Escola de Camins
Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports
UPC BARCELONATECH

TRAMeBUS

Viability of the implementation of a semi-autonomous electric tram without rails or overhead lines in a city.

Final Thesis developed by:
Serrahima i Serra, Sergi

Directed by:
Garola Crespo, Àlvar & Vélez Sabater, Gemma

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Agraïments

Aquest treball marca el final d’una etapa, una etapa enriquidora i entretinguda.

Una etapa en la que, any rere any, tots els professionals de l’escola han demostrat que importava la persona i no només l’enginyeria.

Quedo especialment agraït als meus tutors, Àlvar i Gemma, que fa quatre anys van despertar en mi l’interès per entendre com es justifiquen les inversions en grans infraestructures publiques.

Ha estat una sort poder comptar amb ells i la seva confiança.

Summary

This study reviews the current state of development of new Trackless Tram Systems (TTS) and finds that the technology is ready and reliable enough for implementations all around the world.

The study focuses on the last version of TTS developed by CCRC Locomotive and nicknamed TRAMeBUS all throughout the study.

As there is currently a public transport problem in a central avenue (Av. Diagonal) in the city of Barcelona the project analyses if this could be solved taking advantage of the TRAMeBUS vehicle.

Currently the central section of the Avenue acts as a wall and prevents the two Barcelona's Tramway networks from joining and providing a better service to citizens.

A revision of the already studied alternatives for the Diagonal Avenue delivers two scenarios to consider. Unifying the last stations from each tramway network through an on-surface link (4 km) or, unifying them analogously by building a tunnel (2 km) and an on-surface link (2 km) covering the same path.

Then, four scenarios are built from these alternatives them being either exploited by TRAMeBUS or conventional Alstom tramway units.

A Cost-Benefit Analysis of them is made to compare the new system to the conventional light rail one.

The obtained results clearly state that, due to its smaller Capital Expenditure requirements a TTS benchmarks much better than their conventional counterparts.

A merely financial analysis is made to see the economic profitability of the alternatives. All alternatives deliver good results. Both on-surface alternatives might require a similar grant from public authorities.

A Multicriteria Evaluation is also made to assess all the non-monetizable characteristics of both systems and compare them. Again, the on-surface TRAMeBUS alternative gets the best results.

Despite the chosen alternative being very robust to the sensitivity analysis the over conservative scenario build might indicate that, in a real case implementation it is logical to expect lower costs and, consequently, higher overall profitability.

Thus, this study finds that the reasonable investment for a city trying to implement or expand a conventional light rail network is to build a Trackless Tram System.

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Notation

AI – Artificial Intelligence

ART – Autonomous Rail Rapid Transit

ATM – Autoritat del Transport Metropolità

CAPEX – Capital Expenditures

DGPS – Differential Global Positioning System

GPS – Global Positioning System

IRR - Internal Rate of Return

ITeC - Institut de Tecnologia de la Cconstrucció de Catalunya

NPV – Net Present Value

OPEX – Operational Expenditures

PEC – Pressupost d'execució per Contracte

PEM – Pressupost d'Execució Material / Material Execution Budget

STPR - Social Temporal Preference Rate

SAIT – Sistema d'Avaluació d'Infraestructures de Transport

TMB – Transports Metropolitans de Barcelona

TTS – Trackless Tram System

UTS – Units (For Tram vehicles)

VAT – Value Added Tax

VoT – Value of Time

1. Introduction

For anyone born and raised in Barcelona how one of the main streets (Av. Diagonal) should be arranged has been always subject of discussion and debate.

This still to be made decision has aroused concern on how this street should be built. Nowadays we are nearly halfway the start of what would be a city changing project, building a light rail all along the avenue to communicate “efficiently” what’s been call “the two Barcelonas”.

Is it worth it? Shall we still be building light rail in the middle of the cities on the 21st century?

The main problems are that trains, provided they share the same rails, cannot surpass each other. That has been always a problem on railway management whenever rails are shared by freight and passenger trains. Or in subways whenever trying to merge direct lines with normal lines. That should not be much of a problem if it was not because light rail usually travels on surface, merging with cars, pedestrians and any kind of issue derived from that. In the end, all little problems of any type quickly involve a major affection of all the lines rolling on that rails.

As its been empirically proved, it is difficult to resolve, taking a look to the Barcelona light rail service (“Tramvia”) is possible to observe it has been averaging nearly two incidences each week for the past year (2019).

Another problem derived from the use of rails is its price, they cost huge amount of money and all charges comprised might account for the lion’s share of the budget.

So, would not be great to have light-rail without rails?

One should never forget the aesthetic impact the overhead line has on the cityscape. Or the need to put it over 4,5m of height to prevent any absent-minded truck driver from creating a big problem.

So, in the technological era is not there any possibility to avoid that?

In fact, there is one. One that in addition to that it combines self-guiding (and even driving) possibilities. This is the so-called Autonomous Rail Rapid Transit (ART) or Trackless Tram Systems (TTS) which, for instance, does not have a physical rail.

This technology has been baptised by the author with the name **TRAMeBUS** in order to show its a light rail service with unique characteristics from the bus. A hybrid combining the best of the two worlds.

Figure 1: TRAMeBUS the 21st century public transport

This technology was firstly developed by the Chinese (by Zhuzhou CRRC Times Electric).

The purpose of this thesis is to provide a review of the technology and study the viability of the solution. For that a case analysis of its possible implementation in Barcelona will be made.

2. Methodology

This work first focuses on providing enough information to understand the technology its advantages and limitations. This review will also try to assess future technology performance.

In order to properly do it a revision on how other “similar” or meaningful systems work is given. That is why the study will talk about light rail and bus systems of different cities.

After that, and as a proof of concept, it is analysed the socioeconomical viability of the system in a real-case scenario. As Barcelona is currently planning to extend its tramway service to connect two end stations, the study will try to assess how this new technology might fit.

For that, the methodology introduced in “Sistema d’Avaluació d’Inversions en Transport – SAIT” (2015) is followed and a Cost-Benefit Analysis is performed as proposed there. As different studies have been made about Barcelona’s new light rail connection, some advantage will be taken from some of them, in particular “Conexió del Trambaix i Trambesòs. Implantació d’una Xarxa Tramviaria unificada. Estudi Informatiu.” [Roig, JM et al. 2017] and “Projecte de sistemes i avantprojecte d’explotació d’una xarxa tramviària unificada.” [INGEROP 2017].

As it will be necessary to work with prices from different countries and services mainly expressed in USD (United States Dollars) whenever not stated differently they will convert them to euros at the rate 0,9 USD = 1 EUR.

As TTS is a new technology recently being implemented in different places without extensive review or detailed assessment whenever a incertitude is introduced the study will always overestimate its impact with the intention to construct a very conservative scenario and prevent harmful unforeseen impacts undermine the conclusions. In this manner it is possible to assume that the real scenario would be, at least, a little bit better than the constructed one in terms of cost or socioeconomical impact.

3. The Technology

For the sake of simplicity, the reader might first understand it as an articulated electric bus, when getting into the details, one will quickly notice it has a lot more sensors and special capabilities derived from them.

This involves the system does not need a physical rail, it is prepared to follow a virtual path i.e. a painted line in the floor with the aid of AI path recognition systems and many other systems (as GPS). In addition to that, some sensor might be installed in the path to know exactly in which section the vehicle is.

Obviously, it must have a driver or supervisor, nowadays state-of-the art technology is not enough to assure the required safety measures for anything mixing with traffic and pedestrians. Neither do current legislation, so it cannot be operated as an autonomous public transport system completely segregated from pedestrians or other vehicles as some underground lines from different cities.

Up to here the TTS might start resembling the evolution of the Light-Rail Car's everybody is used to see in the cities. But the system does not need to be continuously connected to an exterior power source as it is packed with powerful batteries.

As the vehicle is built with a low floor, accessibility within all types of collectives is guaranteed.

Currently 3 and 5-carriage version have been produced by CCRC corporation. Capacity depends on the desired configuration. 3-carriage tram might carry up to 300 passengers.

Despite all these amazing features the cost might be labelled as economic, the price of the 3-carriage version is 2.2 USD. [Engineers Garage 2017].

Figure 2: Grand opening of a new line in Sichuan, China. Font: Daily Mail

Moreover, the new guiding methodology developed might give the passenger an smoother and more comfortable ride as the vehicle will now where it needs to turn and the track would not need to exert any force on the vehicle to make it turn.

This differentiates the technology from the rubber-tyred vehicles guided by a steel rail or those metros with guiding wheels.

CCRC corporation started working on the technology around 2013 and conducted real tests in 2017. Since then more than 9 lines have been built in different cities most of them in china on the regions of Hunan, Jiangxi and Sichuan.

From special interest is the line build on Harbin, northern china made to assess how the technology behaves in a cold environment. Or the tests made in Doha previous the 2022 FIFA Football competition.

3.1 Battery & Charging

Battery might always be a major concern, but it’s been stated it can run 40 Km on a full charge [Railway-News (2019)], with possibility to charge at the end of the line for 10 minutes guarantying 25Km [Zhang Lipeng (2017)] without forgetting the possibility to charge on stations [Peter Newman (2018)].

So, to put in perspective the capabilities of the vehicle one can calculate if normal service in Barcelona might cause problems due to lack of battery. Under the hypotheses that 10 minutes of fast charging through pantograph gives 25 km and understanding that during night-time it is possible to charge the entire fleet. [Zhang Lipeng (2018)]

Analysis should be made on the worst possible route, provided no big hills are needed to be climbed that would be the longest one.

If one vehicle goes from Gorg (end station from line T5) to Glories it will need to cover 7kms from there to Francesc Macià a new link will be built spanning 4 km and from Francesc Macià to the furthest station (Llevant – Les planes) another 11,4 Km. That adds up to 22,4 km.

This route will have 43 stops. A study made by CENIT in 2017 measured that the average time one of the vehicles from Barcelona Light rail system spends in a stop is 20.6 seconds.

That would involve 860” in this route, which translates into 14,33 mins, if the vehicles are able to charge the 75% of that time, they will be charging for 10,75 mins. Without requiring considering the time at the end stations it is possible to assure they will not have problems due to battery capacity.

Furthermore, in this hypothetical route the total distance travelled without the aid of an electrified overhead line would be of no more than 4km. Moreover, the studied section is eminently flat (less than 40 m of unevenness).

Figure 3: Seville and Nize tramway. Font: Wikipedia

Thanks to the high-power storage capacity the transport authority might be tempted to expand the lines at the end stations with little to no cost at all.

Despite that wireless electric powered vehicles sounds like a new development from the past five years on 2010 “metrocentro”, the tramway of Seville (a city in the south of Spain) has been running on battery charging on the stations through a pantograph. The 20 seconds spend in each stop give the tramway enough power to reach the next one. This occurs in the section between 4 stops near the city centre were citizens criticised the aesthetic characteristics of the overhead lines.

Similarly, and in order to preserve the beauty of some buildings and zones of the city, Nice (France) planned on 2003 a Tramway system that didn’t need overhead lines in a couple of sections of around 600 and 200 m.

Many other sectors have been interested in pursuing and obtaining efficient electric performance throughout the use of batteries, it is necessary to emphasize a couple of facts.

In 2012 Tesla Motors launched they insignia car, the model S, an electric car production model which had an estimated range of around 230 – 330 km.

For the last years concern around human driven climate change arouse, leading big (and not so big) cities pursuing greener alternatives for their public transports systems in the race to lower carbon and particles emissions.

Currently Barcelona is trying to fully electrify a line from the new bus network, H16. This line running on a flat surface near the coast spans for near 28km. The buses have 18m of length, a capacity of around 150 pax and a pantograph for rapid charging. They are manufactured by two enterprises, Solaris and Irizar.

Figure 4: Barcelona Irizar electric bus charging at the end of H16 line. Font: Author

This new articulated bus unitary price can be estimated to cost around 610,000 € and 1,100,000 € built, customised, and rolling in Barcelona[1]. After talking to the drivers of some of them, they declare they are happily satisfied with the buses highlighting a lot of features but, in particular, the new side mirrors that have turned into cameras helping them not suffer with trees on the sidewalk or any other infrastructure susceptible of getting hit by them.

