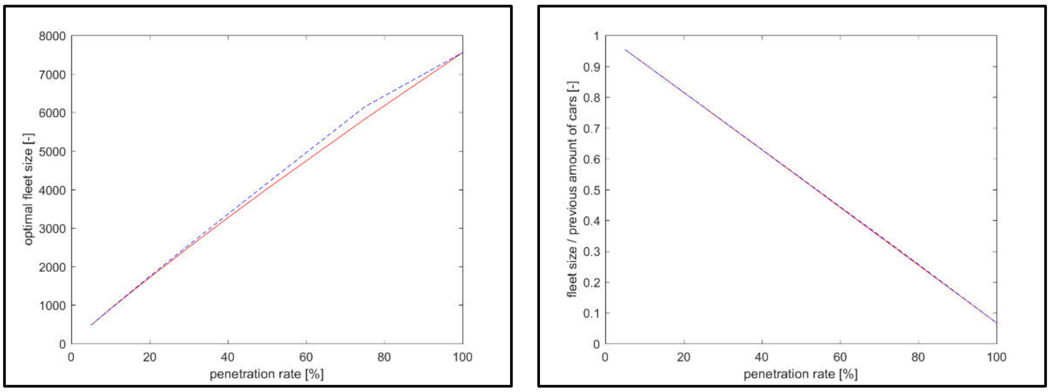


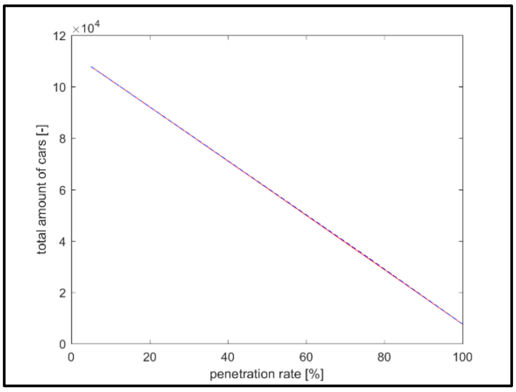
Figure 18: Absolute optimal fleet size (left) and proportion of fleet vehicles with respect to original conventional vehicles (right), as a function of the penetration rate

The optimal fleet is determined for the time of the day in which traffic volumes are highest. In the case of Barcelona, the hour with most intensive car travel is between 6 and 7 pm. Demand at this particular time of the day range from 2,000 to 45,000 trips in just an hour. To deal with this demand while minimizing the total system costs, the obtained fleet increases linearly with the penetration rate, which is in line with the way the fleet size is formulated.

As for the relationship between the fleet size and equivalent number of vehicles required to serve the same demand with conventional cars, findings suggest a higher impact than that of previous research studies. For the Zurich and Austin regions, an autonomous carsharing fleet was found to be able to replace around 90% of vehicles. The present results indicate that a given demand can be served with around 1 every 15 conventional cars of today.

Furthermore, a scale effect is observable when optimizing the fleet. The higher the carsharing demand is, the more efficiently the demand is served, and the lower the share of AVs with respect to the required conventional car number is, for the same fleet. This result might arise from the fact that a higher density of both trip generation and vehicles leads to shorter empty ride distances and times.

Thus, the effect of a penetration rate increase has two positive effects. First, it contributes to optimise the service operation. Second, there are more passengers that give up the inefficiently used privately owned car (or expensive taxi service) to become a new user of service, which has a higher user/vehicle ratio. Combined:



Speaking in absolute values, the carsharing service, in the futuristic case where a 100% adoption is achieved, a fleet of around 7,500 vehicles would be enough to serve the entire current car travel demand, as opposed to the currently 108,000 cars needed to serve the same demand.

