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Doctoral dissertation

Transport and Infrastructure - XXXI Course

Designing innovative transport systems, electric and automated on priority corridors

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Executive Summary

The world of transport is on the cusp of three revolutions in transportation: vehicle automation, vehicle electrification, and smart technologies. Separately or together, these revolutions will fundamentally change urban transportation around the world over the next decades.

Road automation and electric mobility have the potential of significantly change not just the way we travel but also the way we live and the world economy. With such mobility revolution all aspects of our life, economic, social and environmental will be impacted.

Present dissertation studies an innovative transport system enabled by those technologies. It focuses on a transport system concerning electric and automated vehicles in specific and certified corridors infrastructure which can be used effectively by fully automated vehicles, equipped with necessary charging technologies.

Same vehicles are used for last mile transport to serve a pre-existent mass transport or even, if there isn't one, a corridor for electric and automated vehicles. It works with different level of automation, from partial automation to full automation in dedicated lanes or in a shared environment with other road users. Those systems can be implemented in place with dimension from little towns (satellite of big cities) to medium and big cities with or without invariant transport systems. Each corridor should have at least 1000 pax/h and up to 9000 pax/h.

The objective of this thesis is to develop a new methodology allowing to design such innovative systems.

Transport is one of the most interdisciplinary sectors in science putting together different branches of engineering with social sciences, law and others. Automated transport and electric mobility are even more interdisciplinary, they involve technology development and research on mechanical and electrical engineering.

This dissertation includes a state of the art and literature review of two fields: automated road transport systems, electric powertrain and charging infrastructures. Then, it aims to describe main concepts of a methodology of designing for this innovative transport system, leaving impacts evaluation to future studies.

The methodology foresees six steps, they can be repeated with an iterative change of parameters in order to compare different results. Steps are:

- Parameters and input data. They concern transport demand and road graph with a traffic assigned.
- Itinerary analysis and corridors identification. Starting from transport demand it generates call lists then for each call it identifies itineraries and potential corridors.
- Corridors choice and speed profile generation. This phase describes how to choose between potential corridors which are feasible and their speed profiles.
- Vehicle choice and fleet dimensioning. It concerns pool generation based on transport demand and fleet dimensioning.
- Electric traction needs and specifications. It estimates electric consumption, location and specifications of charging stations.
- Results evaluation. It describes which results and how to evaluate them.

It represents a milestone in planning of innovative transport systems with electric and automated vehicles, that can be deployed today with off the shelf technologies. It could have great impacts to social aspects of cities and citizens, to the economy and thanks to electric traction systems enabled by fast charging technologies to the environment.

These systems work with highest comfort and performance levels, typically owned by private transports, even if they are public ones. Cost benefit rate and economic result, as revenues minus costs, can be positive even if those systems supply social transport services as in sprawled areas, while now most transport systems require subsidies.

Core phases of methodology are: “corridors identification”, “corridors choice” and “speed profile generation”. First includes a risk assessment procedure of corridors with safety up to railway standard, second core phase allows to reduce, and choice corridors based on feasibility and characteristics. Last one, the speed profile generation, detects low speed points in road paths that can be highly hazardous, at same time it allows to re-think them in a safest way (introducing possible infrastructure intervention or sensors).

Iterative approach of methodology allows to restart it when there are changing of initial conditions and parameters, on one hand it rises time for calculations but in the other hand it allows changing of transport model or charging method, technology and so on.

The methodology has been applied to Mentana, a little town in the outskirts of Rome with twenty-thousands of inhabitants. The 40% of Mentana commuters (3648) go to Rome daily, 42% of them commute by train and 47% by car. The high car modal choice is due to train station distance.

Several potential corridors have been identified in Mentana, but only one was selected accordingly with parameters adopted, it links Mentana centre to the Monterotondo-Mentana train station be distant eight kilometres.

The vehicles used (up to 9-place capability) will be driven by one of the users, who will collect the other users of her vehicle and who will receive an incentive to be the vehicle driver, by allowing her to travel free of charge to her destination.

In order to relocate the vehicles left at the railway station, people arriving in Mentana by train (e.g. workers coming from other municipalities) will drive the vehicles till corridor entrance (first mile), taking the driver of the next trip to the station before they arrive at destination.

If there isn't a counterflow demand, as people arriving there by train (in most case, little satellites have a unidirectional demand to big cities), an operator relocates six vehicles at once through platooning function. In this way the vehicles are continuously circulating to and from the railway station.

Results demonstrate a fleet of almost ninety vehicles (nine sets) and seven operators, it is able to serve up to 1600 daily commuters from Mentana to Rome by train, the vehicle occupancy rate is equal to ninety percent. Financial results are positive, revenues cover operative costs and the whole system doesn't require subsidies.

If there were a legal framework enabling such systems ready to deploy with off the shelf technologies, current methodology will allow dimensioning of it in a ground-braking way and it will keep negative impacts down leading transport revolution.

Abstract

Designing innovative transport systems, electric and automated on priority corridors

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This study focuses on two great technologies improvements, they are vehicle automation and newest fast charging methods that could enable new and innovative transport systems.

Automated and electric vehicles could will enable first/last mile efficient transport services, economically and environmentally sustainable that could be useful to improve transportation services in rural sprawled areas with a low density of transport demand. It is proposed an innovative system concerning electric and automated vehicles in specific paths called priority corridors, it is described a methodology of designing leaving the detailed analysis and impacts analysis to future studies.

Automation, Internet of Things and smartphones are revolutionising mobility and with it the economy. With such mobility revolution all aspects of our life, economic, social and environmental will be impacted. Automated vehicles can be deployed as personal vehicles or as shared vehicles; while personal vehicles are not yet ready for deployment shared vehicles are.

This work aims to propose an innovative transport system with off the shelf technologies and a methodology of design dealing with vehicle automation, current designing methods and environmental impacts.

The methodology foresees six steps, they could be repeated with an iterative change of parameters in order to compare different results. These steps are: Parameters and input data, Itinerary analysis and corridors identification, Corridor choice and speed profile generation, Vehicle choice and fleet dimensioning, Electric traction needs and specifications, Results evaluation.

Four categories of results are considered: vehicles and operators needed, energy consumption, transportation and socio-economic evaluation. After the results calculation, it is required an evaluation of them.

Methodology is applied to Mentana, a little town in the outskirts of Rome. Mentana has only one corridor that links city centre to train station be distant eight kilometres. Economic results are positive, revenues cover operative costs and the whole system doesn't require subsidies.

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Abbreviations and acronyms

ADAS	Advanced Driver Assistance Systems
APM	Automated People Movers
ARTS	Automated Road Transport Systems
BRT	Bus Rapid Transit
CAGR	Compound Annual Growth Rate
CBA	Cost Benefit Analysis
DARP	Dial-A-Ride Problem
EPA	Environmental Protection Agency
GHG	Green-Houses Gas
IEC	International Electrotechnical Commission
LEIV	Low Environmental Impact Vehicle
MTOP	Many-To-One Problem
MTMP	Many-To-Many Problem
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
PPE	Personal Protective Equipment
TaaS	Transport-as-a-Service
TSP	Travel Salesman Problem
UML	Unified Modelling Language
VMT	Vehicle Miles Travelled

Introduction

The world of transport is on the cusp of three revolutions in transportation: vehicle automation, vehicle electrification, and smart technologies. Separately or together, these revolutions will fundamentally change urban transportation around the world over the next thirty years, as Lewis Fulton said ([1]).

Road automation has the potential of significantly change not just the way we travel, but also the way we live and the world economy. With such mobility revolution, all aspects of our economic, social and environmental life will be impacted (see [2] and [3]).

The growing visibility on media of advanced driver-assist system trials, following the Google publicized research program on the matter and the enthusiastic announcements of some OEM leaders, have led many to believe that fully automated cars will be deployed on roads around 2020.

However, people working to automate cars, in most cases, have very different views; “*Electronic chauffeurs that can handle any driving conditions with no human input are decades away*” according to Shladover [4].

The divergence in views is caused by a taxonomy confusion. OEM started (after Google) by using the term ‘autonomous’ vehicle for any kind of driver-assist system (like those now available in Tesla and called by Tesla Autopilot), thus creating the expectation of a car that can drive itself, delivering instead a vehicle that require presence and engagement from a driver.

Impacts could be positive or not, they depend on points of view and mainly they relate the following fields: economy, social, energetic, ethical, etc. Economic impacts include new business models such as: entertainment, information, shopping, work, communication, and so on. These businesses could affect passengers or even goods; for example, a project deployed by “Ford Motor company” and “Domino's Pizza” deliveries pizzas with automated vehicles [5]. Social impacts may concern accessibility, user behaviour and employment.

Quantifying impacts on energy consumption, the USA Environmental Protection Agency (EPA) estimated it to range from minus 50% to plus 100%. It depends on whether people will share automated vehicles and rides more, reducing overall the Vehicle Miles Travelled (VMT), or whether people behaviour will become even more individualistic and VMT will explode.

Ethical and legal impacts, studied for example by Alessandrini [6] and Csepinszky [7], are related to responsibilities and vehicle behaviour in case of technical failure or even unexpected environment/situation.

A recent survey of “The Guardian” proposed by Ian Sample [8] reveals a moral dilemma of programming autonomous vehicles “Should they hit pedestrians or avoid and risk the lives of occupants?”. Results show that 76% of people agreed that a driverless car should sacrifice its passenger rather than plough into and kill 10 pedestrians.

As shown in Figure 1, if automated vehicle detects someone in pedestrian crossing ahead, it starts an emergency braking, but it also could act in two ways: drive straight through pedestrian crossing (left side of figure) or try to avoid them turning on its left and hitting the barrier (right side of figure).

Both cases cause injuries or even deaths, which one is the best choice?

There are many scenarios like this one, and all of them presents the same moral dilemma. Maybe, the correct answer is that automated vehicles as manual ones shouldn't kill anybody! As everyone knows, it is impossible to do any errors both for humans or even automated technologies; in fact pedestrians are flouting the law by crossing on the red signal and any vehicle approaching there run over them. In this case, automated vehicle shouldn't hit them, but it can happen.

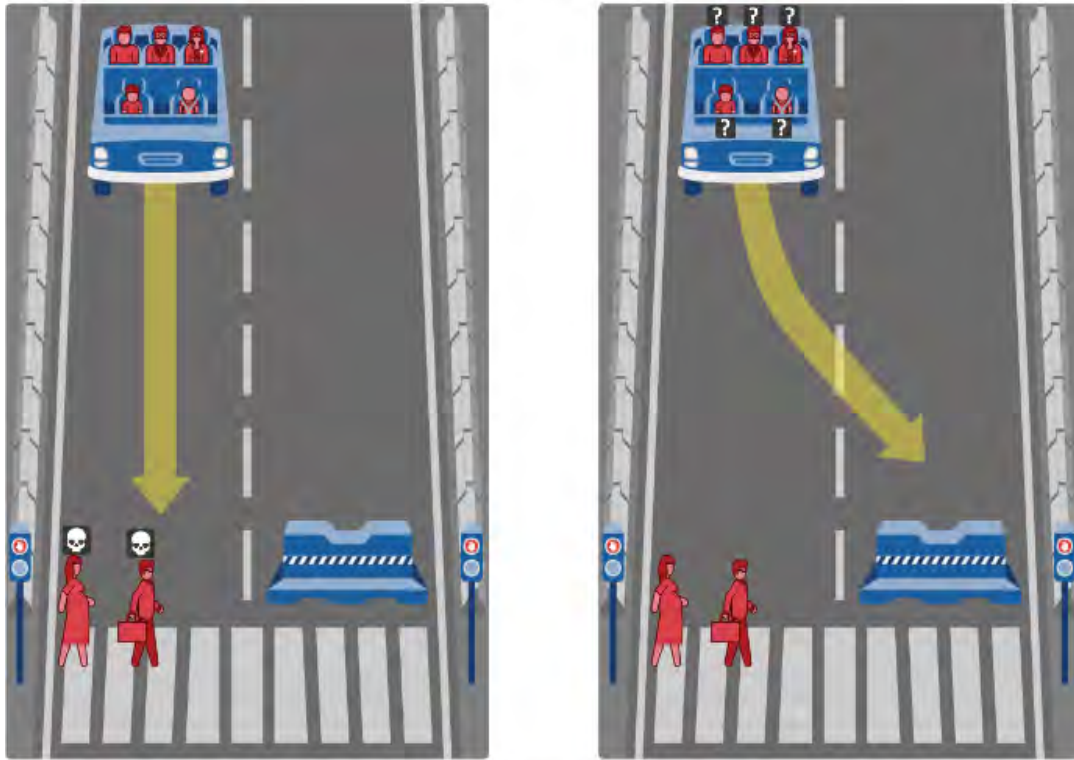


Figure 1 A scenario proposed by “Moral Machine” survey (source moralmachine.mit.edu/)

So, one of the biggest barriers to vehicle automation is the legal framework, partially analysed in CityMobil2 project ([6]) and missing in most countries, in Europe, only Greece and Finland have it. Mostly, national regulations require a human driver ready to intervene at driving seat if necessary, even when vehicle drives itself, and the human driver is responsible for any accident.

Optimists around the world predict that it will overcome in 2030s and between 2040s and 2050s almost a half of circulating fleet will be autonomous (Figure 2).

Electric mobility such as automation is revolutionising mobility and the economy with it. The witness of the electric revolution are the growth of vehicles and electric charging stations sales in every market around the globe (see Figure 3).

Foremost, long-standing issues of electric vehicles are the limited mile range and the low energy density (in comparison with fossil fuel), the fast charging should tackle these limits, but it remains a trade-off between power that an Energy Storage System (ESS) manages and the amount of energy stored. ESS means that there can be different energy storage devices in same system (as batteries and capacitors).

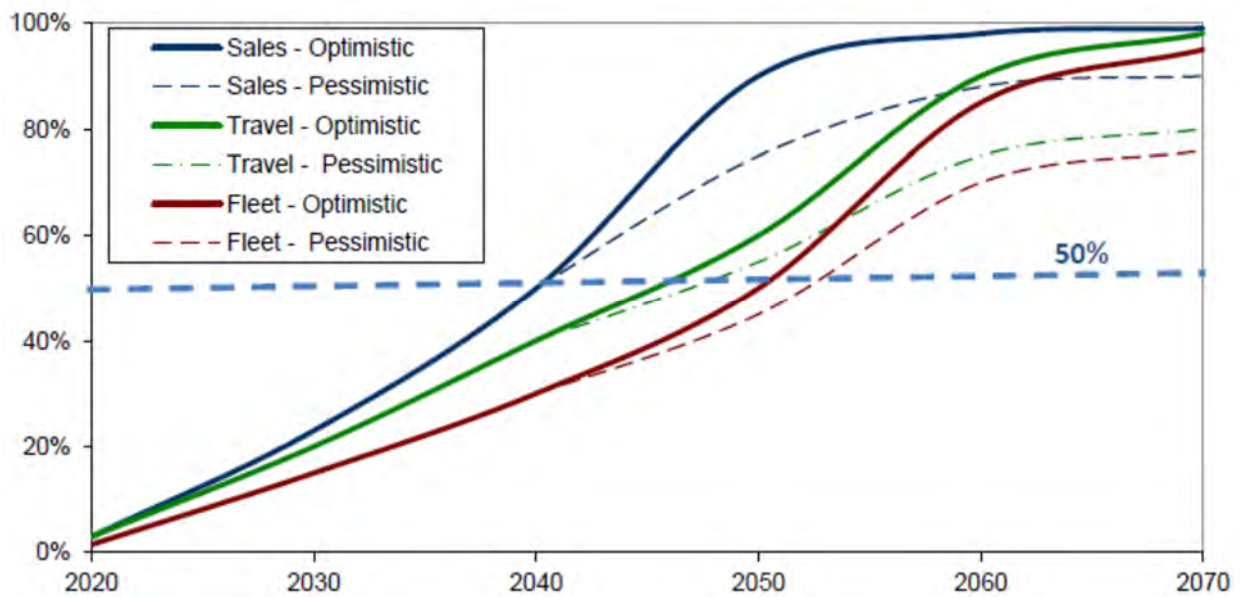


Figure 2 Autonomous Vehicle Sales, Fleet and Travel Projections. Source [9].

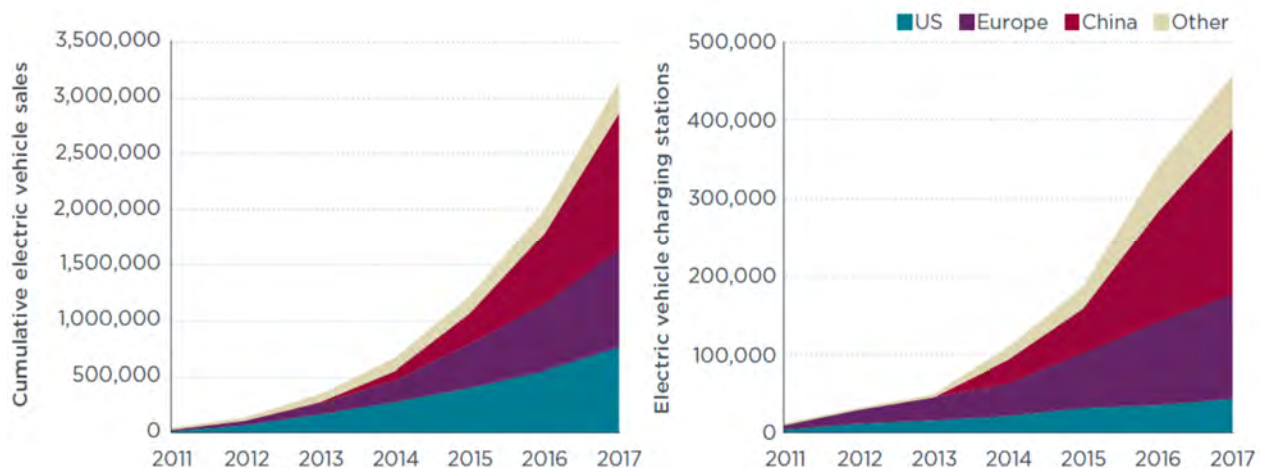


Figure 3 Global electric vehicle sales and charging infrastructure deployment by region 2017 [10]

Nowadays, there are two technologies performing high power in very short time (a few minutes), they are the Lithium batteries and supercapacitors, Lithium batteries are the most diffused storage systems and have many alternative chemistries with different performances (Li-Po, LiFeSO₄, LiNiMnCo and so on).

Supercapacitors are less diffused but recent technology improvements as new performing materials and multi layers architecture make them suitable for transport applications, they allow to use them for energy storage that undergoes frequent charge and discharge cycles at high current and short duration.

Moreover, these two technologies can be charged very quickly, mainly there are two ways: fast charge and flash charge.

Transport is one of the most interdisciplinary sectors in science, putting together different branches of engineering with social sciences, law and others. Electric and automation applied to transport add more complexity.

They involve research and technology development on automation, electronic, mechanical and electrical engineering. So, these two fields are the subjects of literature review.

This work represents a step forward in scientific research due to an innovative approach to automation systems design, it will require future efforts to convert it in a handy tool also by introducing further functionalities and models.

During the first two years of PhD, the candidate had the honour and opportunity to elaborate sensors data provided by CM2 project demonstrations, these elaborations allow to make a risk assessment procedure for automated corridors, partially published in the book “Implementing Automated Road Transport Systems in Urban Settings” edited by Alessandrini [11] and also presented by Michel Parent at PhD seminar at university Sapienza in October 2018, called “Driverless vehicles: state of the art and generation of a safe speed profile”.

From the second year of PhD to present day, Fabio Cignini participated in several national projects focus on electric powertrains and fast charging technologies, mostly in collaboration with ENEA-Casaccia research centre.

These occasions allowed the candidate to study and develop some prototypes and present them in international forums.

Meanwhile, last year was spent in two other EU founded projects named Co-Exist and Life for Silver Coast: the first one focuses on vehicle automation and its impact to transport planning, while the second one focuses on multimodal transport system with low environmental impacts deployed in Monte Argentario territory.

All these opportunities have enlarged the vision of this project, they give access to useful data for simulation and new perspectives about latest developments in fields of vehicle automation, electric powertrain and shared mobility models.

The dissertation is divided into seven sections over this introduction.

Section 1, called “Automated road transport systems state of the art, project and literature review”, describes latest technologies of vehicle automation and some main known impacts.

Section 2, called “Electric powertrain and charging infrastructures state of the art, project and literature review”, provides a description about the state of the art and literature review on those technologies, they could have great benefits in transports due to enabling electric traction systems even in place where they weren't feasible.

Following, chapter no 3 called “An innovative transport system” describes an innovative electric and automated transport system. Such system is based on small/medium shared electric vehicles for last mile transport, which platoon on specific paths called priority corridors.

Whereas, a last mile transport aims to serve a pre-existent mass transport or even, if there isn't one, an automated corridor. Those systems can be implemented from little towns, satellite of big cities, to medium and big cities with or without invariant transport systems.

They should have at least 1000 pax/h and up to 9000 pax/h in each corridor. It works with different level of automation, from partial automation to full automation in dedicated lanes or in a shared environment with other road users.

Section 4, called “Design methodology of an innovative transport systems”, describes the methodology; it foresees six steps that could be repeated with an iterative change of parameters in order to compare different results.

The steps are:

- Parameters and input data. They concern transport demand and road graph with a traffic assigned.
- Itinerary analysis and corridors identification. Starting from transport demand, it generates call lists, then for each call it identifies itineraries and potential corridors.
- Corridors choice and speed profile generation. This phase describes how to choose between potential corridors which are feasible and their speed profiles.
- Vehicle choice and fleet dimensioning. It concerns pool generation based on transport demand and fleet dimensioning.
- Electric traction needs and specifications. It estimates electric consumption, location and specifications of charging stations.
- Results evaluation. It describes which results and how to evaluate them.

Section 5 called “Example: city of Mentana” describes how to apply this methodology to a case study, which are feasible corridors, and which results are expected.

Following, Section n°6 proposes some conclusions of this work and the Section 7 some future developments.

1. Automated road transport systems state of the art, project and literature review

SAE defined five automation levels (six including zero) in its standard J3016 [12].

- No automation
- Driver assistance: Individual activities which assist steering or acceleration/deceleration are partially automated.
- Partial automation: Several simultaneous activities which assist steering or acceleration/deceleration are partially automated.
- Conditional automation: In certain driving scenarios, all dynamic, non-strategic driving activities (e.g. vehicle control but not route choice) are automated but human is expected to intervene when required.
- High automation: In certain driving scenarios, all dynamic driving activities are automated and vehicle that cope with human not intervening if and when requested, key to Transport-as-a-Service (TaaS).
- Full automation: Always and everywhere, all dynamic activities are automated with no need for human intervention.

Moreover, SAE puts a key distinction between level 2, where the human driver performs part of the dynamic driving task, and level 3, where the automated driving system performs the entire dynamic driving task. Such distinction is needed mostly for legal purposes. While up to level 2, the driver is ‘in control’ of the vehicle and therefore entirely responsible for it, from level 3 on, at least on some infrastructures and for certain time periods, the driver is no longer ‘in control’ and therefore legislations need to be updated.

Another key distinction, though not highlighted by the standard itself as the previous, is from levels 3 and 4 on one hand and level 5 on the other. Level 5 implies, by definition, its applicability everywhere, while level 3 and 4 functions can be restricted to certain infrastructures and geographical areas.

In this light, US DoT and NHTSA, in drafting the US Federal Automated Vehicles Policy [13], have included operational design domain (ODD), thus implying that some automation functions can only be employed in certain predefined conditions and infrastructures and not everywhere.

So, the OEM agreed upon a roadmap in which driver-assist systems will progressively relieve the driver from driving task up to eliminating it. In such a roadmap, the role of infrastructures is never discussed, and it is generally assumed that the progressive automation of the driving will not require any modification of the driving environment.

A different roadmap has been proposed since proposal stage by the CityMobil2 project; it moves from automated people movers (APM) and automated metros, which are operational for decades but with different levels of segregation, reducing to ‘nothing special’ the infrastructural modifications in the highest levels. Automated metros are (most of the times) fully segregated with a protected way and platform doors, but people mover can be less hardly segregated. The Rivium ParkShuttle of 2GetThere, for example, has its own way, but it has intersections at grade, and sometimes (even if they should not be allowed), cyclists and pedestrians use the shuttle way.

Decision makers at all levels (local, regional, national and transnational) will need to guide automation take up, promoting the most promising scenarios of connected, cooperative and automated driving systems based on a comprehensive impact assessment and knowledge base.

So far however, this “revolution” has been industry-led and the paths for it has been set by the different industries participating. Vital to an overall assessment of the benefits of road automation, is a societal

perspective that highlights the opportunities as well as the risks to provide unbiased advice on the way forward.

This advice is urgently needed by stakeholders, which will be affected by automation and/or will influence the penetration of automation, such as transport operators, highway authorities or local transport authorities. The ERTRAC road map shown in Figure 4, depicts automation deployment paths across different levels of automation (in ordinate) as progressive take up of driver assistance functions with the first significant market applications for fully automated vehicles coming not earlier than 2030 (abscissa).

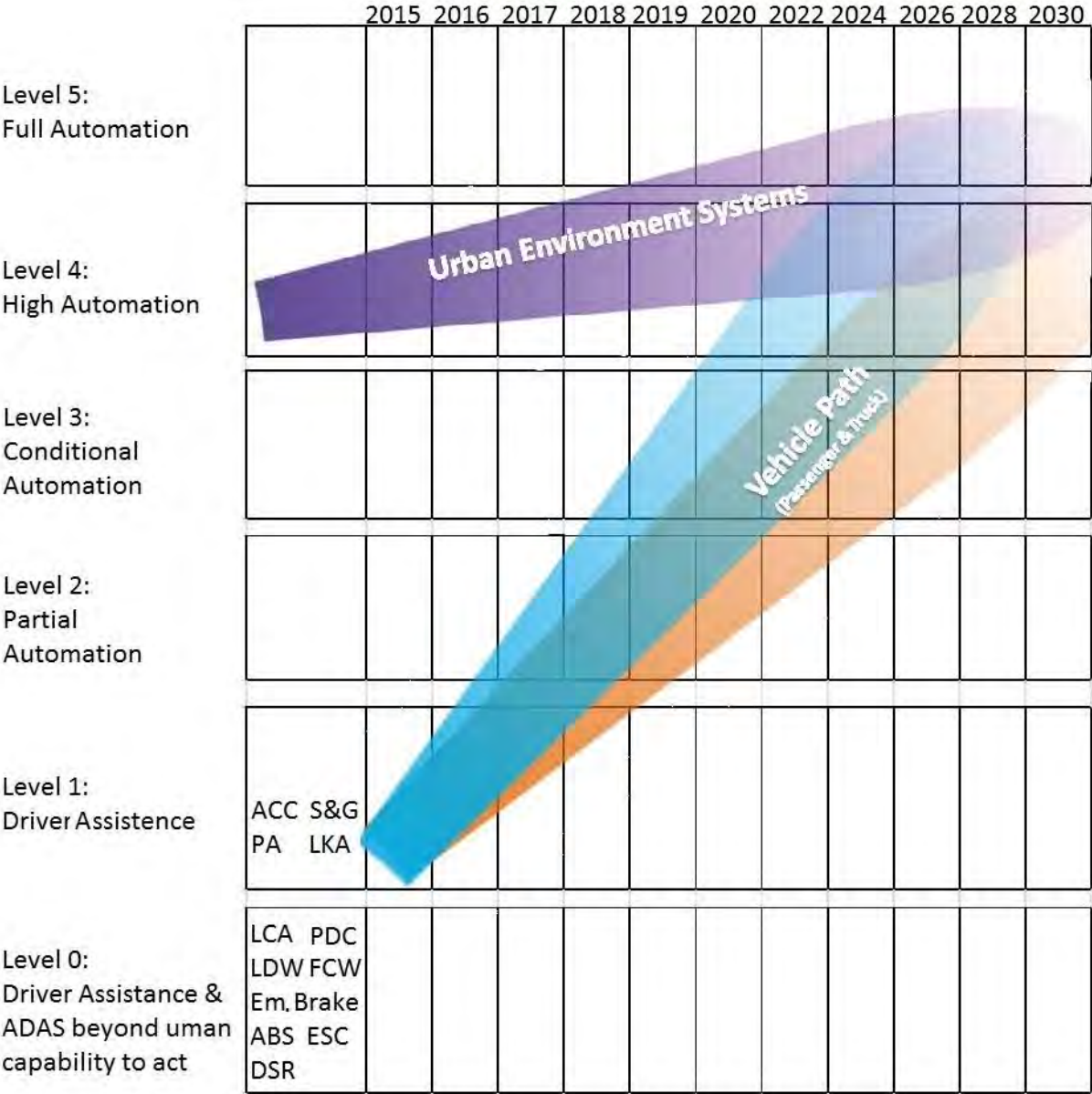


Figure 4 ERTRAC road map to automation

In fact, there is still a huge uncertainty on the date of market availability of fully automated vehicles (Level 5); many technology experts (Aria Etemad from Volkswagen and Steve Shladover from California PATH of UC Berkeley just to mention two of the most prominent) are not expecting level 5 vehicles before 2050.

These paths are composed by new automation functions being released, commercialized and then becoming widely adopted. Such functions can range from lane departure warning (Level 0), to lane keeping (Level 1), to congestion assistant (Level 2) or congestion autopilot (Level 3), to motorway autopilot (Level 4) and full automated vehicle (Level 5).

Not all functions will however follow a progressive path; some urban functions (lower speeds higher complexities) might come earlier than some motorway ones.

These roadmaps are technology-based. However, the first real breakthrough, in terms of impacts on the lifestyle, will come when daily transport and its dynamics will be affected and new ways of moving made available; in other words, when automated vehicles will allow unprecedented flexibility for private transport and for making economically viable transport services, which today are too expensive to be widely implemented even before being fully automated or level 5.

Such new services and new ways of using private cars enabled by automation, will lead to a paradigm shift in vehicle usage and to consequent impacts. But what will be the prevailing business model for the new transport services enabled by automation?

On one hand, automation will allow for more convenient use of the personal car, allowing to use differently (e.g. working) the time otherwise spent driving and relieving from parking seeking burden, pushing a more diffuse use of the private vehicle. On the other hand, driverless shared services will complement mass transits and add the flexibility and capillarity not economically feasible for conventional public transport, making the new public transport more attractive and financially self-sufficient.

Which one will come first? Which one will prevail? Which impacts on the environment, on the city landscape, on congestion, on land-use and ultimately on the economy at large and on the economic growth each will have? Will there be one preferable to the other depending on the local situation and can there be local, regional and national policies the governments will want to adopt in order to favour one path over the other, depending on the expected impacts of each of them?

These questions about the likely evolutionary path for automated transport have been much debated in recent years. However, the current debate is informed by expert opinion and heuristic analysis ('educated guessing'). Thus, the outcomes can be more accurately described as 'expectations', rather than benefits that might be quantified (see [14] and [15]).

Impacts related to road automation can be various: economic, social, energetic, ethical, etc. Economic impacts include new business models [16], such as: entertainment, information, shopping, work, communication, and so on ([17]). These businesses could affect passengers or even goods, for example, a project deployed by "Ford Motor Company" and "Domino's Pizza" deliveries pizzas with automated vehicles [5].

There is then a great research need to reliably quantify how people will react to new transport services enabled by automation (see [18]). Researchers have implemented several demonstrations with automated road transport systems in European cities, measured the attitude of people toward automated public transport and derived behavioural models out of it, which proves that people like automated buses more than conventional ones. Though, the experimental nature of the deployed services, always performed with prototypical technologies never completely legal, has limited the effectiveness of the supplied transport services, making difficult to measure the revealed preference of people.

Social impacts may concern accessibility, user behaviour and employment. Accessibility is related to increase mobility and social inclusion of impaired and elderly people (see [19], [20] and [21]). The way users behave depends on how vehicle automation is deployed, as personal vehicles or as shared vehicles. While personal vehicles are not yet ready for deployment, shared vehicles are. Employers currently working in car market ([22] and [23]), from selling to driving (public and private services), could be

re-employed in other activities (i.e. art, high quality and personalized services, entertainment, teaching and so on [24]).

Quantifying impacts on energy consumption, the USA Environmental Protection Agency (EPA) estimated it to range from minus 50% to plus 100%. It depends on whether people will share automated vehicles and rides more, reducing overall the Vehicle Miles Travelled (VMT), or whether people behaviour will become even more individualistic and VMT will explode.

So, ethical and legal impacts, studied for example by Alessandrini [6] and Csepinszky [7], are related to responsibilities in case of accident.

There could be defined two main categories of transport systems using automation:

- Autonomous vehicles, they can (in principle) go anywhere.
- Automated road transport systems (ARTS), they are conceived to perform one certain transport task, from one place to somewhere else, using known paths on the known infrastructures

Autonomous vehicles have immediate behavioural implications:

- They need to continue to work, even when something is malfunctioning, thus needing redundant energy supply and redundant actuators, and basically they need to guarantee that even if they are not in a condition to proceed, they are capable (on any infrastructure and traffic situation) to reach a safe stop condition.
- They need to detect everything on their own, without relying on any cooperation with infrastructures or other vehicles; an often-used example is the needed capacity to detect the roadworks ahead or eventually policemen and school buses, so to change their behaviour accordingly.
- They need to predict other user's behaviours as a human driver would do.

Though the technologies to respond to these needs are amazing and are fuelling a race between tech industries, they are useless for ARTS and, at least in the first stage, very dangerous because technology failure can lead to disasters.

ARTS behaviour is completely different. ARTS need a certified lane (following the technical approach described) with dedicated aspects in the light cycle and some protection depending on the speed of the flow. In other words, ARTS use off-the-shelf technology at best and adapts the environment (or reduce speed) to minimize (or eliminate) risks of accidents.