Moreover the battery they have is more than enough to fully make the route without requiring to stop to recharge, this gives them a lot of confidence and makes them charge in the end stations for the allocated time or, whenever the next vehicle arrives which allows to gain some time and prevent delays.

Despite that, a new charger has been built just before the previous one to increase capacity. Due to the electric requirements not only, it has been needed to build new electric transformers, it has also been necessary to connect them to the metro line electric service.

Irizar promises in their 2019 catalogue that their 18m electric bus units might be able to run for 220-250 km with a total 525 kWh battery pack which would translate on an energy consumption of 2,4 kWh/km which might turn to be higher in reality.

The battery pack is highly customisable and might comprise a Super-Fast charging module, a Fast charging module and a Slow charging module depending on client requirement.

[1] Estimation made through the buying statement published by TMB in 2017 and 2020 published in <https://noticies.tmb.cat/sala-de-premsa/tmb-compra-7-autobusos-electrics-articulats-amb-carrega-rapida-pantograf> and <https://noticies.tmb.cat/sala-de-premsa/tmb-compra-23-autobusos-articulats-demissio-zero-continuar-electrificant-xarxa> consulted on the 15th June 2020. (Low precision estimation).

To have a reference one might compare it to the consumption of a three carriage (32m) Barcelona tramway (which can transport 200 pax) which is estimated to consume on average 4,5 kWh/km[2].

One should expect, for similar sized vehicles, higher energy consumption of rubber-tyred ones in comparison with those running on tracks as friction is much higher.

3.2 Mechanics

From the mechanical point of view lots of things must be pointed out.

Rubber tyres can give the vehicle better grip so making the system able to climb steeper gradients (up to 18% in the case of the Solaris ie tram model) whereas traditional light rail might be only able to handle 4-6%.

For the same reason, rubber-tyred vehicles might behave better under rainy conditions or have reduced braking distance than their counterparts running on steel wheels.

The studied system is made up of different cars joined with a cabin at each side. Each car has their own steering system which allows for turning radius smaller than 15m without the need of invading other lanes.

These cars go on top of train-type bogeys with improved stabilization technologies based on suspension and hydraulic systems designed to prevent sway and bounce maximising passenger comfort and minimising road damage.

3.3 Capacity

The 3-carriage tram has a similar size to most light rail units of different brands, 32m long, 2,65 meters wide and 3,4 meters high and, as nearly all public transport vehicles the interior is highly customisable where the operator might choose how to distribute seats and other features.

This might be translated in different capacities depending on the chosen configuration so an approximation to a theoretical maximum capacity based on the comfort level has been made.

To do this approximation it is understood that the normal European capacity for public transport should be near (or immediately below) 2.9 pax/m^2, taking also into account the number of people that are seated.

The value comes from considering that 1/3 of the passengers are able to take a seat (~0,45 m^2) and the left space for standing up passengers at a ratio 4 pax/m^2. No special seats or reserved space for elders, pregnant women, people with reduced mobility or

[2]Infographic published by PTP (Associació per a la Promoció del Transport Públic) in 2015. Available at: <https://transportpublic.org/images/pdf/20150408-infografia-diagonal.pdf>

any other collectives with special needs is considered. Besides no place has been accounted for compact bicycles or personal mobility devices (as electric scooters, hoverboards, skates etc.).

These considerations make the obtained number a theoretical maximum. Despite that, the number might be surpassed at peak hours.

Devoted cabin length is assumed to cover 2.1m at each side.

After considering all figures one gets 214 pax as the nominal capacity for each vehicle.

The 3-carriage trackless tram vehicle developed by CCRC has 3 double doors and 2 single doors on each side which might extend a little bit boarding and alighting time by comparison to the current required time.

3.4 Sensors

3.4.1 Lane following system

The main thing to describe is the capacity of the vehicle to follow “virtual tracks”, in fact the vehicle is more suited to follow a line path painted on the floor.

The technology is nearly the same as the “lane departure warning systems” and “lane keeping assist” most new cars now have and the software behind self-driving capabilities in autonomous cars.

The vehicle mainly relies in the processing of the image its video camera takes plus the information obtained thanks to the LIDAR (Laser Imaging, Detection, And Ranging) being assessed always by other sensors such as GPS.

The system receives the information from the sensors (i.e. an image of the road) and after applying colour correction and enhancing algorithms the Canny Edge Detection algorithm is applied.

This algorithm is based upon the fact that edges have high colour gradients (for instance in purely black and white images an edge involves changing rapidly from black to white or vice versa).

The program might define a region of interest inside the picture as it would not want to work with all the edges that have appeared on the images and, after that, apply Hough Line Transform which is a voting algorithm that search the lines that best fits a series of data.

This process will be recalculated for each recorded frame and the cameras and sensors will be recording several frames per second, averaging the obtained Hough lines, and extrapolating them when analysing dotted lines, a trustworthy result will be obtained.

The process is schematised in the next figure (Figure 5), the reader should note that the real algorithm uses much more information than the one provided by the video camera in order to enhance the results increase reliability and limit the influence of factors such as heavy rains or snow.

Once it has the lines to follow the on-board computer compares its actual path with the desired one and, if needed, steers the wheels.

See Figure 5 for a close-up of the process.

Due to legislation constraints and the intrinsic risk of a transportation system which merges with normal traffic and pedestrians this system has been transformed into a “lane keeping assist” system that will have the vehicle centred in the path as long as the pilot doesn’t intentionally maneuver to divert from it or deactivates the system.

This gives a huge advantage because it is capable to avoid a traffic jam derived from a crash or any marathon or parade that decides to cross the tracks.

So, as it is programmed, the system aids in guiding the vehicle to keep running on its track and warns whenever it drifts away from the lane. [Neha Rastogi (2017)]

It is important to note that optical guidance system is not new, in fact, since 2008 an optical guidance system developed by siemens has been installed in the trolleybuses of TRAM line 1 (UJI – Parc Ribalta) in Castellon (Spain) (8 km section) (see Figure 6). The system enables the automatic driving of the vehicle and ensures a separation from the platform smaller than 5cm. [Serrano, V. 2008]. This implies that people with reduced mobility does not need a ramp or any other assist device to get inside the vehicle.

But Castellon was not the first city to test the system, the French city of Rouen installed in 2001 what they called an “optical guidance and docking system” for all their TEOR lines (Transport Est-Ouest Rouennais). Since then they have expanded a lot the service using different buses with the same system.

Despite this, Las Vegas city has not been so lucky with the system as they had different problems. AS the University of Sydney published in 2019 “For many years, the technology was deactivated due to poor reliability arising from the desert sun, dirt, grease and oil build-up on the road diminishing the pavement marking’s contrast, despite the system stated to work even if just one-third of the stripes are visible.” [The University of Sydney 2019]

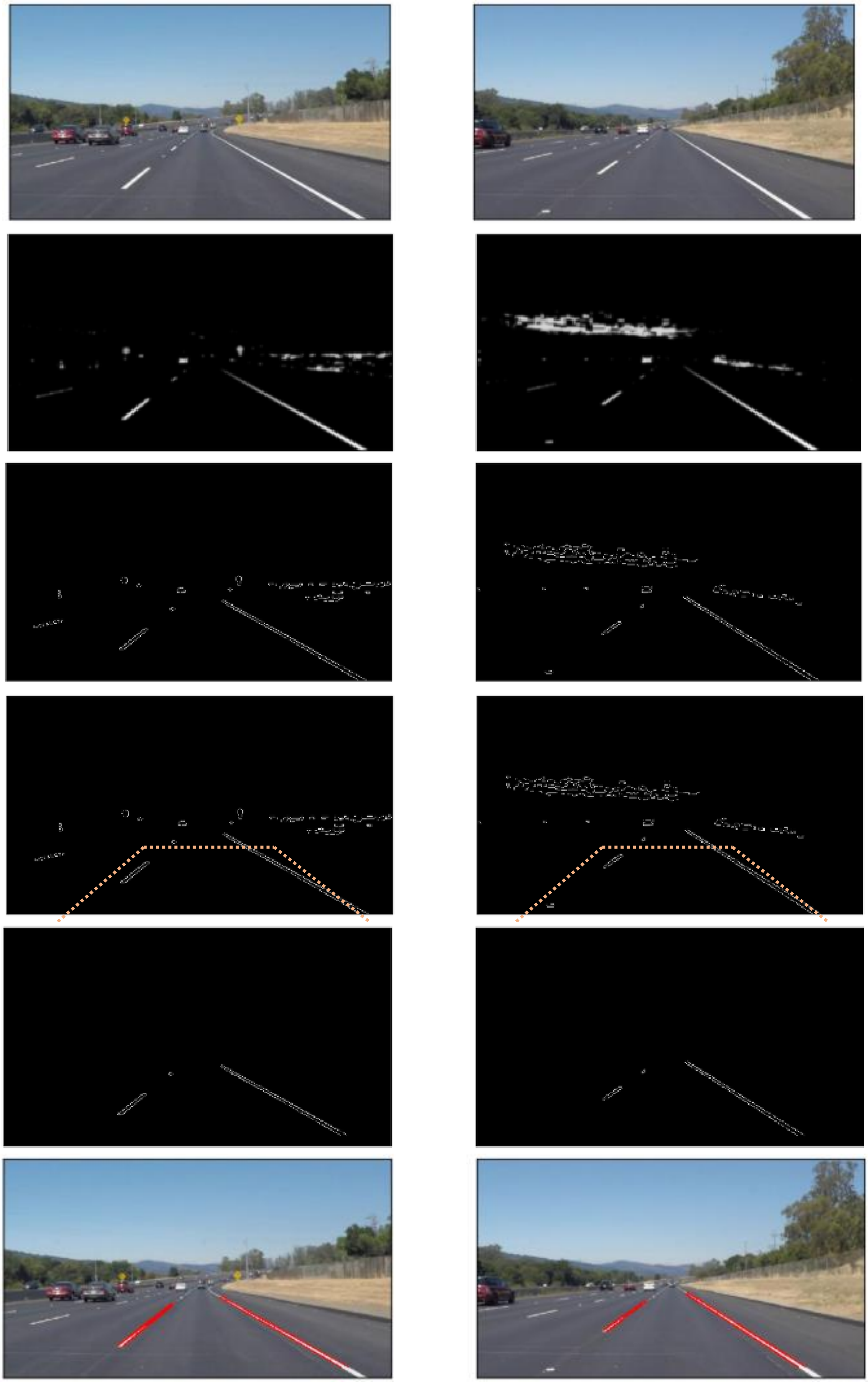


Figure 5: Schematised process of image analysis for self-driving software. Font: [Naoki Shibuya (2017)]

The system used in these three cities was developed in France by MATRA and later bought by Siemens.

Proof of its usefulness is that TEOR has opted for the same system whenever expanding their BRT (Bus Rapid Transit) network currently spanning 32km in 2020.

Or the different videos of Rouen or Castellon where one can see the vehicle self-steering without the driver help.[3]

Figure 6: Line 1 in Castellón (Spain). Font: [Serrano, V. 2008].

[3] *Opticguide trolleybus Iris Civis in Castellon* <https://www.youtube.com/watch?v=4tP0s7MM5Zg> & *TEOR Rouen* <https://www.youtube.com/watch?v=ZrAm-1jVwf8> viewed the 8th of June 2020.

3.4.2 DGPS driving system

Due to safety reasons and reliableness a system should never exclusively depend on one group of sensors or algorithm. Or, whenever trying to improve accuracy the system might merge information obtained through different group of sensors.

That is the point of using Differential Global Positioning System (DGPS) in the vehicle or, more precisely, Real Time Kinematic (RTK).

For the sake of simplicity RTK could be defined as the technology based in DGPS that allows to precisely monitor the position of a moving point in the space.

GPS, and other merely civil-satellite-based positioning systems have a wide margin of error whenever computing the position from a receiver. This precision never gets to the sub-metric range and might be estimated to be around 3-5 m for expensive devices working in proper conditions.