Figure 19: number of cars needed to serve the entire car travel demand, as a function of the carsharing adoption level

Operating cost

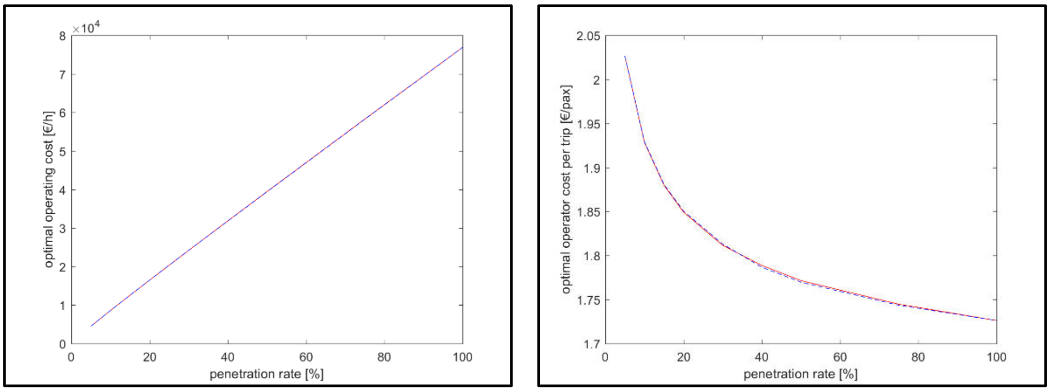


Figure 20: optimal operating cost (left) and optimal operator cost per trip, as a function of the penetration rate

Operating costs have been previously defined as:

$$€_{op} = m(t_w) * v * €_{km}$$

They are in the order 10,000 to 80,000€ at the peak hour and for the entire system. These costs are very similar for both mean speed cases accounted. It is thought that it is due to two opposite effects balance out in when mean velocity increases.

On the one hand, the higher the velocity, the longer the travelled distance per hour for an active vehicle will be. Hence, being the operator costs calculated from a price per km approach, it should rise the operator cost per AV.

On the other hand, higher velocities allow the fleet size to be lower. From a theory of queues perspective, the higher the speed of the fleet, the higher the rate at which it can serve the total the trip requests, and so the same demand can be covered with fewer vehicles.

Total costs

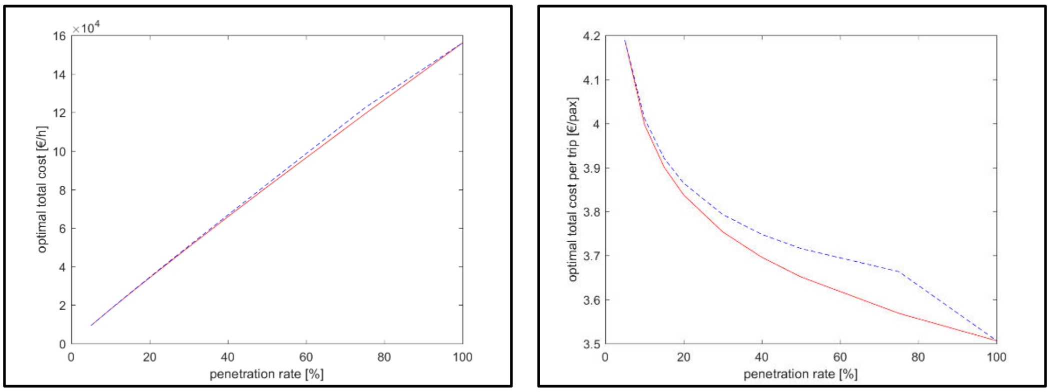


Figure 21: Optimal total costs (left) and optimal total cost per trip (right), as a function of the penetration rate

The total cost of the system is found to linearly increase with the penetration rate. In this case, the lower bound velocity scenario yields higher overall costs. As seen above, while operating costs variation is insignificant, user costs decrease for higher velocities and thus lower service times, which explains the difference in total cost of the system.