The future of ARTS starts from CityMobil2 but will grow to city level and out of the 10-passenger shuttle concept so many today identify with CityMobil2. Within CityMobil2, given the resource available and the demonstration sites proposed, two fleets to 10-passenger shuttles were selected. One of the big demonstration sites was the city of Trikala in Greece, Figure 5 shows the vehicle working in mixed environment of the city, even with a lot of pedestrian and cyclist close to vehicle lane.

However, the future of ARTS will need to cover from 4-passenger vehicles to 50-passenger vehicles depending on the demand.

The vehicles will need to have a shared taxi-like service in the city outskirts where the demand is less intense up to corridors where they will form platoons and reach BRT-like capacities to go to city centres and main network nodes to interchange with existing and innovative systems.

The ARTS will not only cover the last mile but also can be an integrated last-mile long-distance service. The interesting aspect is that the CityMobil2 demonstrated technology is already enough (combined with more traditional ITS ones) to provide such services today.



Figure 5 Trikala demonstration site (CM2 project)

What is still to be demonstrated is that the envisaged model can bring public transport out of subsidies and in the profit-making realm, motivating private investors to invest on it as much as companies are investing in the automated private car.

Today, the main investors in automated vehicles are Tier 1 suppliers and OEM; both wishing to sell millions of vehicles (and billions of parts) to have the investment returned. Some like Uber, Lyft and its investors, imagine a future of “Mobility-As-A-Service” (MaaS); a mobility which, as Uber and Lyft are demonstrating, follows money more than sustainability and which might be causing an increase in the VMT.

The only sustainable solution is sharing. Sharing ownership, but mostly, sharing rides. So the size of the vehicles needs to grow with the density of the demand or congestion will always get worse. If a ride-shared system designed to be sustainable can also prove to be profitable, it will attract investors and invert the current trend.

However, it is not clear yet if it is possible and what it takes to get people to share rides in small vehicle with no official driver (an authority figure which decreases the “fear of attack”, always present in shared vehicles). Some policies (push and pull measures toward innovative transport systems) can only be implemented by cities after they have clear how citizens will react to them and which will be the impacts of it. Simulation and scenario analysis are therefore necessary.

While efforts are being made to update supply simulation tools to consider automated vehicles, although this is proving difficult because nobody has yet clear how autonomous car will behave on the roads, a strong push in the demand research is needed. The Co-Exist project has already implemented an alpha-test version of the PTV-Vissim microstimulator which embeds three possible automated vehicle behaviours. In Co-Exist the PI helped defining 4 exemplary driving logics for automated vehicles on the road which PTV engineering team then embedded in the software. The tool is being tested and validated these days.

The vehicles are conventional four-to-fifty seats electric vehicles, which are transformed to become automated. They will keep the manual driving possibility. Automation technology will enable the vehicles to follow precisely a precomputed trajectory (lateral position), the longitudinal position can be

decided either by a driver actuating acceleration and braking (as a tramway) or fully automatically. Up to 6 vehicles can follow each other in a platooning mode.

On the technology side, the key technologies are the lateral guidance, the obstacle detection (only in full automation mode) and communication to synchronise acceleration and deceleration when in platooning mode.

Two technologies are the most effective for lateral guidance. The SLAM (simultaneous localisation and mapping), which uses a lidar to create in real time a three-dimensional map of the surrounding environment and compares it with a map from the archive, recognising the position with a centimetric accuracy. To increase precision also in places with limited environmental benchmarks, this is normally fused with DGPS. This technology has been tested effectively up to 80 km/h. The second positioning and lateral guidance technology is based on odometer recalibrated with magnets put in the asphalt. The vehicle calculates its position, depending on the previous known position and the instantaneous velocity vector; it makes an integration of the speed vector to calculate the position. The calculation is very precise in the short but being an integral, calculation errors are added one another becoming bigger with time. The position is therefore re-calibrated when the vehicle passes on a magnet of which position is known and preventively mapped.

The project is technology-agnostic and will buy the technology from the market.

Obstacle detection (and tracking) is more delicate; it is normally done by fusing different sensing technologies (lidar, radar and cameras) and its accuracy is affected by a number of external factors. In ABC New Mobility obstacle detection is important but not crucial. Being only partly automated, the vehicles can benefit from it but are not dependent on it.

2. Electric powertrain and charging infrastructures state of the art, project and literature review

The international trend in transport is changing from Internal Combustion Engine (ICE) to less environmental impact powertrain as electric, hybrid or even CNG and LPG engines.

Because of the reliance on petroleum-based fuels and their dramatic growth rates in recent decades, all transports (road, air and sea) are responsible for significant emissions of traditional (criteria) air pollutants (e.g. sulphur oxides (SO_x), nitrogen oxides (NO_x)) and greenhouse gases such as carbon dioxide (CO₂) and other pollutants. Some suppose that ICE could be banned from transport in a decade [25].

Main national countries adopt their own policy, for example one of the European policy about the fight to greenhouses gas emission (GHG) and climate change is the Decision No 406/2009/EC ([26]) where EU Member States should continue to collectively reducing their emissions of greenhouse gases in the order of 30 % by 2020 compared to 1990, and in a later documentation (see. The Green Paper: A 2030 framework for climate and energy policies, [27]) there are some hypothetical targets for 2030 but under assessment yet. Moreover, other countries adopt national guidelines to push diffusion of this technologies and catch this challenge (see [28] and [29]).

Indeed, it is well known that policy guidance and planning played a vital role to the growth of new electric vehicles industry (see [30]) but it does not concern this study.

The automotive and bus market offers a lot of solutions for transport (for example see [31]), the most promising are Low Environmental Impact Vehicles (LEIV) that share with traditional one (ICE): transmission, suspension, brakes, main safety systems (as ABS, EBD, traction control and so on), accessories and auxiliary systems, and in some cases chassis also; but the LEIV adopt different powertrains.

Public transports are particularly suitable for a precise dimensioning, due to repetitiveness of certain missions (transport lines) with a pre-determined path, so it is easy to evaluate how much energy is required to do a complete ride with significant precision.

Mostly, a LEIV with an electric powertrain has three main components: an electric motor/generator (could be two separated devices), an electronic converter (often called Inverter) and an Energy Storage System (ESS).

The ESS could be a tank (for fuel), a stack of batteries, a chain of supercapacitors or even a mixed solution of them. There are several uncommon solutions as flywheel or air compressed energy storage systems but due to their low diffusion and different purpose of this dissertation, their study was omitted.

All ESSs have in common the evaluation of energy stored on board. There are a few models of LEIV: full electric vehicles (Figure 6), hybrid (ICE and electric) in series or parallel configuration (Figure 7), or a fuel-cell vehicle (hybrid hydrogen-electric) as shown in Figure 8.

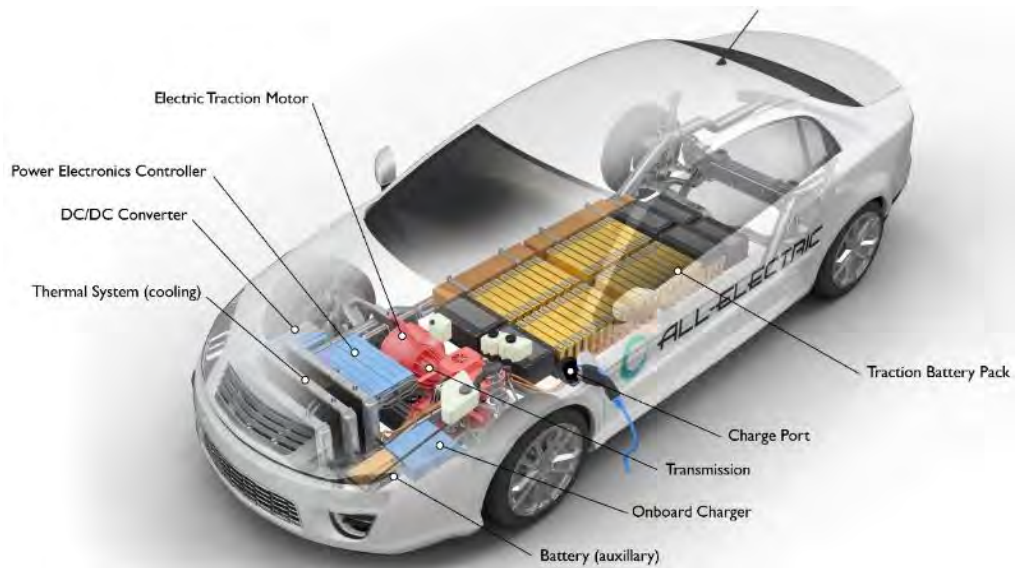


Figure 6 Full electric vehicle. Source “afdc.energy.gov”

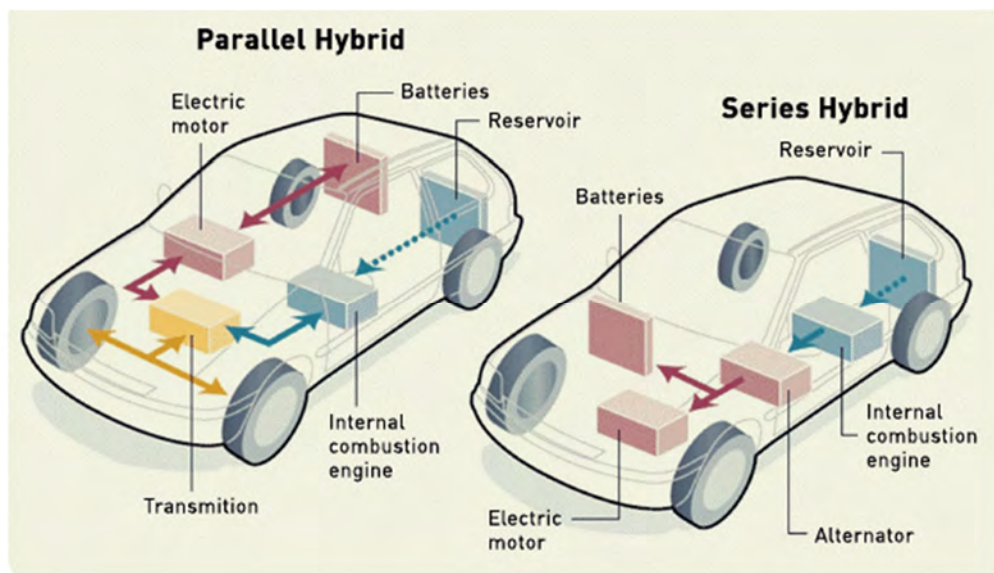


Figure 7 Two main hybrid layouts

A lot of studies explore this field of research (see [32], [33]), even more it develops every day due to improvement in chemical of materials used by batteries and ESS.

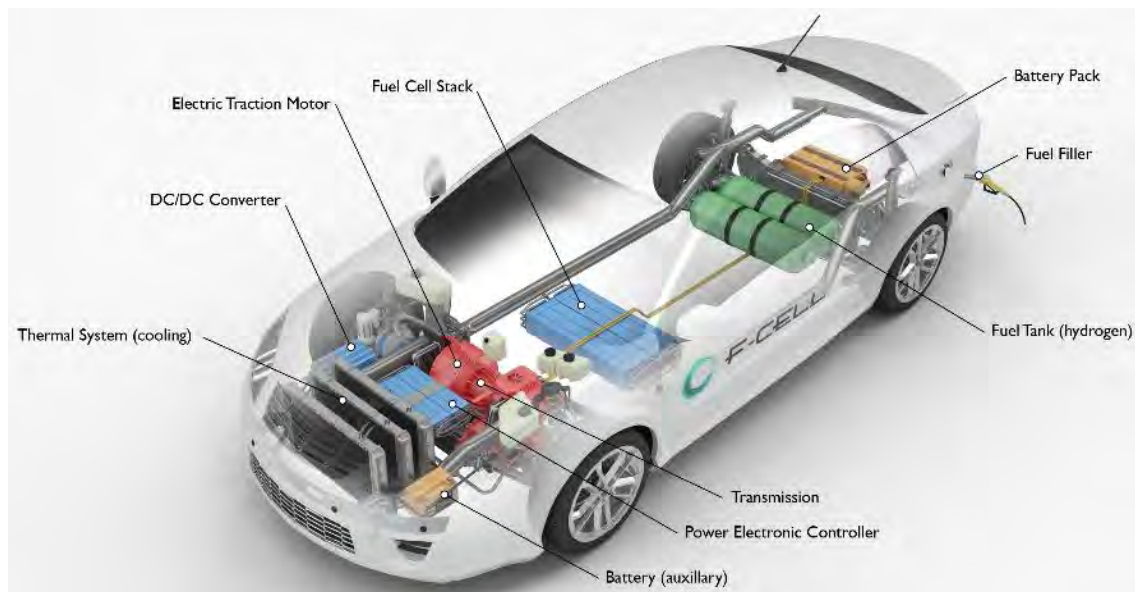


Figure 8 Fuel cell vehicle. Source “afdc.energy.gov”

Moreover, the charging methods and infrastructure have a huge role in the economic feasibility of electric traction systems.

Oldest charging methods for Lead-Acid batteries was limited by maximum charging current, which usually work at 0.1 C rate, it meant that charging time rose to 8 or 10 hours, often they were charged for a night and it required a charger for every electric bus.

So, some manufacturers as the Italian company Tecnobus S.p.a. carried out the swapping of batteries with a smart packaging of them and a bus frame specifically designed. Unfortunately, they had three huge issues connected to battery swapping:

- charging time remained high and of bus was limited to daytime
- they required a twice amount of batteries with a dedicated charger that worked alternatively on them during the day
- the bus had to return to the depot to do the swapping operation, the time wasted was cut from transport operating time.

So, the charging of batteries (or better ESS) is one of the biggest challenges for electric mobility.

The long-standing issues of electric vehicles are the limited mile range and the low energy density (in comparison with fossil fuel); the fast charging should tackle these limits, but it remains a trade-off between high power that an ESS could manage (for charging phase or during operation), and the energy needs of the systems.

Recently, it has opened a new and promising front of research in fast charging technologies; partly enabled by new ESSs, these are the subject of many research experiments ([34], [35] and [36]) and it has a precise regulation from IEC [37].

Nowadays, there are two technologies performing high power in very short time (a few minutes), they are the Lithium batteries and capacitors (also called supercapacitors or supercap).

Anyway, there are some technological limits when high power and energy are transferred in short time. Those restrictions come from “conduction” of materials (or from its reciprocal the “resistivity”), it is an intrinsic property of elements and semi-conductors.

Electronic components, wires, power connections, relays (or contactors) and several devices that usually equip electric vehicles have the same difficulties with high electric current. The Ohm and Joule laws suggest that the greater is the power, the more there should be voltage in order to reduce current, which is responsible for overheating and energy losses.

The increasing of voltage causes some impacts to:

- Safety; people that interact with this technology should wear specific Personal Protective Equipment (PPE) and an additional frame and shell isolations for passenger's safety (as in tram there is galvanic insulation).
- Electric and magnetic insulation; some fragile components should be insulated from all others, in some cases a magnetic field and/or electric field generated by high current or voltage fluctuation is enough to damage an electronic board, for example circuit boards of CAN communication shield should be opto-isolated from casing, from power supply and other circuits
- Certification; to achieve common standard certification the high-power electronic devices require more tests than low-power one, and they cost more.
- Measuring; it concerns fields generated by electricity, all sensors and Electronic Control Unit (ECU) that manage powertrain and ESS require a specific designing (increasing costs) and a reserved power supply to avoid measure mistakes.

Those limits are well-known from electric and electronic engineering ([38]) in this dissertation they have a marginal role, but due to their important impacts to designing of an electric transport system, they are mentioned.

Mainly, the high-performance Lithium batteries and supercapacitor include these impacts enable two fast charging systems:

- Fast charge of a battery
- Flash charge of an ESS (mixed battery and supercapacitors)

The technologies proposed could have great benefits in transports, due to enabling electric traction systems even in place where they weren't feasible.

For example, the energy charged have to guarantee a complete ride (or mission) or at least one or two stops in a transport line (opportunity charging). The first one can be done at terminus while the second one can be done at an intermediate line stop (with higher costs due to more charging stations).

Figure 10 shows a battery prototype made in ENEA research project "Minibus with fast charge policy" (see [39], [40] and [41]) aiming to develop an innovative storage system with Lithium batteries (LiFeO₄ cathode). They allow to charge at 3C charging rate for 2 minutes an amount of 1.4 kWh, enough energy to do almost 3 km (Figure 9).

High-performance batteries allow to reduce costs of ESS due to less energy stored on board; thanks to its high-power capability the ESS allows to fulfil power requirement for a minibus, then fast-charging allows to overcome the mile range limit. High modularity and safe standards are also kept.

Those systems often require a Battery Management Systems (BMS) designed ad hoc to manage electric connections, including safety devices (fuse, contactors, resistance) and active controls to solve the equalization problems. In fact, if recent developments aim the manufacturer to make batteries (or better is littlest building module a cell) always with high performance and similar, the chemistry of each cell still has some uncertainty.

As a result, each cell is unique, when they are assembled and connected in series and/or in parallel there could be some disequalization problems, due to tendency of electricity to follow lesser electrical resistance path.

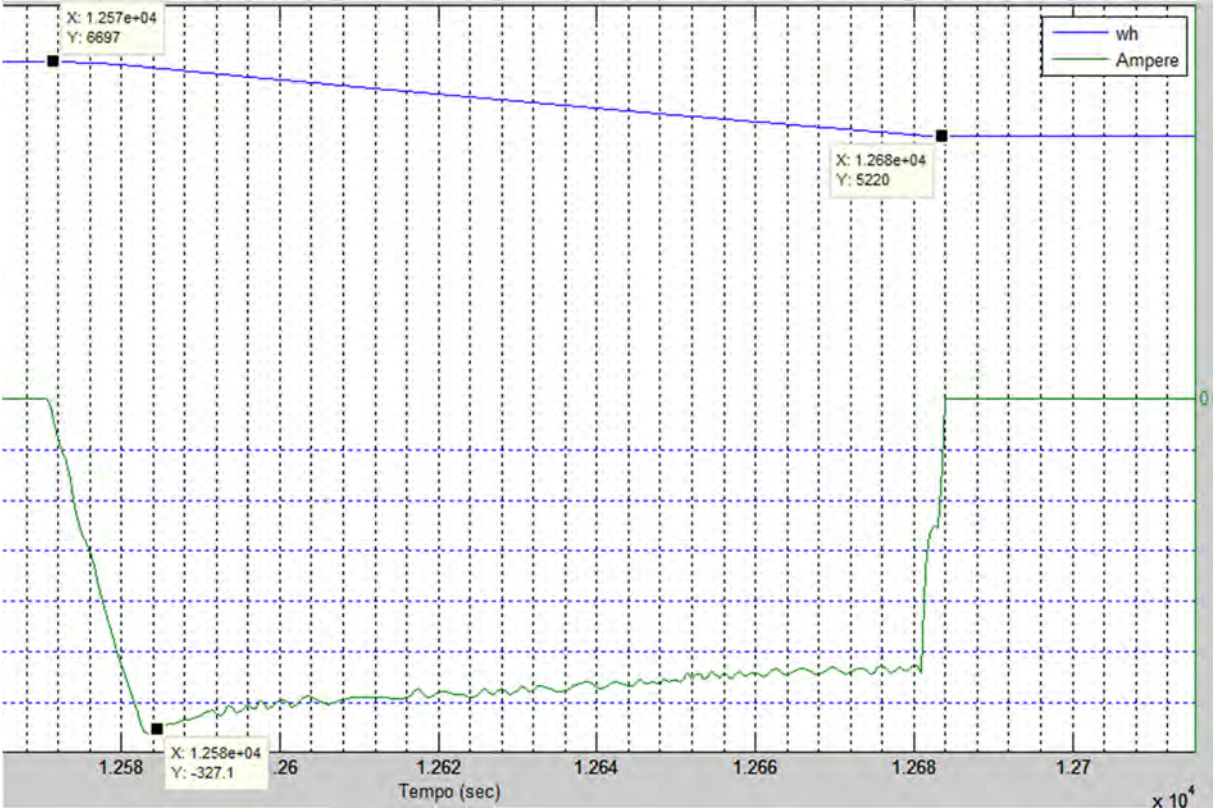


Figure 9 Charging performance of project "bus with fast charge policy"



Figure 10 The prototype of ESS used in project “minibus with fast charge policy”

Figure 11 shows a render of the minibus houses the ESS on its back (right part of the Figure), the bus was manufactured by “Tecnobus” S.p.a. and it is property of University of Florence [42], [43] and [44]. Project “Minibus with a flash charging system”, led by ENEA, was developing a prototype starting from the old bus model “ESP520” and which is revamped with an innovative ESS composed by three supercapacitors (provided by Maxwell, see Figure 12) connected in series and by lead-acid batteries. This system is capable to transfer the energy needed to do a mission (complete ride or reach another charging stations) in 30 seconds.

Figure 13 shows the pantograph that should be mounted on the bus roof to intercept and overhead electric line, or even a socket, the bus shown in Figure 11 has been reinforced with an internal steel frame in order to support the pantograph on the roof.



Figure 11 The render of electric bus used in project “Electric minibus with flash charge”



Figure 12 A supercapacitor used in vehicle traction (made by Maxwell)



Figure 13 A pantograph used to connect vehicle to overhead electric lines (made by Shunk)



Figure 14 Fast charging technology, TOSA project

Moreover, a few charging solutions came from industry fitted for different applications:

- Opportunity charging for electric buses at stops or terminus (Figure 15), it uses a modular design with power from 150 kW to 600 kW and it is capable to charge buses in a few minutes
- Multi-standard DC fast charger with “Chademo” standard (Figure 16), with maximum 50 kW of power, it can charge a car in maximum 30 minutes
- Inductive charging or wireless charging, it will be a charging method to use opportunity charging at stops, but it has dozens of kilowatts as maximum power available on the market (Figure 17).



Figure 15 ABB Flash charging station at bus stop



Figure 16 Chademo DC fast charger

The opportunity charging strategy with a fast charging technology, take advantage of those wasting time situation, or where vehicle is doing other tasks as get-in or alight passengers at stops, even if this time lasts a couple of minutes. The opportunity charging can also be done when the bus rests at terminus, where it waits for the following ride or for driver shift change.

Thanks to this methodology, perhaps the charging time is not enough to charge completely the battery, but even to give a part of its daily energy needs to sustain and increase operating time. During night, when a bus could rest at depot, a slow charging could fill up the battery.

It is possible to use this time (otherwise wasted) and charge the battery of the electric (or electric-hybrid driveline), hence the name Opportunity Charging.

The inductive charging has a great margin of improvements in the fields of:

- Dynamic wireless charging could charge a vehicle/bus while it drives at pre-determined speed
- High-power wireless charging; thanks to improvements in isolation materials, charging power could be rise to 200 kW and it will receive in 5 minutes enough energy for it to roll on its next route

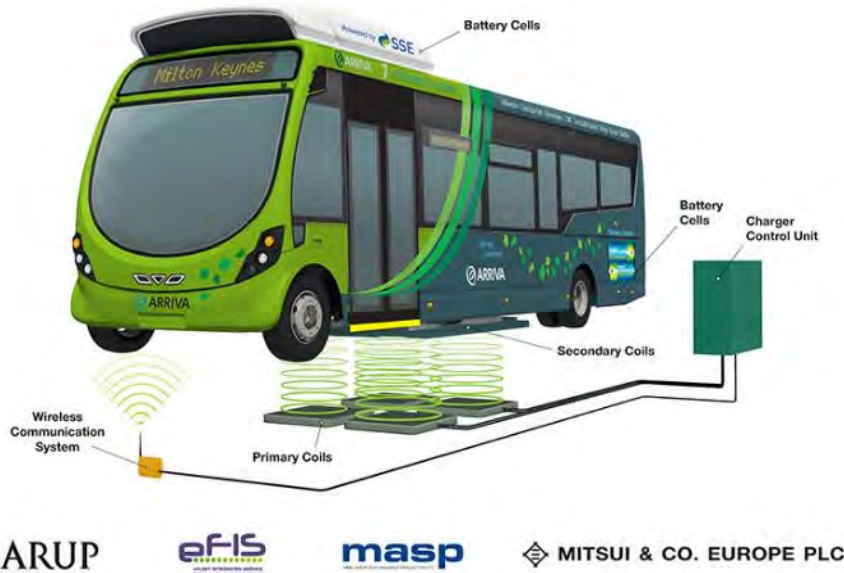


Figure 17 wireless charging systems

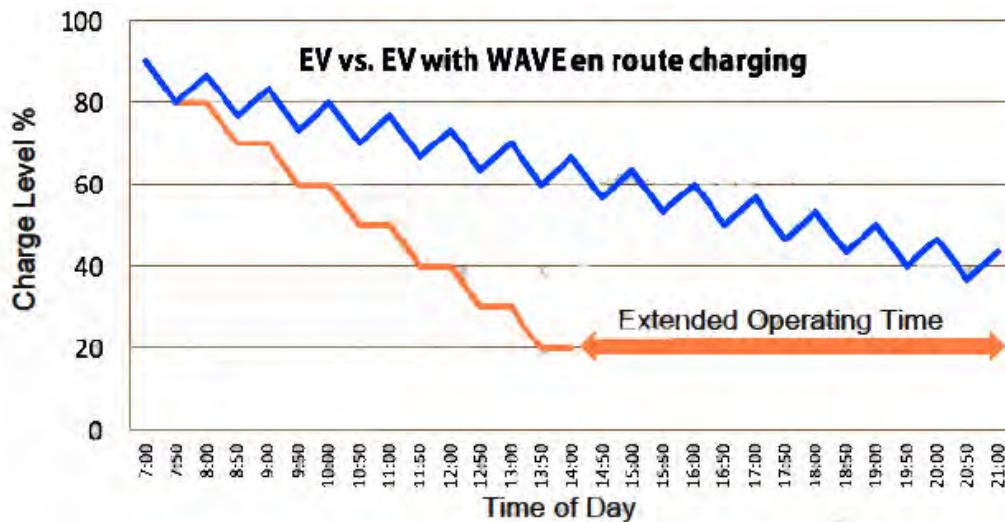


Figure 18 Use of energy with opportunity charging strategy

There are further solutions that can be used, for example the corridors could have an electrified overhead line, also for a few arcs, so the vehicles equipped with a sliding pantograph (as those used in railway) can be charged or even fast charged with enough energy to achieve a complete ride and return up to same corridor to charge itself again.

3. An innovative transport system

The technologies previously mentioned in chapter 1 and 2, could enable infinite new transport systems, this PhD proposes a study on a today feasible transport system with technologies available on the market. They have a TRL level 7 (system prototype demonstration in operation environment, see [45]) or even 8 (system complete and qualified).

The innovative transport system proposed concerns two transport systems:

- First/Last Mile on-demand
- Long distance system with high capacity and which uses same vehicles of first/last mile

A system that could work with different level of automation, from partial automation to full automation in dedicated lanes called priority corridors. If there are pre-existent mass transport systems in city the innovative concept could link first and last mile to them, for example through train station, metro or tram interchange stop. While, if there aren't pre-existent mass transport systems, the innovative one could use priority corridors to reach some interchange location and/or destination.

The complementarity of first mile on-demand and long-distance systems could produce financial synergies making each one less dependent from public financing, as currently last mile is ([46]). Both concerns private and public transport indiscriminately, with any vehicle dimension.

These systems could use electric powertrain to reduce environmental impact and increase efficiency in energy use, but it is not mandatory and traditional vehicles could be adopted in any case.

Anyway, the term “priority” for corridor concerns road regulations, so automated vehicles while travelling in a priority corridor could have the right to travel in mixed roads and some adaptation in infrastructure to reduce hazards, but the key point is that each corridor must have its own risk assessment to evaluate transport performance and safety measures, independently from the priority.

A road arc could be part of a corridor even without any infrastructure adaptation, only due to its strategical position in road network, maybe via risk assessment procedure it needs speed reduction for safety reasons in mixed traffic but with proper legal framework it could self-ride in those certified corridors.

Figure 19 shows a hypothetical city (simplified) where there is evidence of road infrastructure and some points of interest, this city does not have any invariant infrastructure (i.e. railway, tramway or metro). The red dotted lines are two priority corridors that intersect themselves in one point.

A city could have different density of transport demand, decreasing from city centre to outskirts (Figure 20), those area could have different transport needs, so the innovative transport system are capable of more flexibility.

When the transport demand is low, a transport service could use the system with individual vehicles that use corridors, such as private cars. The corridors link a generation node with an attraction node, each vehicle takes a corridor where it is possible (in some specific entrance), without waiting other vehicles to form a platoon. A user drives close to corridor entrance, then he can push the automated driving function and leave vehicle drives itself for entryway operation up to a desired exit.

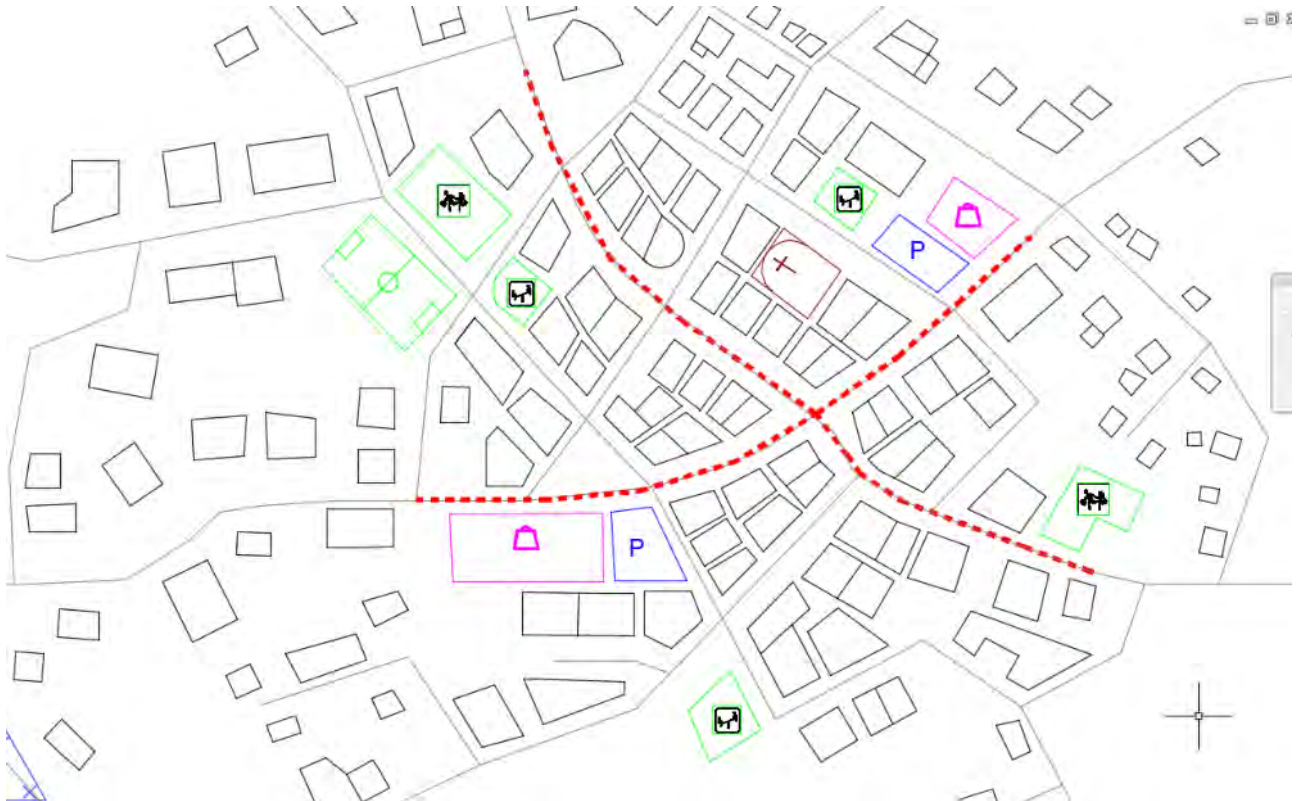


Figure 19 A city road network with points of interest and two main corridors



Figure 20 Density level of transport demand

The key question is: where is it possible to make priority corridors?

The answer is: not everywhere.

Due to complexity of urban areas, but especially due to high costs of automation technologies, infrastructure sensors and adaptations (i.e. mitigation measures), risk assessments and usefulness (benefits that come from improvement) not all cities are suitable for this concept as whole.

It is evaluated that a corridor with one lane per direction could be feasible for at least 1000 pax/h (passengers per hour) and up to 9000 pax/h. Those limits come from road capacity and automation performances, but each situation has its socio-economic evaluation to discriminate which is feasible or not.

For example, upper limits come from:

- Maximum platoon length. The Italian regulation could validate a maximum platoon length of 60 m accordingly to tramway regulations, but for road platoons there isn't a given limit, it should be up to 40 m
- Minimum headway between two consecutive platoons, it set to maximum headway in a mixed road environment. A platoon length less than 40 m which passes once per minute means 60 platoons per hour of capacity, independently from vehicle size,

Indeed, the maximum corridor capacity depends on vehicle size and seats available:

- A platoon of 7 vehicles with 4 available seats (4 m length with at least 0.5 m of separation) hauls 28 people at once; it means that 60 platoons per hour haul 1680 pax/h.
- A platoon of 5 vehicles with 30 available seats (5.5 m length with at least 0.5 m of separation) hauls it means that 60 platoons per hour haul 9000 pax/h.

Moreover, little vehicles are a good solution to solve transport problems, but it has an important consequence to propensity in an individualism behaviour and often due to high costs of vehicles and automation technologies the socio-economic evaluation could reject this solution.

The proposed concept of innovative transport system involves cities with demand from 1000 to 9000 pax/h in several road arcs, with possible congestion problems and a transport demand oriented to a few attraction poles.

There are a lot of situations with Many-to-One-Problem (MTOP) or a Many-To-Many-Problem (MTMP) that can be divided in two MTOP and a long corridor to restore the continuity of problems.

A corridor does not have a minimum length to be feasible, due to its costs and complexity it is required a risk assessment and socio-economic study. The longer it is, the better is its feasibility and its benefits even accepting less level of demand.