Satellites might have little errors in their clocks, orbits that do not exactly adjust to the expected ones due to many reasons and their signal might not be perfectly transmitted as all the layers of the atmosphere might provide a slight distortion and a tiny delay. This, and many other factors contribute to the inaccuracy of GPS signals and condition the computed outcome of the receiver.

In other to achieve greater precision, the system corrects its position from the signal received from a ground antenna. The position of this antenna is well known and thanks to that it is possible to compute the tiny errors GPS signal might be carrying and the way to correct them. DGPS systems need, at least, a ground receiver at a precisely known position and an antenna to emit its position and obtain the required corrections to make to the GPS signal.

Thanks to this technology sub metric precision is achieved, never surpassing 10 cm and of the other of 1 or 2.

This technology it is already developed (used since long time ago in the civil engineering field) or recently implemented in extensive agricultural fields despite being available since 1996 [Bell, T. 2000].

Currently, the technology, allows agricultural machinery to precisely move, steer and, at the end, operate. These systems automate the driving system while the pilot should still take care of the other tools. Thanks to them no land is left without seeds or fertiliser and the path, braking and acceleration are optimised to save fuel.

Current development gives “ground” antennas working ranges of up to 20km, in the city, despite correctly placing them on top of strategic buildings it should not be expected an effective range higher than 10-12km depending on the layout of the tracks.

3.4.3 Other sensors

In addition, and to increase safety 360 cameras and radars are installed so the vehicle has the capacity to see and monitor the surrounding road conditions and facilities in all aspects. [Zhang Lipeng (2018)].

This translates into an efficient Collision Warning System

The collision warning helps the driver maintain a safe distance with other vehicles on the road and whenever the proximity reduces, it shows a sign to provide a warning. [b] This aids in avoiding any fatal success due to something situated in a dead angle.

CRRC is sure that software upgrades will enable explotation in "double" composition as distance monitoring sensors combined with other ones and telecommunications between vehicles might let a second TRAMeBUS follow another one while keeping a fixed distance (see Figure 7).

Other special capabilities are packed inside the TRAMeBUS such as intelligent communication with traffic lights to have step priority and avoid the needs of braking in road crossings improving this way public service and minimising delays and tram bunching.

Whenever enough and sufficient digitalisation of the traffic lights is made TRAMeBUS crossings could be managed as those near different firehouses in Barcelona where a special signal is lighted up when an emergency call to the firefighters is made (see Figure 8).

Figure 7: TRAMeBUS in double composition. Font: CCTV reportage

Figure 8: Firefighters special traffic light in Montjuïc (Barcelona). Font: Francis Lenn.

3.5 Drawbacks

The TRAMeBUS vehicle, as it rolls on rubber tyres will not be able to roll in top of the current Barcelona tramway tracks embedded in grass. In order to solve this problem an additional budget needs to be made to replace that grass with asphalt or concrete pavement.

This disadvantage it is also a problem for cities trying to green wash their image as it would be never be possible to put the same square meters of grass that in the normal tramway case.

3.6 Cost

According to Neha Rastogi from Engineers Garage the basic cost for the rolling stock is 2,2 M$.

If each TRAMeBUS unit might need 3,5 40ft (12m) Shipping container as some parts might need to be dismantled.

Transporting each container from the factory to the port by truck should cost around 0,86 $/km [He Huifen (2020)] and it is a 1100km journey (Zuzhou, Hunan to Shangai International Port).

As seen in different places shipping a container from Shangai to Barcelona should not cost more than 4.000$ on average.

In addition to that cartage costs might be added, they should be of the order of 550 € per container. [Dean Ramler (2012)]

Shipping insurance cost could be taken as 1% of the value of goods (22.000 $).

Taking 4 containers for each TRAMeBUS total shipping and insurance costs might get near 40.000 €

If one assumes that the TRAMeBUS consumes 50% more energy per kilometre than the Barcelona light rail service (thus 6,75 kWh/km) when desiring to travel at least 40 km on a single charge, a battery pack of 270 kWh will be needed. Which is not much. For instance, Irizar ie tram model might packs up to 525 kWh.

Despite the quantified minimum requirements, the manufacture states that its vehicles have a 600 kWh battery pack.

2019 Bloomberg report augurs that by 2023 batteries will cost around 100 $/kWh although some manufactures claim they have already reached the milestone. [Carlos Noya (2020)]

So, the cost of battery replacement is expected to be around 24.300€. Despite the manufacturer stating that its lithium ion phosphate batteries might last for 25 years [Newman P. et al. (2018)]. The study though, expects to replace it 1,5 times during the service life of the vehicle (30 years) as other manufacturers guarantee 15 – 20 years and fast charging modules might wear faster than expected. Then, the expected battery replacement at 15 years plus the change of worn modules when needed will add up to 81.000 € more.

It is still required to add up the required on-board systems and their replacements due to its smaller service life (like operating aid and ticketing systems) which has been quantified to 229.000€ by [Roig, JM et al. 2017].

Due to uncertainty, tariffs, other fees and, again, to prevent surprises it has been decided to add 8,6 % of the rolling stock cost as an over cost so the study ends considering 2,5 MEURs/unit for the TRAMeBUS 3-carriage vehicle.

All costs are detailed in the next table. See Table 1: TRAMeBUS Price Summary. (in euros)Table 1: TRAMeBUS Price . Please, notice that all costs have been added up and converted to euros.

TRAMeBUS Price Details (€)	
Unit Price	2,500,000.00
Rolling Stock	1,980,000.00
Ticketing	60,000.00
On-Board systems	169,000.00
Overcost	170,160.00
Shipping	20,040.00
Insurance	19,800.00
Bateries	81,000.00

Table 1: TRAMeBUS Price Summary. (in euros)

3.7 Current implementation

Currently this new technology is being implemented in sixteen different projects. One of those outside mainland China.

Leaving aside the 3km test track first build in Zhuzhou (2018) the most interesting case is the Yibing ART line, which is 17,7km in length and required an investment of 142 MEUR (Conversion from yuan to euro as of 19/06/2020 equals 0,13). [Hunan Provincial Government (2019)]

This investment proofs what CRRC has been stating about their new technology, an ART line can be built for less than 10MEUR/Km.

Despite that, the most interesting case is the new line that has been built in Doha, Qatar; for the 2022 FIFA World Cup. Tests started in July 2019 and they are expected to be conducted throughout the year. At the end of the inauguration, the Qatari Minister of Transport & Communications declared to be very happy with the technology and expecting ART to help them in meeting their efficient transportation requirements.

Qatar performance review will be key in assessing how batteries behave in a hot environment.

Figure 9: ART Trial run in Doha, Qatar (left) and Harbin, China (right). Font: CCTV and Chinadaily.com

4. The 20th Century Light-Rail

Nowadays citizens are used to see light rail installed in the centre of cities, as it is been empirically proved it is an efficient mode of transportation, capable of transporting huge crows quickly. This high capacity is normally paired with a good perception/evaluation given by users.

Cities quickly realized of that and built tramways in their centres

For the purpose of the study the Alstom Citadis Dualis is analysed and used as an example. Many European Light Rail transportation systems (including Barcelona's) are exploited with that model.

The Citadis has capacity for around 220 people (highly depends on configuration).

Symmetrically composed by 5 modules communicated all through its length with a cabin at each end; feature which facilitates a lot changing direction at the end stations.

The extreme cars are the ones mounted on top of motor bogies.

Spanning all along 32 m does not have problems taking turns due to its 4 articulations between modules. According to [Castañer, C. 2010] the minimum radius in Barcelona current layout is 23 m.

Possibility to unify 2 units (Adding up to 10 modules) directly doubling capacity.

It is obviously 100 % accessible to people with reduced mobility.

Price at around 3MEUR and still the reposition of all the system which smaller life span than the vehicle (30 years) should be added. All together might account for 229.000€ more according to [Roig, JM et al. 2017].

Figure 10: Alstom Citadis Dualis, Barcelona. Font: La Vanguardia

4.1 Overhead Lines

Directly omitting the “third rail” alimentation system due to its potential danger and sharing the remarks made by [Roig, JM et al. 2017] where it is clearly stated that the best choice is the “Tramway Overhead Line” which includes just one cable mechanically compensated.

Provided that the system is being designed for a densely populated urban environment, the speed constraint of 100km/h will not be considered as one should not expect to surpass 50 km/h (maximum permitted velocity). Besides, the rolling stock might be capable of travelling at speeds of 70 km/h or even struggle to reach 100 km/h depending on the layout.

Hence, taking into consideration the other options the “Rigid Overhead Line” and “Flexible Air Catenary” might be discarded.

Both are being casted aside due to aesthetics reasons and price.

Particularly the Rigid Overhead Line requires a metal bar to conduct the electrical current. Due to its higher weight it requires a lot more supports, nearly each 8 – 12 m depending on the speed, which cannot surpass 100 km/h. So, the system has no advantage different than lower maintenance costs (not justified if lots of supports are needed) or no buckling (vertical deformation) which does not pose a problem in the other solutions. For these reasons rigid overhead line gets only sense inside tunnels.

While the Flexible Air Catenary is used in long and fast railway lines due to the possibility to travel faster or the capacity to install posts at longer distances from each other. Provided it requires a more complex layout of cables (visual impact) though requiring building even higher posts and taking into consideration its higher building and maintenance cost a single advantage could not be found for urban layout.,

Trolleybus layout basically discarded due to its small capacity not comparable to the tramway.

In the end, the overhead line will require building posts with a design distance around 40 m and possibility to extend it up to 50 m at a distance of 1.7 m of the median line of the rails capable of getting further in curves depending on the radius.

The line will be mechanically tense in sections no longer than 1000 m with a 1500 kg tension. The current system based on a hanging mass does not pose problems due to thermal expansion and contraction.

Lines are made by electrolytic copper of 150 mm^2 section with a subterranean feeder of equal properties. Supplied at line tension (750 V) on direct current. [Castañer, C. 2010] & [Roig, JM et al. 2017].

This system is made by lots of enterprises so not supplying concern should arise.

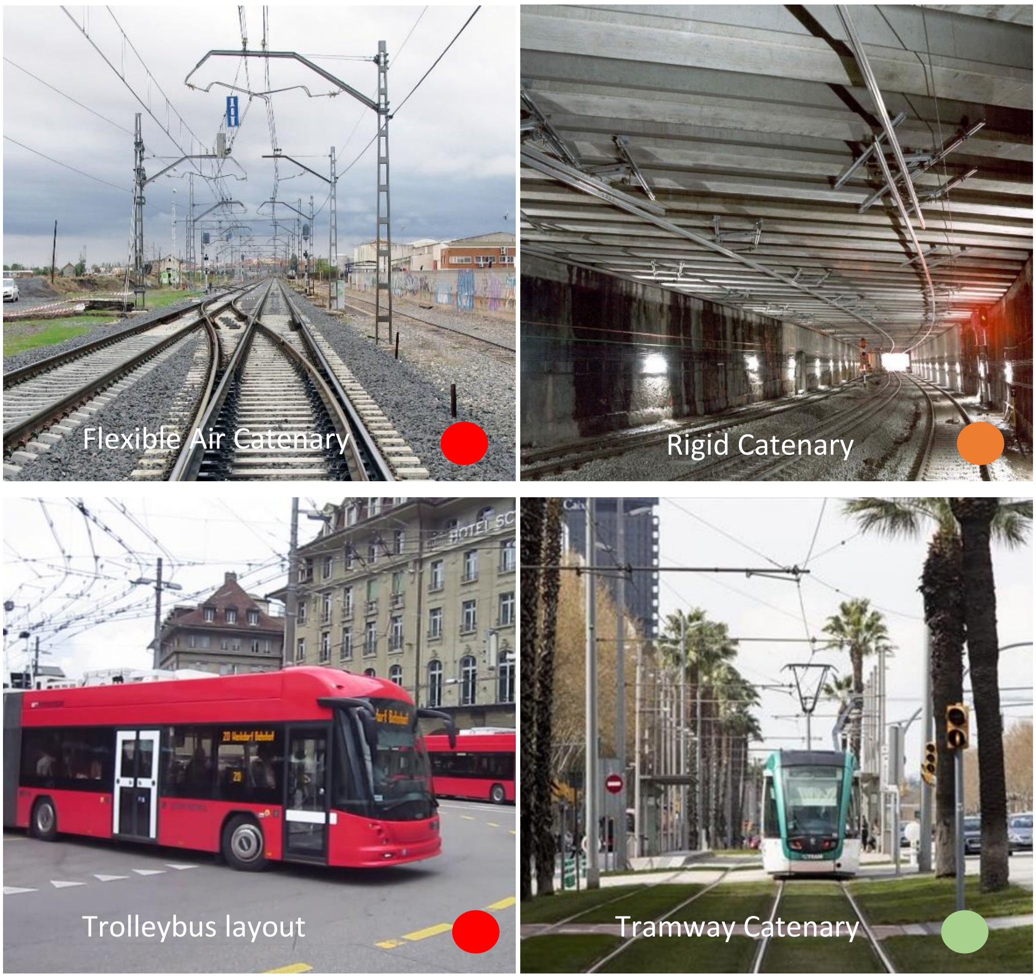


Figure 11: Overhead line types. Fonts: ADIF, PANDROL, TRANSIRA & El Periodico

4.2 Rails

Although it might be evident, railways need rails and so does a "light rail" service.