Fleet operation

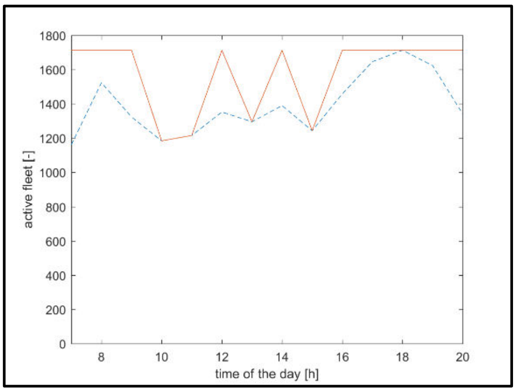


Figure 22: cost optimal (blue) and maximum user LOS (orange) fleet management strategies throughout the day

In the image on the left appears an example of how the AV fleet would be operated. Previously it had been thoroughly explained, and here a case with real numbers is presented. The available fleet of the system is obtained by optimising the total costs in the most restrictive case, i.e. for the peak hour. During the day however, each of the vehicles needs to stop for an hour to refill its battery. For this purpose, 4 hours between the morning and the afternoon peak are chosen for active fleet to decrease to the necessary fleet for than specific period of time.

10. Limitations

In the first place, the lack of an O-D matrix for the different times of the day has been an important drawback. It is true that an analysis of the different land uses in Barcelona has been carried out, and despite the acceptance of the assumption of a constant spatial distribution of trips at all times as valid, the results need to be assessed critically. To solve this problem, the obtention of hourly trip behaviour statistics should be captured, and such information is not available for the city as of today.

In the second place, one of the major challenges of autonomous technology lies in the fact that it is highly uncertain to determine people's reaction to it. How comfortable we will find to travel on an autonomous vehicle, whether we will prefer to share a vehicle with a stranger or not, or if parents will rely on them for the transportation of their children, or even goods, are some of the questions that remain unanswered. Autonomous cars being out of the reach of the general public in everyday situations makes it problematic to predict the aspects that we already know about other modes of transportation. In the context of this work, the estimation of a new value of time for the time spent inside the vehicle has not been performed due to the lack of data about it.

A proposal for somebody wishing to give continuity to the present piece of research, is to take a closer look at the proposed new parking facilities. Given that this work has been more oriented to transportation planning, the suitable areas for the construction of such facilities are indicated. For the sake of completeness, and with the aim of providing planners with more specific solutions, it would be of help for them to perform a cost-benefit analysis of terrains suitable for the new constructions.

Conclusion

The exercise of the literature review has consisted in synthesising the state-of-the-art researcher's recent work on the field of autonomous driving, by determining the purpose of the investigations and its results. Rather than just being conceived as a self-preparation for the posterior practical study, this review is thought to have a value *per se*, serving as a guide for a transportation or administration planner, or simply a somebody interested in the upcoming transformations in the transport profession.

To recap, I proceed to mention all the positive outcomes of the irruption of autonomous vehicles: people unable to drive can also use a car on their own; increases road capacity, therefore allowing for a high reduction of congestion; makes travel time more enjoyable and/or productive; travelling out-of-pocket costs are lower; access distances and times are reduced because of pick up and parking operations being done autonomously; safety is increased; indirectly reduces on-street parking, and frees up public space. Additionally, autonomous fleets can bring along some improvements, such as: a heavy reduction of the vehicles on the streets; and a decrease on gas emissions. If the mobility service allows for *ridesharing*, both waiting and travel times drop. If the future of cars is electric, gas emission's problem would be solved.

On the contrary, there are some drawbacks to consider. First of all, the attractiveness of car travel could skyrocket, and so the associated demand could do as well, leading to a saturation of the traffic network. Second, cars travelling empty also add an extra load to the network, that is currently not visible on conventional cars. Third, the transition to a fully autonomous mobility scenario will be challenging in terms of short term traffic improvements, and policy requirements. Finally, the probable electrification of vehicles will incur in shorter ranges and longer charging times than what's needed to get fuel engines going.