When transport demand is comparable with 9000 pax/h, other transport solutions could be considered in a feasibility study. They are: Metro, Tram, or maybe a BRT.

In case of pre-existent rail, the corridor selection focuses on to not be in competition, indeed it has to complement it, both will have great benefit in term of occupancy rate and economic results, together they could reduce negative impacts that came from transports.

For example, corridor could serve a circular way and link (as greater ring road of Rome) some train station or other important poles external to city centre. This solution allows people to go directly from an outskirt to another, avoiding radial roads or transport systems. It brings great benefits in terms of less congestions, less pollution and also in terms of time saving and minor costs of travel.

There is another perspective of use for corridors, they can be useful for relocating vehicles. In fact, a lot of cities having the characteristics mentioned and suitable for priority corridors, have also another issue linked to monodirectional demand: when a vehicle reaches the destination (i.e. the train station), who relocates it?

There are two valid answers:

- There is a counterflow demand of people that alight at train station and work or study there, they need a transport to reach destination. In many cases, if there is no public transport neither there is a counterflow demand. So, the introduction of a system like this could attract new incoming demand.

- There is no counterflow demand, due to lack of secondary schools, university, big stores and public entities.

Both cases have the same problem of vehicles relocation. A solution could be the platooning technology; in this case a professional driver could lead a platoon from the aggregation point at train station up to next their destinations.

The platoon can use same corridors of inbound trips, destinations are near the door of user that booked a trip from the city centre to train station. Then, corridors can be used twice, with higher positive impacts.

Figure 21 shows the potential corridors for a transport service of Mentana, a little city of about 23000 inhabitants in the outskirts of Rome (more information are provided in Chapter § 5), this city has a relatively low density of demand, but people who want to go to Rome by train have to travel for 8 km of same road up to Monterotondo train station.

If all the 3600 daily commuters from Mentana to Rome, 40% of them by train, at the morning peak hours (from 6:00 to 9:00), should reach Monterotondo train station and there were several road arcs with about 1200 pax/h, with a car ownership rate of 0.7 car/person and the average occupancy rate in private transport of 11 pax/veh 1200 pax/h. it means 1090 veh/h and is close to road capacity limit (one lane per direction). This is one case where an automated corridor could be useful.

Figure 22 shows some potential corridors for city of Latina (about 120 000 inhabitants) in the North-North East city side, Figure 23 shows the same image but from the opposite side.

Latina has no tramway and neither a metro line, the railway which links Latina to Rome and Naples is 10 km away from city centre. Latina is the Italian city with the highest value of Low-Density Area ratio (LDA) [47], it means that it is a sprawled city. The first of two figures shows the corridor that links train station to city centre, the second figure shows the other main corridor that links city centre with the seashore of Latina, both are 10 km long and almost straight, with a few intersections. In both figures, there are other secondary corridors aiming to serve high residential areas of high attraction locations.

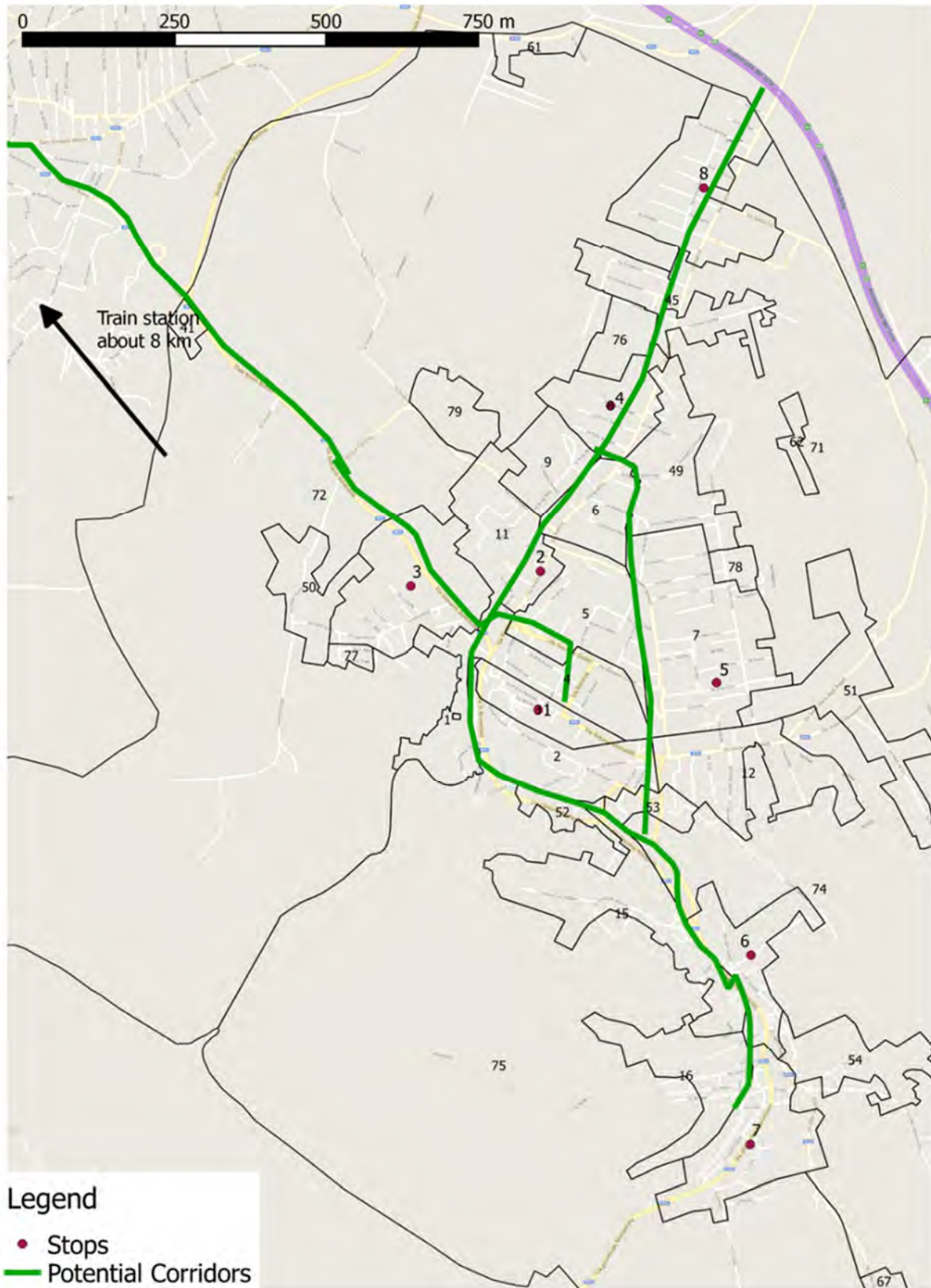


Figure 21 Some Mentana (Rome) potential corridors

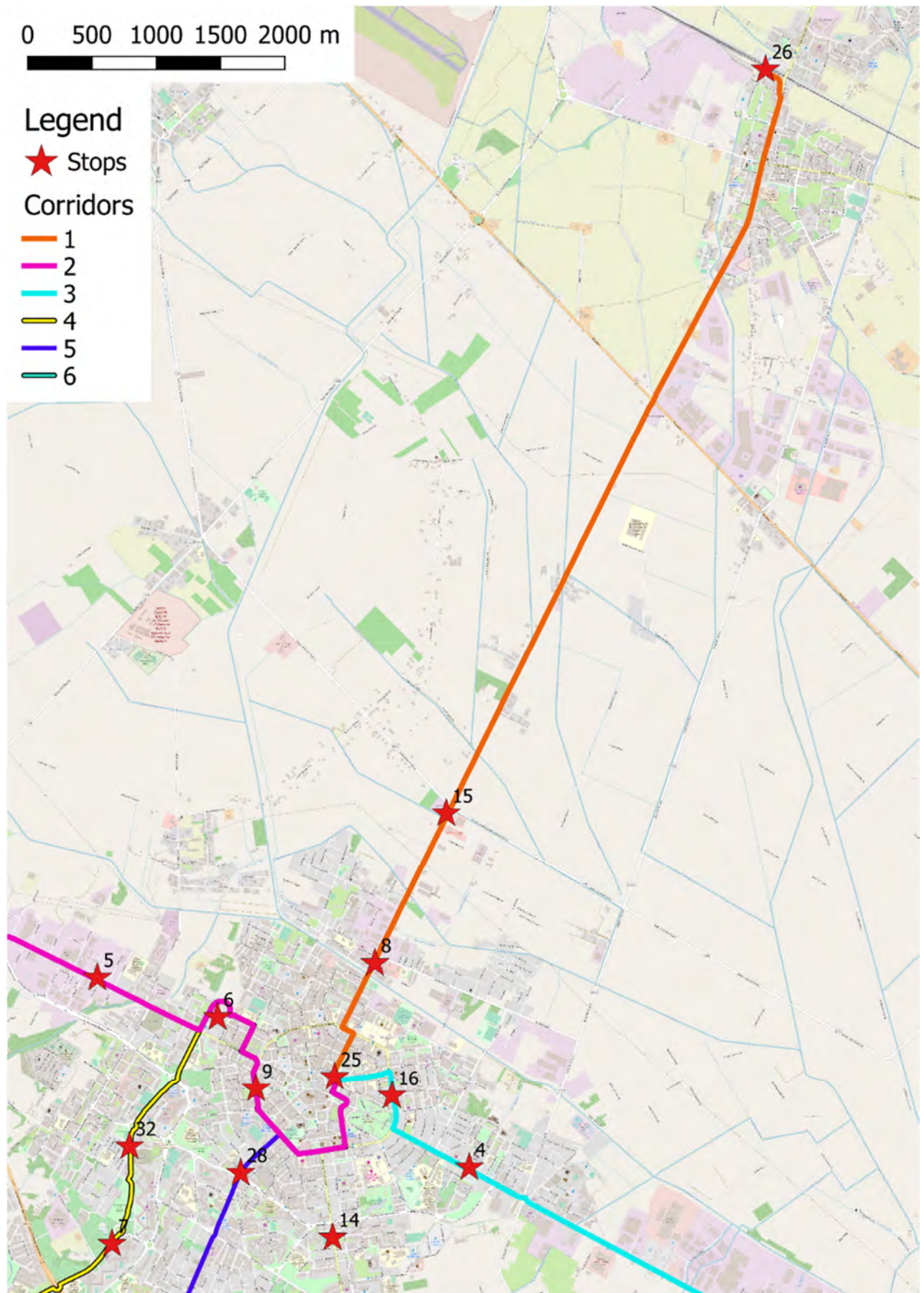


Figure 22 A few Latina potential corridors, a first view

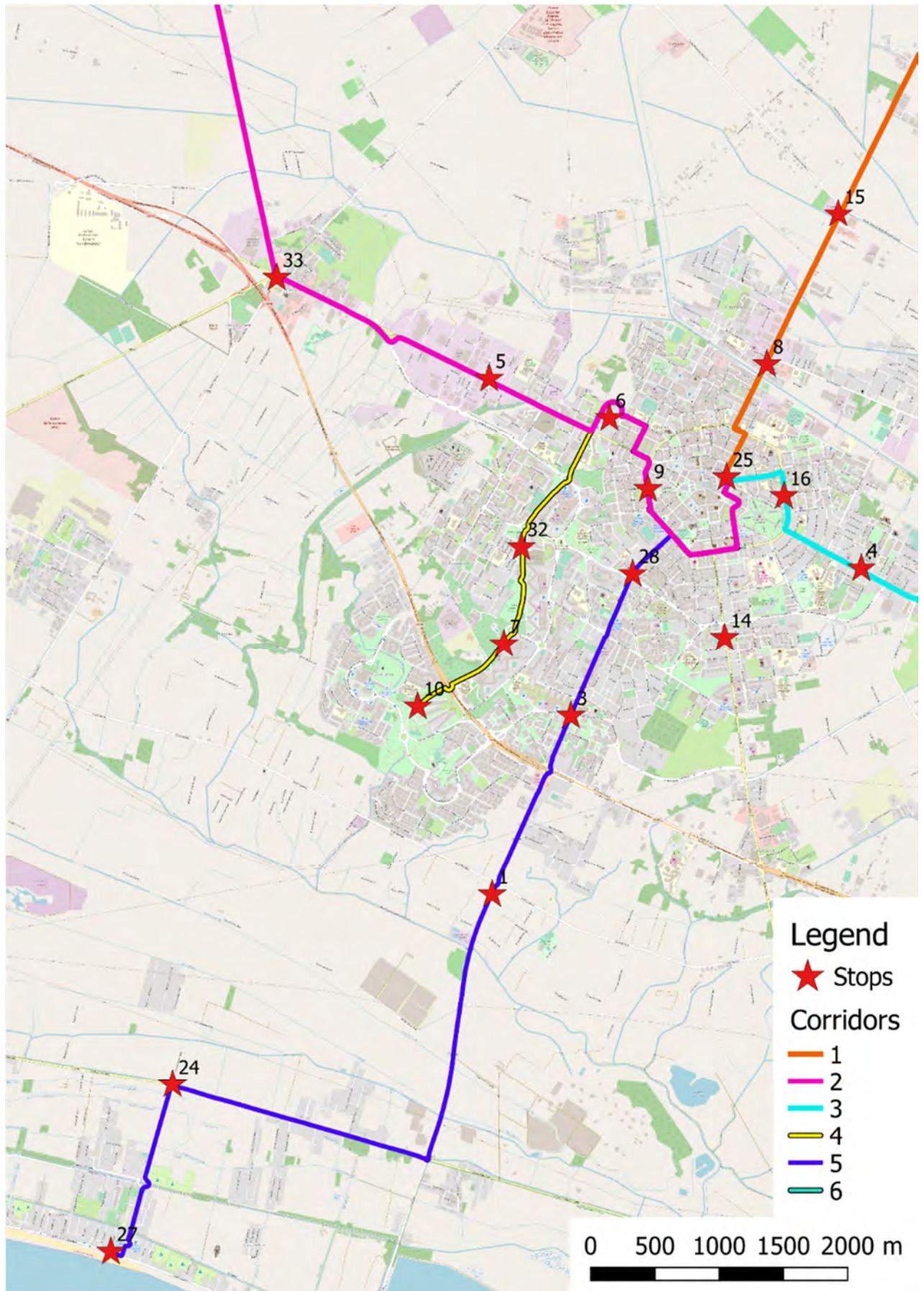


Figure 23 A few Latina potential corridors second view.

If there were some invariant infrastructures as a railway and some territorial natural division (i.e. a river), this innovative transport system could be divided into virtual zones, each with its own transport needs.

An integrated approach considering train stations and train commuters, could solve step by step this challenge, different solutions and level of automation can be applied in each city zone.

For example, the invented city of Figure 24 is divided into three zones; to reduce computational costs each zone can be solved alone with this methodology (or any other). A zone has its own level of automation, and its corridors serve the closest points of interest, as train station.

To allow trips between zones some continuity solutions are required, with length, time and cost.

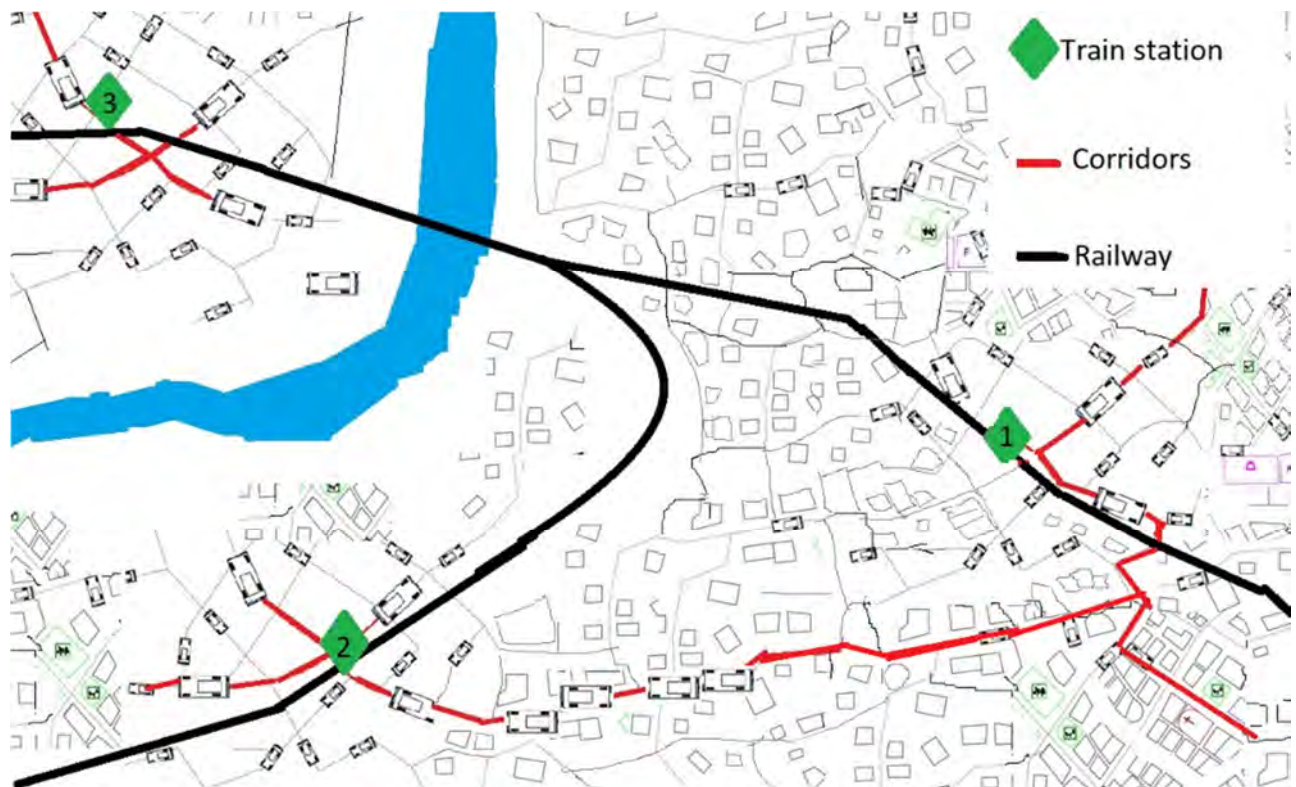


Figure 24 City with pre-existent railway

Moreover, thanks to platoon technology, road capacity of corridors can increase and overcome the road capacity with standard condition and Brick Wall Stop (BWS) braking model, or even with right safe distances between vehicles. In a sprawled city with a lot of corridors, this solution could be useful to achieve the possibility of dynamic merging and diverging of platoons, people reach their destination without any intermediate reloading.

In some cases, depends on country and its regulations, the first vehicle of the platoon could be driven by a human to achieve official certification. The automation technology could allow to avoid platooning techniques because it has precise speed profile objectives and sensors to increase safety also with lower headways. Platooning remains for those situations that have mixed and shared lanes (for example reserved lanes shared with traditional TPL).

There are also secondary solutions to maximize corridor capacity and feasibility:

1. Increasing vehicle size starting from first mile
2. Increasing vehicle size starting from corridors entrance, it requires a modal change or vehicle change.

The first solution maintains flexibility in corridors, but loss of drivability in tight streets and maximum vehicle dimension is limited by driving license of people who drive up to corridor entrance.

People can reach with their own vehicle and do a modal change from private vehicle to bus; the empty vehicles can park themselves with automated parking garage pilot function. This solution loses in flexibility, but it can reach high level of payload with high travel frequency of buses within corridor, it is also easier to develop and obtain certification for automated vehicles.

The main impacts brought by automation technologies are summarized in following:

- Ethical and Legal impacts due to responsibilities of damage and accidents by using automated vehicles as the “survey reveals the moral dilemma of programming autonomous vehicles: should they hit pedestrians or avoid and risk the lives of occupants?” proposed by Ian Sample [8] and studied by Alessandrini [6] and Csepinszky [7].
- Safety. The vehicle automation technologies, as Collision avoidance and Obstacle detection [48], probably will increase safety but in the early stage of vehicle automation implementation, traffic composition will be a fleet of mixed vehicles, mostly manually-driven and several with different level of automation. It becomes significant to study behaviours of all users and all road safety issues. It represents “*the border of a new kind of road safety paradigm*” [49].
- Security. There are a lot of study for personal data protection and implications [50], moreover the fear of attack could have an impact due to vehicle automation, without the driver for example an efficient surveillance system related to public order will be needed.
- Social impacts, they may concern:
 - Employment. As a study of McKinsey Global Institute [51] says, “advances in AI and robotics will have a drastic effect on everyday working lives, comparable to the shift away from agricultural societies during the Industrial Revolution. In the US alone, between 39 and 73 million jobs stand to be automated — making up around a third of the total workforce.” Employers currently working in car market (see [22] and [23]), from selling to driving (public and private transport services), could be re-employed in other activities, jobs could be saved thanks to other technology improvement (e.g. in connectivity and communications systems) [24].
 - Accessibility especially for impaired and elderly people, there a lot of studies such as [19], [20], [21].
- Economy. New business models [16] can arise thanks to vehicle automation, such as: entertainment, information, shopping, work, communication, and so on ([17]). These businesses could affect passengers or even goods. For example, a project deployed by “Ford motor company” and “Domino’s Pizza” to delivery pizzas with automated vehicles [5].

There are also several other impacts nonetheless important, such as:

- Non-automated public transport should be adapted and calibrated with automated ones as a whole.
- Boundary conditions variability (atmospheric conditions, other road user speed, traffic regulations and so on) could stress vehicle sensors and blind its vision systems, for more detail see [52].
- Planning methods should consider different automated transport modes, with their usability, accessibility and performances.
- Transition time between current SAE level of automation (level 3) to full automation (level 5) will requires decades, meanwhile it will need some adaptations that should be upgraded by time.
- Social, as labour union agreements with all workers categories involved.

Electric cars and automation are important, but they will not change much about how we move throughout our cities and could even make traffic congestion worse.

The innovative transport proposed requires a new methodology of designing to consider:

- 1) Safety standards of automated driving;
- 2) Highlight hazardous locations for automated driving in road network;
- 3) Selection of corridors for automated driving;
- 4) Driving cycle design for automated vehicle inside corridors for a comfortably ride;
- 5) Vehicle choice and fleet dimensioning;
- 6) Energy needs for electric vehicles;
- 7) Position, choice and design of charging infrastructure;
- 8) Integration of others transport services even non-automated, since their planning and designing.

4. Design methodology of an innovative transport systems

Transit network design has a vast literature corpus, there are many books and theories in transportation system design which treat in depth how to design a traditional system, whether “Frequency” models (see [53], [54], [55], [56] and [57]) or “On demand” models ([58], [59], [60], [61], [62] and [63]).

They include the design of route layouts and the determination of associated operational characteristics such as frequencies and rolling stock types.

It is common practice to divide the planning process into strategic, tactical and operational decisions. Scientific literature on transit network design typically deals with strategic decisions and focuses on the problems of design of routes, although the choice of the size and types of the rolling stock is a very relevant issue for the strategic planning, as it affects both costs and performances of the transit system.

As widely described in [64] most travel demand models are based on the following fundamental assumptions:

- People have needs which require movements. Planning and performing a movement requires decisions where individuals select from a set of alternatives. They assess each alternative and chose the alternative which they believe is optimal, for example maximizing their personal utility.
- The perceived utility of an alternative is influenced by information available, that can be incomplete.
- Individual choices can influence the state of the transport network.
- The travel demand and the network are in a steady state over a long time period. It permits a learning process where individuals can collect information on the traffic state and adapt their choices which finally leads to an equilibrium state. In this state the travellers stick to their choices so that the traffic state and the resulting utility of alternatives is constant.
- Real time traveller information systems can improve the level of information and influence choices.

So, design methodology of current transportation system, as four-step model, includes these four sub-models:

- Trip generation models determine the number of trips generated from each origin and attracted from each destination;
- Trip distribution models determine the number of trips between origin and destination;
- Modal-split models determine for each origin-destination pair (or od-pair) the number of trips using mode
- Route choice or assignment models determine the number of trips on route connecting an origin zone to a destination zone by each mode.

This is the traditional approach to design of transport systems, with recent improvements and opportunity of movements, enabled by intermodality with sharing private/public transport models and by new ICT technologies there is a necessity of improving designing methods.

Frost & Sullivan [65] has revealed predictions that demonstrate how multimodality and inter-modality are expected to accelerate the demand-responsive transit (DRT) market from \$2.8 billion in 2017 to \$551.61 billion in 2030, at a compound annual growth rate (CAGR) of 50.3 per cent.

Moreover, there come out on top new transport systems (Figure 25) in the field of shared mobility, systems that have no predetermined designing procedure. These new systems as Car Sharing (with different declination) and Ride Sharing are enabling a new disruptive smart mobility [66].

Shared Mobility

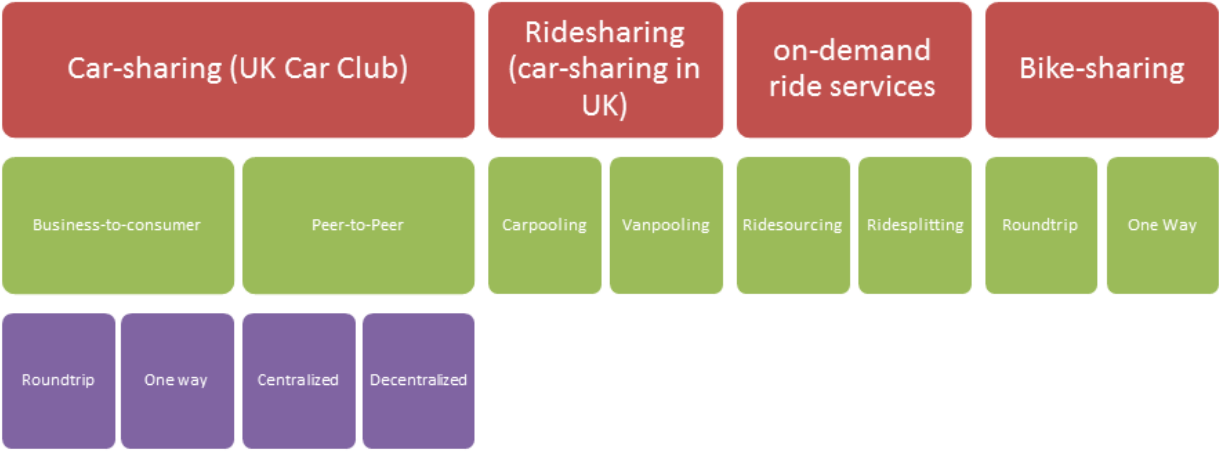


Figure 25 Sharing mobility models. Source [67]

The global smart transportation market size was valued at USD 56.25 billion in 2016, expanding at a CAGR of 22.5% over the forecast period (Figure 26). The primary factor responsible for market growth is the increasing interest of governments in building smart cities. This is anticipated to drive its demand as it is an integral part of smart city projects.



Figure 26 North America smart transportation market size. Source [68]

There are many companies that promote these new models of transport, for example all car-sharing platforms (from Car2Go to Enjoy and so on) or the ride-sharing ones (as Uber and Lyft) shared a rising part of transport demand in cities (Lyft market share up 8% among business travellers). A recent study by Roland Berger Strategy Consultants has shown, for the four most popular services (car sharing, ride sharing, bike sharing and Shared parking), annual growth rates between 20% and 35% and revenue forecasts from 2 to 6 billion dollars for 2020.

Furthermore, the advent of the Internet of Things (IoT) and artificial intelligence (AI) will also be playing a major role in popularizing smart transport, extending its reach across the masses [69].

Figure 27 shows unitary costs for different modes of transport, the innovative transport system can be placed in following graph before “tram” curve, partially overlapped with bus curve accordingly with capacity of transport ranging from 1 000 pax/h to 9 000 pax/h (for 8 h/day it means from 8 000 to 72 000 pax/day).

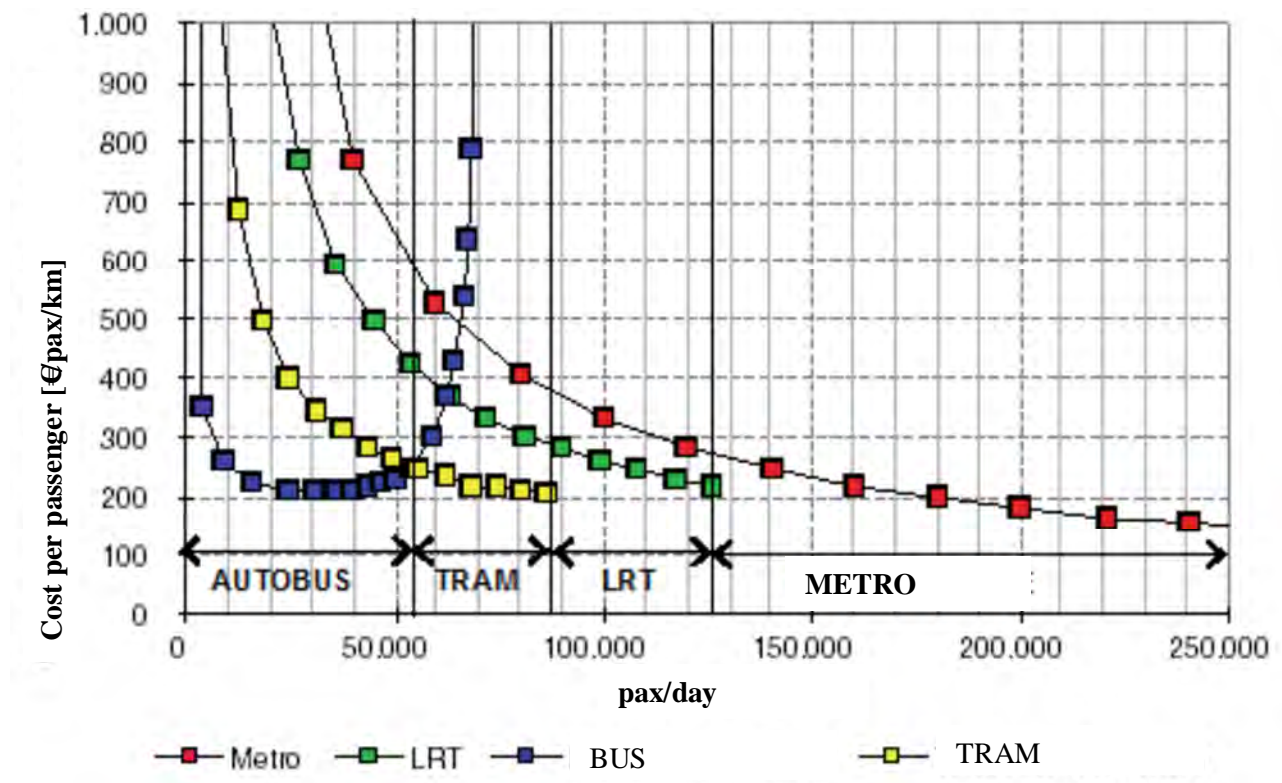


Figure 27 Costs per passenger*kilometer for different modes of transport [56]

So there are other needs that require new design methodology, for example:

- Corridor identification and choice for automated vehicles
- Simulation techniques for automated road transportation system in order to evaluate their impacts
- Risk assessments for urban environment and locationing of safety issues for road users belonging to automated corridors
- Energy needs evaluation through simulation, including newest electric transport systems and charging infrastructures
- Fleet dimensioning with variable vehicle capacity

All those requirements suggest to re-think design methodologies with a new point of view. So, current dissertation proposes a new methodology, based on traditional ones, including some new features, described in following paragraphs.

4.1. Methodology definition

Methodology proposed here aims to design a transport offer of an innovative public transportation system with a given demand. The character innovative comes from use of electric and automated vehicles on corridors.

It shares some ideas of CityMobil2 (CM2) project and partly developed in [70] and [7], it starts from safety standards that belong to railway field.

In fact, the segregated railway signalling and braking model (BWS) allows to reach a higher level of safety, CM2 applies this safety concept to road, adopting a dedicated lane instead of a segregated one, and uses sensors to detect something unexpected in a predetermined trajectory and its surroundings.

Avoiding segregation is one of the challenges won by CM2. Due to its costs and building complexity in urban areas, CM2 chose to use existent road infrastructure in mixed traffic condition and when conditions are too hazardous, the automated vehicle must slow down before arriving there.

CM2 adopts some measures for traffic calming, hazard mitigation and to control some awkward points (i.e. static sensors focus on some cars or pedestrians' crossings).

This methodology, as the one of CM2, can be applied to each city with any existent transport infrastructure and transport service, it is also compatible with any smaller city, obviously it fits easily to little cities, that have less alternative of transport and only a few options for going from A to B. When city dimension increases, it could be necessary to do some adaptations and problem reduction.

It has to be carefully applied to large cities, because urban network complexity, variability of transport needs (with high volumes), existent transport services, even mass transit as metro or railway (regional and or at national level), airports and so on, make very difficult to represent transport demand precisely. In some cases, there could be other policies and social reasons to push a specific system and these reasons are not considered herein.

The methodology uses a set of OD matrixes independently from their size and shape, they can be homogenous or heterogenous, with a preferable direction or not. But the goal of this methodology is to solve first/last mile problems by adopting automation, so it was focused on daily commuting trips.

Moreover, it can be applied both many-to-one (MTOP) and many-to-many (MTMP) problems indiscriminately, but as traditional transportation system designing the first one is easier to solve, mostly the MTMP can be simplified with two MTOP and a mass transport (with two modal interchange) that link them.