There are lots of different rail types, looking to the tramway Ri55N rail (the one used in Barcelona) one can see that it needs a lot of steel to put in place (around 55,55 Kg/ml).

However, the steel price (around 1.250 €/tn which will involve more than 1 MEUR for 4km) is not the only responsible of the huge investment costs of a tramway system. These rails need to be welded and properly anchored to the floor which must be previously prepared with minimal longitudinal imperfections. Moreover, this system requires to be embedded inside the pavement which translate in the need of joints, and the placement of the rail before the finishing coat (asphalt, concrete, gras etc...). All those things make the rail layout much more expensive than a normal asphalt layout.

4.3 Bogies

Bogies are what sustain trains, tramway, and other railway vehicles. They made be though as a little car sustaining the vehicle.

Strategically spaced they are normally made by two axes with each one with a couple of steel wheels, they also pack suspension, brakes, and power trains.

They are the responsible of enabling vehicles without steering system to make turns. Wheel shape help as they have a flange to avoid derailing and a semi-conical shape that acts as a differential when turning.

Bogies and the rail vehicles are heavy that is why a lot of effort is put in the bogie suspension to prevent wheels impacting rails and rapidly wear them. That is also one of the main reasons why rails should ensure minimum track defects.

Thanks to the care taken in the design and construction of the bogies and rails, railway vehicles are normally very comfortable to the passenger as big vertical and lateral accelerations are avoided at all costs.

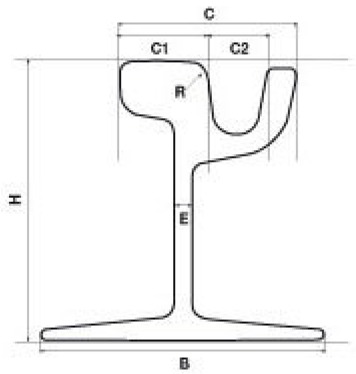


Figure 12: Grooved rail profile. Font: AcelorMittal and Alstom Citadis bogie. Font: P. Rouanet - La Voix du Nord

4.4 Capacity

The Alstom Citadis 302, which serves the current tram network in Barcelona, is a 32,6 m long unit with five modules. It has a cabin at side.

The width of the unit, which can circulate in double composition, is 2,65m and its height without pantographs 3,27 m.

The vehicles have two simple doors in the end modules and four double doors in the two suspended modules. This set of doors in each side are the ones that allow the vehicle to stop, on average 20,6” in each stop (deviation: 7,6”) according to [F. Rossell et al. 2017]

Following the same methodology that for the CCRC vehicle one might figure out that the capacity for the Alstom Citadis 302 is in the range of 219 passengers.

This model can work in double composition which involve unifying two different vehicles and exploiting them as a big one, directly doubling capacity. All the daily passenger forecasts made hitherto foresee the need of double composition in order to give a proper service at peak hours.

Figure 13: Barcelona's Alstom Citadis profile. Font: Antonio Lajusticia Bueno

5. Actual Situation

In order to assess potential demand and the possibility of implementation it is important to understand how everything is working today.

Taking the "Enquesta de mobilititat en dia Feiner 2018" [ATM 2019A] as a source to know which modality of transport people rather choose, it is easy to appreciate that Barcelona's citizens prefer non-motorized vehicles whereas non-citizens public transport.

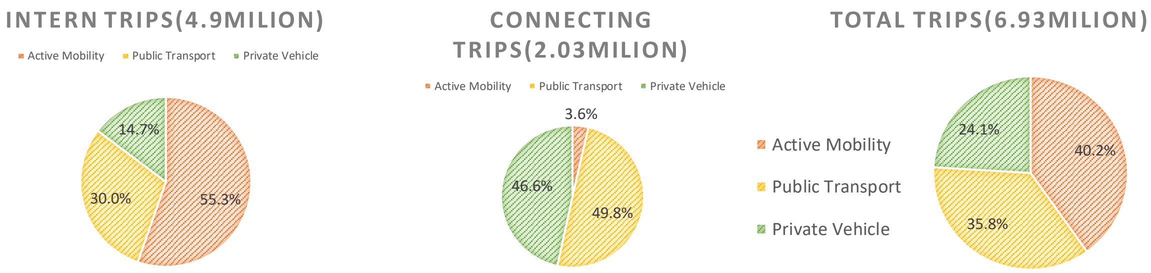


Figure 14: Modal Distribution in Barcelona. Font: [EMEF 2018].

Getting the attention to the study section this project is analysing, the tramway's stops with higher passenger affluency (Francesc Macià & Glories) are also those which are planned to be connected [ATM 2019b].

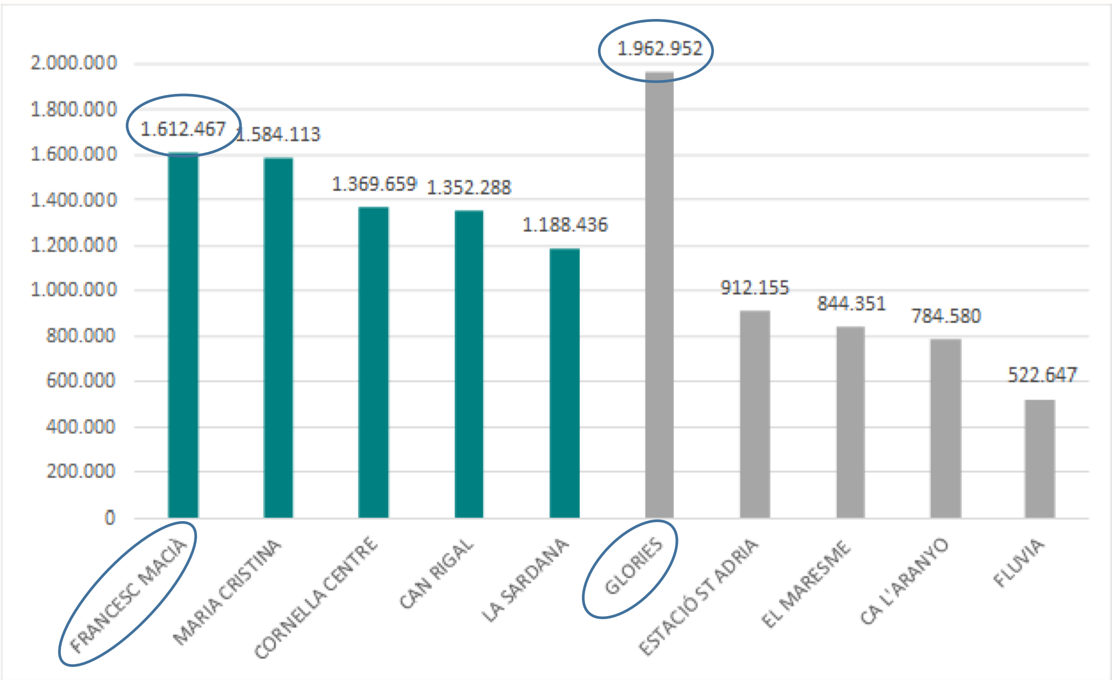


*Figure 15: Passengers on working days /stop*year. Font: [TRAM 15 Years (2019)].*

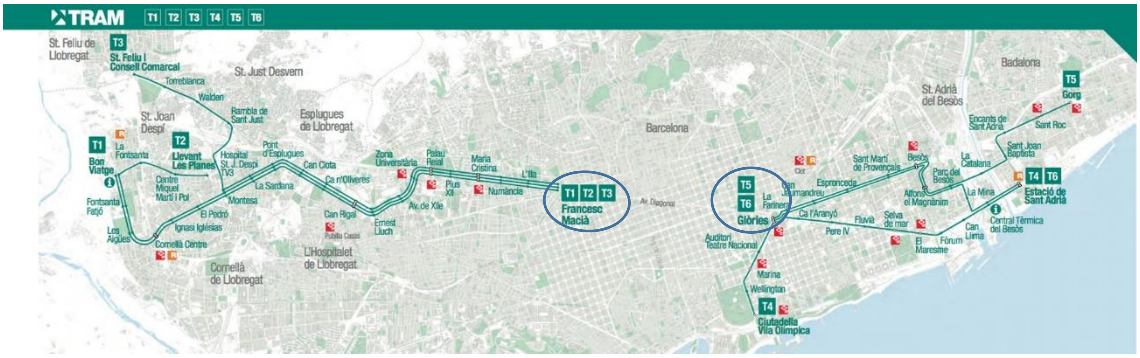


Figure 16: Francesc Macià and Glòries stops in Barcelona's light rail network. Font: ATM.

In addition to that, the Barcelona's Tramway system has always been the best ranked of all public transport possibilities by users, getting a 7.4/10 in the last survey (EMEF 2018). [ATM 2009] to [ATM 2019A].

5.1 Bus

Barcelona's bus service started in the first decade of the XX century while the city's public transport infrastructure offer was monopolised by the tramway companies.

Despite the failure of the first bus line in 1922 a private company started another bus network which had nothing to do with what people is used to see today and resembled more inter-urban buses where everybody gets their seat.

After the Spanish war due to economic problems only the lines connecting the centre with the peripherical neighbourhoods were maintained.

Around the 50s the town hall started buying shares to start managing the public transport service but, it was not until the mid-60s that the number of buses surpassed the number of tramways.

From then buses kept replacing the light rail system until today were only the "blue tramway" is left as a survivor from the period were tramways monopolised the public transport service and nowadays works as a tourist attraction.

The network, then, was captive of the tramway heritage and new lines were implemented to cover the growing demand without serious planification.

That is the reason why, until 2012 the bus network disserved users that wanted to go from a neighbourhood to another without approaching the city centre. Potential links that have kept growing since the end of the war.

In 2012 though, the New bus network started deployment. This new network deployed mainly vertical, horizontal and some diagonal lines taking advantage from the grid-shaped streets of Barcelona.

Figure 17: New bus network, Barcelona. Font: TMB

This new BRT (Bus Rapid Transit) network (Figure 17) improved a lot the previous one by better spacing and placing stops, linking with important transportation nodes, obtaining higher commercial speeds, and helping with line transfers. In the end, bringing the different points of the city closer to everyone, making it smaller.

Nowadays the bus network is a hybrid from the ancient one and the new. The resulted network gives service to all the corners of the city while approaching the overall service to a high capacity bus service.

Despite that there are still some potential links that are not served by the bus, this network currently fails in making the connection all throughout the diagonal avenue, but, specifically, between the “Francesc Macià” and “Las Glòries” stop. There is though, some bus option but they might just serve to get someone to the midpoint (see Figure 18).

In 2019 Barcelona’s bus network moved 215 million passengers at a mean commercial speed of 11,8 km/h.