The benefits of vehicle automation, together with those that derived from operating an autonomous fleet has led to the investigation of the how well an autonomous carsharing fleet would work in Barcelona. Below, some reflections on the assumptions and results yielded from the practical work are explained.

An important concept that has been used in this research is the bounding of the speed between a minimum and maximum impact case arising from vehicle automation. The associated results are close one another, setting a reasonably accurate range for the real, unknown values of waiting times, optimal fleet and system costs. Furthermore, obtaining results for different velocity cases has allowed to interpret them more easily. I recommend using the approach described in section 5.3, or a similar one, to have a higher confidence on the calculations that involve high uncertainty.

Some of the findings of the present research are in line with those of the papers seen in the literature review.

In the first place, the AV fleet is found to perform in a much more efficiently than conventional cars. In Figure 18 (right) it becomes clear that the higher the carsharing service mode share is, the lower the total amount of vehicles on the streets is. This is probably caused by the continuous trips service of autonomous cars, that spend most of the time bringing passengers around. On the contrary, privately-owned vehicles only perform trips with its owner inside or for parking and picking up operations, and they spend the rest of the time parked, and the vehicle utilization is much lower.

In the second place, the mean speed increase not only decreases the user's cost by making travel times drop, but also total cost (i.e. the whole system) benefits from the increase of vehicles' velocities for lower congestions, even without considering a unitary operating cost per unit time. Furthermore, the increase in mean velocity, rather than just contributing to higher in-vehicle travel times allows for a lower optimal fleet size that can still deliver a high level of service.

In the third place, it is also found that different strategies can be used in order to manage the fleet effectively. During the times when the optimal fleet can be lower than the available fleet, two approaches are to be taken into consideration: whether to use the total available fleet or just the one needed (i.e. the optimal one). This is the case, for instance, of the service between 12 pm and 1 pm, and between 2 pm and 3 pm. For the sake of cost minimization, it is proposed that the active fleet matches the optimal fleet when possible. Just in case e.g. an especial event is taking place, or merely there is an interest to offer a better service to the customers by reducing waiting times, the extra number of vehicles can be used without compromising the vehicles' autonomy.

Finally, two suggestions are dedicated to planners.

First, the findings of the practical study have shown a rapid decrease of the cost functions for low adoption levels of the service. This is probably due to the fact that the higher the number of subscriptions to the service is, the more intense the trip generation is, and the corresponding optimal fleet is able to serve the demand more effectively. Inctuition should then tell us the following: whereas initial investments on the acquisition of new vehicles and new parking facilities are surely going to be high, additional investment on promoting the service in order to make it profitable could not be necessary thanks to the rapid cost drop for small penetration rate increments. Once the service has reached a certain level of adoption, it may well need some intervention to keep growing. However, the scalability of carsharing seems to indicate that both investments (initial and promoting) could be carried out not simultaneously.

Second, from the urbanistic point of view, vehicle automation has the potential to bring many benefits. One of them, as it has been recalled in the first lines of the present section, is the liberation of a high proportion of the space that is currently reserved to on-street parking. One of the questions that immediately arises from this possibility is "Should they be used to increase the link's capacity, or else turn it into walking or cycling spaces?". While being the answer still unclear to me, results from this work suggest that some of it should be reserved to road space. More road space means more capacity, less congestion and higher speeds which, as we have proved, leads to a less costly operation of the carsharing service. It also becomes more attractive for the user. And promoting AV space usage also results in higher penetration rates for this new mode, and helps to make conventional cars obsolete and obtaining more street kerb-to-kerb space.

References

D. J. Fagnant, K. M. Kockelman, Preparing a Nation for Autonomous Vehicles: Opportunities, Barriers and Policy Recommendations for Capitalizing on Self-Driven Vehicles, in: 93rd Annual Meeting of the Transportation Research Board, Washington DC, 2014.