Before explaining the methodology, it is necessary to summarize some definitions (as defined in [71]):

- **Corridor.** A sequence of road arcs where a vehicle can drive itself, they are determined with a specific procedure (see § 4.4.1).
- **Itinerary.** Route connecting each OD couple, composed of a series of paths, generated with a dedicated algorithm and for which the duration in time and length are defined;
- **Path.** Set of continuous road graph arcs composing the itinerary, including intermediate and terminal nodes;
- **Routing.** Path scheduling, with defined start-and-stop time (intermediate and final stops);
- **Pool.** Group of people using the same vehicle during a single routing. They can board the vehicle in different times and/or places. For example, a vehicle with a route planned from the point A to point B starts its route in A, then it reaches two intermediate points C and D to pick up some users, then it goes to the destination B and deliveries all the users previously picked up.
- **Pick-up/delivery time.** Time spent at the stops for pick-up and delivery the passengers into the vehicle.
- **Detour time.** Estimated time to be spent for each intermediate stop (other than for picking up and delivering people).
- **Maximum vehicle capacity.** Number of places in a vehicle and maximum allowable people for a pool. It is the core parameter of the fleet dimensioning (see next section 2.6) and it has to be adapted if during the request list generation many trips happened simultaneously at the same time and/or in the same place.

However, the increasing or decreasing vehicle capacity has to consider other linked variables, such as vehicle costs, possible congestion generated in those paths with highly concentrated requests, people using the vehicles during the peak hours.

Figure 28 shows the process of methodology in UML (Unified Modelling Language), it is divided in six phases:

- 1) Parameters and input data
- 2) Itinerary analysis and corridors identification
- 3) Corridor selection and speed profile generation
- 4) Vehicle choice and fleet dimensioning
- 5) Electric traction needs and specifications
- 6) Results evaluation

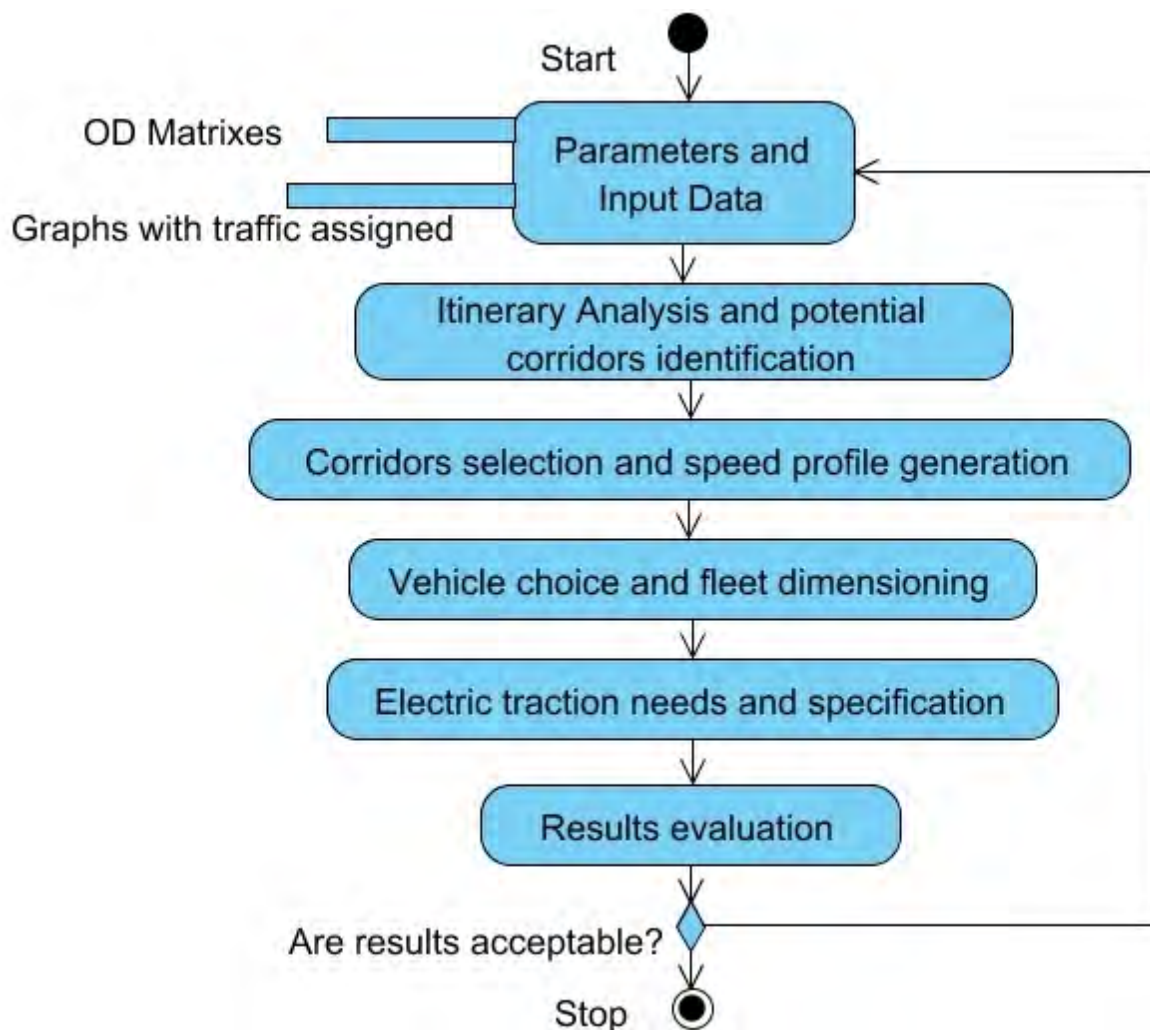


Figure 28 Process of the methodology

All steps could be evaluated several times, with an iterative process in order to adjust specific parameters and enlarge them up to acceptance limit, if necessary. The last step is required to change some parameter and restart the methodology, if some conditions aren't fulfilled.

Each step is described as follows.

4.2. Parameters and input data

The first step allows us to estimate the number of potential users of the system, and to locate them inside the different zones to be served, it is not a pre-defined format for input data. In this study, it was used a worksheet to collect data and to do some tests.

The input activity concerns the collection of these data:

- I. OD matrixes, with time distribution of demand;
- II. Road graphs and other transport (invariant infrastructure included);
- III. Automated vehicle parameters and general parameters of simulation;

Each one is described in the following paragraphs.

4.2.1. Transport demand matrixes

One of the crucial issues in transport modelling is matrixes dimension, or rather an area of study divided into zones and nodes (number of origins and destinations). An ideal point of view is the larger they are, the more realistic is the demand representation. Besides, higher numbers of nodes bring high computational costs, then how many zones and nodes are necessary?

Main criteria to divide the area of study into zones (see [72], [55] and [73]) are:

- Zone dimension, at least following census section (ISTAT) dimension or through by fusion of one or more sections;
- Each zone has its own node of origin/destination;
- Which transport mode it wants to analyse.

In most cases, it is useless to have high precisions and have a lot of adjacent nodes, especially with public transport modelling system.

While the concept proposed in chapter § 2, represents mobility from home door to door of destination, it will be better to have higher nodes, but it is necessary to find a trade-off with computing time.

Therefore, this input phase can be divided in two sub-steps:

1. Demand identification;
2. OD matrix definition (based on demand data).

Different techniques can be adopted for the identification of the demand to serve. For example, it could be estimated through specific surveys, like those described in [74] and [75]. As an alternative, the demand could come from transport census data [76], where available, or it could be obtained through a mixed approach (surveys complementing transport census data).

Once the demand has been estimated, a preliminary analysis should be realised to have a first rough spatial classification of the user trips, considering the potential site where the ARTS has to be operated. Moreover, there is often a big city nearby, a potential site that could become an attractive pole from transport. As shown in Table 1, they should be divided according to three main categories: inner, in-going and out-going.

Such analysis allows to simplify the OD matrix generation and, if requested for computations, to divide it into three different matrixes, one per category. Furthermore, in case of demand estimation through surveys, it could be useful to cross-compare the results with census data (where available) to verify if the data obtained are representative of the three different trip categories.

In the OD matrix definition sub-step, all the transport modes used in the potential site should be included [72]. The size of the OD matrix in terms of number of nodes (i.e. origins and destinations) directly depends on the technique used for estimating the demand. The larger the number of nodes is, the more complex the problem (and the associated travel costs).

For example, the Italian census agency (ISTAT) provides a commuting matrix including all trips between each Italian Municipality, divided per transport mean and travel reason. The census data can represent a good starting point to estimate the transport demand and to generate OD matrix when they are not available in other ways.

Table 1 Trip categories

Trip classes		Description
A	Inner	People living in the potential site and travelling daily inside.
B	Out-going	People living in the potential site and daily travelling outside. They were divided into two subcategories: - B1 are those trips from potential site to attractive pole - B2 are those trips from potential site to other cities (different from attractive pole)
C	In-going	People not living in the potential site and coming daily from outside. They were divided into two subcategories: - C1 are those trips from attractive pole to potential site - C2 are those trips from other cities (different from attractive pole) to potential site

Table 2 shows the commuting matrix provided by ISTAT ([77]) with mode of transport divisions, it focuses on commuting trips from Monterotondo to Rome and vice versa. Rome is the attraction pole for Monterotondo, in fact it has a high volume of trips. This table had required an intermediate step of elaboration to manage big data provided by ISTAT.

Table 2 Commuting matrix of Monterotondo divided by modes of transport

Cat.	Train	Car	Bus urb./ extraurb	Motorcycle	On foot	TOTAL
A	0	823	6279	3504	0	10606
B1 (Rome)	3220	281	4561	160	3220	8222
B2 (Others)	158	199	1999	14	158	2370
C1 (Rome)	196	72	935	1	196	1204
C2 (Others)	182	2105	4047	69	182	6403
TOTAL	3756	3480	17821	3749	28806	3756

Figure 29 shows a map with ISTAT data for Grosseto (a province of Tuscany, Italy) it had 78730 inhabitants (2011 census) divided by census section, inside each section is reported the number of them, sections are coloured accordingly with number of inhabitants (see legend) in figure.

Figure 30 and Figure 31 report, for each census section of Grosseto, the number of inner and outer trips respectively, the maps are coloured accordingly with ISTAT data (see legends in each figure).

The blue lines in those figures represent railway track.

ISTAT data, partially shown in following figures, allow to build OD matrixes with an “all or nothing” assigning and by adoption of distribution models (i.e. gravitational, bi-proportional, etc...).

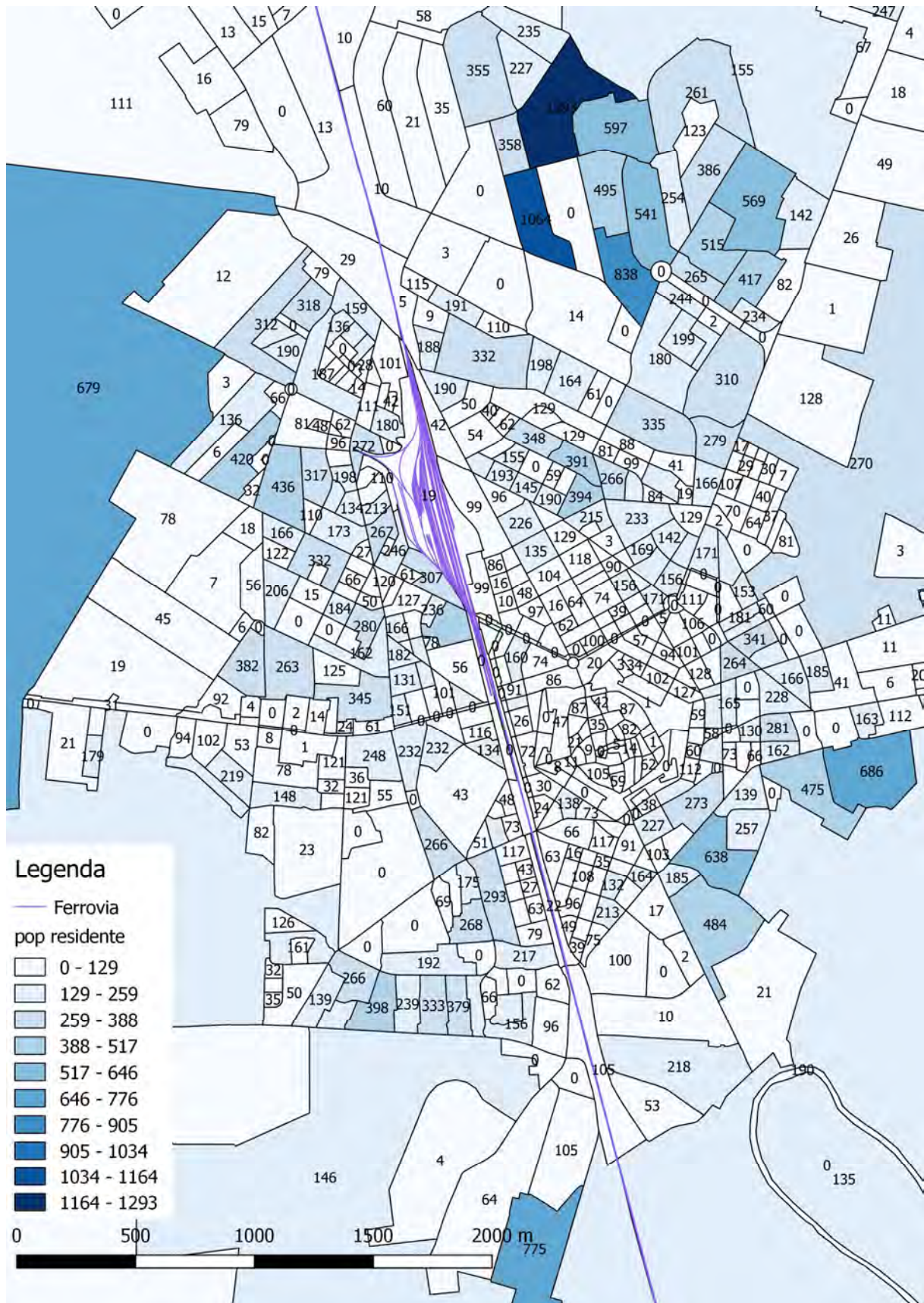


Figure 29 Inhabitants of Grosseto divided by census section

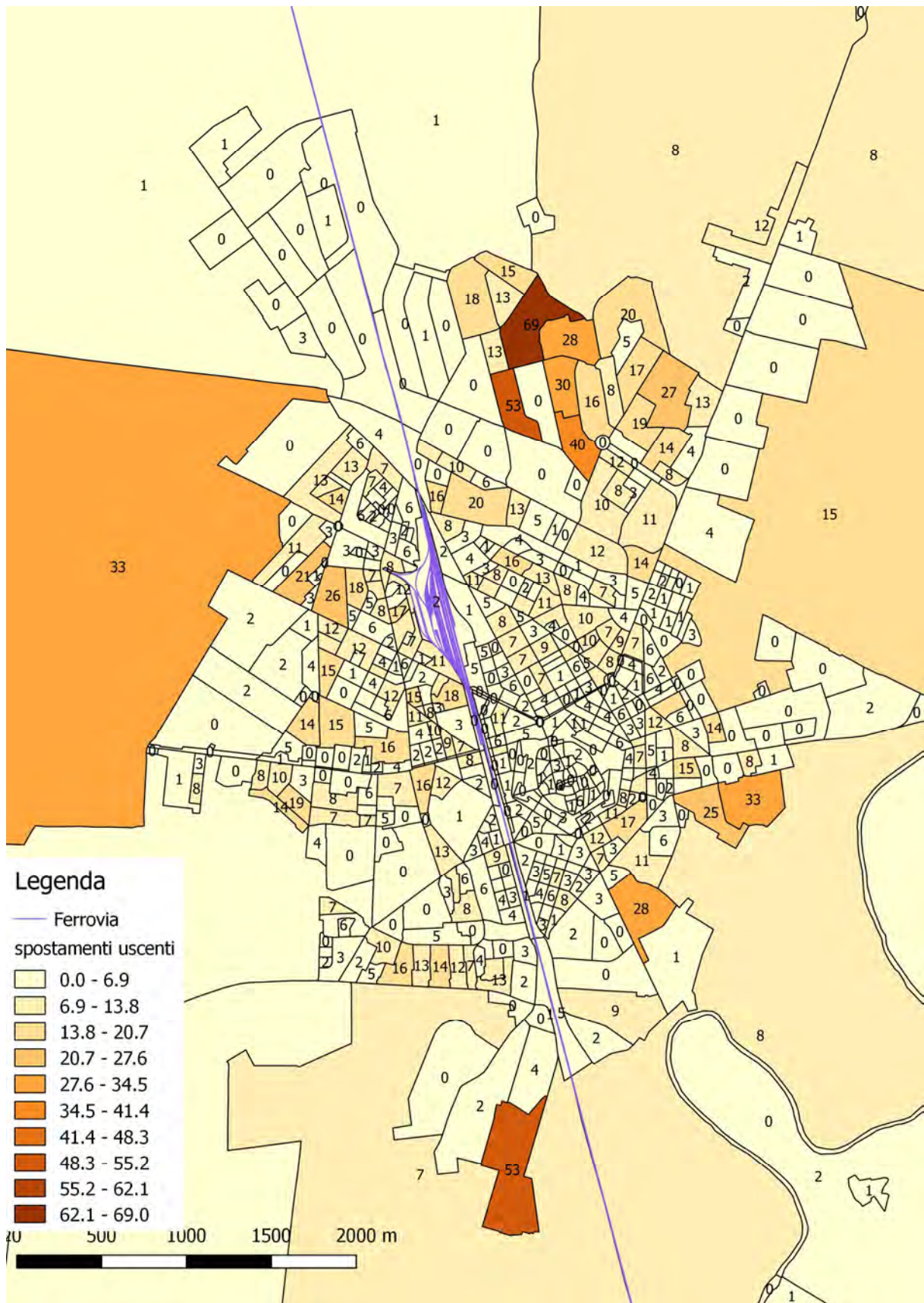


Figure 30 Out-going trips of Grosseto divided by census section

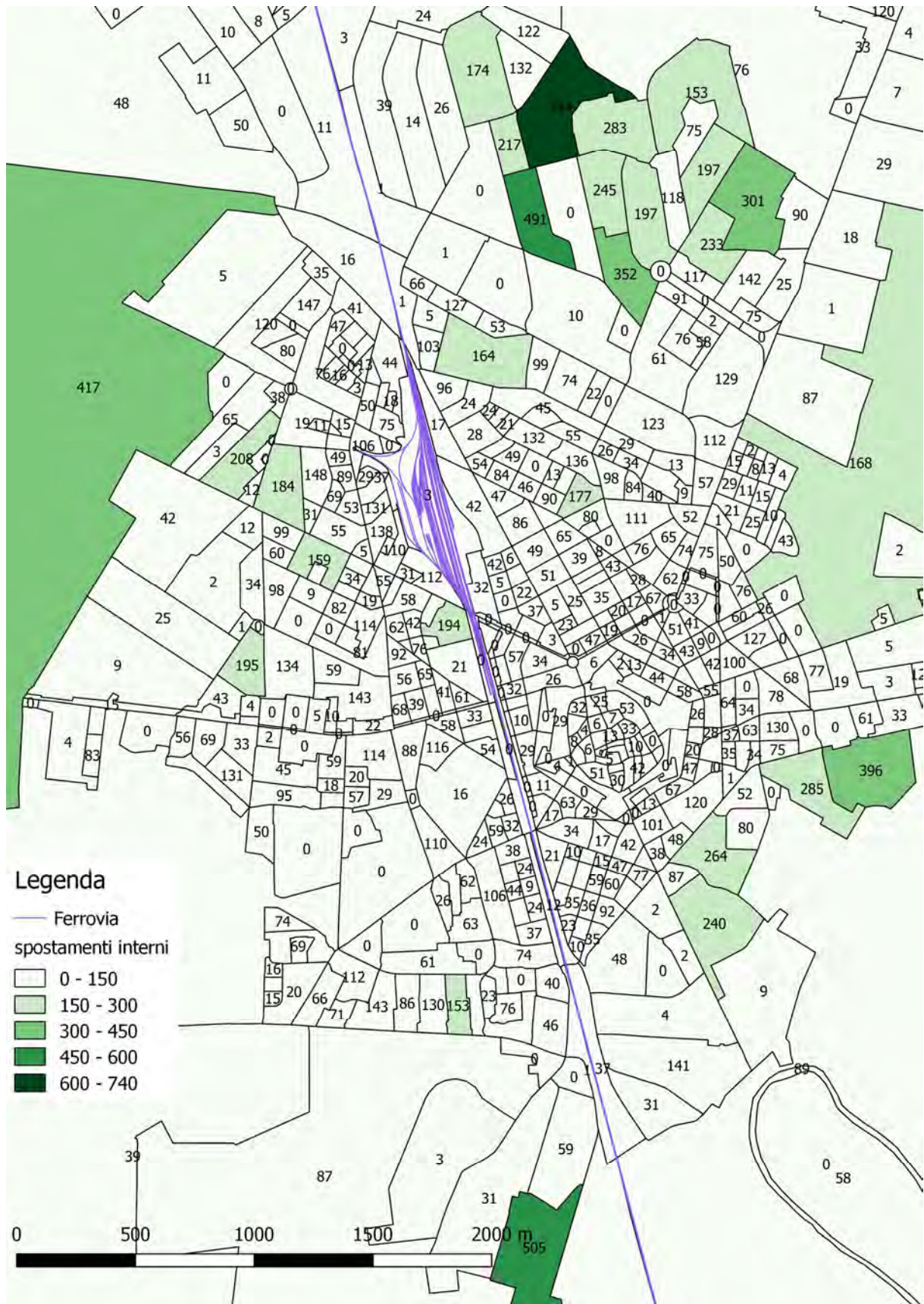


Figure 31 Inner trips of Grosseto divided by census section

4.2.2. Road and invariant infrastructures graphs with a traffic assigned

The second source of input are graphs concerning road and invariant infrastructures.

Road graphs must have a traffic assigned to determine the fastest path from A to B (Figure 32), traffic allows to determine effective travel time.

Invariant infrastructure graphs are needed in order to know where are stops with high density of ridership and how to build transport demand matrixes, they allow to build less complex sub-matrixes and divide a wider transport service into many parts of transport with simpler matrixes (as monodirectional).

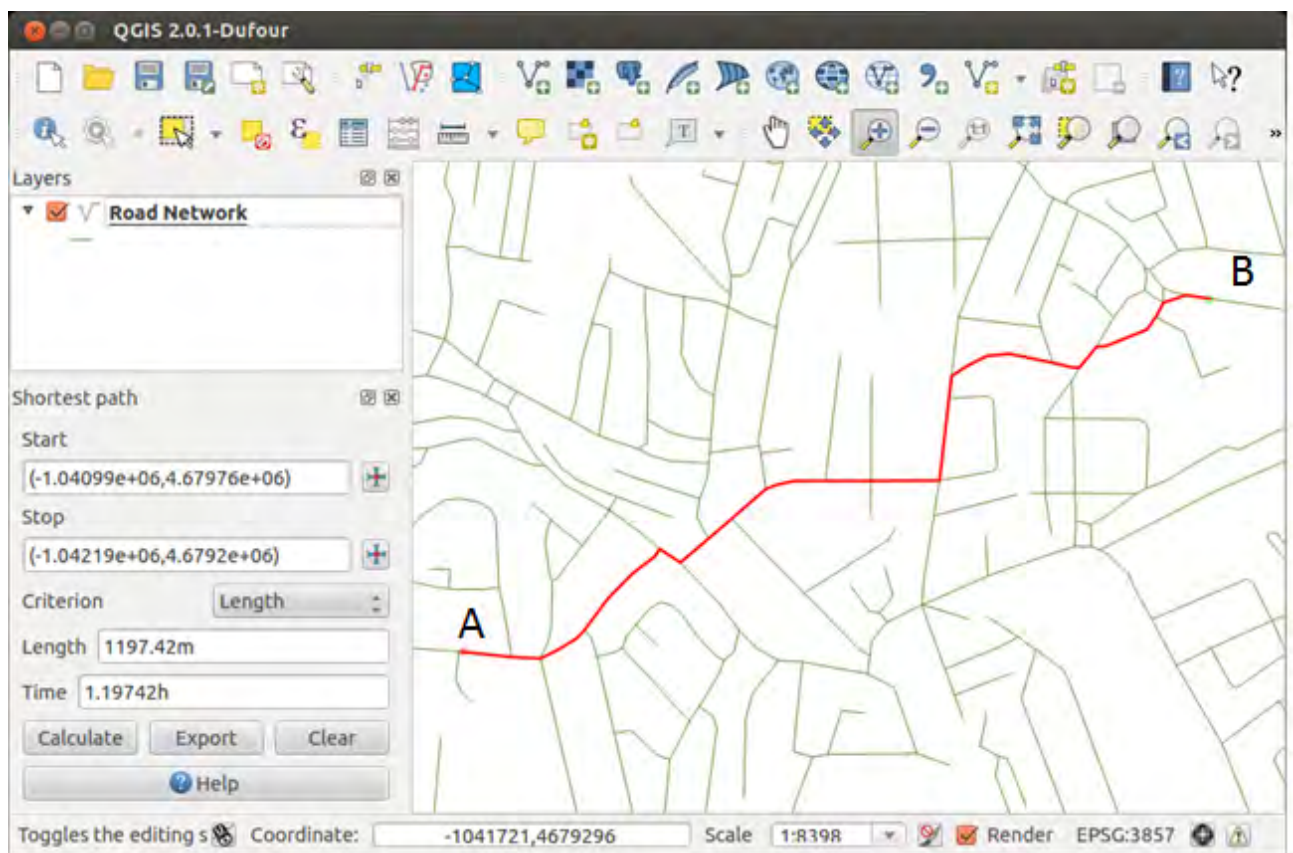


Figure 32 A road graph visualized in the software QGIS

4.2.3. Automated vehicle and general parameters of simulation

The analysis can use the same trip categories reported in Table 1, inner, out-going and in-going, and is based on an in-depth investigation of the lists of requests.

These parameters should be set to a “desired value” (i.e. time tolerances) and only when results obtained are not sufficient they can be changed up to the limit of acceptance. The parameters are divided into two categories, belonging to different fields: automated vehicles and simulation procedure.

Automated vehicle parameter concerns:

- MaxDec Brake performance (maximum emergency deceleration), measured in m/s^2
- MaxAcc Maximum acceleration, measured in m/s^2
- MaxJ Maximum jerk (for a comfort acceleration and deceleration), measured in m/s^3
- MaxSp Maximum speed, measured in m/s
- S Number of seats

There are some parameters regarding simulation procedure:

- N Set of calls “ n_i ”
- I Set of Itineraries “ i_i ”
- C Set of Corridors “ c_i ”
- Q Number of itineraries “ q_i ” that haven’t a corridor assigned
- T_{ct} Time tolerance for call request time
- T_p Passenger get-in time
- T_d Time wasted for detouring (deviation from main itinerary to reach another passenger)
- c_{tt} Time Tolerance for transit in same Corridor
- DTT Direct Travel Time
- TTT Total Travel Time (could be greater than TDTT)
- PD Number of vehicles forming a platoon
- N_C Number of vehicles which share same road arcs at same time
- NMC Number of Modal changes
- NAMC Number of Acceptable intermediate modal changes
- a_{MC} Weight Coefficient for Modal Change

The coefficient a_{MC} can be zero when it isn’t important how many MC there are, for example in case of full automation and with low transport demand, vehicle could take corridors and drive itself without any interruption, stops, modal change and so on (in this case a_{MC} is set to zero).

Moreover, there are a few parameters concerning corridor selection and electric traction systems that will be described in detail in respective next paragraphs, due to complexity of their considerations.

4.3. Itinerary analysis and corridors identification

In order to analyse itineraries for all OD couples, it is required a call list generation. A call list can be:

- Real measured lists (survey or counting)
- Generated with assigning models
- Generated with random assigning based on a defined distribution

The distribution adopted for random assigning could be a gaussian or, for example, a real distribution measured at train station. During the testing of the methodology, some call lists with random assigning, based on people arriving distribution at train station of Monterotondo scalo, are generated (see Figure 33).

Abscissa of Figure 33 represents leaving time of trains.

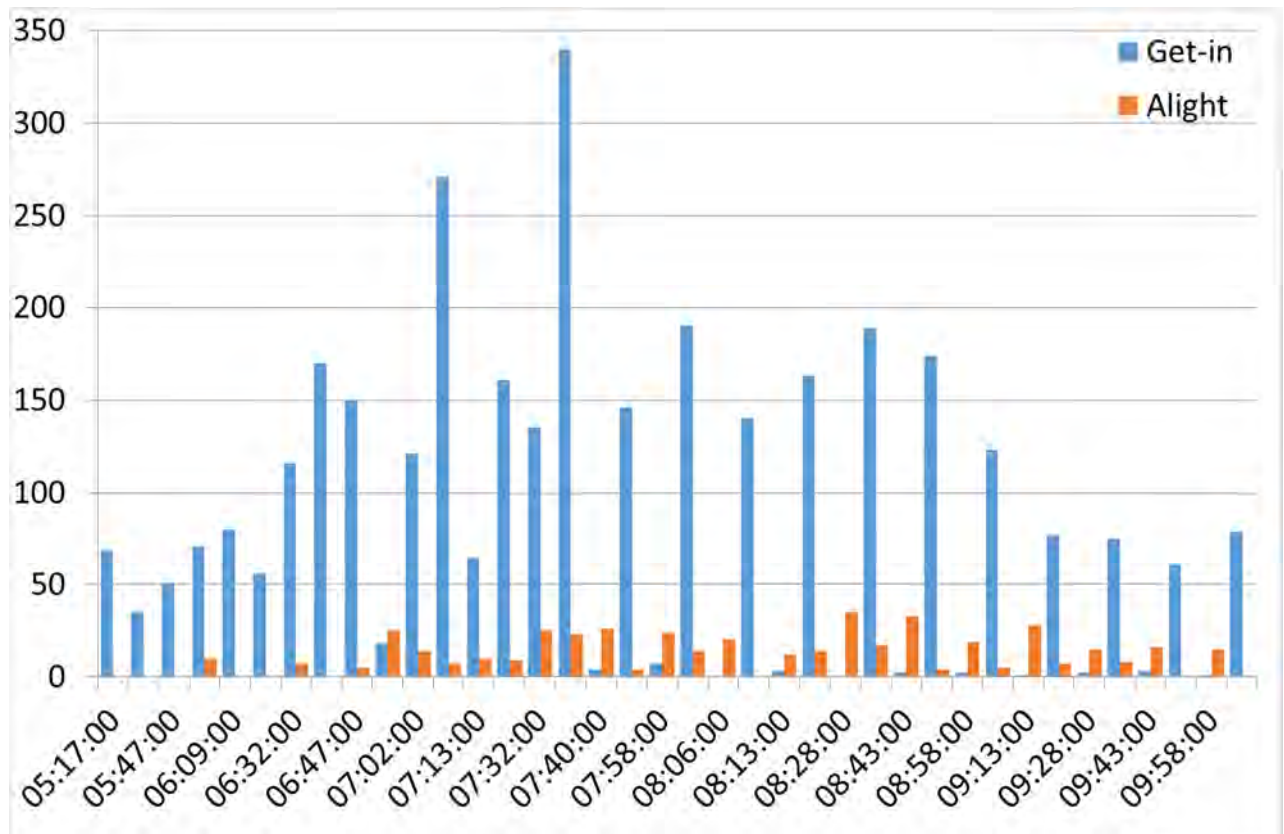


Figure 33 Time distribution of people at Monterotondo station

Table 3 shows a call list generated with random time assigning.

Table 3 A part of calls list for morning trips from Monterotondo to Rome

O	D	No. people	6:15	6:24	6:30	6:46	7:05	7:12	7:25	7:32	7:37	8:08	8:33	9:02
1	14	22	1	1	2	3	4	3		4	1		2	1
2	14	29	4		1		1	5	1	6	4		3	3
3	14	16	1	1	1	2	4	3			1	1	2	
4	14	21	1	1	4	3		2	5	3				1
5	14	15	1	2		1	2	3		1	1	2	1	
6	14	24	2	2			4	5	2	4	1		1	3
7	14	26			1	2	4	2	4	3	2	1	2	4
8	14	10	1	1		1		2			2		2	
9	14	19	2			1	2	1	4		2	1	2	3
10	14	24	3	1		1	4	4	4	2	2	1	1	1
11	14	22	1	1		2	2		1	5	6	1		2
12	14	29	4		3	4	3	2	3	4	1	1	3	1
13	14	25	3	3	3	2	2	1		1	2	3	4	1

The itinerary analysis provides trip length, trip duration and road arcs involved for each OD couple pf the OD matrixes, and it is referred to a requested time.

An itinerary could be found by applying a minimum path algorithm on the road graph with a traffic assigned. The candidate uses a common web service provided by Google Maps, for example the two

API used are Distance Matrix API [78] and Direction API [79], these two APIs allow to query Google Map servers with five main inputs:

- GPS coordinates of Origin (or address)
- GPS coordinates of Destination (or address)
- Starting time (or arrival time)
- Mode of transport (driving, public transports, walking or bicycling)
- Restriction (i.e. avoiding ferries or traffic limited zones)

Distance Matrix API returns distance from A to B and time required, whereas Directions API returns also road directions (Figure 34), turns and it includes all modes of transport. Both require a personal API key used for billing.

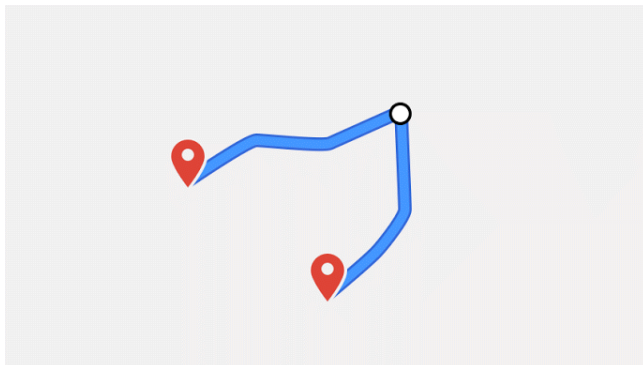


Figure 34 Google Maps itinerary obtained with an API webservice

The itinerary analysis begins to determine a set of “I” itineraries for all “N” calls listed, as each call does not have effect on transport network, and in a first hypothesis $I=N$.

Then, it follows a road arcs analysis to count how many vehicles pass in each road arcs at same time within a time tolerance.