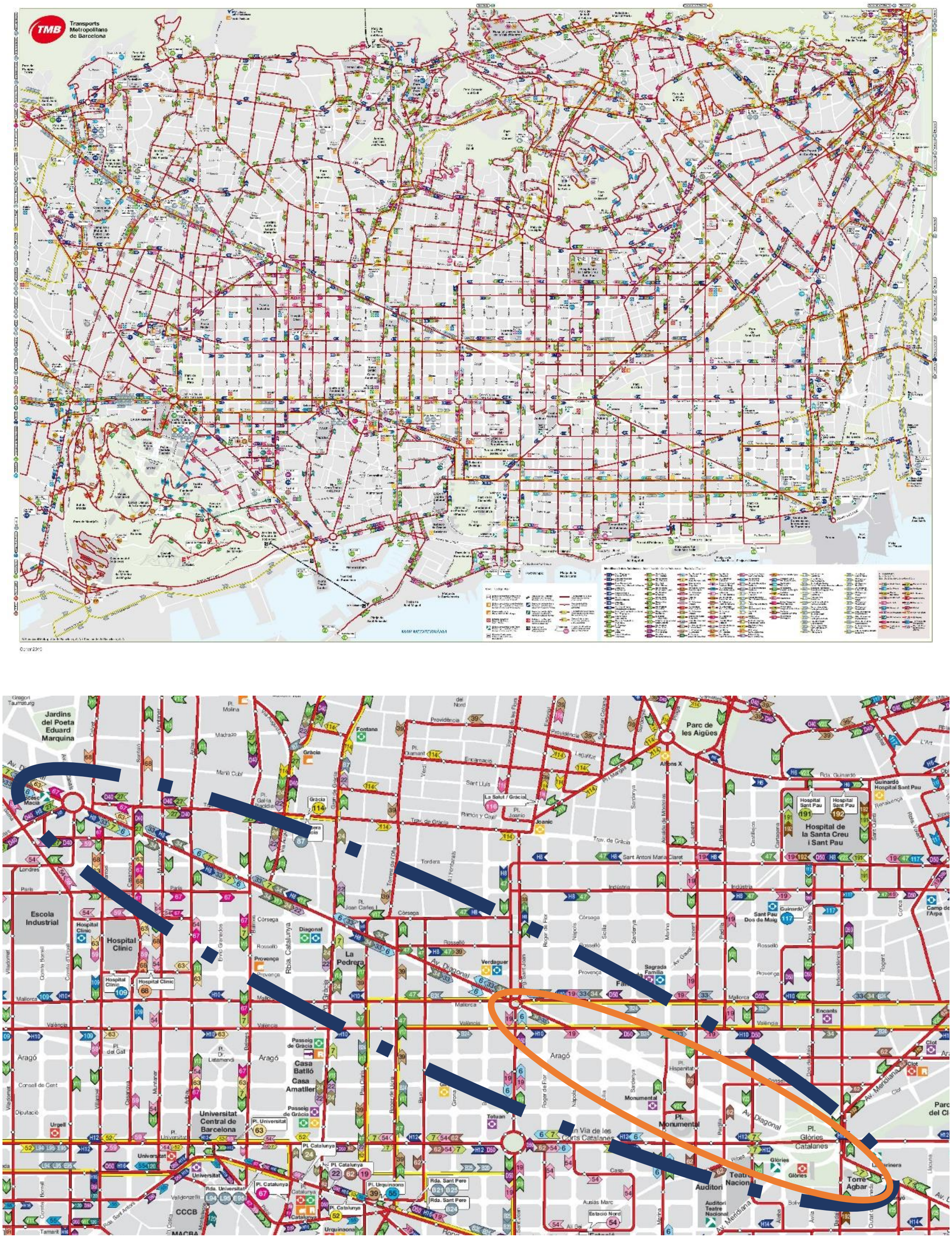


Figure 18: Actual map of the bus network in Barcelona and section of interest (blue). Font: TMB

5.2 Metro and other urban railway system

First urban railway system was built in Barcelona in 1863 but it was not until the late 20s that a serious development was made.

Different lines kept enlarging their tracks, getting covered or improving their stations in a nearly non-stop progress since then.

Two different operators (TMB & FGC) exploit most lines and another railway operator aiming to connect Barcelona with their adjoint populations (Renfe) another 6.

At the end of 2019 they were able to move a total of around 620 million passengers, the lion’s share of the total public transport users of Barcelona.

	Línies	Longitud xarxa (km)	Estacions	Trens /hora punta i sentit	Cotxes-km (milions)	Δ 19/18 (%)	Viatges (milions)	Δ 19/18 (%)	Recaptació (M€)
Metro	8	121,4	160	143	95,1	0,8%	411,9	1,1%	275,81
FGC	17	150,0	80	49	33,2	0,8%	91,1	4,4%	72,99
Rodalies de Catalunya (Renfe)	6	515,8 (5)	119 (6)	36	101,5	-0,1%	119,3	2,7%	155,24
TRAM	6	29,1	56	23	2,6	-0,7%	29,8	2,4%	15,55
Total Transport Ferroviari	**37**	**816,3**	**415**	**251**	**232,3**	**0,4%**	**652,1**	**1,9%**	**519,59**

Table 2: Barcelona's railway data. Font: [ATM 2019Ac].

One of the things key of the metro system relative importance might be their high capacity and the ability to get faster to destination than the other mass transport alternatives. It is then important to highlight that Barcelona’s metro system has an average commercial speed of 28 km/h.

It is then of utmost importance for the project to understand the affection that the planned growth of the metro network might have in our project.

It should be pointed out that the extension of the L8 line (dashed light pink line in Figure 19) should be opening in 2025 covering an alternative but also joining Francesc Macià and Glories tram station. This may imply a decrement in the potential users studied considered in the project.

When the works carried on the central part of L9 and L10 (dashed blue and light orange lines) come to an end, they might alter our study. These two lines started construction in 2003 and since then have suffered an innumerable amount of inconveniences and problems that have delayed their start and raised the price. They will encircle Barcelona from the north and might imply a minor affection as they do not run parallel to our section of study, but they are capable to connect some Trambaix stations with some Trambesos ones.

As seen in the case of the public bus service, no metro line directly covers the link between Francesc Macià & Glories stations.

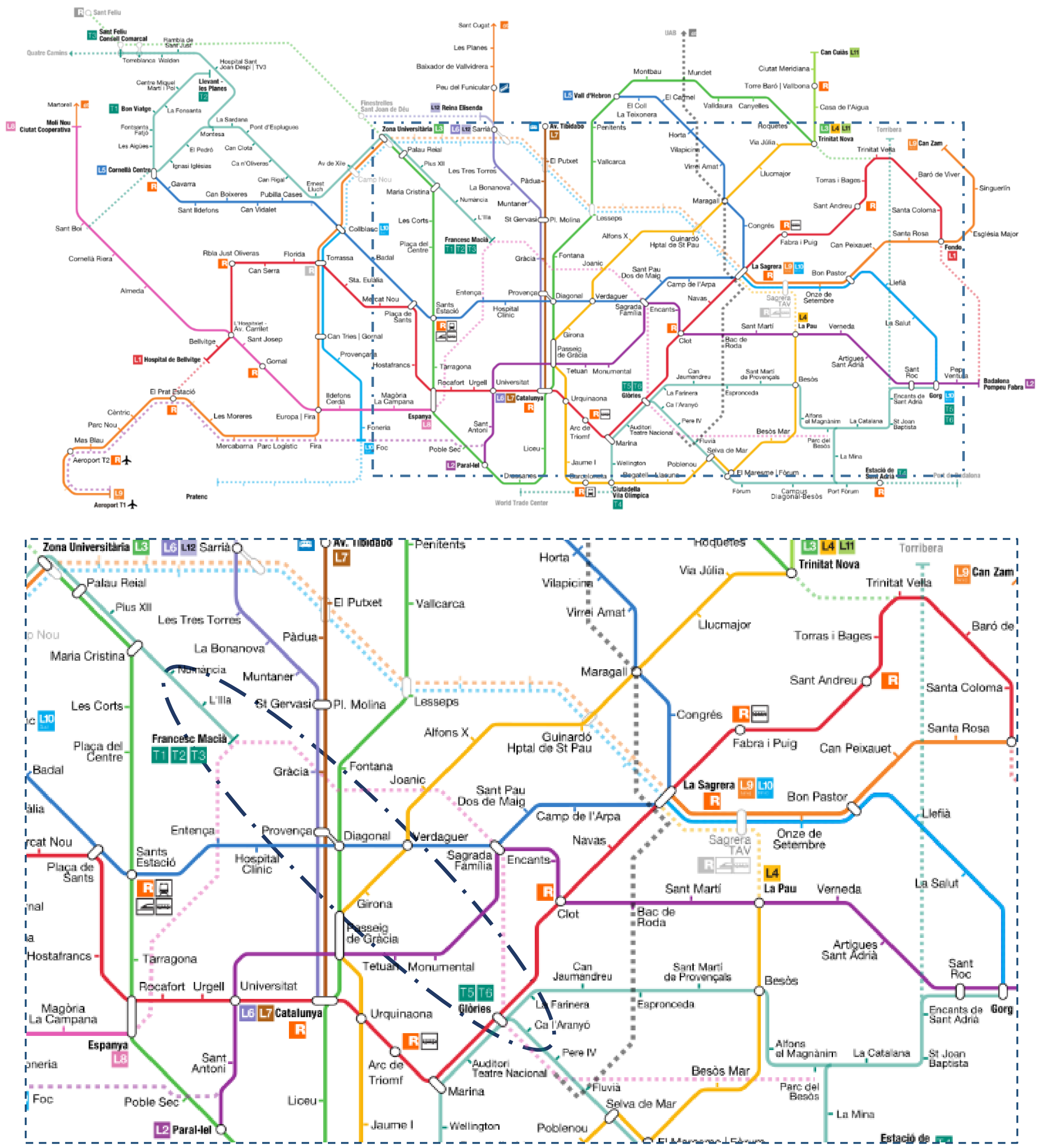


Figure 19: Barcelona's rail systems and their programmed future expansion. Font: Wikipedia

5.3 Other transportation systems

5.3.1 Bike infrastructure

The Urban Mobility plan of 2013-2018 included the objective of tripling the number of cyclable kilometres by adding bike lanes, improving the existing ones and pacify the traffic by adding “30 km/h” zones and other upgrades of different streets.

In that sense Barcelona might count today more than 209 km of bike lanes by contraposition to the 116km it had in 2015. Despite that the town council plans are very ambitious and hope to construct enough bike lanes as for the 95% of the population to have one at 300 meters or less from their home.

As of 2020 Barcelona has planned new bike lanes and has made a remarkable progress in boosting the infrastructure thus attracting users to use them. As riders or people taking advantage to the new electric personal mobility vehicles.

In Figure 20 it is possible to appreciate how this cyclable paths are distributed in Barcelona, it might be observed the split between bike lanes (red line), 30km/h zone (light green zones), green paths (green lines) and cyclable streets (blue).

As shown in the figure, it seems like Av. Diagonal is well connected by cyclable infrastructure (Diagonal red line in the figure). Despite that, users complaint that there are car-bike intersections that could be resolved in a better way.

That might be the reason why the project in the diagonal avenue improves the existing bike lanes and gives them more space and a different layout.