J. M. Lutin, A. L. Kornhauser, E. Lerner-Lam, The Revolutionary Development of Self-Driving Vehicles and Implications for the Transportation Engineering Profession, ITE Journal 83 (7).

Harper, C., Mangones, S., Hendrickson, C.T., Samaras, C., Bounding the potential increases in Vehicles Miles Traveled for the non-driving and elderly populations and people with travel - restrictive medical conditions in an automated vehicle environment, in: 94th Annual Meeting of the Transportation Research Board, Washington DC, 2015.

B. Friedrich, Verkehrliche Wirkung Autonomer Fahrzeuge, in: M. Maurer, J. C. Gerdes, B. Lenz, H. Winner (Eds.), Autonomes Fahren, Springer-Verlag, Berlin, 2015, Ch. 16, pp. 331-350. doi:10.1007/ 978-3-662-45854-9_16.

S. Le Vine, A. Zolfaghari, and J. Polak, Autonomous cars: The tension between occupant experience and intersection capacity, in Transportation Research Part C: Emerging Technologies, vol. 52, pp. 1 – 14, 2015.

J. D. Ortuzar, and L. G. Willumsen, “Modelling transport,” 4th ed., Chichester: Wiley, 2011.

P. M. Bösch, F. Becker, H. Becker, K. W. Axhausen, Cost-based Analysis of Autonomous Mobility Services, Working Paper 1225, IVT, ETH Zurich, Zurich (2016).

Marchant, G. E., Lindor, R. A., The Coming Collision Between Autonomous Vehicles and the Liability System, Santa Clara L. Rev. (2012), volume 52.

International Transport Forum (2015) Urban mobility system upgrade: How shared self-driving cars could change city traffic, Technical Report, OECD.

Meyer, J., Becker, H., Bösch, P.M., Axhausen, K.W., Autonomous Vehicles: the next jump in accessibilities?, Research in Transportation Economics 62: 80-91.

World Urbanization Prospects: The 2014 Revision, Highlights. Department of Economic and Social Affairs

Burns, L. D. (2013) Sustainable mobility: A vision of our transport future, Nature, 497, 181–182.

D. J. Fagnant, K. M. Kockelman, The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios, Transportation Research Part C: Emerging Technologies 40 (2014) 1-13.
doi: http://dx.doi.org/10.1016/j.trc.2013.12.001.

Spieser, K., Treleaven, K., Zhang, R., Frazzoli, E., Morton, D., Pavone, M. (2014) Toward a Systematic Approach to the Design and Evaluation of Automated Mobility-on-Demand Systems: A Case Study in Singapore, Road Vehicle Automation, pp. 229-245.

R. Zhang, K. Spieser, E. Frazzoli, M. Pavone, Models, Algorithms, and Evaluation for Autonomous Mobility-On-Demand Systems, in: American Control Conference (ACC), 2015, pp. 2573-2587.

Bösch, P. M., F. Ciari and K. W. Axhausen (2016) Required autonomous vehicle fleet sizes to serve different levels of demand, Transportation Research Record, 2542, 111–119.

Fagnant, D. and K. Kockelman (2015) Dynamic ride-sharing and optimal fleet sizing for a system of shared autonomous vehicles, paper presented at the 94th Annual Meeting of the Transportation Research Board, Washington DC, January 2015.

Àrea del Transport Metropolità (2016) Enquesta de Mobilitat En dia Feiner.

Àrea del Transport Metropolità (2007) Enquesta de Mobilitat I Transport.

Daganzo, C.F. (2010) Public transportation systems: basic principles of system design, operations planning and real-time control.

Additional support:

Google API for derivation of distance and time relationships:
https://maps.googleapis.com/maps/api/distancematrix/json?units=imperial&origins=&destinations=,NY&key=YOUR_API_KEY

"The convivial city", slides by Prof. Mateu Turró in .ppt format