A corridor can be defined as the set of road-connected arcs travelled more frequently than others (between all possible solutions and origin to destination itineraries). Only connected road arcs could form a corridor.

So, the road arcs analysis generates a set of corridors “C” of which at least a minimum number “Nc” of vehicles travel within a time tolerance “Tc”, there isn’t a predefined number of corridors, it depends on road local network, city dimensions and from both parameters Tc and Nc adopted.

If there isn’t any corridor, it means that parameters Tc and Nc require a fitting and it is necessary to do another iteration.

During the methodology further iterations are foreseen and this number could change.

Figure 35 shows an example of itinerary analysis for the city of Monterotondo, 30 km away from Rome. In this figure, census sections (with numbers), and the current public transport services with 4 lines (red, green, blue and sky-blue lines), are shown. There are also a few census sections highlighted in yellow, they show those sections badly covered by public transport services.

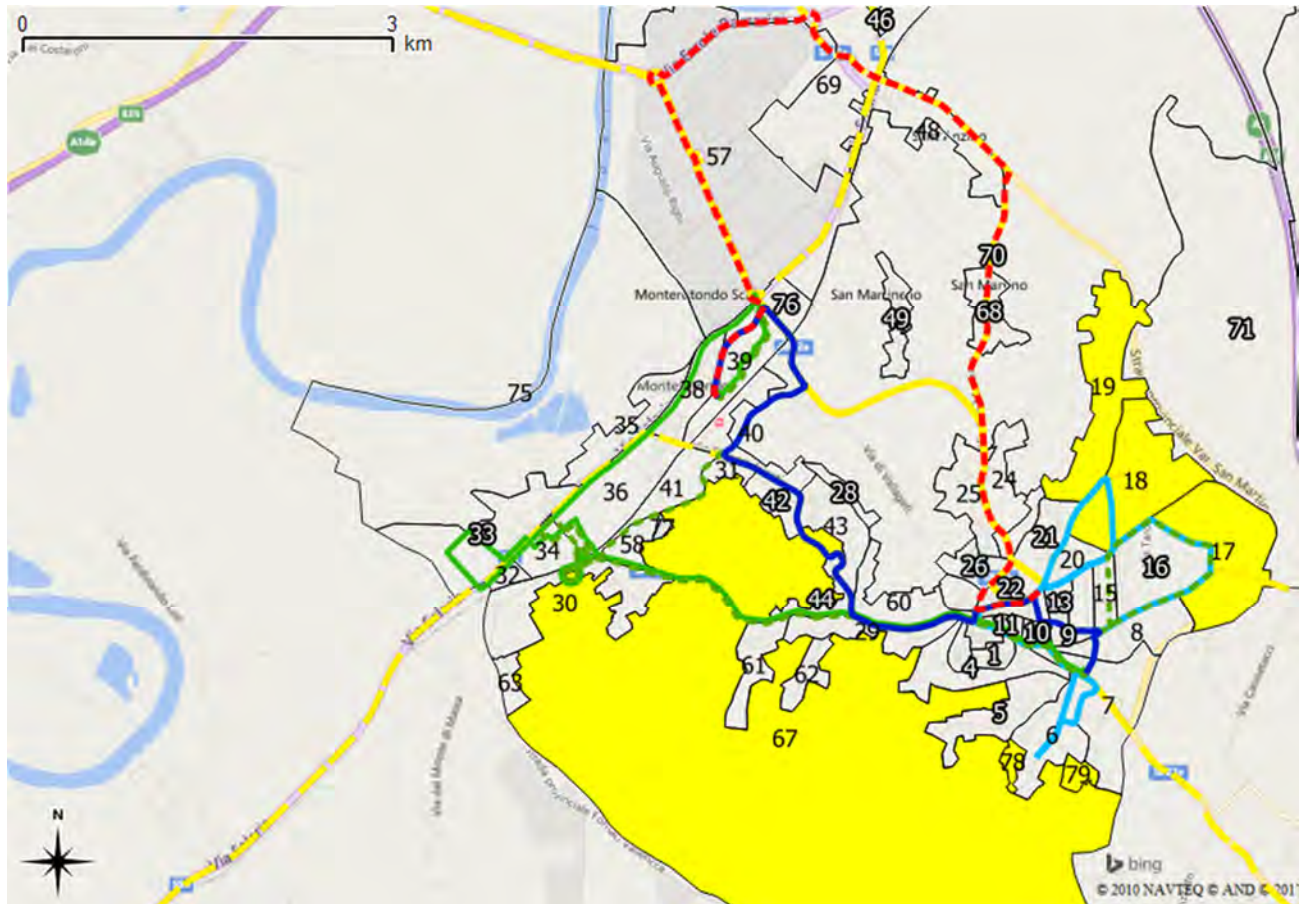


Figure 35 City of Monterotondo, Itinerary analysis

Figure 36 shows an example of corridor selection. The city of Monterotondo has at least two main corridors (Corridor 1 and Corridor 2 in blue and red colours, respectively), and up to 7 potential corridors (green dotted lines) that satisfy previous conditions.

For example, that circular corridor in city centre could be used to relocate vehicles in the centre with platooning technology.

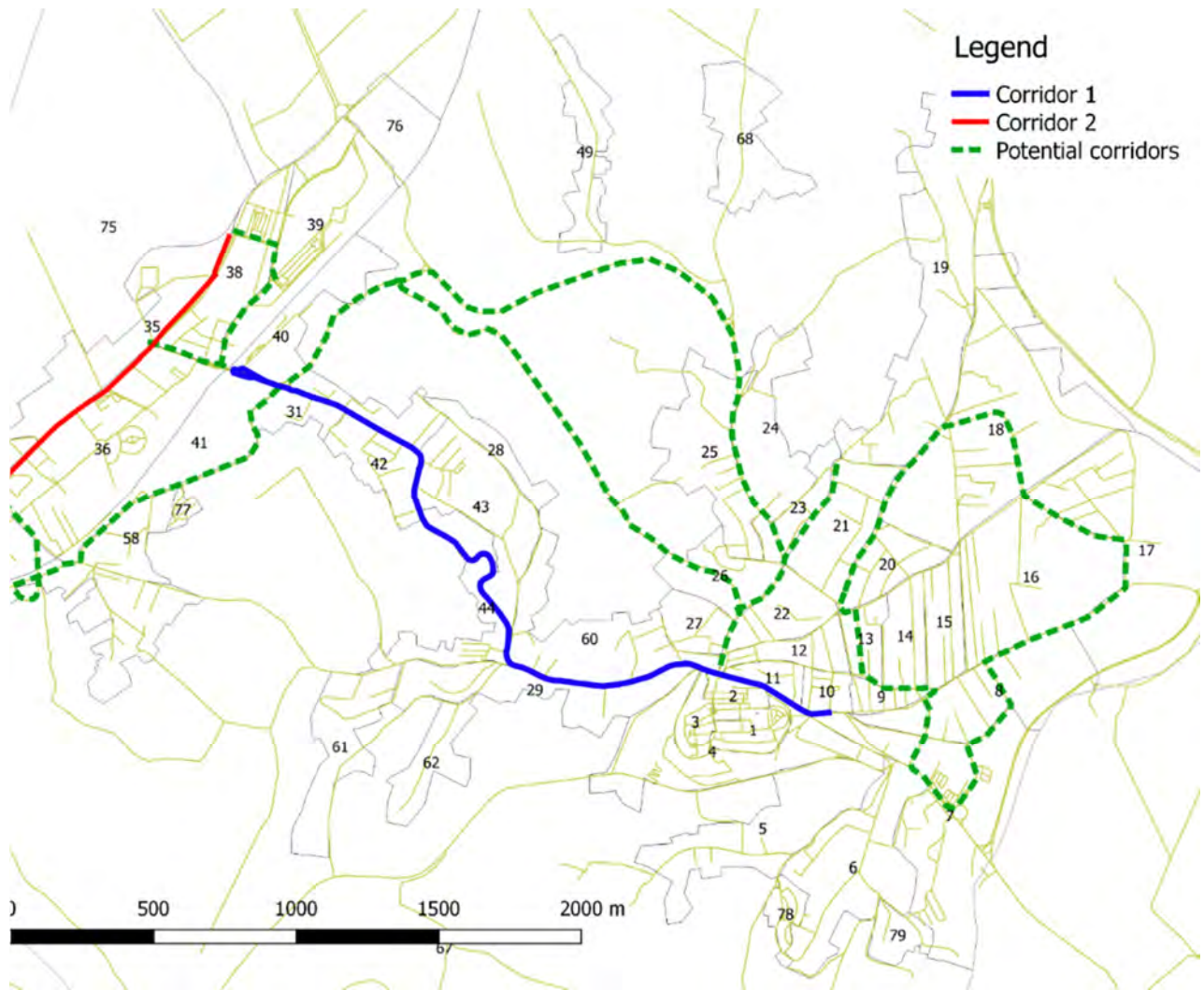


Figure 36 Potential Corridors in city of Monterotondo (Rome)

Next phase will evaluate what corridors could be avoided.

4.4. Corridor selection, speed profile generation

During the previous phase, a few potential corridors have been determined, but many of them could be useless, so why is this selection necessary?

Next, some of the reasons:

- Some corridors could be similar (i.e. they could use parallel arcs), in this case a little itinerary changing for some OD couples in order to share corridors with others, could increase global efficiency;
- The suppressed corridors could be re-used in other ways;
- Some itinerary couldn't use a corridor (due to fastest path algorithm), but if it uses the closest corridor, it could be even faster, or in time but with a great improvement in comfort and travel opportunity.

For example, an user could choose to use a corridor if she can do other tasks while vehicle drives itself; moreover, a corridor could have some advantages in high congestion roads and could allow reduction of travel time, even if travel distance increases in comparison with other paths (outside corridors)

- Fewer corridors mean lesser costs
- Computational costs
- Minor use of additional static sensors (i.e. pedestrian crossing or cycling lane crossing)
- Eventually less adaptations (traffic calming measures as bumpers, traffic lights, speed check and so on)

This phase concerns three sub-task: corridors selection, maximum speed evaluation (for each corridor) and the last one is the transport capacity evaluation.

4.4.1. Corridor selection

In order to choose corridor, a clustering algorithm (see [80]), starting from a first set of corridors generated before (see § 4.3), consists of five steps:

- 1) Starting from:
 - a. set Q , of q^i itineraries, which do not have an assigned corridor
 - b. set C , of c^i corridors (with parameters N_c and c_{it})
- 2) It tries to insert “ q_i ” and force its itineraries to pass into a “ c_i ” corridor (using the same faster path algorithm used in §4.3 but passing through the key point of corridor entrance). Corridor insertion attempts start from the most used corridor to the least used one .
- 3) When all q_i are finished, it continues with set C of corridors, it tries to change itineraries of all vehicle belonging to a c_i and force them to pass into another corridor c_j ($j \neq i$) with more usage rate, to reduce number of corridors (from C to C^R).

The deviation from main itinerary, with a direct travel time (DTT) to another one, points 2 and 3, is considerate acceptable when the both following conditions are satisfied:

- If travel time respects this inequality:

$$TTT \leq c_{TT} \cdot DTT$$

- Each deviation from a key point is considerate as intermediate modal change (NMC) only if it requires the change of vehicles:

$$NMC \leq a_{MC} \cdot NAMC$$

It could be possible that all itineraries q^i can't be deviated in any of corridors c^i , also without a little part of them.

So, in this case an adjustment of both parameters TDDT and NAMC could be possible, but due to their importance of acceptance from people, they can't be rise too much. In this case, those itineraries won't use corridors with all consequences in road transport network, which will not benefit from their deviation.

This step ends when TDDT or NAMC reach their limit, then it should be required a Cost Benefit Analysis (CBA) to compare different results. The CBA is not evaluated in this context and it is left for further development.

If we go back to Figure 36 of Monterotondo potential corridors, this analysis brings up to reduce number of corridors to first two (red and blue ones). It occurs because the first two corridors satisfy the greatest part of itineraries, the itineraries using potential corridors could deviate to the main two with little and acceptable time wasting.

4.4.2. Maximum speed profile evaluation on the corridors

This phase was developed during first and second year of PhD, it was partially published in [70] and is an improvement from [81], [82], [83].

Time to collision evaluation allows to design a safety speed profile with high level of comfort for passengers.

It begins with the concept of safety braking model, the safest is Brick Wall Stop (BWS) adopted in railway; it assumes that forerun vehicle could stop instantaneously and the safe distance between two following vehicles needs it. An exception is represented by platooning phase, vehicles following a leader are automated and connected with each other (see [84]). In this case, safety distance between vehicles depends on control systems requirements, performances, robustness and reliability.

The maximum speed profile evaluation concerns three phases: the concept of maximum allowable speed, the designing procedure of speed profiles and the Low speed points location.

4.4.2.1. Concept of maximum allowable speed

Each infrastructure and path have implicit hazards, because of their measures, shape and traffic conditions.

CM2 conceived a speed profile designed in order to minimize hazards [70]. If the vehicle trajectory crosses a pedestrian cross or cycling lane, the vehicle should decelerate just in time and proceed at low speed near the intersection, to enable vision systems. If sensors detect an unexpected obstacle close to vehicle trajectory, it allows to brake comfortably and safely avoiding any collision. The speed profile designing was done manually by technicians.

As described in [7] and in Figure 37, where there is a blind spot, the maximum allowable vehicle speed has to decrease up to a value that aims to stop vehicle with an emergency brake, if another user comes from blind spot. The maximum allowable speed depends on user speed: if the user is a pedestrian, it could move at 6 km/h and by referring to Figure 37, when he moves out of blind spot, he will collide with vehicle in 2.7 seconds, if in the blind spot there is a cyclist moving at 25 km/h, he could collide in 0.64 seconds. When vehicle arrives in this position and detects a bench that occludes vision, it should reduce speed up to 34 km/h or up to 8 km/h; if behind the bench there is a pedestrian or a cyclist, it can stop itself before collision with an emergency brake of 3.5 m/s^2 .

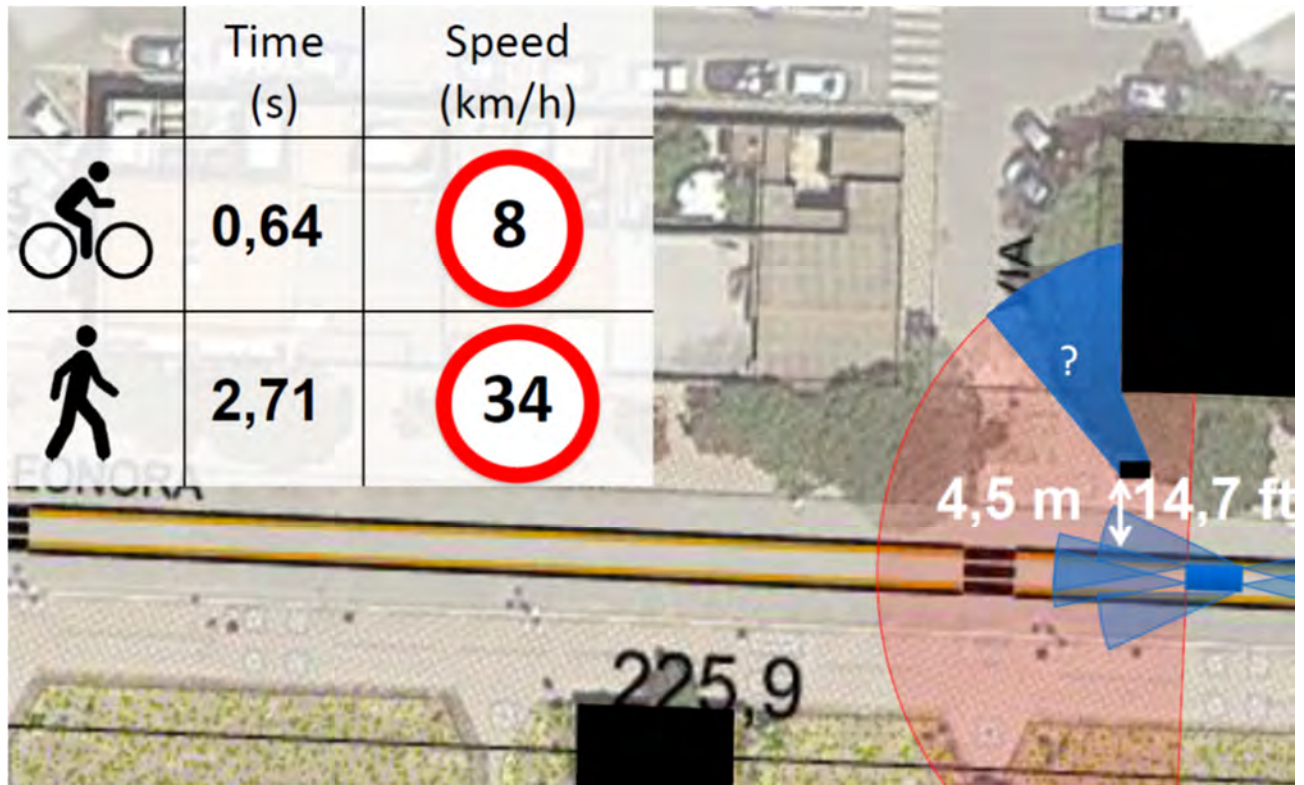


Figure 37 CM2 hazards evaluation

In this PhD study, the candidate developed a procedure to use data collected with Laser Imaging Detection And Ranging (LIDAR) sensors to build a map with distances from vehicles to obstacles for each point of the path.

4.4.2.2. Designing of vehicle speed profiles

Any vehicle operating on such lane can't see if there is someone (for example a pedestrian or a cyclist), going to cross the lane.

In order to prevent any possible collision with any user that could move behind possible obstacles in the environment, the vehicle has to choose a safe condition to avoid collision; it means to consider that any user could cross vertically (worst condition) its lane.

In this case, vehicle must decelerate up to maximum allowable speed and the methodology proposed aims to calculate it. This procedure is called "time to collision", it consists of:

- I. Other users speed knowledge
- II. Orthogonal distance measured between a possible obstacle and the vehicle trajectory
- III. Time to collision calculation
- IV. Maximum allowed speed calculation
- V. Location of the maximum allowable speed on trajectory
- VI. Speed profile generation

Other users speed knowledge

The other users speed calculation consists of a road inspection (or aerial imaging evaluation) with the purpose to know which user category (i.e. cyclist, pedestrian or car) crosses the corridor,

It also consists of maximum speed evaluation of these users, for example if there is a cycle-lane, the average speed is 13 km/h and the speed limit reach 30 km/h [85].

A bump or dedicated barrier could mitigate the maximum speed; this action has to do close to the crossing with corridor, to guarantee the action forcefulness.

For pedestrians 1 m/s can be assumed as average speed.

Orthogonal distance measured between a possible obstacle and the vehicle trajectory

The calculation of the distance between obstacles and vehicle can be done with an experimental technique or a cartography analysis.

The experimental technique consists of a data collection phase, where a vehicle equipped with LIDAR sensors scans the path around environment to collect all unmovable obstacles. Several rides are required to avoid false positives obstacles [86] due to objects and vehicle temporary parked.

Figure 38 shows the path of CityMobil2 demonstrator in Trikala (Greece), it has 2.3 km lane length with 8 stops.

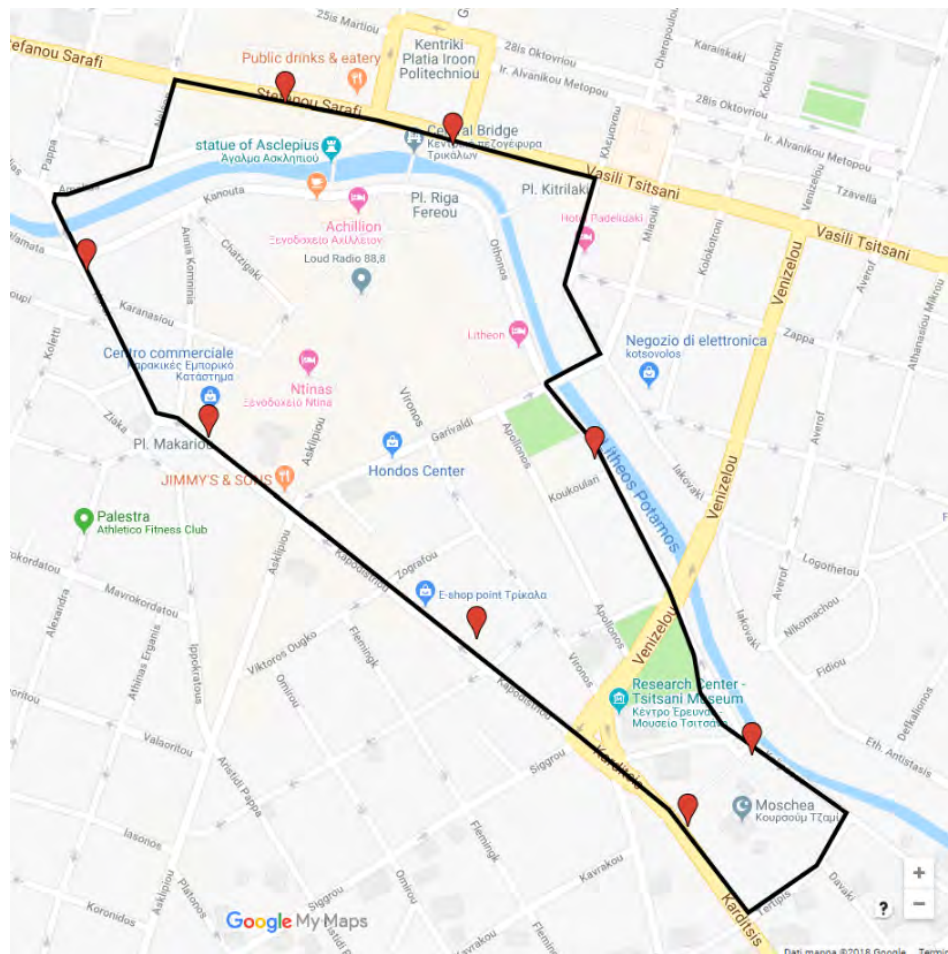


Figure 38 CM2 large demonstration: City of Trikala (Greece)

The experimental technique uses a vehicle equipped with some laser imaging detection and ranging sensors (LIDAR) that measures the distances directly on field; it measures distances between physical objects and the laser emitter. Commonly, sensors measure up to 30 meter (H) from sensor emitter with an angular range (β) of 180 degree (Figure 39 and more info at [87]); usually, the sensors are in the front of the vehicle.

Otherwise, if the direct measurement is not possible, a detailed cartography is sufficient, or aerial imaging systems to measure roads, sidewalk, buildings and all possible objects (as trees, hedges, benches, walls, hurdles, etc...) less than 30 m away from the path.

Figure 40 shows the same path with an elaboration of LIDAR data, and Figure 41 a zoomed view of it. In both figures, the blue points represent unmovable obstacles, so they represent a simplified view of the surrounding environment, as seen by automated vehicles.

Green and red points belong to vehicle trajectory, the green one means a point where maximum distance between vehicle and a closest object is over 1 meter, while if distance drop up to 1 meter the point of trajectory becomes red.

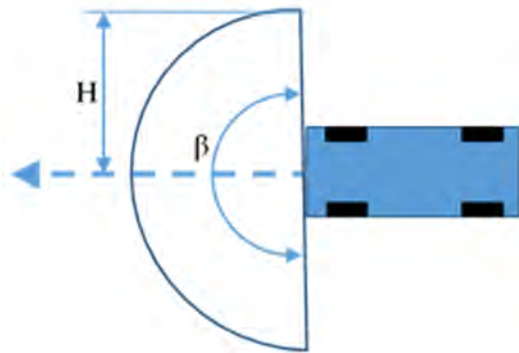


Figure 39 Vehicle measuring with LIDAR sensors

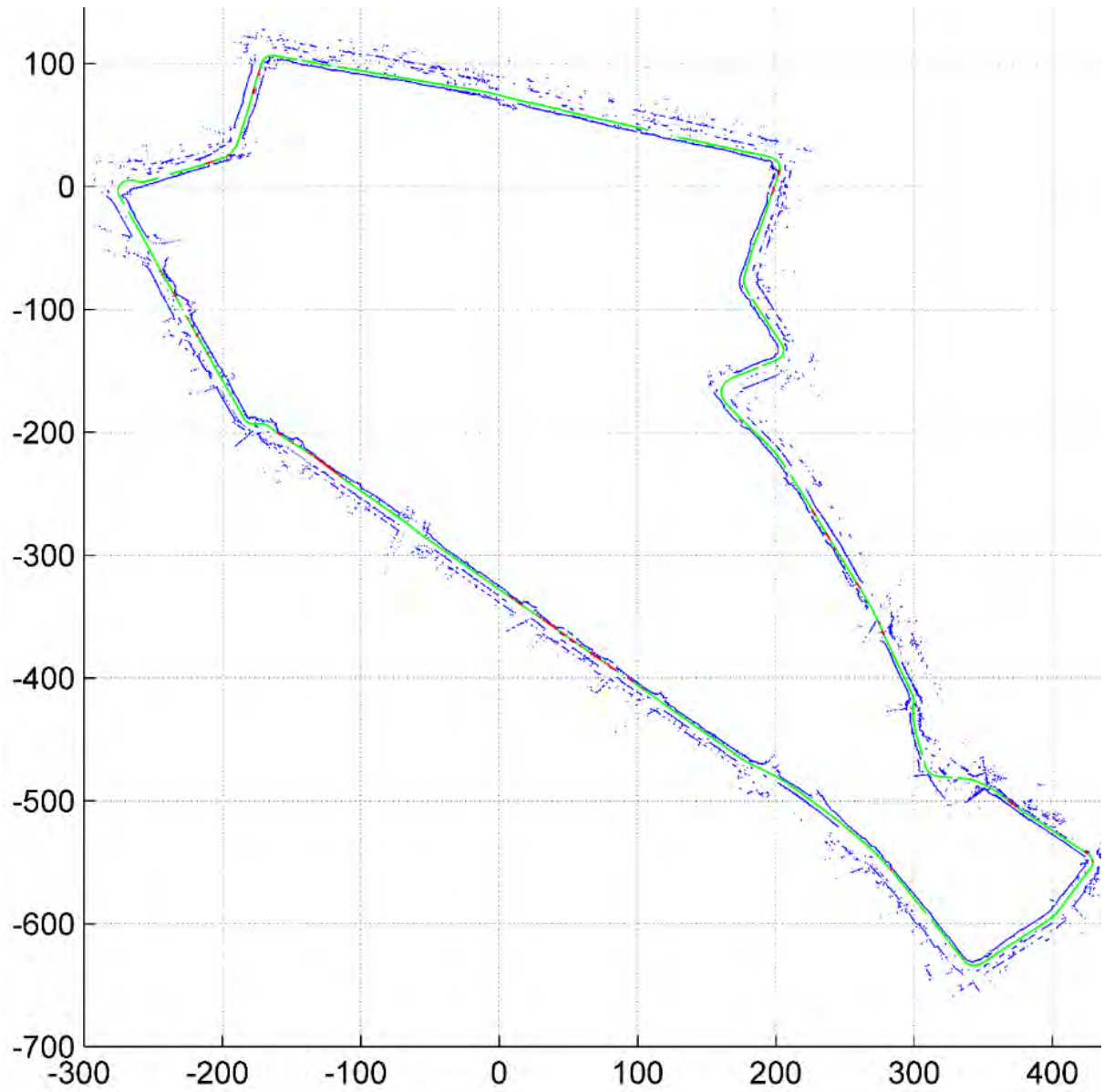


Figure 40 Elaboration of LIDAR data

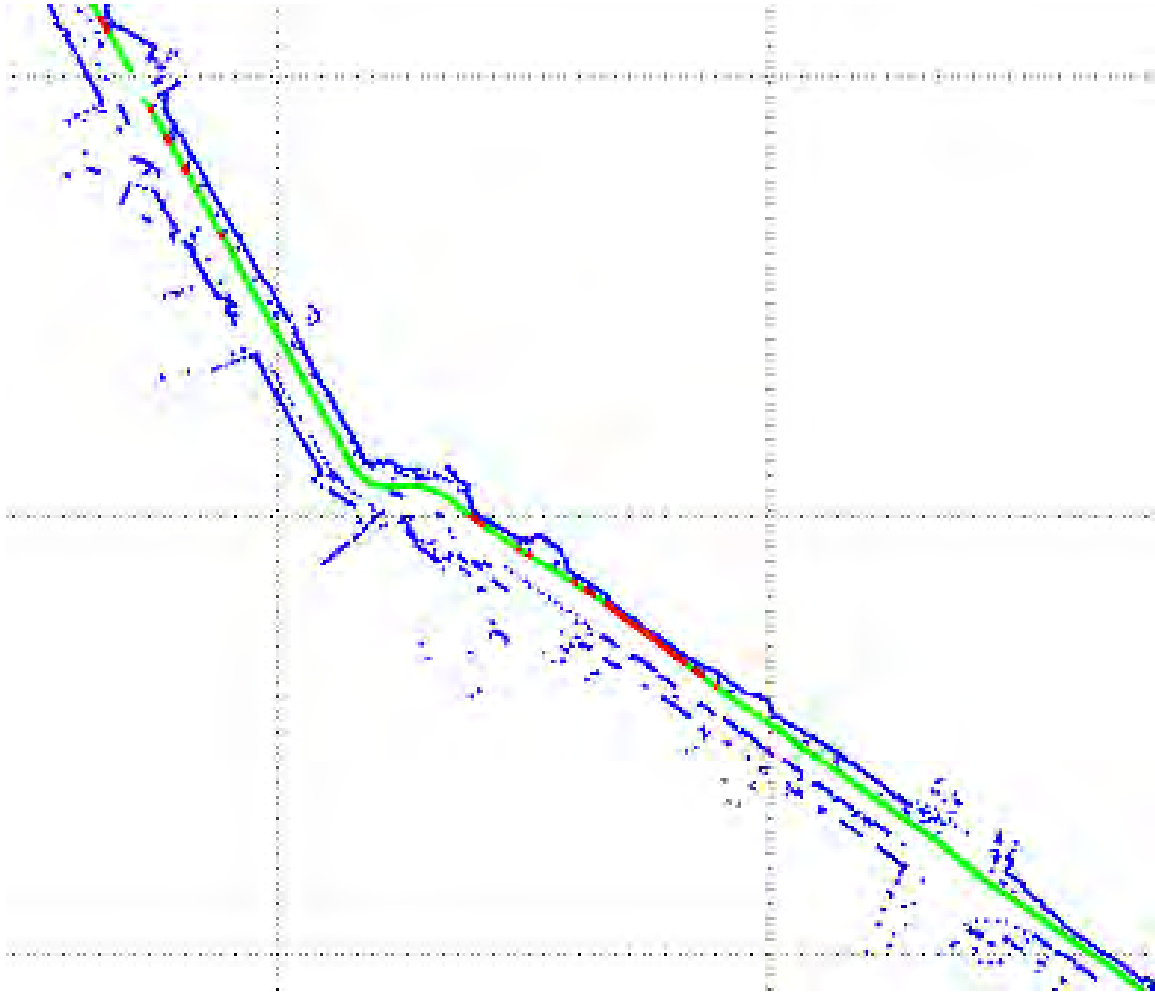


Figure 41 A zoomed view of “Elaboration of LIDAR data”

Time to collision calculation

Figure 42 shows the schematization of time to collision problem. Each object is pictured as a point, and consequently, some tolerances are considered in the distances, usually half of maximum vehicle width or length.

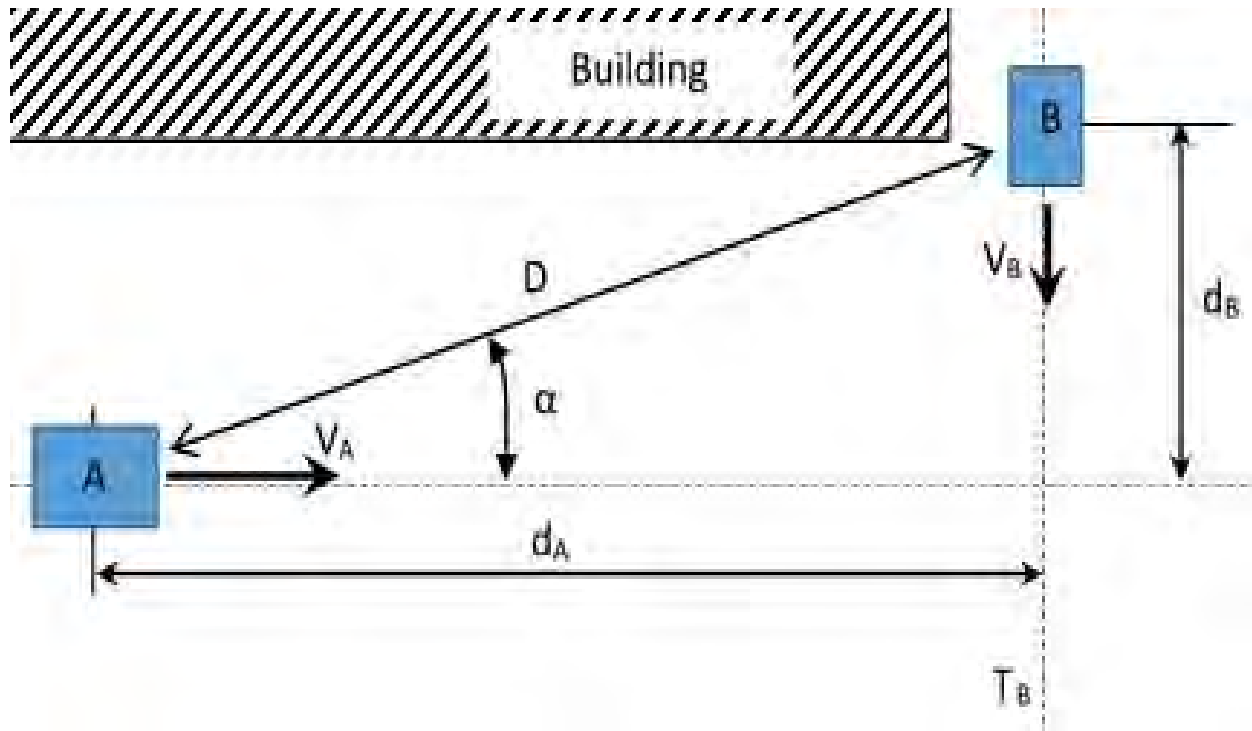


Figure 42 Time to collision problem schematization

The automated vehicle A moves along T_A trajectory with constant speed V_A .