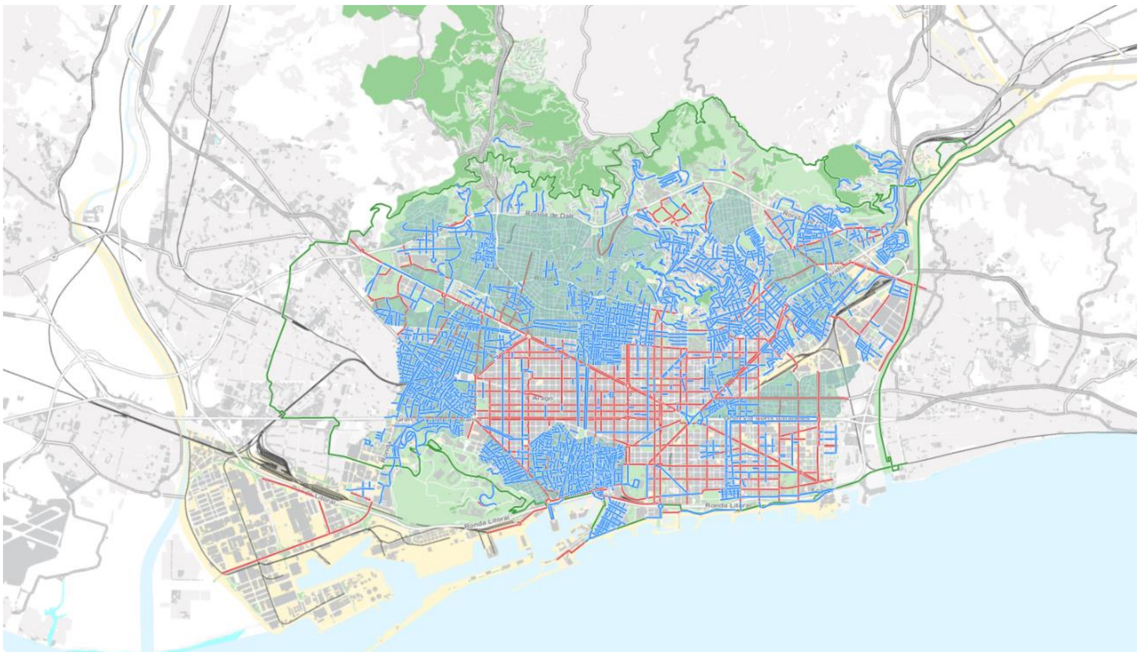


Figure 20: Barcelona's cyclable paths (February 2020). Font: Ajuntament de Barcelona

Cycling is thought to be one of the most efficient ways to travel within cities due to the minimal energy consumption per kilometre (see Figure 21Figure 21), withholding of greenhouse gasses, promotion of a healthy lifestyle and its easiness to store upon arrival to destination.

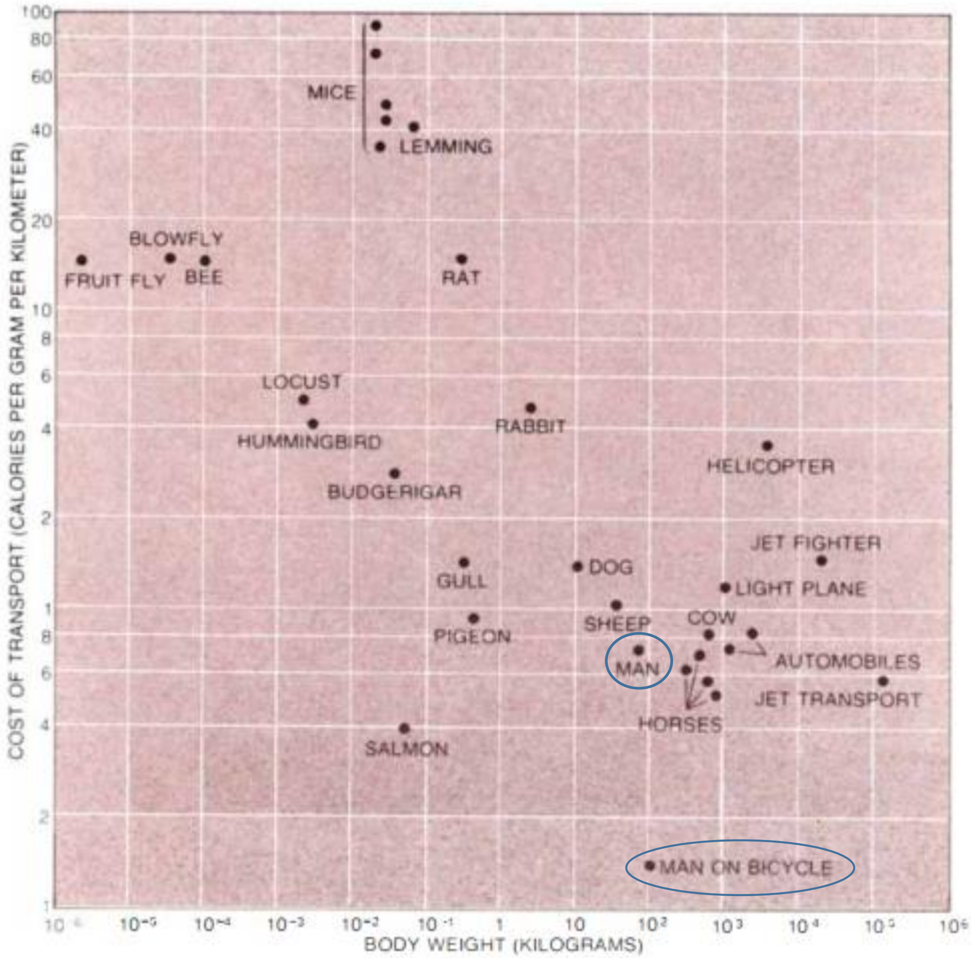


Figure 21: Energy consumption for each transportation mode. Font: Vance A. Tucker, Duke University

5.3.2 Walking infrastructure

The studied section of diagonal avenue might be simplified into three layouts.

In 2015 the upper half of the diagonal avenue was reformed leaving this part with more than 7,5m of sidewalk per side.

The lower part is divided in a zone with two central boulevard with 5m devoted to pedestrians and tiny sidewalk adjacent to the buildings that in some zones is not wide enough for someone with a wheelchair.

The “final” studied part is just a central boulevard with decent adjacent sidewalks.

This unevenness of the avenue along with other factors ended implying an uneven pedestrian travel intensity being the upper part the one with higher demand.

5.4 Urbanism

All along the studied section there are mainly residential houses with some offices (from around 6-8 floors). And some high-rise office buildings.

This distribution is pretty constant all along the avenue, even though, in the upper part more restaurants and terraces are observed (as it is the place where the layout allows them).

As one goes from Francesc Macià to Las glorias it is possible to notice a decrement in the private vehicles lanes and even the disappearance of the bus lanes.

Close to the middle of the studied section the avenue crosses "Passeig de Gràcia" another major city avenue full of pretty tourist attractions.

See Figure 22 for a detailed close-up of the different sections.

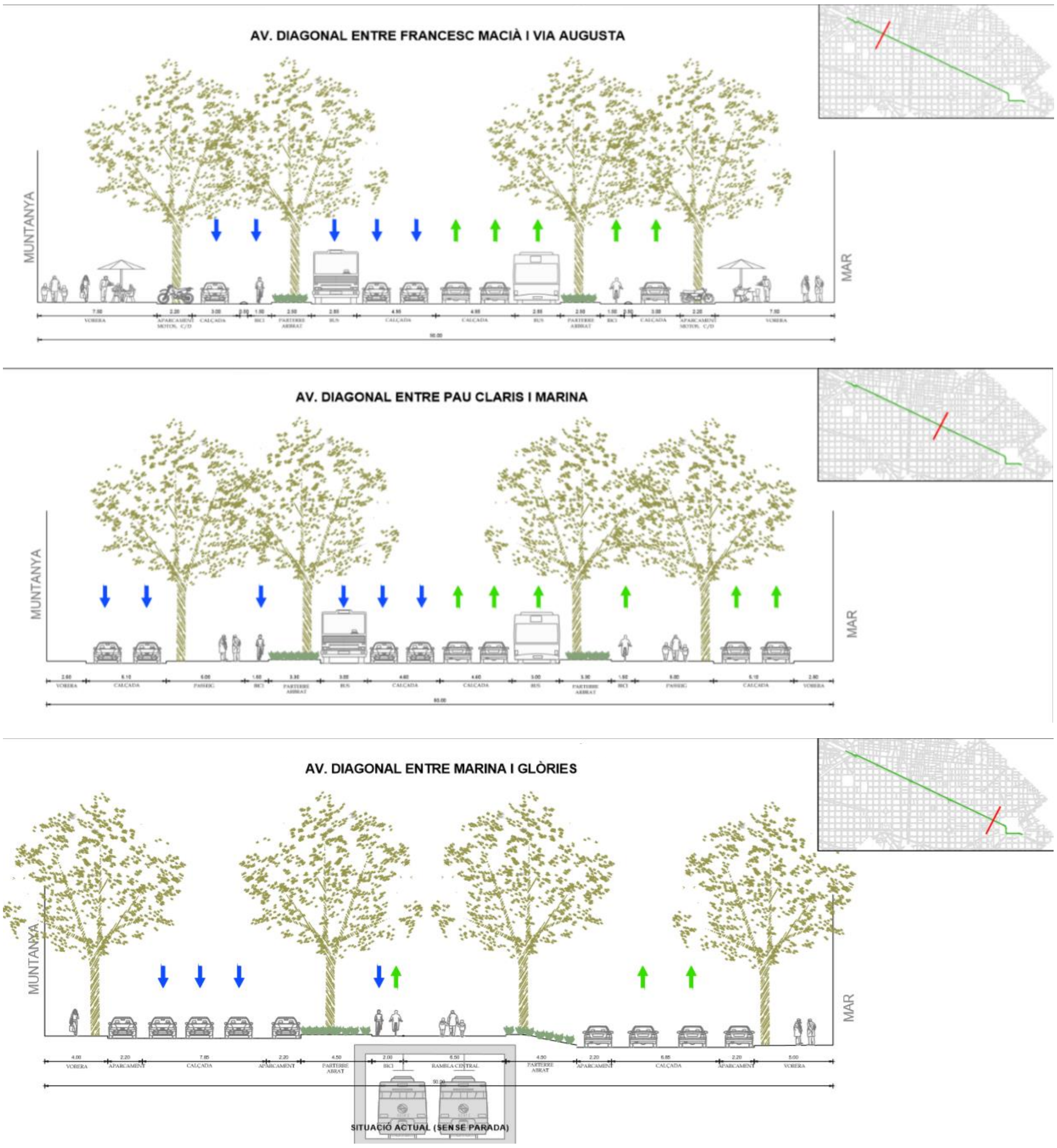


Figure 22: Current layout of the studied section.

5.5 Private vehicle

Private vehicle development in the 20th century had led cities to approach design from a car-centric view, which has proven problematic.

It should already have been understood that to reduce congestion and average travel time adding a lane for the car never solves the problem, but it makes it worse in the long term. Los Angeles city might be the example of the place where is proved that if your only approach to urban mobility is adding lanes in the freeway you end up with a collapsed system.

Cars normally run on a combustion engine which does not even achieve a 40% efficiency, that implies that around 2/3 of the fuel is not used to move the car but lost.

Not only cars emit exhaust fumes near the inhabitants of the city (which has serious health issues), they are noisy and cause lots of traffic accidents.

In addition, they spend around 97% of their life parked, and, at least, 10% of the actual travelling time is devoted to search parking or to take it to the garage.

The newer electric car-sharing options could be thought as a way to solve some of the private vehicle's issues if one does not think about the space cars require. Even in cities with big highways it would be impossible to move if everybody required a space of 6,5m^2.

Lots of researchers, professors, artists and even citizens have realised that the transportation mode developed until today is unsustainable. That is the case of Dr. Knoflacher former head of the Austrian Institute for Transport planning and global pedestrian representative of the United Nations. He has embarked in several "demonstrations" to show people the infeasibility of the car-centrist transportation mode.

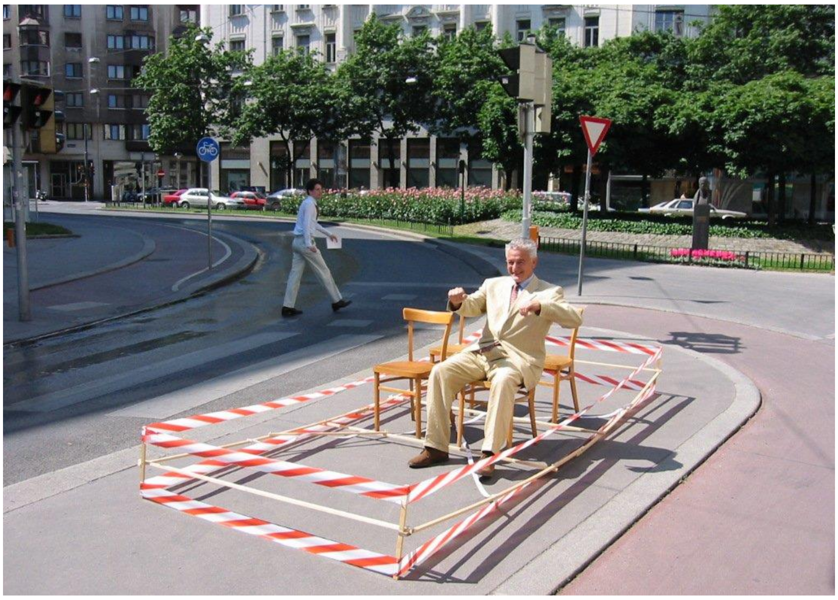


Figure 23: The "walkmobile". Dr. Hermann Knoflcher.

5.6 Pollution

The sustained cities development and their car dependency throughout the years ended implying that nowadays citizens have noisy cities with unbreathable air breaking the European directive.

It arises then no surprise when throughout the air or noise pollution maps, one can perfectly assess where the streets with higher car intensities are. As an example see Figure 25 for transit intensities in Barcelona and Figure 24 for a close-up of NO2 immision in the region of interest.

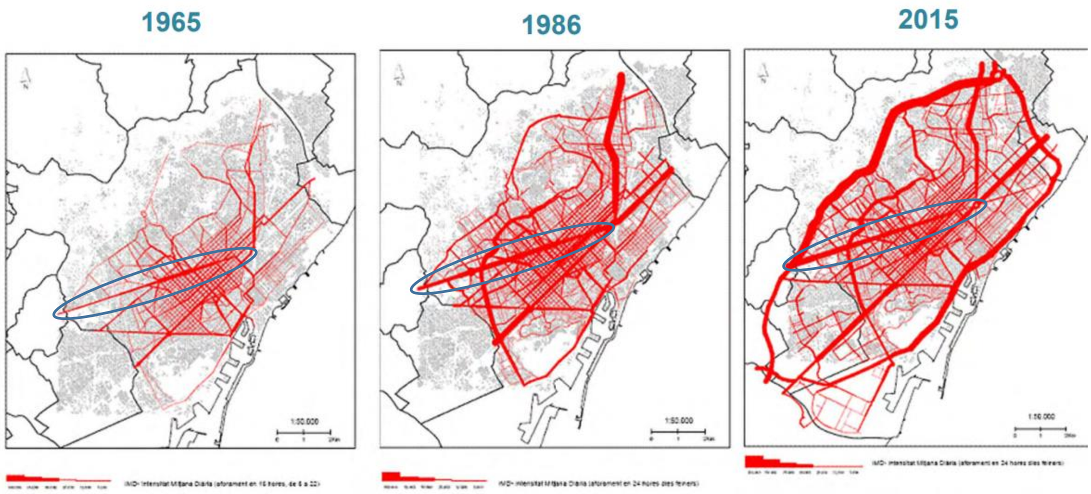


Figure 25: Transit intensities in Barcelona throughout the years. Font: Ajuntament de Barcelona

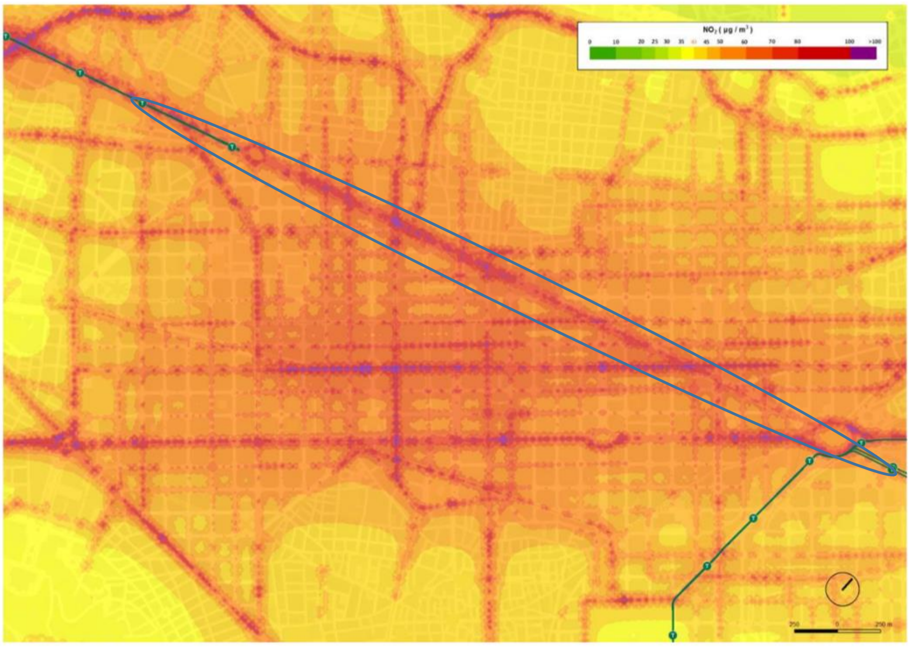


Figure 24: Average annual NO2 immision (2013). Font: [Montelló, M. et al. 2017] and Ajuntament de Barcelona

5.7 Strategic Plans

Long time ago Barcelona started developing plans to tackle the increasing demand of transportation in the city. For that different plans were made.

In 2006 Barcelona's Council was already talking about complying with Kyoto protocol, actively trying to reduce noise and other contaminants. All this was included in the 2006 Urban Mobility Plan. [Ajuntament de Barcelona 2006].

But this was not the last time the city hall talked about improving the transport within the city or building a greener and more efficient one.

It is then remarkable all the progress that has been made towards the objective. New cities layouts are currently being assessed, layouts like the SuperBlock model (see Figure 26) where it is intended to give back to people all the space held and monopolised by cars.

But much before the superlock prime implentation the planification office of the city mayor has made remarkable progress in decentralising the city and make it more liveable.

They went great lengths to achieve what they have called "the 10-minute city" where they expect the lion's share of the population to completely live taking advantage of all

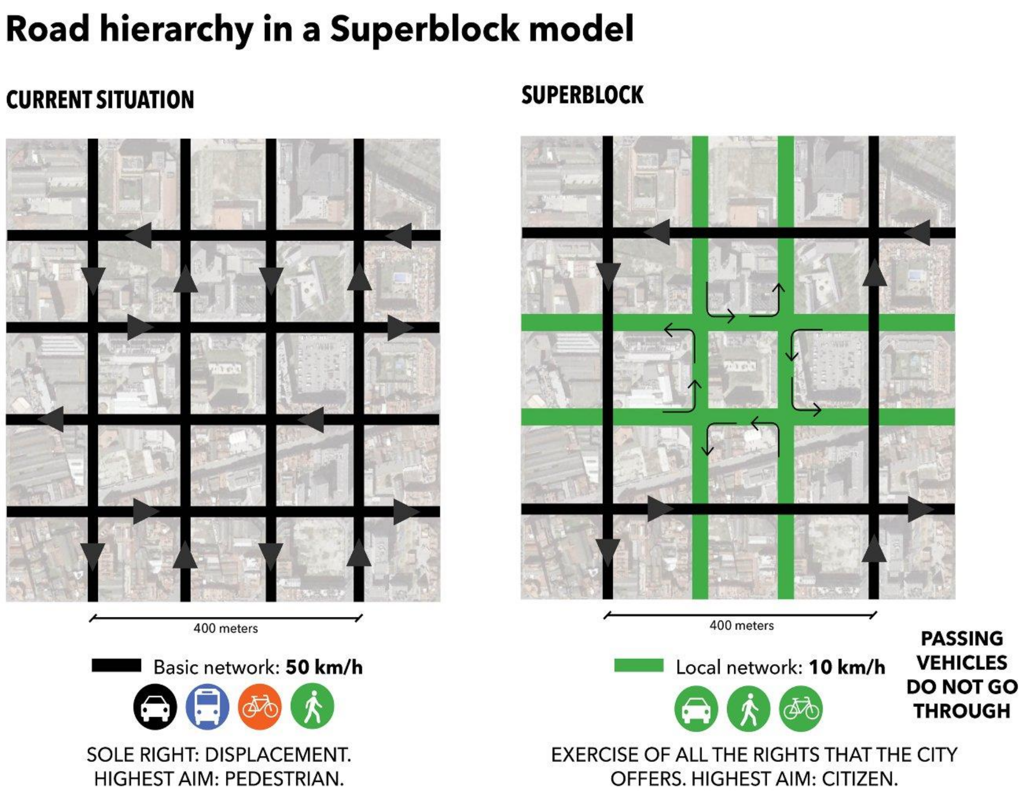


Figure 26: Superblock model. Font: Vicente Guallart.

the equipments at a 500m from their home (from school, to supermarkets or hospitals), and work in the same radius.

Lots of efforts have been put to make the plan reality and notable progress has been made since then (for instance now all the neighbourhoods that need them have either a market or a shopping centre).

The former chief architect of Barcelona, Mr. Vicente Guallart, mapped all this equipements (see Figure 27) and quantified the needs of a better public transport system to connect these decentralised nodes or the required number of bikes or bike parking per citizen.

Despite that, there is still some progress to be made.

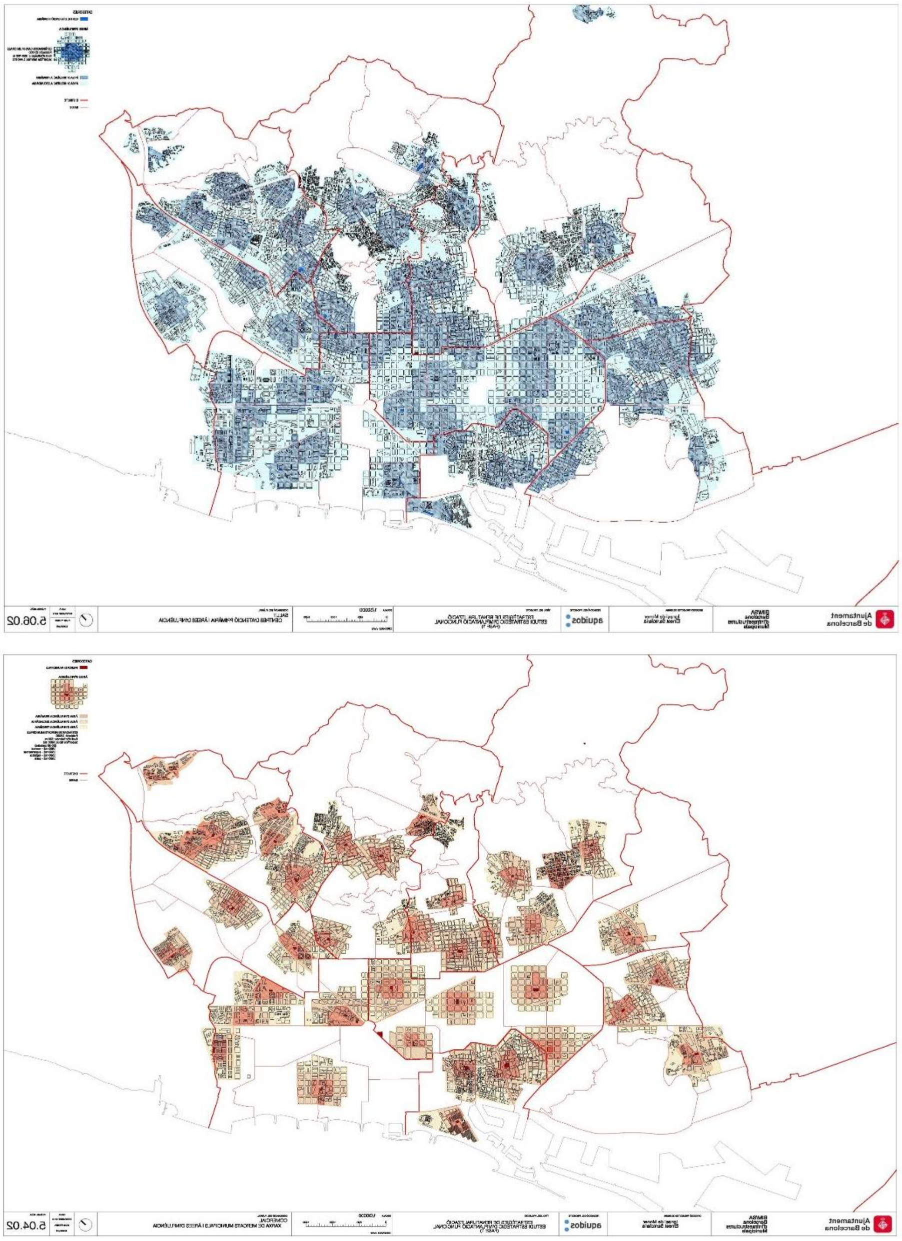


Figure 27:Primary care centers and Markets distribution in Barcelona around 2013

5.8 Summary

As seen in this section public transport in Barcelona misses to connect and operate around one of the major arteries of the city. An important avenue around which lots of shops, offices and houses are located.