Vehicle B (or pedestrian, cyclist etc.) moves along T_B trajectory (perpendicular to T_A) with constant speed V_B and it has a distance d_A from the vehicle A trajectory.

Such a scheme is valid as long as B is able to reach the intersection between the two trajectories T_A and T_B first.

LIDAR sensors gauge the direct distance D and the angle of detection α , and then it identifies both d_A and d_B .

When A detects B, it needs a reaction time " t_r " to elaborate the data and activate a suitable countermeasure (like emergency braking); during this time, it moves with a uniform movement (see e.1, e.2 and e.3), then it brakes with maximum constant deceleration until it stops (uniformly accelerated movement in e.4 and e.5); the maximum braking distance to avoid collision is d_A .

Vehicle B moves with a uniform movement (see e.6, e.7 and e.8).

The following equations represent what happens from time t_0 , when A detects B, to time t_1 when B intercepts the trajectory of A.

Input data are the speeds V_A ($V_{A0} \neq 0, V_{A1} = 0$) and V_B (constant), distance d_B , time t_r and acceleration a (or deceleration with negative sign).

The reaction time is usually set to 0.3 s [88]; it depends from the technology adopted and from the algorithms that manage the automated vehicle. For a comparison, a driver has 1.37 s as average reaction time [89].

Maximum comfortable deceleration " a " (with negative sign) of vehicle A depends on vehicle type and passenger situation inside it.

For example, if passengers sit face-forward and use a conventional safety belt, the maximum allowable braking deceleration is up to 5 m/s² [90]. Instead, a vehicle with standing passengers and no safety belts is allowed to have 1.2 m/s² maximum deceleration.

$$\begin{array}{l}
 \text{Vehicle A} \\
 \text{Time } t_0 \div t_R \\
 \left\{ \begin{array}{l} V_{AR} = V_{A0} \\ S_{AR} = S_{A0} + V_{A0} \cdot (t_R - t_0) \\ d_A = S_{AR} - S_{A0} \end{array} \right. \begin{array}{l} (e.1) \\ (e.2) \\ (e.3) \end{array} \\
 \text{Time } t_R \div t_1 \\
 \left\{ \begin{array}{l} V_{A1} = V_{AR} + a \cdot (t_1 - t_R) \\ S_{A1} = S_{AR} + V_{AR} \cdot (t_1 - t_R) + \frac{1}{2} a \cdot (t_1 - t_R)^2 \end{array} \right. \begin{array}{l} (e.4) \\ (e.5) \end{array} \\
 \\
 \text{Vehicle B} \\
 \text{Time } t_0 \div t_1 \\
 \left\{ \begin{array}{l} V_{B1} = V_{B0} \\ S_{B1} = S_{B0} + V_{B0} \cdot (t_1 - t_0) \\ d_B = S_{B1} - S_{B0} \end{array} \right. \begin{array}{l} (e.6) \\ (e.7) \\ (e.8) \end{array}
 \end{array}$$

The maximum distance d_A came from previous equations. Moreover, from the point S_{AR} where the vehicle A begins to decelerate, the speed profile is also determined up to stop the vehicle. This condition happens when vehicle A detects someone as vehicle B.

If vehicle A does not detect someone, it has to decrease its speed in order to avoid collision, if someone arrives at the crossing.

If someone suddenly appears, the vehicle has to brake. For this reason, the speed has a higher limit that depends on the speed of object B and its distance from the trajectory.

The time to collision of B has to be equal to the stopping time of vehicle A.

Moreover, further developments could spring if we consider the non-uniform deceleration of vehicle A at time t_1 , in fact it has a constant speed between t_0 and t_1 , but when it starts to brake in t_1 , it can't reach maximum deceleration instantaneously, depending of jerk, so it reaches the maximum braking performing by t_{\max_br} (see e.9).

$$t_{\max_br} = \frac{\max_{dec}}{\max_j} \quad (e.9)$$

During time t_{\max_br} , deceleration increase up to maximum, it allows to keep high standard of comfort and safety, due to limitation set: maximum deceleration (\max_{dec}) and maximum jerk (\max_j).

To simplify process and calculus, this step was avoided, and it was considered at time t_1 vehicle could perform maximum deceleration.

Maximum allowed speed calculation

The maximum allowable speed V_{A0} is automatically determined with equation e.10, and it is valid for any t_0 . During the deceleration, "a" is a negative value.

$$(t_1 - t_0) = \frac{d_B}{V_{B0}} = t_R - \frac{V_{AR}}{a} \Rightarrow V_{A0} = V_{AR} = a \cdot t_R - \frac{a \cdot d_B}{V_{B0}} \quad (e.10)$$

When vehicle A is supposed to reach first the intersection of the trajectory with B, it could accelerate again.

This equation is valid only if the ratio between d_{B0} and V_{B0} is greater than t_R .

The braking distance is "Δ", equal to the difference between S_{A1} and S_{A0} (see e.11).

$$\left\{ \begin{array}{l} (t_1 - t_R) = \left(-\frac{V_{AR}}{a} \right) \\ \Delta = S_{A1} - S_{A0} = (S_{A1} - S_{AR}) + (S_{AR} - S_{A0}) = -\frac{1}{2} \cdot \frac{V_{AR}^2}{a} + V_{AR} \cdot t_R \end{array} \right. \quad (e. 11)$$

For instance, a bus can have 1.2 m/s² of maximum (negative) deceleration “a”, the “t_r” is equal to 0.3 s, and there is an obstacle (i.e. a bench) 2 m far from vehicle side that hide another user “d_B”.

If behind a bench there are only pedestrians (with maximum speed of 1.5 m/s), the maximum allowable speed of that vehicle when it detects the bench is 1.2 m/s (less than 5 km/h). The braking distance is 0.96 m.

A car with 4 m/s² of maximum deceleration aims to reach 4.1 m/s (less than 15 km/h) of maximum speed, with braking distance 3.33 m.

The main difference between a bus and a car is their maximum allowable speed, due to the allowed maximum deceleration; it means that a car has a bigger capacity and it needs to maintain this speed within the braking distance from the obstacle.

Locate of the maximum allowable speed on trajectory

The braking distance “Δ” is useful to determine the distance from the detected obstacle where to satisfy the maximum allowable speed condition.

So, from the intersection between obstacle and vehicle trajectories (orthogonal) called location of collision, the maximum allowable speed concerns about a backward location of vehicle trajectory (with a back translation in predefined trajectory), the translation is equal to Δ plus a length tolerance. The location determined by backward translation identifies where to set speed limit.

Theoretically, when automated vehicle passes the brake location, it could accelerate again because any user with speed up to the design speed, arrives at intersection after the automated vehicle. Indeed, there are so many hidden obstacles that put likewise speed limits in different trajectory positions.

So, each obstacle includes a speed limit that implies a time to collision computing for forerun trajectory (due to maximum distance seen by LIDAR sensors, compute concerns up to 30 meter before).

Speed profile generation

The previous phase locates/pinpoint all speed restrictions due to hazards of interaction between vehicle and other road users, and other speed limits imposed by road regulation.

The generation of a speed profile begins with a first filtering phase of speed limits by generating an involute speed profile.

Next, an iterative process generates the comfort speed profile, assuming a maximum jerk for acceleration and deceleration phase and a maximum vehicle speed as shown in Figure 43.

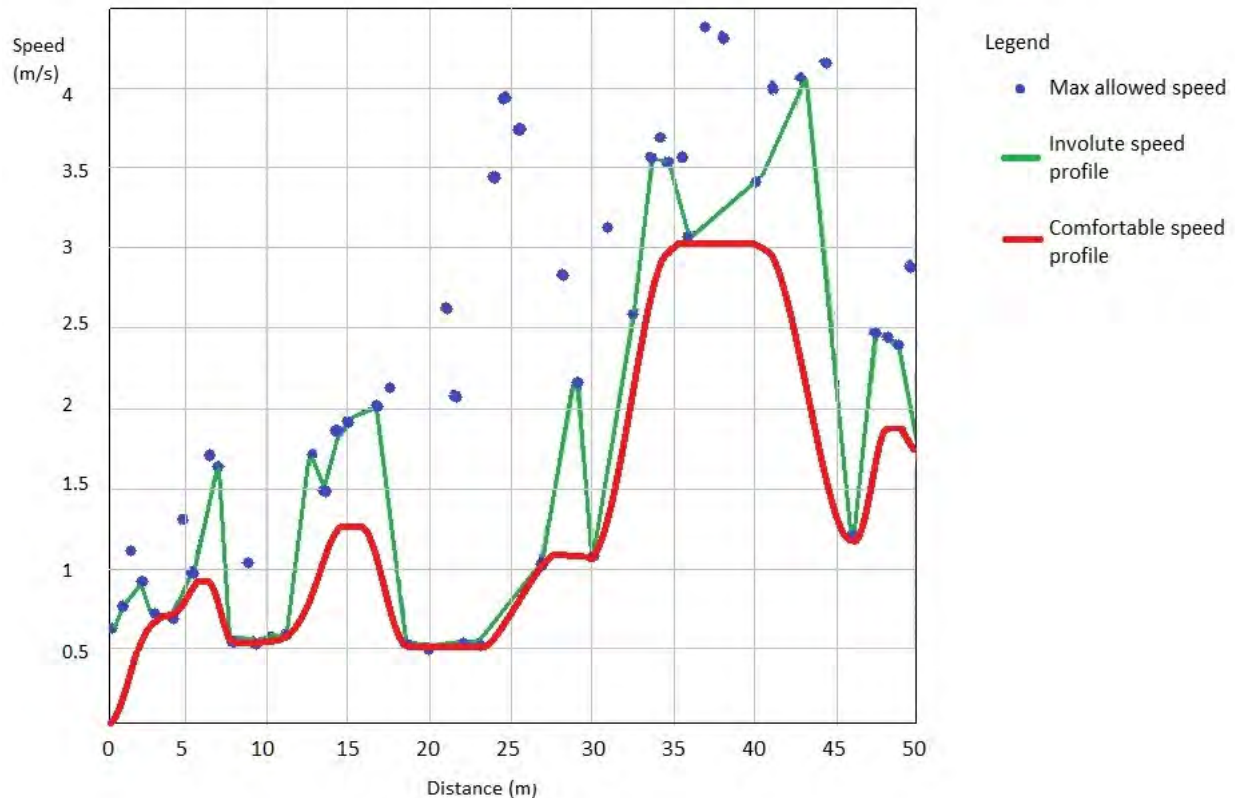


Figure 43 Speed profile generation

4.4.2.3. Low speed points location

The speed profile, just generated, highlights the low speed points location, whereas there are some intrinsic hazards due to environment and infrastructure.

The speed profile can be compared with the average road speed in traffic condition, if there is a significant difference, the location will be a low speed point.

Once these locations are known, three solutions can/will be possible:

- suggesting an intervention aimed at increasing safety of infrastructure itself (by using infrastructure sensors, segregation lanes, priority crossing lights, barriers and so on).
- suggesting a change of corridor with another one that has fewer low speed points, perhaps the second corridor increases VMT but with less difficult situations for automation and maybe more quickly.
- doing nothing. Vehicle speed profile, just generated, allows to detect someone comfortably and safely, but it can't be guaranteed an high efficient transport with high capacity.

This sub-section aims to explain some possible actions to improve safety of corridors. Two different ways are possible:

- I. Speed reduction of other vehicles/users that can cross automated vehicle trajectory, by using a barrier puts off-carriageway paths in order to mitigate highest speed, as:
 - o pedestrian barriers (Figure 44),
 - o bumpers for bicycle (Figure 45) or for cars (Figure 46).

- II. Speed reduction of automated vehicle, together with alert signal provided by infrastructure sensors. The infrastructure sensors light the blind spots that automated vehicle cannot see and provide to it a signal of the other vehicle/user presence with enough time to allow a comfort deceleration; this solution allows to reduce the speed of automated vehicle before arriving at the crossing, only if someone is going to cross there.



Figure 44 Pedestrian barrier



Figure 45 Bumpers for cycling lane



Figure 46 Bumpers for road

Such actions regard environmental analysis of the whole automated corridor. It aims to detect traffic islands, sidewalks, benches, trees and other non-conventional obstacles (i.e. flower boxes, fountains or sculptures) and the crossing with other roads (more detail at [91]).

Table 4 shows the impacts of two proposed solutions (speed reduction of other road users or speed reduction of automated vehicle). It has been proposed in a scale from 1 to 3 (1 means low/poor, 2 means medium and 3 means high/good). All values represent the average solution for both types, but they depend on the mitigation action achieved.

Table 4 Mitigation actions impacts

Solution	Corridor capacity	Safety	Reliability	Cost
I	3	3	3	2
II	2	2	2	1

Table 4 demonstrates that solution I is preferable, but sometimes the infrastructure intervention to mitigate speed of another vehicle could be too expensive.

Some of the possible mitigation actions are:

- A physical barrier, to slow down users (pedestrian and cyclist) or to avoid the passing of them;
- A physical un-traversable barrier, to avoid pedestrian crossing outside of zebra crossing;
- Bump above-ground or under-ground (road level);
- Crossing lights or smart lights;
- Speed cameras.

At the moment, there are a few prototypes of electronic devices (as electric bump, smart crossing lights, etc.) that produce the desired mitigation only for high-speed users without slow down the other ones.

Figure 47 shows a low speed point in Trikala (Greece), the same path of Figure 38. The LIDAR data analysis (Figure 40) shows this location as a possible source of hazards, due to a newsstand that hides a pedestrian in a cycling area; in this case, someone could come behind there rapidly and the vehicle has to decelerate, to reduce risk of a possible collision, Figure 48 shows the point of view in the back of the newsstand and the cycle rack. There is also another hazard, coming from the intersection between path and road on the right (in top-right corner of Figure 47 and in Figure 49).



Figure 47 One of the low speed points in Trikala



Figure 48 Same location of Figure 47 with a different point of view

Then the automated vehicle must decelerate, because there is a curved path, a vehicle parked on the right side of the road and a non-regulated road crossing.

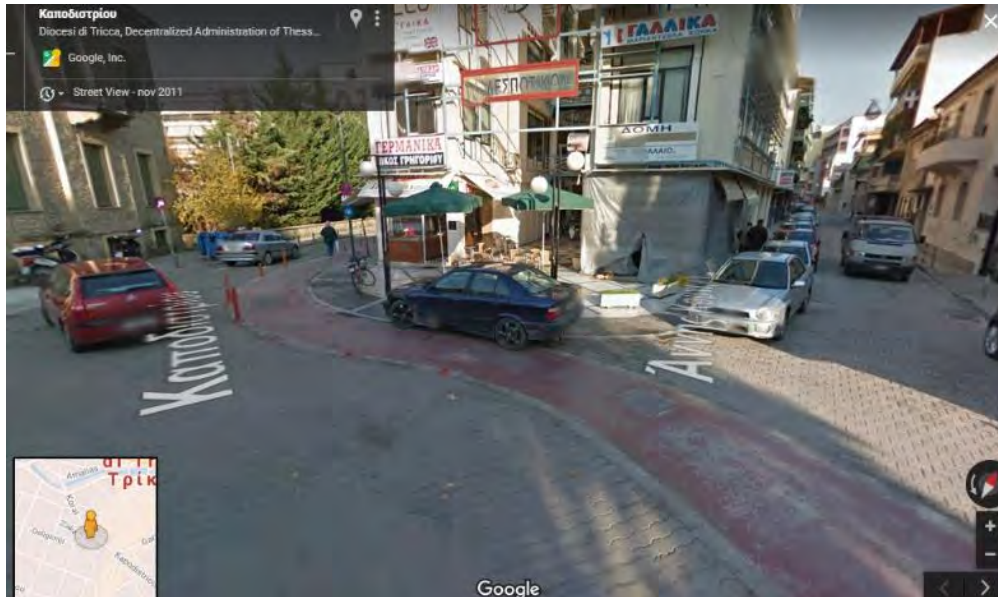


Figure 49 Illegally parking vehicle in highly hazardous location

Figure 50 shows another low-speed point in the city of Oristano (CM2 project). Indeed when a vehicle proceeds in the right lane, it sees the bench but not behind it. A pedestrian or even a cyclist could approach rapidly up to cross the vehicle trajectory, and the vehicle sensors are unable to see it before they overcome the bench (more information at [92]).

So, the automated vehicle must decelerate just before arriving there or, even if there are some mitigation measure for speed users coming from there the vehicle could use a greater speed [93].

Figure 51 reports a Japanese road with lane delimiters, which allow to cross the dedicated lane and to use it. It creates a respect area in the centre by augmenting distances between two lanes.

Figure 52 shows an integration example on Dutch street, the lane on the left of the picture is separated by a hedge and cannot be crossed by vehicles neither by bicycles, the bushy edge allows a respect area for cyclist also, in case of accidents, and it also allows an automated vehicle to see what is behind the edge. Moreover, the lane on the right can be crossed. The tight carriageway is considered a speed mitigation measure for vehicles. Besides, the sidewalk on the right of the figure is large enough to accommodate the pedestrians and it has no obstacle that obstruct the vision systems of the automated vehicle.



Figure 50 A low speed point in Oristano



Figure 51 A Japanese suburban road



Figure 52 Example of an integration on Dutch streets

4.4.3. Transport capacity evaluation

A section-by-section calculation determines the maximum allowed speed for automated vehicle (see equation e.10). Thereafter, a filter operation to obtain the smoothest possible and comfortable speed profile is required.

The e.11 shows the corridor capacity “ C_C ” that depends on capacity “ V_C ” and maximum frequency “ f ”. Corridor capacity increases with vehicle speed (frequency inside of corridor rise) [94].

$$C_C = V_C \cdot f \quad (e.11)$$

The necessary time to complete the path for a vehicle (t_{occ}), with the just determined speed profile, represents the first step to determine the capacity of the lane.

Moreover, the frequency depends on the following variables:

- Corridor speed;
- Vehicle length “ V_l ”;
- Braking strategy as brick wall stop or vehicle maximum deceleration [94];
- Vehicle type or, if available, its maximum braking capability;
- Passengers condition inside of the vehicle (standing, sitting, with or without safety belt).

As a general remark, the frequency follows the equation (e.12). The “ n_v ” is the number of vehicles available for the lane.

$$f = \frac{1}{t_{occ}} \cdot n_v \quad (e.12)$$

Vehicle size changes the corridor capacity. Some mitigation solutions could reduce the speed of other users and allow a boost of the speed of an automated vehicles.

An iterative procedure evaluates the collision time for every section of the path, it builds the speed profile and calculates the corridor capacity for some types of vehicles (with different braking capabilities).

Moreover, it could assess several different mitigation actions in those crucial points with low-allowed speed and calculates the variation of corridor capacity for them.

It could happen that large vehicles (as a bus with 30 passenger capacity) produces less capacity than a little vehicle with same headway (as a car with 4 passenger capacity, with seated passengers and seatbelt).

This happens because a lower maximum deceleration is required for the bus, and it needs to decrease its speed more than a car. It is the same issue for the acceleration phase after passing the crucial point.

Moreover, a bus has more stops to pick-up and deliver passengers from vehicle, more passenger means more stops and more time wasting for accelerate and decelerate the vehicle comfortably.

The whole ARTS network capacity is equal to the minimum corridor capacity from those of all corridors of the network.

Therefore, it is important to use appropriate mitigation actions in order to increase the capacity of those lanes with dangerous situations. Otherwise, it would be necessary to adopt more vehicles to obtain the same passenger capacity, resulting in further costs and possible congestion on the route.

4.5. Vehicle choice and fleet dimensioning

The inputs of this phase are:

- OD Matrixes
- Corridors
- Nodes of interchange and stops
- Road network and graphs

The output of this step is a first fleet dimensioning, which can include the following data:

- Requested trips served;
- Number of vehicles used for the service;
- Working time of each vehicle;
- Vehicle mileage;
- Passenger-km travelled;
- Average travel time;
- Deviation from the average travel time;
- Vehicle occupancy.

Some simulation can be led in series, by changing vehicle parameters (such as seats and performance) but with the same level of demand and the same call list, to compare which solution is the best .

Moreover, the tools to be used for the simulations can be chosen according to the route complexity and to the degree of accuracy requested.

Anyway, the fleet dimensioning is a ride sharing problem starting from such data, so there are two main phases, described in the following sections: the ride sharing analysis and a fleet dimensioning.

4.5.1. Ride sharing capability analysis

This step is the core of the fleet dimensioning, it aims to verify the ride sharing capabilities of a system and to simulate its operations based on the ride sharing, in order to improve the service in comparison with other solutions.

So, to improve the number of passengers per vehicle, the spatial and time distribution of the demand has to be analysed. Some requests could be in the same time windows, with a close (or equal) origin and destination. If such the case, the same vehicle could be used to serve them and the ride sharing capabilities have to be simulated.

Before explaining the ride sharing capability analysis procedure, the following definitions of parameters to use, have to be provided:

- **Pool.** Group of people using the same vehicle during a single routing. They can board the vehicle in different times and/or places. For example, a vehicle with a route planned from the point A to point B starts its route in A, then it reaches two intermediate points C and D to pick up some users, and then goes to the destination B and delivers all the users previously picked up.
- **Pick-up/delivery time.** Time spent at the stops for pick-up and delivering of the passengers into the vehicle.
- **Detour time.** Estimated time to be spent for each intermediate stop (other than for picking up and delivering people).
- **Maximum vehicle capacity.** Number of places in a vehicle and maximum allowable people for a pool. It is the core parameter of the fleet dimensioning (see next section 2.6) and it has to be adapted, if during the request list generation many trips happened simultaneously at the same time and/or in the same place.

However, the increasing or decreasing of the vehicle capacity has to consider other linked variables, such as vehicle costs, possible congestion generated in those paths with highly-concentrated requests, people using the vehicles during peak hours.

The analysis can use the same trip categories reported in Table 1 (inner, out-going and in-going), and is based on an in-depth investigation of the lists of requests.

The investigation is based on the following phases:

- **Initial pool generation:** some nodes of the route generate several trips to fill one or more vehicles (same origin and destination with same request time). The minimum size of a pool is half of vehicle capacity; the maximum size is the vehicle capacity. These are the pools.
- **Final pool generation:** starting from the initial pools generated in the previous phase, for each pool the requests with same origin and destination but with a different time are investigated. The ride-sharing capability could result in a little changing of request time for people. The time tolerance for accepting this changing is a parameter that has to be set during the simulation. According to such procedure, people accepting slight changing of time are inserted in the same initial pool (if not already full), thus generating the final pool.

All requests of time changing can be considered as accepted, thus allowing the insertion of further users in the initial pools generated before and increasing vehicle occupancy rate.

For example, in municipalities where people daily commute outside by train, those could be asked to change their request time from one train to the previous, or the next. Usually in peak hours, the high frequency of trains allows to change train in little timing distances (maximum 15 minutes).

- **New path generation:** the changing of request time and the insertion of new users on the same vehicle can result in different paths. Thanks to the geo-mapping of all nodes, it is possible to know which path is planned and if there are people that can be picked up during this travel before arriving at the destination.

To include detour time to spend for each intermediate stop, other than picking-up and delivering people, it is necessary to estimate such parameter into the planning of route.

For example, if there are people with same destination but different origins and with different request times, they can be included into the same pool with consequent path change.

- **"Lonely" trips analysis:** all the trips that cannot be included in the pool generation phases, need to be planned. For each of them, it has to be checked if a new pool can be generated and /or if they can be inserted in existing pools with the techniques of train changing and picking up along the path.

Table 5 shows results of initial pool generation for morning trips of Mentana. This is only an example with a call list random generation for only one level of attraction.

It highlights 4 pools, the yellow-filled rows show 9 calls, 7 of them start from node no 1 (ID orig.) and go to train station (ID dest. no 9) the others start from node no 3. Desired time of arrival is related to train departure time from Monterotondo Scalo train station, a person has accepted a time change from his desired train to the previous one (see the ID train number).

Table 5 Initial pools generation for morning calls

ID orig	ID dest	Pax	Total pool users	ID pool	ID train	ID veh	Travel time (s)	Distance (m)	Train dep. Time (hh:mm:ss)	User dep. Time (hh:mm:ss)	User Arr. Time (hh:mm:ss)	Veh time availability (hh:mm:ss)	Revenue of pool (€)	Pax* km
1		7			1		978	9915		5:53:42	6:10:00	6:14:00		
3	9	1	9	1	1	1	843	9450	6:15:00	5:57:57	6:12:00	6:14:00	24	88.3
3		1			2		843	9450		5:57:57	6:12:00	6:14:00		
4	9	5	5	3		3	902	9787	6:15:00	5:54:58	6:10:00	6:12:00	12	48.9
6	9	7	7	4		4	1169	11235	6:15:00	5:50:31	6:10:00	6:12:00	18	78.6
1	9	4	8	6	2	7	978	9915	6:24:00	6:02:42	6:19:00	6:23:00	21	82.0
5		1					1064	10860		6:03:16	6:21:00	6:23:00		
2		6			2	8	954	10027		6:03:06	6:19:00	6:21:00		
2	9	2	8	7	2	8	954	10027	6:24:00	6:03:06	6:19:00	6:21:00	21	80.2

As an important milestone, the driver in ride-sharing model does not pay the ride. This condition is required because he assumes some responsibilities with driving other passengers and not so many people appreciate the driving tasks. Thus, when automated transport services will grow wiser in legal framework as well, the driver will not drive yet, but it will ask him to pay attention on the road and hit the emergency button in case of danger. Nowadays, this incentive should encourage people to drive.

The final output of this step is provided by the final pools generated for all users, ready to be assigned to the vehicles.

4.5.2. Fleet dimensioning

The fleet dimensioning starts from the final pools established in previous step and assigns each of them to a vehicle. For each vehicle, the following iterative procedure for the route planning is provided:

- It starts its first route from the origin of the first out-going pool, therefore such pool is assigned to this vehicle;
- It follows the planning route for the first pool and when it fulfilled the pool requests, it becomes available again;
- The vehicle is at the destination position of the first pool, thus it "searches" users in the inner and in-going pools:

- If there is one with origin equal to the present vehicle position, it begins a second route and the vehicle arrives to the destination of this second one. The pool is assigned to the vehicle and vice versa.
- If a combination with inner or in-going pools for the return route is not possible, the vehicle starts empty and the scheduling depends on travel time needed to reach the origin of a next available pool.
- After that, the vehicle is able to serve other pools and it continues the iterative procedure until it serves all pools available.

If there are pools not assigned to a vehicle, a new vehicle will be required, and for each operating vehicle, a procedure similar to the one previously described, will start.

The number of vehicles requested for the fleet (and their capacity) is automatically defined when all pools have been assigned and it represents the output of this step and the final output of the procedure (supply).

Table 6 shows a summary of vehicles scheduling, it reports the total number of passengers, distance, revenues, trips and operating time.

Firstly, there are the most used vehicles, while the latest are the least used ones (with less trips and passengers),

Table 6 Vehicle scheduling

ID veh	ID pool	Total pax vehicle (pax/veh)	Total dist. (km)	Pax*k m	Tot Morning revenue (€)	Trips	Operating time (s)
1	1	26	39	255	66	4	6589
2	3	30	40	300	78	4	6928
.							
6	7	12	32	123	27	3	5247
7	10	14	21	149	36	2	3262
.							
19	65	8	12	88	21	1	1356

After the fleet dimensioning, it is required the working time planning of operators (Table 7). These workers relocate vehicles and they could do other non-driving tasks, but it is required a precise planning for their work hours, in order to fulfil relocation of vehicles, just before the following request of availability from another users.

Table 7 also shows which vehicle the operator has to relocate, its time constraints, origin and destination, also the platoon length.

Further development should include human operators' operating time with observing of collective labour agreement.

Table 7 Operator working time scheduling

ID op	Platoon length	ID platoon	Starting time (hh:mm:ss)	Arrival time (hh:mm:ss)	Op. availab. time (hh:mm:ss)	Id veh	ID origin	Id dest
1	6	1	6:12:00	6:27:40	6:32:40	2	9	4
1	6	1	6:12:00	6:27:40	6:32:40	6	9	5

1	6	1	6:12:00	6:27:40	6:32:40	3	9	6
1	6	1	6:12:00	6:27:40	6:32:40	5	9	2
1	6	1	6:12:00	6:27:40	6:32:40	1	9	1
1	6	1	6:12:00	6:27:40	6:32:40	4	9	1
1	6	2	6:45:00	6:59:35	7:04:35	15	9	4
1	6	2	6:45:00	6:59:35	7:04:35	9	9	1
1	6	2	6:45:00	6:59:35	7:04:35	11	9	3
1	6	2	6:45:00	6:59:35	7:04:35	10	9	2
1	6	2	6:45:00	6:59:35	7:04:35	12	9	5
1	6	2	6:45:00	6:59:35	7:04:35	13	9	6
1	6	3	7:36:00	7:48:37	7:53:37	5	9	8
1	6	3	7:36:00	7:48:37	7:53:37	3	9	2
1	6	3	7:36:00	7:48:37	7:53:37	2	9	1
1	6	3	7:36:00	7:48:37	7:53:37	4	9	6
1	6	3	7:36:00	7:48:37	7:53:37	6	9	7
1	6	3	7:36:00	7:48:37	7:53:37	1	9	4
1	3	4	8:05:00	8:20:40	8:25:40	3	9	2
1	3	4	8:05:00	8:20:40	8:25:40	4	9	6
1	3	4	8:05:00	8:20:40	8:25:40	2	9	1
1	1	5	15:03:13	15:19:20	15:24:20	1	5	9
1	1	6	15:35:14	15:50:03	15:55:03	2	1	9
1	4	7	16:05:14	16:20:03	16:25:03	4	8	9
1	4	7	16:05:14	16:20:03	16:25:03	3	4	9
1	4	7	16:05:14	16:20:03	16:25:03	1	1	9
1	4	7	16:05:14	16:20:03	16:25:03	5	1	9
1	6	8	16:41:00	16:55:27	17:00:27	6	4	9
1	6	8	16:41:00	16:55:27	17:00:27	7	5	9
1	6	8	16:41:00	16:55:27	17:00:27	2	1	9
1	6	8	16:41:00	16:55:27	17:00:27	8	6	9
1	6	8	16:41:00	16:55:27	17:00:27	9	7	9
1	6	8	16:41:00	16:55:27	17:00:27	4	2	9
1	4	9	17:20:14	17:35:03	17:40:03	4	3	9
1	4	9	17:20:14	17:35:03	17:40:03	10	4	9
1	4	9	17:20:14	17:35:03	17:40:03	6	8	9
1	4	9	17:20:14	17:35:03	17:40:03	2	1	9
1	6	10	17:46:52	18:01:19	18:06:19	5	2	9
1	6	10	17:46:52	18:01:19	18:06:19	1	1	9
1	6	10	17:46:52	18:01:19	18:06:19	7	4	9
1	6	10	17:46:52	18:01:19	18:06:19	3	1	9
1	6	10	17:46:52	18:01:19	18:06:19	8	1	9
1	6	10	17:46:52	18:01:19	18:06:19	9	4	9
1	1	11	18:35:14	18:50:03	18:55:03	1	1	9
2	2	12	6:21:00	6:35:35	6:40:35	8	9	8
2	2	12	6:21:00	6:35:35	6:40:35	7	9	6
2	2	13	6:43:00	6:58:40	7:03:40	14	9	1
2	2	13	6:43:00	6:58:40	7:03:40	16	9	1

2	4	14	16:50:14	17:05:03	17:10:03	3	1	9
2	4	14	16:50:14	17:05:03	17:10:03	5	2	9
2	4	14	16:50:14	17:05:03	17:10:03	11	5	9
2	4	14	16:50:14	17:05:03	17:10:03	1	1	9
2	4	15	18:03:00	18:21:44	18:26:44	10	7	9
2	4	15	18:03:00	18:21:44	18:26:44	4	8	9
2	4	15	18:03:00	18:21:44	18:26:44	2	2	9
2	4	15	18:03:00	18:21:44	18:26:44	6	1	9
2	1	16	18:50:14	19:05:03	19:10:03	2	1	9
3	1	17	7:02:00	7:14:37	7:19:37	1	9	8

4.6. Electric traction needs and specification

ESS choice and dimensioning need the following inputs:

- Average energy consumption
- Daily mileage
- Vehicle dimension (linked to transport demand)

Moreover, the existence of an electric infrastructure (i.e. overhead electric line shared with other transport services) could push the choice of trolley buses or similar, as widely described in [95], there are many alternatives and there will be more with future improvements.

General idea of this step is to introduce a module into methodology that considering vehicle electric needs and charging infrastructure requirements. This step can be updated (as other ones) with new technologies improvements and opportunities.

So, if an ESS is incapable to store enough energy to fulfil a daily transport service, the dimensioning will provide a fast-charging station positioning.

Instead of using average value, it could estimate energy needs from microsimulation of vehicles dynamics during its transport service, by following a determined speed profile, including slopes and stops of a city road network.

This phase includes two sub-steps: energy needs, choice and locate of charging infrastructure.

This work does not consider all implication linked with grid needs and impacts on electrical networks.

4.6.1. Energy needs evaluation

Energy needs depend on vehicle type, each vehicle has its own, the number of seats is employed as discriminant for choosing vehicle type in a transport system designing. Next, there are the main parameters divided by field:

- Vehicle characteristics
 - Available sets
 - Length
 - Weight
- Vehicle dynamics
 - Tyre friction coefficients

- Wheel radius
- Aerodynamic coefficients
- Vehicle frontal area
- Technological parameters of powertrain
 - Transmission efficiency “ η ” can be a constant value and it depends on differential gear and/or gearshift
 - Motor efficiency “ η_m ”, it is a map depending by revolution per minute (RPM)
 - Torque map
 - Moment of inertia
 - Traction wheel (front, rear or both)
 - Energy consumption (average value or a map).

Table 8 shows the main value of parameters for some vehicle types, and they can be found online provided by vehicle manufacturers or by other research projects (e.g. [96]).

For example, an interesting approach to evaluate vehicle consumption is through average energy-specific consumption (see [97]). This project proposes a trend of consumption in relation with average speed (Figure 53) for three vehicles types, the thickness of curves is linked to weight variability.

Table 8 some parameters for different vehicle types

Variable	Abbrev.	Values					Unit
Vehicle type	Veh	Golf cart/ Little Car	Medium Car/ Minivan	Minibus	Bus	Tram/ TrolleyB	n.a.
Available seats	Max_pax	4	9	30	90	170	seats
Energy average consumption	Ec	0.2	0.3	0.5	1.2	2.0	kWh/km
Length	L	3.5/4	4.5/5	5.5	12	18	m
Weight (empty)	W	0.5	0.8/1.2	4.5	13	16	Tons

Table 9 Value at minimum of specific energy consumption

Value	Vehicle Lenght Unit	Vehicle		
		6 m	12 m	18 m
		TECNOBUS Gulliver	MAN A37	IVECO CN
Average speed at lowest consumption	km/h	18.0	22.0	23.0
Average consumption without passengers	kWh/km	0.32	1.20	1.90
Average consumption with maximum number of passengers	km/h	0.40	1.45	2.35

Moreover, if it wants to evaluate precisely the energy consumption, especially where a lot of slopes are present, a microsimulation that includes, in a real-speed profile, all vehicle parameters, could be done.

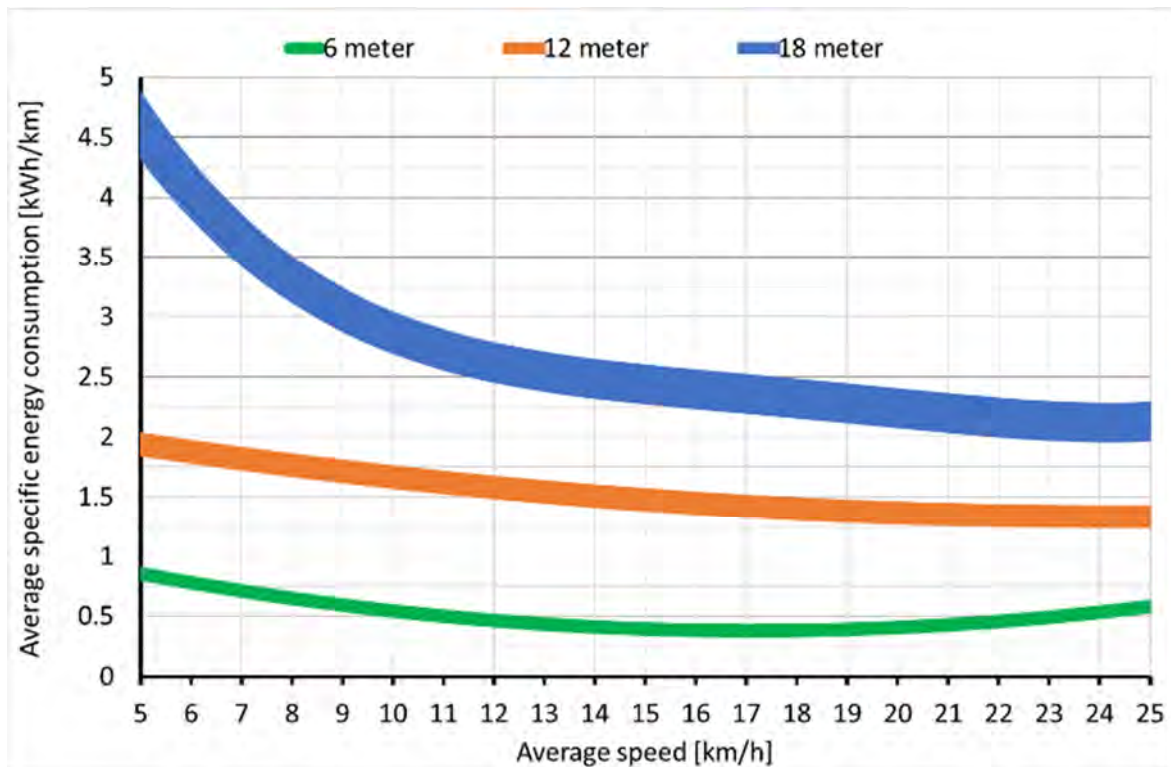


Figure 53 Average specific consumption for all vehicles

Table 9 includes the minimum values of curves shown in previous Figure 53, they are the average speed with minimum value of consumption and the consumption itself; in particular, the consumption is shown in two values: the consumption at maximum weight (with all passengers) and the consumption at minimum weight (without passengers).

Table 10 Value at minimum of specific energy consumption

		Vehicle		
Vehicle Length		6 m	12 m	18 m
Value		TECNOBUS Gulliver	MAN A37	IVECO CN
Average speed at lowest consumption	km/h	18.0	22.0	23.0
Average consumption without passengers	kWh/km	0.32	1.20	1.90
Average consumption with maximum number of passengers	km/h	0.40	1.45	2.35

Moreover, if it wants to evaluate precisely the energy consumption, especially where a lot of slopes are present, a microsimulation that includes, in a real-speed profile, all vehicle parameters, could be done.

Microsimulation allows to calculate the power required to motion and spent to overcome “resistances to motion” as follow and widely described in [98] (forces and resistances are measured in N):

- R_r rolling resistance (see equation e.13)
- R_a aerodynamic resistance (see equation e.14)

- F_g grade force (see equation e.15)
- F_i Inertia (see equation e.16)

$$R_r = \left(m \cdot g \cdot \cos \alpha - \frac{1}{2} \rho \cdot v^2 \cdot S \cdot C_z \right) (f_0 + k \cdot v^2) \quad (e.13)$$

$$R_a = \frac{1}{2} \rho \cdot v^2 \cdot S \cdot C_x \quad (e.14)$$

$$F_p = m \cdot g \cdot \sin \alpha \quad (e.15)$$

$$F_i = -m_c \cdot a \quad (e.16)$$

Where m_c is the mass corrected with inertia of gearbox and differential gear (see e.17), but in case of an electric powertrain the third fraction term of sum can be avoided.

$$m_c = m + \frac{I_r + I_p r_p^2 + \eta_t I_m r_p^2 r_c^2}{R_r^2} \quad (e.17)$$

Parameters of previous equations are:

- V , speed (m/s)
- m , vehicle mass (kg)
- g , gravity acceleration (m/s²)
- α , road grade (degree)
- r , air density (kg/m³)
- f_0 , first rolling resistance coefficient (adimensional)
- k , second rolling resistance coefficient (s²/m²)
- S , frontal area (m²)
- C_z , tyre lift coefficient (adimensional)
- C_x , aerodynamic drag coefficient (adimensional)
- a , longitudinal acceleration of vehicle

The term “R” is the algebraical sum of previous forces and resistances, it represents the resistance to motion and allows a vehicle to move under an acceleration “a”. While, the product of R with instant vehicle speed “v” and with a global efficiency term “ η ” represents the power supply from the energy storage system (see eq.18).

$$P = v \cdot R \cdot \eta \quad (e.18)$$

Passing from mechanical power to electric power requires one more step, in fact an electric powertrain has a few variable efficiencies that depending from:

- motor efficiency, it can be calculated from the specific motor map (Figure 54)
- conversion efficiency between energy storage system and motor, it depends on devices installed (DC/DC, Inverter, chopper, ecc) and wires
- charge and discharge efficiency

All those efficiency can be summarize in a map or with constant values.

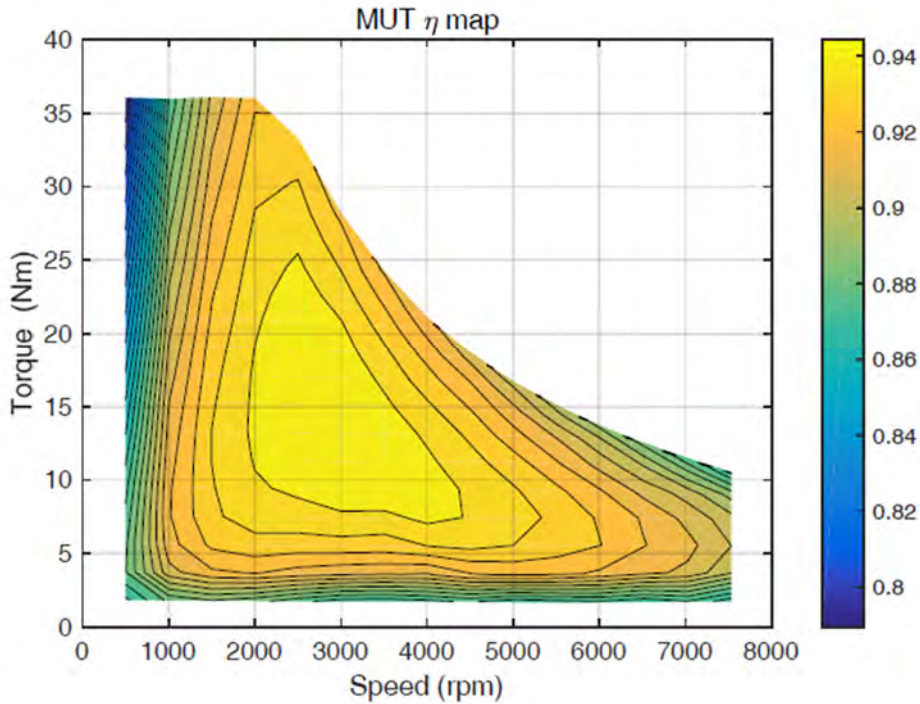


Figure 54 Efficiency map of an electric DC brushless motor

Figure 55 shows a real-speed profile, measured during a project of “sustainable mobility” in collaboration between University of Florence, ENEA and TPER s.p.a. (Bologna, Italy), where ZoI are “Zones of Integration” that include a part of speed profile (minimum length of 500 m) between two stops, speed collected by GPS, filtered speed on GPS data. This procedure aims to collect and measure consumptions during driving cycles.

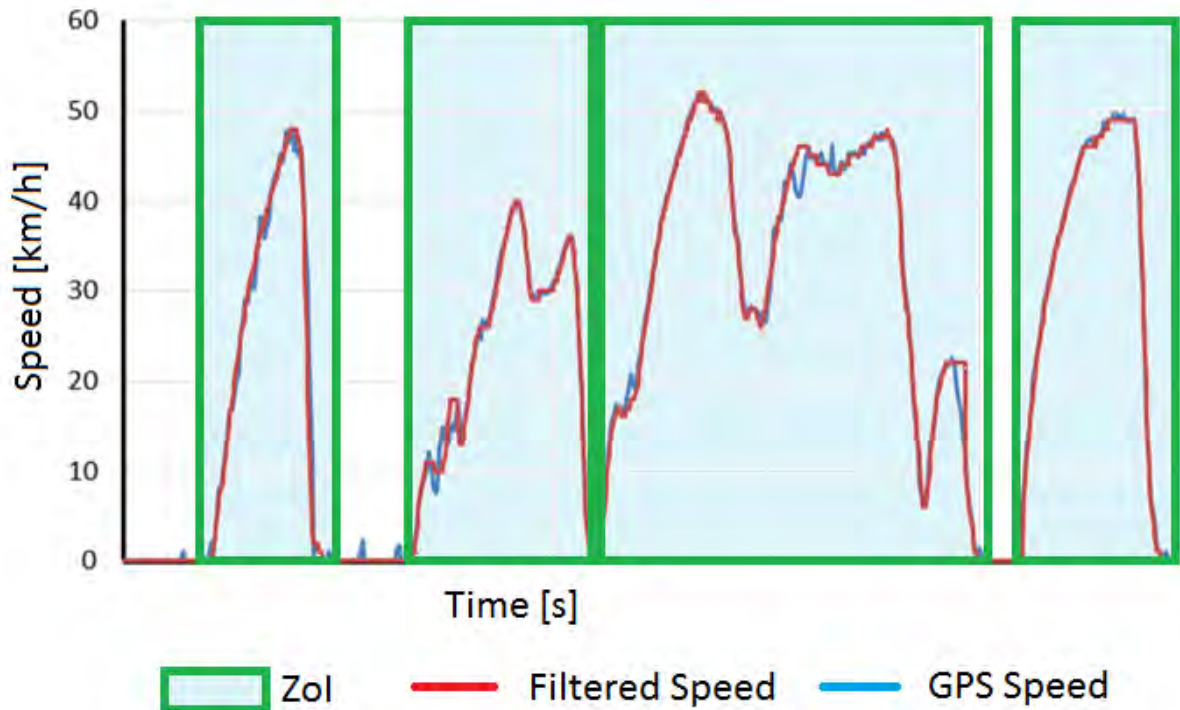


Figure 55 Measured speed profile in Bologna

This driving cycle could be used to evaluate electric consumptions with a software of simulation as an “electric vehicle simulator” made by ENEA in (Figure 56), by writing dynamic equations for resistance to motion (seen before from e.13 to e.18) in a software as Matlab Simulink, Excel or even with pre-designed blocks (i.e. LMS Amesim, see Figure 57).

Some software allow to build complex model of vehicle, in order to achieve a realistic estimation of energy consumption in all devices, for example they include following sub-models:

- Vehicle
- Wheel slip
- PID controller
- Mechanical Transmission
- Electric Motor
- Electric converter
- Energy storage system
- Power losses in heat exchanger

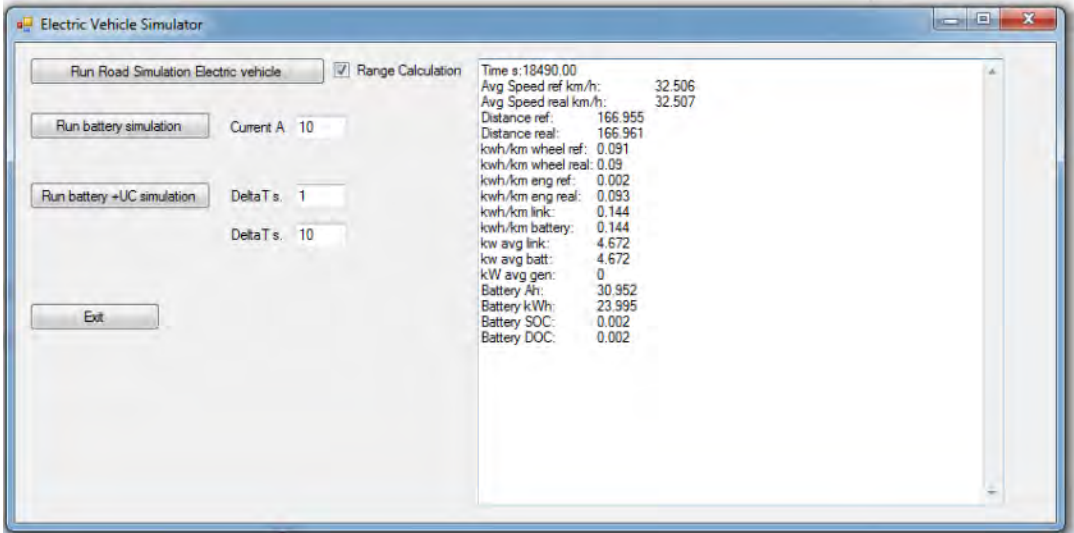


Figure 56 Electric vehicle simulator

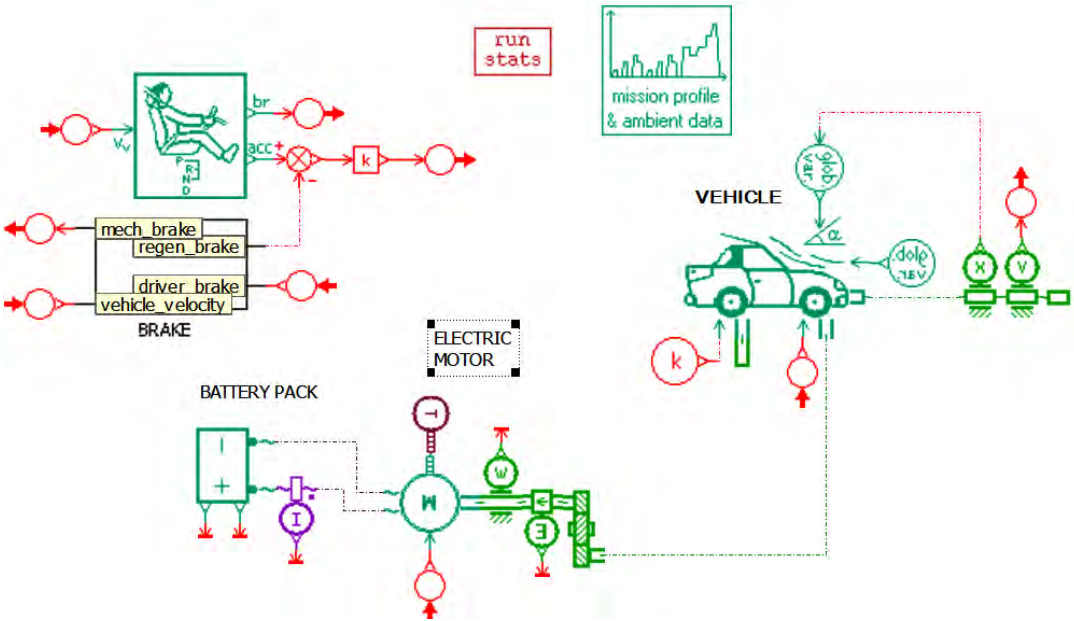


Figure 57 Amesim Model of a battery electric vehicle

Figure 58 shows results of simulation with one of these software, in particular it shows the current provided by ESS (blue line) and the energy exchanged (red line). This model considers recharging brake feature, in fact, while during braking phases the current becomes negative and energy decreases.

The energy exchanged can be calculated from the mechanical power required or, depending which software and which model have been used, by an integration of instantaneous electrical power exchanged from ESS, the electrical power is the product of current (“C”) per voltage (“V”), see e.19.

$$W_{tot} = \int_{t_0}^{t_1} C \cdot V dt \quad (e.19)$$

After the sampling of simulation, the integral with continuous variables becomes a numerical integral (see e.20), where “Δt” is the sampling step and “n” are the number of samples.

$$W_{tot} = \sum_{i=1}^n (C_{i-1} \cdot V_{i-1}) \cdot \Delta t \quad (e.20)$$

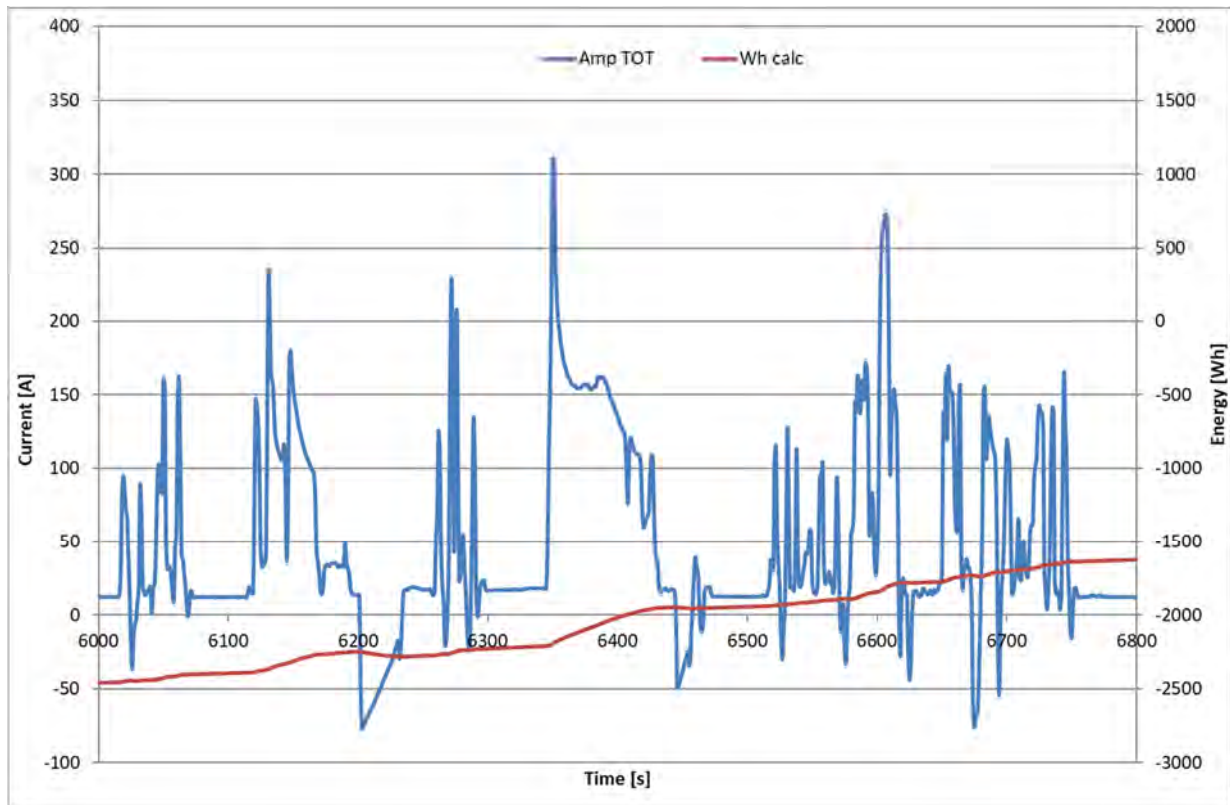


Figure 58 Simulation of energy consumption

Microsimulation allows energy needs evaluation and after that, it is proposed a comparison between possible solutions. A useful approach is to compare different technology alternatives, as proposed by [99] and [95]. With this aim in view, analysing pre-set alternatives is more effective than the application of an optimization procedure, since it allows to appreciate the role of the different design variables and to identify the most promising future lines of research. This comparison will be considered in a socio-economic analysis.

4.6.2. Choice and location of charging infrastructure

The input of this phase is the result of energy needs evaluation just completed, then some possible solutions should be evaluated simultaneously during the simulations, because there are other parameters to consider:

- 1) Number of buses/vehicles
- 2) Minimum capacity of ESS
- 3) How much time is allotted for bus charging?

The first come from fleet dimensioning in the previous paragraph 4.5, the second depends on corridor length and from the average distance travelled outside the corridors, eventually the allotted time for charging is a parameter that could be adjusted before each iteration of the whole methodology.

A financial assessment is required for every solution seen in previous paragraph.

Moreover, the location of charging infrastructure has some matters to consider:

- Medium voltage substation availability
- Electricity grid requirement
- Transport policy

For example, if we consider a fleet composed by fifty minibuses of 5.5-meter length and 30 seats, each requires 0.5 kWh/km, then if the fleet has to be employed for a transport service, 8 hours a day with commercial speed (service continued) of 13 km/h, they require about 350 kWh per hour.

So, every time a bus is connected to a charger with a fast-charging technology, there is a spike of power which could stress too much the electric grid, this spike could be up to 100 kW, in order to charge in 4 minutes the energy needed by the bus to ride another hour. The same consideration could be done with bigger buses and higher power requirements.

A precise planning of charging strategies for all buses could limit this high request, but it has always fluctuations that should be compensated by the grid.

Charging station type depends on vehicle size and energy needs:

- Commercial cars (from 4 to 9 seats) have a pre-determined ESS dimension and a mile range that guarantees to fulfil morning operation (or even more than a day, thanks to the low energy consumption) without charging. After that, there are a lot of moments during the day (as off-peak hour) to charge batteries.
- Buses have higher energy consumption and if the energy stored isn't enough to fulfil peak hour needs, it is necessary an intermediate charge during transport service. it could happen in two ways:
 - o an overhead electric line and a sliding pantograph on the buses roof
 - o a plug and socket (or a static pantograph)
- If vehicles require a physical connection with charging station (i.e. cable), they should be placed near interchange stops, or where there are vehicles waiting for more time, before relocation.
- If the charging should be done during transport services, the location could be close to a path section that requires a great amount of energy

4.7. Results evaluation

This chapter proposes some indicators of evaluation, few of them came from [74]. It seeks to provide clarity on units of measurement and, where it is deemed necessary, advice on measurement or modelling approaches to capture the data.

Indicators are classified into four main categories, described in the following paragraphs: vehicles and operators needed; energy consumption and pollutant emissions, transportation and socio-economic evaluation.

Explanations are provided only where the indicator description is not self-evident.

After the results calculation, it is required an evaluation of them. This analysis could indicate that, if there are some adjustments that could bring better results, the methodology should be restarted.

4.7.1. Vehicles and operators needed

Number of vehicles by type

Number of operators

The innovative transport system requires human operators to relocate vehicles and drive platoons in corridors.

4.7.2. Energy consumption and pollutant emissions

Daily energy consumption

Daily energy consumption is measured as the average daily consumption of energy (over a week) – units KWh

The indicator should be directly measured through the demonstrations and will also be modelled. The indicator should be modelled for the ATS system and, where appropriate, for the city system as a whole. Note that some models may produce outputs in Megajoules. One kilowatt per hour = 3.6 megajoules.

Energy efficiency

Energy efficiency is measured as kwh/passenger kilometre. It is therefore calculated using a combination of the Daily energy consumption and Total passenger-km travelled indicators specifically for the ATS system.

Toxic emissions

Firstly, they are required when this innovative transport system will be compared with traditional powertrain. Then, toxic emissions have a variety of negative health impacts, ranging from increased exposure to carcinogens to risks of exacerbating respiratory ailments. It is most appropriate to investigate such impacts by using atmospheric pollutant concentrations and the EU sets limit guidelines for a range of pollutants.

A possible procedure could be given by COPERT methodology (see [100]).

4.7.3. Transportation

Total Number of trips

The indicator measures the total number of trips by mode. The indicator can be measured directly for ATS systems and should be captured directly at each of the demonstration sites. It can also be modelled at a city-wide level, where applicable.

It can be modelled for the ATS system and for a wider transport network. Where the ATS under consideration is likely to have a substantial city-wide impact, then they should calculate total passenger-km by all modes as there will be interest in both distances travelled on the ATS system but also impacts on total system wide distances (for example from an increased overall public transport system attractiveness).

Vehicle occupancy

The indicator measures the average number of passengers within the vehicle for every kilometre travelled. Measurements of vehicle occupancy are specific to the ATS system. The indicator can be both measured and modelled and incorporates measurement of kilometres travelled by empty vehicles, en-route to collect passengers.

Average journey time per O-D pair

This provides a measure of the average in-vehicle time it takes to complete a specified journey (from origin to destination) in minutes.

This measure is specific to the ATS system rather than city-wide and can be measured and simulated during the demonstrations.

Journey time variability

The standard deviation of the journey time for an O-D pair – Units (minutes). This is calculated from the raw data used to construct Average journey time per O-D pair.

Total delay per trip

This indicator provides a measure of the travel time exceeding the minimum travel time requested to cover the trip.

Average waiting time

This measure captures the average amount of time a passenger spends waiting for their vehicle to arrive – Units (minutes). This will be recorded by on-street surveys for any previous survey, but it should be automatically captured with some ATS systems (time from vehicle request to vehicle arrival). The waiting time can also be simulated. The waiting time measures are system-specific and not city-wide.

Waiting time variability

The standard deviation of waiting times – Units (minutes). This is derived from the measurements for Average waiting time.

Interchange time

This indicator calculates the time spent while transferring from one mode to another – units (minutes). This data is best captured through passenger surveys, since observation of complex interchange behaviour is difficult and expensive. Estimates of interchange time can be provided by modelling but interchange time is more likely to form an input to strategic city-wide models, rather than to be an output.

Effective system capacity

This indicator calculates the maximum number of passengers which can be transported by the system in the time unit per direction.

4.7.4. Socio-economic evaluation

Start-up costs

The measuring unit of this indicator is Euro. In order to calculate this indicator, the data have to be collected for all cost components listed below. Future (operating) costs may also be expressed in the present currency, using the appropriate discount rate (interest rate or social discount rate).

Track construction and civil works

It includes all works that have to be done in civil construction, as lane adaptation, barrier, pedestrian cross, but even proximity sensors, intelligent traffic lights and so on.

Vehicle acquisition/construction

Control system and apparatus

Operating costs

Future (operating) costs should be expressed in the present currency, using the appropriate discount rate (interest rate or social discount rate).

Personnel

Covering costs for the personnel directly involved in the day-to-day operation of the system. It is important not to double count costs incurred for maintenance, which will include personnel charges.

Vehicle maintenance

This should include regular servicing and vandalism allowances.

Track and civils infrastructure maintenance

Note that this should not include substantial upgrades to the system (they should instead be reassessed as a new system evaluation).

Control system maintenance

Revenues

Future revenues should be expressed in the present currency, using the appropriate discount rate (interest rate or social discount rate).

Operating revenues

Fares, advertising and other sundry incomes from the system (Euro).

Subsidies (public or not)

5. Example: city of Mentana

The proposed methodology has been partially tested with the data of Mentana, a town of 23000 inhabitants 30 km away from the centre of Rome.

As shown in Figure 59, the city is directly connected to Rome by a secondary street (via Nomentana) which is often congested, because of heavy traffic and the growing number of quarters just inside Rome ring road (the GRA – Grande Raccordo Anulare).

Mentana train station (called Monterotondo-Mentana by the Rail Manager RFI) is located at Monterotondo scalo (centre of the top side of figure 2) which is 8 kilometres away and on the other side of Monterotondo town.



Figure 59 Mentana map with respect to Rome and Monterotondo Scalo where the railway station is

The following paragraphs are about almost all steps of the methodology described in this PhD dissertation.

5.1. Input parameters

An analysis of Italian census data (ISTAT), reported in Table 11, shows the number of commuters to and from Mentana.

The 40% of inhabitants (3648 people who live in Mentana) commute from Mentana to Rome daily, 33% remain in Mentana (3656), 27% go to the near cities of Monterotondo (22%) and others.

For those commuters who go from Mentana to Rome, almost 42% of them use the train and 47% use car/motorcycle (Figure 60). For those who go by train, all use their own car or motorcycle to reach the train station at Monterotondo about 8 km far.

Table 11 Census data (ISTAT): origins and destination of commuters

Origin\Destination	Rome	Mentana	Monterotondo	Others	TOTAL
Rome	0	152	0	0	152
Mentana	3648	3656	2000	3688	12992
Monterotondo	0	332	0	0	332
Others	0	859	0	0	859
TOTAL	3648	4999	1988	3688	14323

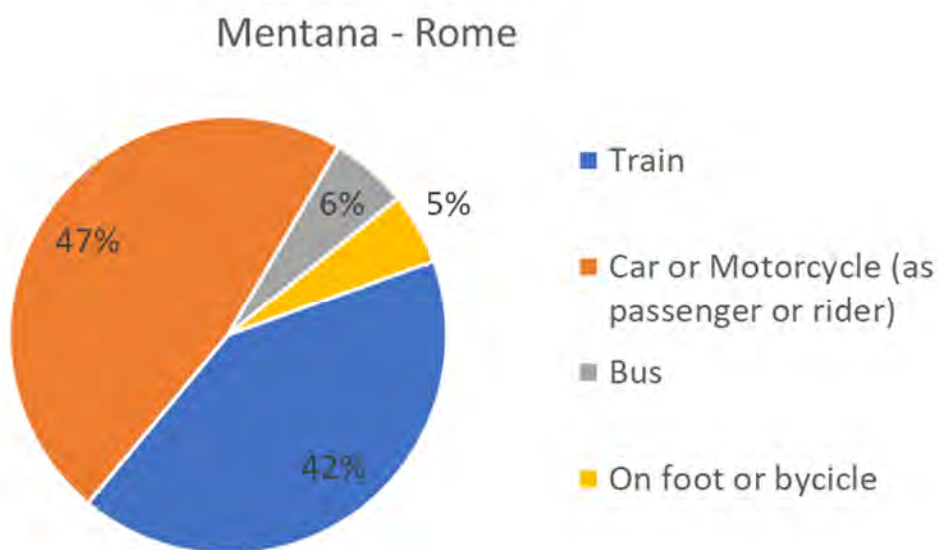


Figure 60 Modal choice of Mentana to Rome commuters

The Municipality of Mentana sponsored a public survey [101]. Its purpose was to evaluate the propension to use a car and ride sharing system; as a result, 75% of people interviewed would try the new transport system.

This attraction percentage can be applied only to the commuters who are the target of the new transport system, so the maximum target in Mentana can be the 3648 people living in Mentana and commuting to Rome.

ISTAT divides the territory in census sections and provides data for each one. The census section is the very first step to organise a preliminary demand analysis. They have been aggregated in terms of population, census, transport infrastructures and geographic cohesion. In order to dimension the transport system, each aggregated section is origin and destination of trips.

Table 12 shows a set of parameters adopted for fleet dimensioning, for the case of Mentana, for two vehicle categories: 4 seats and 9 seats. They differ in:

- maximum length of a platoon in the corridors, for little vehicles allows longer platoons.
- depreciation costs: four-seats vehicles are cheaper.
- energy consumption: a lighter vehicle consumes less

One of the interesting parameters is the transport fee: it is the same regardless of the vehicle dimension, it depends on the travelled distance. It has been assumed 0.4 €/pax*km , a minimum fee of 1 € and a higher limit of 3 €. So we consider a fee of 1€ from 0 km to 2.5 km of trip length and a fee of 3 € for any trip exceeding 7.25 km.

The parameters proposed in Table 12 are only hypothetical, employed to test the methodology. Further simulations could be carried out with different parameters.

Table 12 Simulation parameters

Parameter description	Value	Value	Unit
Vehicle capacity	4	9	pax/veh
Minimum Waiting Time for vehicle at train station	120	120	s
Maximum anticipation time before train departure time (or after train arrival time) at train station	180	180	s
Number of stops	9	9	-
Platoon maximum length (in number of vehicles)	7	6	veh
Time losses for detouring	10	10	%
Average operator returning time	960	960	s
Vehicle annual depreciation (5)	5000	7000	€/year
Vehicle annual taxes, insurance and maintenance	3000	3000	€/year
Minimum transport fee	1	1	€/ride
Maximum transport fee	3	3	€/ride
Variable fee	0.4	0.4	€/pax*km
Vehicle specific consumption (electric)	0.2	0.3	kWh/km
Cost of energy	0.17	0.17	€/kWh
Operator annual costs (professional driver)	32000	32000	€/year

Mentana has 33 census sections and they were reduced to 8 zones inside of the town. As the transport system would (in this first dimensioning hypothesis) serve commuters going to the train station, Monterotondo scalo was add as a further origin/destination (Figure 61).

A time and distance matrix between each OD pair were then built, using a web service.

Several demand levels have been investigated, assuming that the new system will progressively attract more people.

To simulate the service supplied to dimension the fleet for the demand level, a scheduling service was used. The trips directed to the same train from the same zone or from zones in which the vehicle would travel through were anyhow put in the same vehicle.

A counterflow demand was never considered. The morning trips were all to the station, and the afternoon ones to return home.

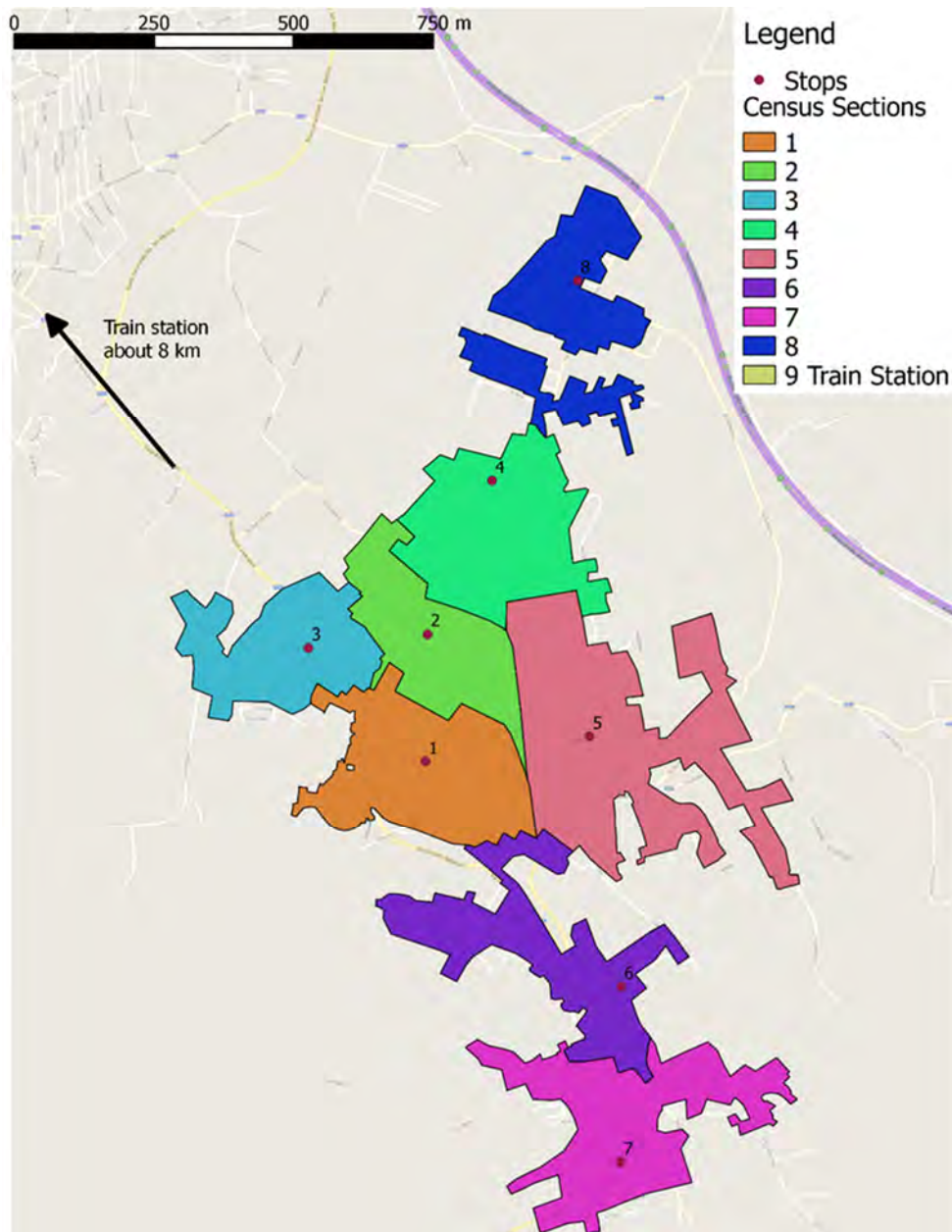


Figure 61 Mentana OD zones

5.2. Itinerary analysis and corridor identification

The itinerary analysis shows several potential corridor paths in common with all OD. Then, there are several shorter corridors in the centre of Mentana which share paths between two or three OD couples.



Figure 62 Potential corridors

5.3. Corridor selection

Figure 63 shows the main corridor, it goes from Mentana city centre through Monterotondo, up to train station ad Monterotondo Scalo. Its length is about 8 kilometers and for this reason, Mentana needs only one corridor. It shares all itineraries with origin in Mentana and destination in Rome (by using train), other itineraries are too short.

In order to keep cheap the corridor adaptation for automation, it is advised to do some intervention only inside of cities, whereas speed profile has a lot of low speed points.

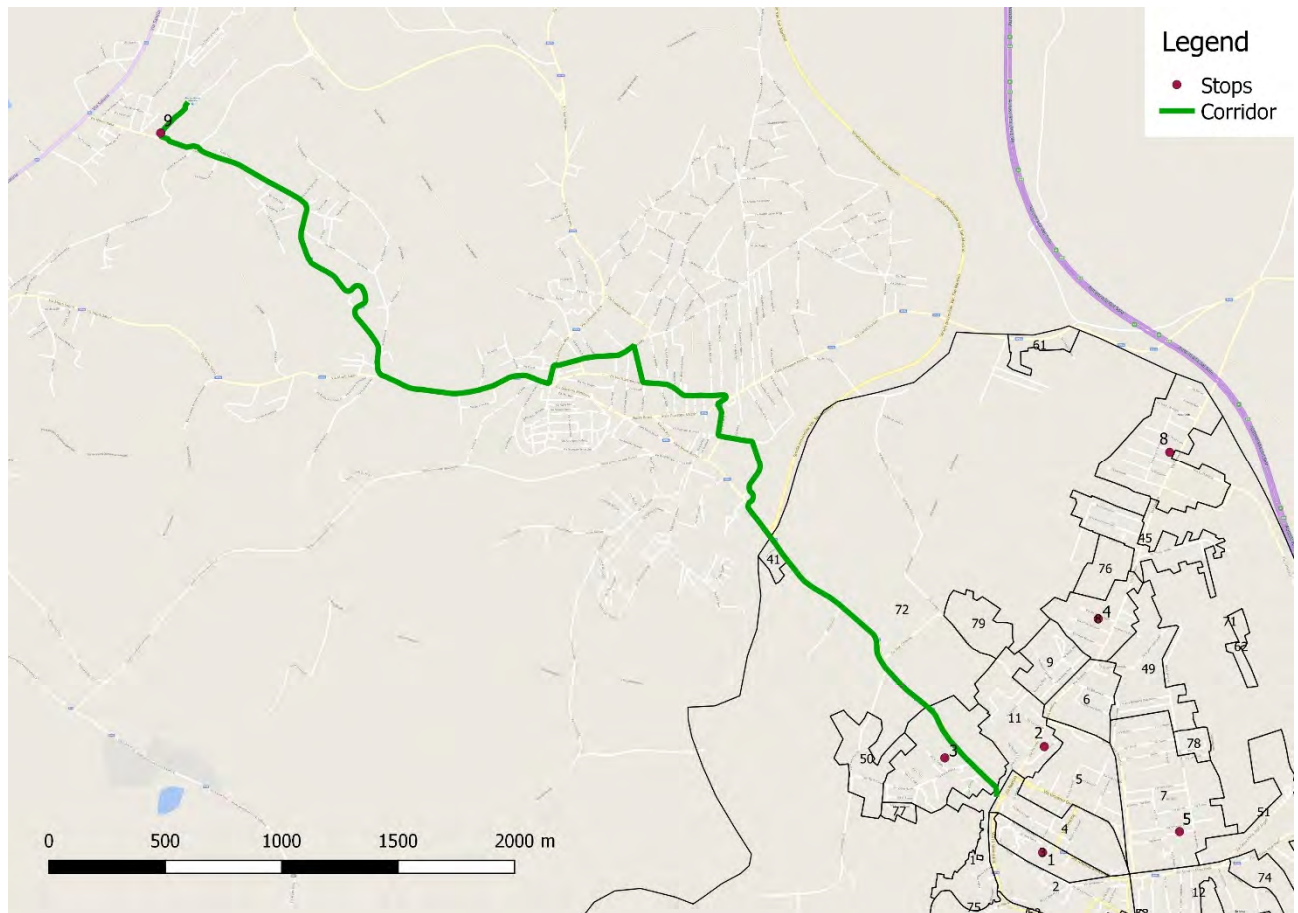


Figure 63 Main corridor for city of Mentana

Market dimension is related to ISTAT census data (Table 11), there are almost 2700 people moving daily from Mentana to Rome and are interested on new transport systems, according with the Mentana mobility survey [101]. Table 13 shows some different percentage of potential users' attraction, these levels are useful to evaluate if and when a specific transport service reach the break-even point.

Table 13 Market dimension

% of potential demand	5%	25%	45%	65%
No. People (morning trip)	406	812	1218	1624

5.4. Vehicle and fleet dimensioning

Figure 64 and Figure 65 show results of two simulation sets: the first one is the innovative transport system with four-seat vehicles, the other one has nine-seat vehicles.

In those figures, there are vehicles number (square dots) and average occupancy (morning trips with triangular dots and afternoon trips with cross dots) by varying the percentage of potential users' attraction.

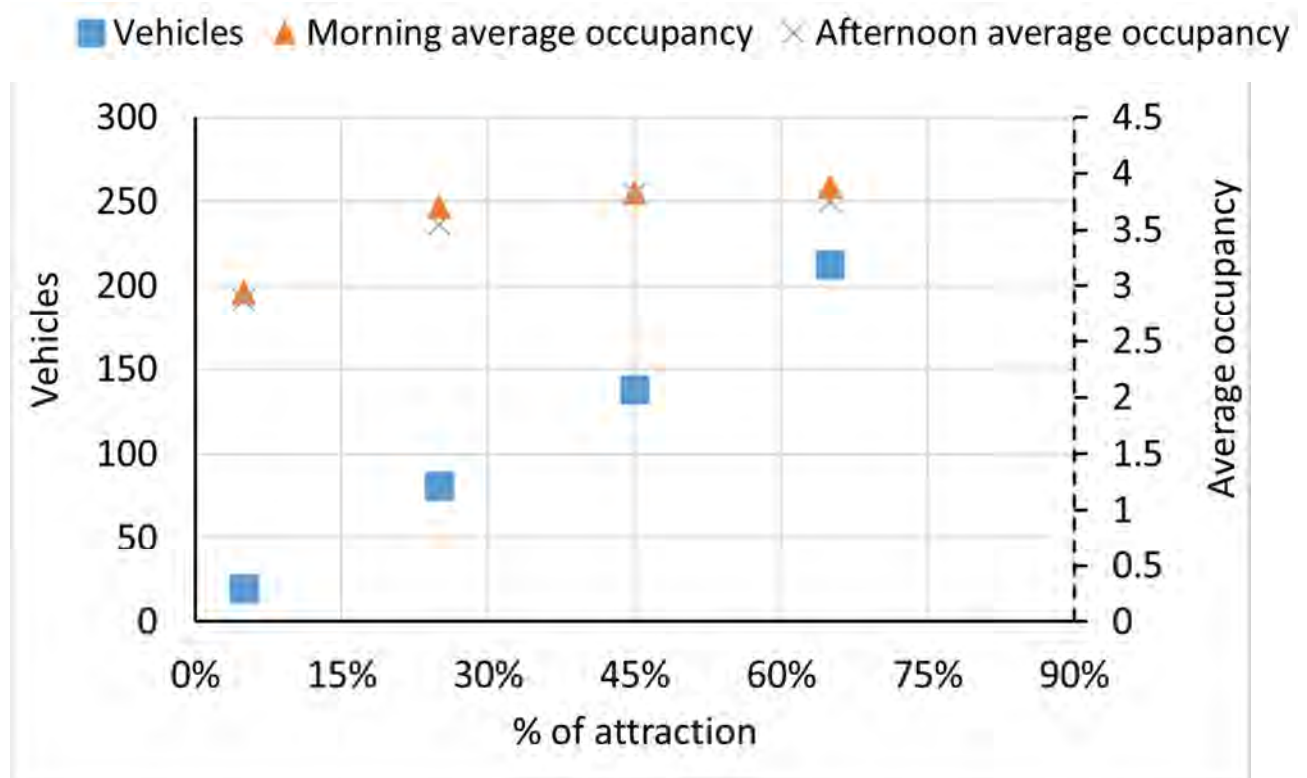


Figure 64 Fleet dimension with 4 seats vehicles

The main differences between two systems are:

- Dimensions of fleet are 210 vehicles for four seats and 95 for nine seats
- When attraction reaches 20%, the four-seat vehicle capacity is saturated, they have 3.5/4 of average occupancy rate. So, this system plans to use more than one vehicle at the same time).
- The nine-seat vehicle reach saturation at 45% of attraction. Average occupancy trend is the same, with a little less occupancy in the afternoon trips. Moreover, higher level of attraction (bigger than 50%) could have many people involved in the same OD at the same time.

For example, if an OD couple has more than nine people, it needs more than one nine-seat vehicle to fulfill transport service, and this happens at the same time and for the same trip.

Simulations for this level of attraction suggest to increase vehicle capacity in order to reduce simultaneous trips with smaller vehicles.

After public surveys in Monterotondo, it has been supposed a level of attraction between 20% and 30%. These values derive from the uncertainty the user experiments when he is called to use such technologies and this new and innovative transport system.

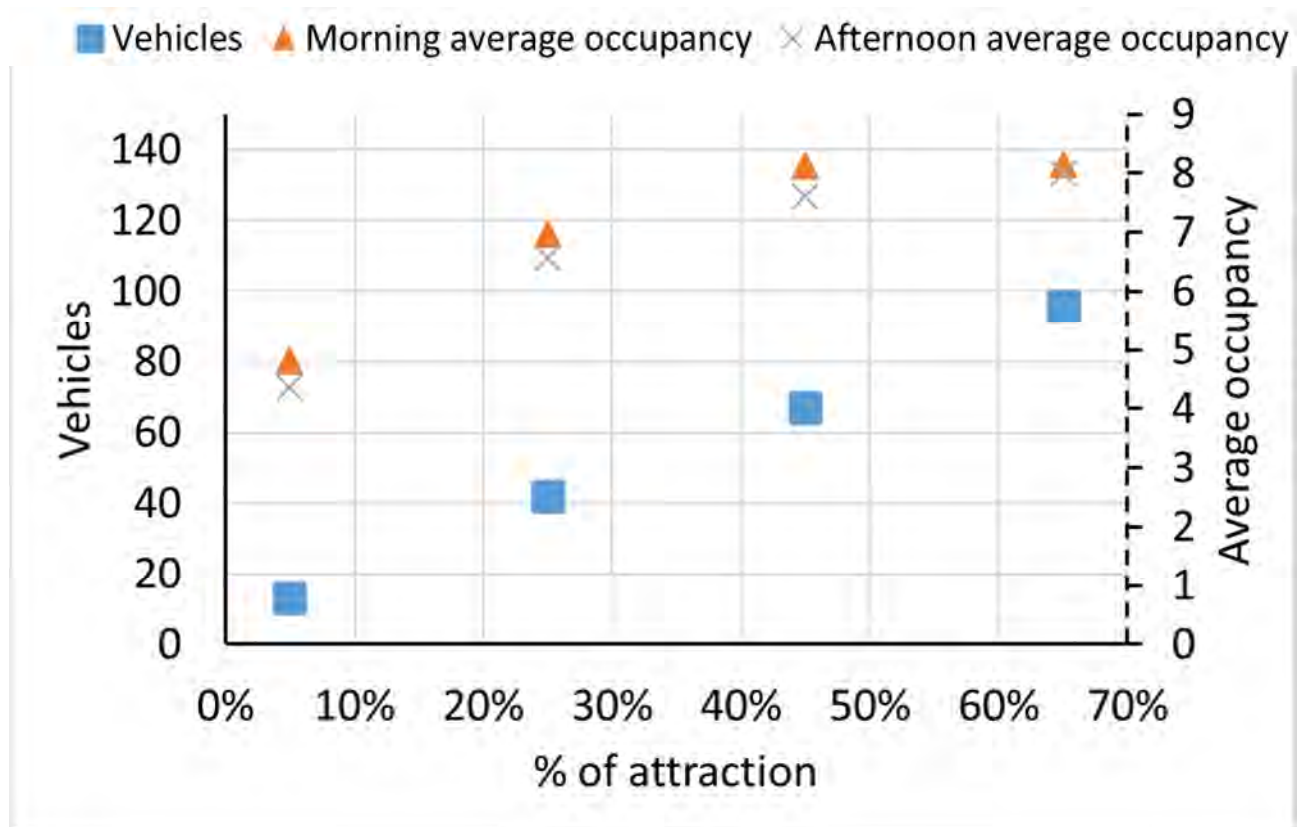


Figure 65 Fleet dimension with 9 seats vehicles

5.5. Charging station location

Vehicle fleet dimension suggests nine-seat vehicles as the best solution, then commercial vehicles (as Nissan e-NV200) have sufficient energy stored on board (24 kWh to 40 kWh) to fulfil more than a day, indeed it needs about 300 Wh of energy per kilometer and it has a mile range from 80 km to 130 km, when average vehicle distance travelled is almost 40 km a day (morning and afternoon), according to simulations.

For the city of Mentana, the corridor links the city centre to the train station of Monterotondo scalo, so vehicles require a cable and a static charging station.

Therefore, it is enough to put a charging station with some parking stalls close to train station. The greater is the fleet, the more stalls are required. They require more or less a stall each ten vehicles, eventually a few charging stations are required as backup option in case of failure, for example at least a charging station should be placed in the city centre, with a barycentric position between all origins.

5.6. Results evaluation

Only main results evaluation indexes are proposed in this analysis. Figure 66 and Figure 67 show the economic result of the two systems proposed (four-seat and nine-seat vehicles). The difference between revenues and costs (blue dots) is always negative in case of four-seat, while nine-seats vehicles reach a break even close to 15% of attraction level. Within the same figures are reported the numbers of repositioning operators (triangular dots).

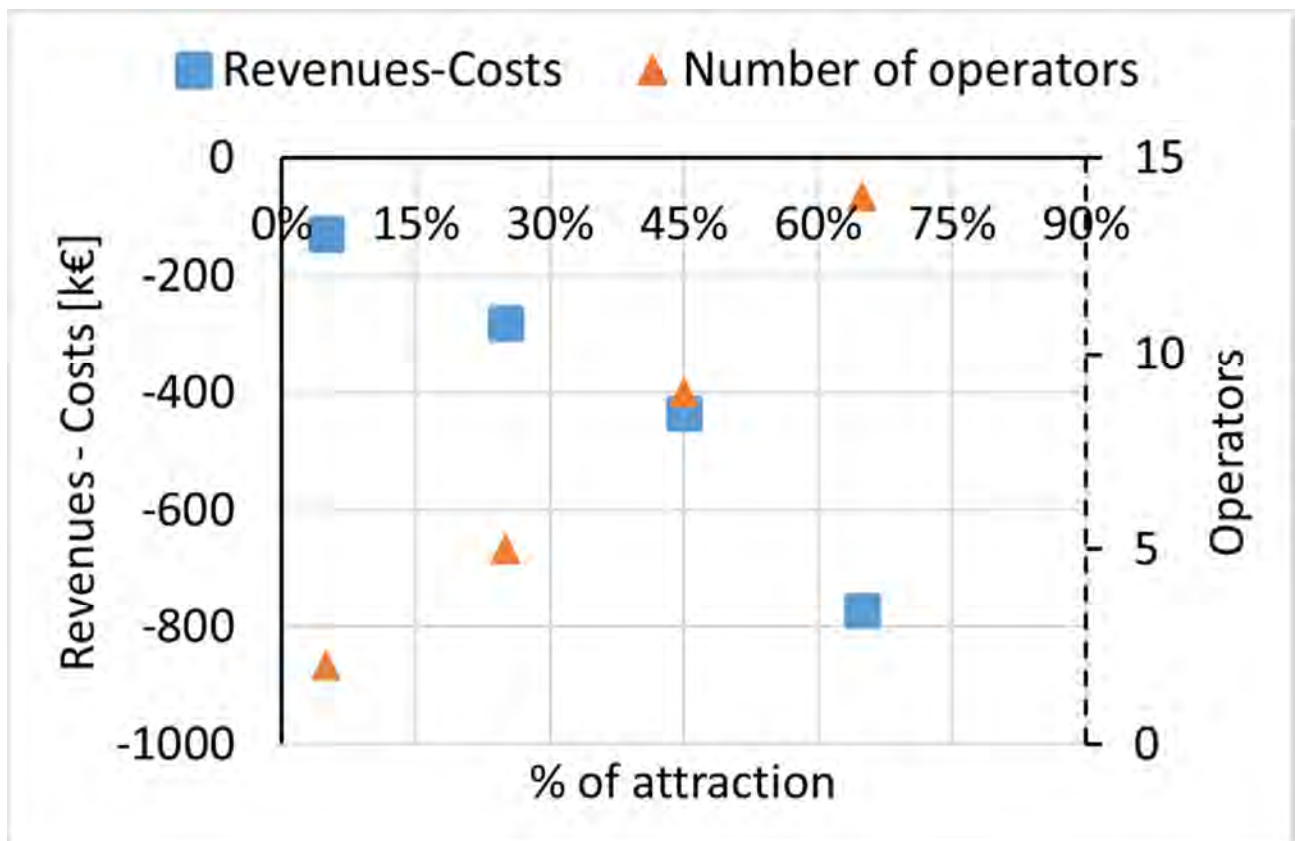


Figure 66 Results for simulation with 4 seats vehicle

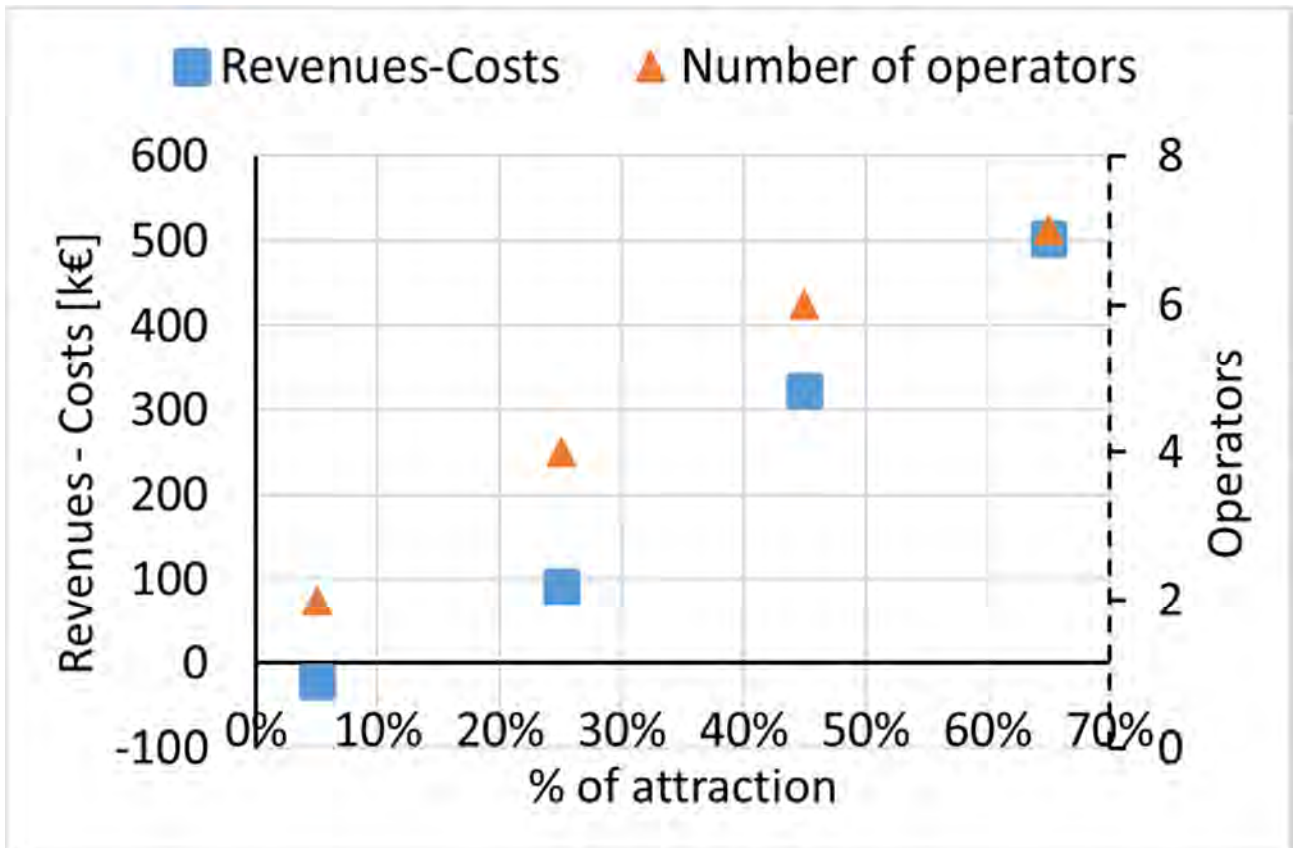


Figure 67 Results for simulation with 9 seats vehicle

6. Conclusions

The present dissertation describes an innovative transport system that can be deployed today with off-the-shelf technologies, it also requires a right legal framework to become commercially available. This work proposes a new design methodology for it as well. Such system is based on small shared electric vehicles for last mile transport, which platoon on specific road arcs called “priority corridors”.

Whereas a last-mile transport aims to serve a pre-existent mass transport or even, if there isn't one, an automated corridor. When these corridors exploit dedicated lanes, rights of way, sensors and smart devices the corridors can be called priority corridors.

Those systems can be implemented from little towns, satellites of a bigger city, to medium and big cities with or without invariant transport systems. Each corridor or mass transport system have to collect at least 1000 pax/h and up to 9000 pax/h to be sustainable under all points of view. It can work with different level of automation, from partial to full automation in dedicated lanes or in a shared environment with other road users.

The methodology is composed by six phases: parameters and input data, itinerary analysis and corridors identification, corridors selection and speed profile generation, vehicle choice and fleet dimensioning, electric traction needs and specifications and results evaluation.

Flexibility and modularity are the strong points of this methodology, as the iterative approach can be restarted when occurs changing of: initial conditions, parameters, levels of demand attraction and/or transport offer. On one hand, these modularity and flexibility rise the calculation time, but in the other hand, they allow to quickly evaluate impacts caused by different transport model, level of attraction, charging method, technology and so on.

It represents a milestone in transport systems planning due to electric and automated technologies, so much that it can be deployed today with current and market available technologies. It could have great impacts to social aspects of cities and citizens, to the economy and, thanks to electric traction systems enabled by fast charging technologies, to the environment.

These systems could work with the highest comfort and performance levels, typically owned by private transports, even if they are public ones.

Cost benefit rate and economic results as revenues minus costs could be positive, even if those systems supply social transport services as in sprawled areas, while now most transport systems require subsidies.

Moreover, this methodology has been tested on Mentana, a little town in the outskirts of Rome with twenty-thousands inhabitants. Mentana has several potential corridors, but only one can be selected accordingly with parameters adopted; it links Mentana centre to train station located in the closer town of Monterotondo, eight kilometres away. People can drive vehicles outside and up to corridor entrance, sharing their vehicle with other users. First mile driver leaves driving task to automated vehicles from corridor entrance to the exit close to the railway station.

An operator relocates vehicles using platooning function that allows to relocate up to six vehicles at once, it depends on vehicle type and length, for example a platoon can be composed by six/seven minivans (9 seats) to three/four minibuses (30 seats).

In those cities with omnidirectional demand (or a counterflow demand), the same users alighting at railway station can use vehicles and do the relocation that should be done by an operator. This behaviour increases system performances and revenues, while at the same time it reduces number of operators and costs because a few vehicles can be relocated by counterflow demand instead by operator.

Results demonstrate a fleet of ninety vehicles (nine sets), which is able to serve up to 1600 daily commuters from Mentana to Rome by train, with a vehicle occupancy rate of ninety percent. It requires at least seven operators to relocate vehicles. Economic results are positive, revenues cover operative costs and the whole system doesn't require subsidies.

The research world foresees that full automation will hit the market around 2050s, meanwhile partial automation is today feasible in some conditions. The main differences are in the use of automation; if it will prevail the shared and public use or the individual one. Traction systems electrification is on the way and just available on the market, since some governments are committed to develop political measures on the matter. Shared mobility is uncertain today, but it is the only feasible solution to reduce social, economic and environmental impacts in cities and the present dissertation can be adapted to each situation.

In conclusion, automated and electric vehicles will enable first/last mile efficient transport services, economically and environmentally sustainable and they could be useful to improve transportation services in rural areas, with a low density of transport demand.

In order to answer the question mentioned in the introduction ([8]): "Will your driverless car be willing to kill you to save the lives of others?" asked in an international survey of The Guardian, the answer should be: nobody! Because this choice must be taken neither by a driver nor by an automated vehicle.

There mustn't be a situation which someone else crosses the automated vehicle trajectory without vehicle has seen it (or infrastructure sensors have informed vehicles) broadly earlier. To do that, an automated road transportation system composed by automated vehicles and smart and certified infrastructure must be designed in a safer way than a human-driven system.

As proposed in "time to collision procedure" it can be possible to evaluate a safe speed profile accordingly with vehicle external environment (see section 4.4, titled "Corridor selection, speed profile generation"), then road arcs must be certified to become corridors, avoiding (as far as possible) unexpected behaviours by other users.

The present work aims to provide a frame of new methodology which allows to catch those challenges in a ground-breaking way. If there was a legal framework enabling such systems, present methodology will be overriding to design them in order to minimize negative impacts and lead to a transport revolution.

7. Future developments

The innovative transport systems proposed here is a concept derived from the new technologies of vehicle automation and electric fast charging. Such system will have impacts in many different fields, so it is crucial to develop tools and methodologies in order to tackle these challenges before these technologies hit the market.

Energy consumptions could decrease due to vehicle automation, platooning and comfort parameters for driving speed. As eco-driving rules for traditional transport systems, an improvement in energy management could be possible, by using charging strategies or even driving speed profiles enhanced with traffic condition in priority corridors.

Electric traction and fast charging technology widely treated in this work could need upgrade and extension of technological models, to consider future solutions.

Further developments could concern impacts on electrical network, it could enlighten possible technological upgrading and strategies in order to manage the energy available of an electrical city grids as a whole.

The human operators' operating time is evaluated with a precise planning for vehicle relocation with observing of collective labour agreement.

The methodology does not conceive an off-peak hour model, for example there are a few complementary solution, as common car rental or free-floating car sharing model; they have some limitation of use but there could be some possibilities of integration between those systems, with relative benefits (more revenues and benefits for the environment, due to sharing vehicles).

The fleet dimensioning includes pool generation with a ride sharing capability, while the ride acceptability time tolerance should follow an evaluation, depending from each city and from social behaviour.

Cost benefit analysis should include detailed costs for corridor selection and adaptation, from the proximity sensors placed at crossings, to smart crossing lights, to speed check, bumpers, edges and barriers, or other mitigation measures. Also, the parameters adopted require a tuning procedure.

This methodology has tested two transport models, both without a pre-existent mass transport: the first one is a little satellite of a big city with a long distance between origin and destination, while the second one is a sprawled city with high transport demand and long distances. A test about a big city with an existent mass transport system, as metro or tram and/or a railway, is missing, so in this case corridors could serve some interchange nodes and link zones otherwise isolated.

There are some parameters for user's acceptability that require behavioural and modal choice investigations, they concern:

- Maximum acceptable time. Waiting, deviation from desired time, losses due to detouring.
- Comfort parameters. Maximum acceleration, maximum jerk, number of seats (vehicle capacity is related to user available space), vehicle type (related to safety and security)
- Economic parameters. Maximum and minimum travel costs and unitary fees
- Technology and performance parameters. as platoon length, headway, energy consumption; others concern system costs as vehicle depreciation, insurance, operator costs and working hours.

All those parameters could be evaluated during system design to do a sensitivity analysis.

It could be promising to add between two iterations of all methodology, an evaluation of user modal choice to assign traffic to road network, with traditional methods.

The interactions between automation, electrification, and shared mobility are not clearly understood. It is, however, clear that the metric that will determine the net impact on energy is not the absolute number of EVs, but Vehicle Miles Travelled (VMT); as the three disruptions will manifest in the ways in which they change people's travel behaviour.

Automation on its own is likely to massively reduce the cost of travel, but probably there can be a 'rebound effect'; in other words, if automated travel becomes so cheap that there is no longer any incentive to ride-share or any need for public push measures discouraging private use, this could lead to an increase in VMT and consequently an increase in energy use and emissions.

On the other hand, vehicle electrification in addition to automation would result in lower energy use, as oil is replaced in transport (the emissions implications of this scenario would depend on the source of electricity). Shared mobility, in addition to automation and electrification, could result in a drop-in vehicle ownership and in the figure for VMT.

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