The current actual layout prevents public transport to efficiently communicate through it and the car-bike intersections present all along the road make some bikers chose an alternative route.

For these reasons, the avenue is only properly serving private car users which involves a higher car daily average index that wat would be desirable in the middle of a city.

The current affluence of cars and their associated problems as pollution do not let this avenue live to the standards it should have in a city like Barcelona.

In addition, pedestrians do not have adequate sidewalks all along the avenue. Thus, despite the avenue having enough trees to provide enough shadow to pedestrians or making it an avenue worth it to walk due to possibility of walking near big trees without going to the park. Unfortunately, that is not the case.

Moreover, the way the avenue is arranged does not fit with the current strategic plans or sustainable development objectives, in the end, to make Barcelona a better city that avenue needs to be rearranged.

This rearrangement has been subject of debate from the past years so lots of literature and different studies have been made to analyse which is the better way of rearranging the street.

The overall characteristics of the street might involve that there is an unserved demand for a public transport system.

This is the reason behind performing a Cost-Benefit analysis to see if its socially profitable to build a transportation line throughout the studied section.

As previous studies have proved the best thing to do is to connect the two tramway end stations along the avenue either rolling on the surface or building a tunnel to cover half the distance and make the remaining section rolling on surface.

6. The study

The Cost-Benefit Analysis as defined in SAIT (2015) results key in project assessment as guarantees the efficient allocation of resources helping in choosing which projects are profitable for the society and which not.

It also helps in discerning between beneficial projects as is also capable of quantifying these benefits.

In order to correctly apply the methodology, one should be able to quantify and monetise different aspects and externalities of our project generating the cash flows for the different project periods.

As suggested in the SAIT manual the study will be assessing this cash flows for a 30-year period as whenever going further high incertitude in the predictions might be introduced without blatant benefits.

The project assumes that two full years are needed to complete the required infrastructure. During this first two years as no vehicles might be able to travel the section no revenue would be gathered from the system.

Works would be planned in the least disruptive way for traffic and citizens. Hence, no negative impact has been considered nor monetised in these first years.

It is of utmost importance for the robustness of the methodology to properly identify and quantify the important variables. That is the reason why variables that might have an important impact in the analysis have been carefully assessed. Those are:

- The number of users this new service will have and their perceived value of time,
- Total time savings,
- The construction budget and other Capital Expenditures (CAPEX),
- Maintenance Cost, and

And, for the merely financial study:

- Revenue obtained by the exploitation of the system.
- Operational Expenditures (OPEX).

As the purpose of the study is trying to discern which alternative generates a higher benefit for the society those variables that do not introduce a major difference between alternatives have not been considered.

In order to correctly perform the study, the base case is defined as the one maintaining the same service as of today. Then the different alternatives are:

- Alternative 1 Alstom/TRAM: As the alternative rolling completely on surface using steel tracks and the vehicles provided by Alstom.
- Alternative 1 TRAMeBUS: As the alternative running completely on surface without overhead lines or steel tracks and the TRAMeBUS vehicle.

- Tunnel Alstom/TRAM: As the alternative rolling throughout a 2km a tunnel section and on on-surface steel tracks with the vehicles provided by Alstom.
- Tunnel TRAMeBUS: As the alternative running throughout a 2km a tunnel section and on on-surface without overhead lines or steel tracks with the TRAMeBUS vehicle.

These alternatives have been selected by the revision of previous studies as they are the ones that obtain higher profitability values.

In this sense profitability will be assessed thanks to the use of three major tools: Net Present Value (NPV), Internal Rate of Return (IRR), the ratio NPV over total investment and Payback.

They are defined as follows:

- *Net Present Value (NPV)*

Net present value is a method to measure the wealth generated by the project at the initial moment. So, it is the difference between today's value of the benefits and today's value of costs.

However, to aggregate costs and benefits occurring at different periods of time the Social Temporal Preference Rate (STPR) needs to be defined. The STPR is the tax that allows us to actualise expected future cash flows.

STPR is a way to measure how society values current benefits compared to future benefits. In the end, it tries to reflect the social opportunity cost as when allocating resources to one project, it might not be possible to fund another one.

As suggested in (SAIT 2015) [Flores, X. et al 2015] STPR is taken equal to 3%.

NPV is calculated with the next formula:

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+STPR)^t}$$

Where:

- T = Number of time periods.
- R_t = Net cash inflow-outflows during the period t.

NPV must be strictly positive to consider the investment profitable.

In order to have an accurate NPV value it is advisable to assess the residual value of the assets. That is why the project considers a linear depreciation of them until a 5% of residual value at the end of their service life.

- *Internal Rate of Return (IRR)*

IRR is simply the STPR that makes NPV equal to zero. It is a measure of the profitability of the project. In order to consider an investment advisable, the IRR should be bigger than the STPR.

- *Ratio NPV / Investments*

It is the relation between the NPV and the investments made. Under the scope of this tool a project with a ratio higher than 0 becomes advisable.

- *Payback*

Payback period refers to the first period of the project where the total of the positive fluxes compensate the negative fluxes of the realised investment. So shorter paybacks periods might be preferable to longer ones.

As the Cost-Benefit analysis is made under the hypothesis that there is a market in a perfect competition regime but, in reality, that cannot be appreciated, as some taxes or grants might alter it, it is required to correct the prices obtained in order to reflect the shadow price.

For that, the project is taking the coefficients exposed in SAIT (2015) and presented in the next table. See Table 3.

	Infrastructure investments	Rolling stock investments	Infrastructure Maintenance	Staff	Stop Services	Energy	General & structural expenses
Shadow price Coef.	0.7	0.7	0.7	0.7	0.88	0.82	0.88

Table 3: Shadow Price coefficients- Font: SAIT (2015) & ADIF (2013)

Once all the computations have been made and the best alternative has been chosen, a sensitivity analysis will be perfomed.

That will involve varying one parameter (such as the Value of Time or CAPEX value) and see how our alternative responds to it. This way crucial parameters will be detected in order to assess the robustness of the alternative i.e. if a little change in the variables could or would not have a major affectation in the social profitability of the project.

Thus, the project will be introducing variations to the different considered values to see how the alternative behaves with them. This might be understood as a proof of the robustness of the model and serve to identify critical variables for future reviews.

Despite varying only one variable at a time, the reader should understand that they might be interrelated. But whenever assuming they are not, it is important to correctly interpret the values and their consequence.

For instance, when value of time decreases a 20% (and so does social revenue) it is easy to extrapolate it as no VoT variation but a 20% decrement in new users. That is the reason behind presenting the results as a percentual variation in the first assumed value and giving its value.

To compliment the cost-benefit analysis a purely financial one is also made, that is to say, an evaluation of real cash flows will be made to predict which project will have higher economical profitability for comparison purposes.

The financial study purpose is showing us the expected economic performance of the different alternatives but should not be thought as an interesting method to choose one alternative or the other.

This merely economical one might give us a glimpse on the theoretical economical profitability or the required grant to properly work.

The same tools presented for the cost benefit analysis will be used.

Those results would be used to further asses the performance of the chosen alternative as it would be always better to recommend an economically profitable option, but no major importance is given as social projects should not be decided based on the economic study rather than the cost benefit analysis.

For this second analysis the study will search which alternative requires a smaller grant (expressed in terms of Fare) to deliver the same economic profitability.

As these two studies share some critical variables; these ones, will be presented first and the ones that are only relevant to one of them would be presented in the corresponding section.

Disgracefully there are some other important variables that ought to be considered but monetising them would not only be difficult but inaccurate.

In order to solve this problem, those variables are taken and a multicriteria analysis is made. This analysis will directly involve assessing as quantitively as possible how much better is an alternative in a particular item with respect to the other ones.

These three studies combined will give us different perspectives on the benefits and advantages of each project but also on their weakness or disadvantages.

6.2 The alternatives

The revision of all the analysed alternatives throughout the years clearly delivers a couple of winners, these alternatives analyse the viability of a connection through Diagonal avenue between Francesc Macià & Las Glòries stations.

To be coherent with previous literature names of the alternatives have been taken as similar as possible to the last published study.

First one, or the so-called Alternative 1 (Alt. 1) aims to connect the two tramway networks through a surface link (3,97 km).

Second one, or Alternative 2 / Tunnel studies to make the same connection but burying 2,1 km of tracks to maintain the current surface layout of the upper half of the avenue. This tunnel starts at Francesc Macià station and emerges after Passeig de Gràcia.

From these two selected alternatives four scenarios are built.

Two scenarios that imply building those alternatives and exploiting them with the same Alstom machinery used hitherto.

Two other scenarios that imply building those alternatives and their required modifications to exploit them with new TRAMeBUS units.

This second scenarios though, ought to wait until all current Alstom units get to the end of their service life. As it is expected to change gradually from one technology to another the first 10 years of the project, the connection will require a transfer from one type of vehicle to another.

The next scenarios are analysed in this study:

- Alternative 1 – Alstom
- Alternative 2 / Tunnel – Alstom
- Alternative 1 – TRAMeBUS
- Alternative 2 / Tunnel – TRAMeBUS

All the details and characteristics of each alternative are explained in this section.

All four scenarios imply huge savings in the exploitation of some bus lines as they will not be needed anymore.

Connecting Francesc Macià and las glorias through a fast link also enables a rearranging of other public transport services that do not only run parallel to the new tracks. Thus, further saving money.

Provided this savings would be common to the four alternatives they are not taken into account even though they would enhance the obtained results.

6.2.1 Alternative 1

As planned this alternative would imply building a 3.972 m of connection between Francesc Macià & Las Glòries stations following the straightest possible path which involves running through the studied section of diagonal avenue.

6 new tramway stops would be built which is translated as 567m of distance between them.

As it rolls through the diagonal avenue, covering the cost of rearranging its layout without the astronomical costs of building a tunnel under a major city avenue, these alternatives are the ones that require the smallest investments.

Alstom

Alt. 1 – Alstom would involve building and exploiting the line with the Alstom Citadis 302 units.

This would enable a total integration of the network since the first day, as it would involve just expanding the current network with the same used system.

On the [Roig, JM et al. 2017] study an additional cost is quantified for the section as it is expected to travel through the main part of it without the aid of overhead lines. The study expects the Barcelona tramway to work in a similar manner as those from Seville, Nice or Bordeaux tram. As at the time of the study the specific technology was yet to be decided, this has been quantified as a CAPEX over cost to be detailed in further studies.

TRAMeBUS

Alt. 1 – TRAMeBUS will not be rolling from extreme to extreme of the actual network. That would involve substituting all the current Alstom Citadis units before the end of their service life. Despite that, in Francesc Macià station they would not have problems in fitting at the same time on the platform as this would be long enough to accommodate two vehicles in double composition (2 Alstom units + 2 TRAMeBUS units).

On Les Glòries station there is also enough space to ensure a quick comfortable transfer, if that was not the case, due to each current state of urbanization this space would be obtained at a ridiculous cost.

As it will be seen in this section, the TRAMeBUS alternative eliminates the need of a transfer the year 2032 were all the current conventional tramway units would have come to the end of their planned life.

6.2.2 Alternative 2 / Tunnel

The tunnel alternative makes the connection following the same path than the alternative 1 but, burying an important section of the layout (2 km) to not disturb current surface traffic on the upper part of the studied section.

This alternative involves building 5 new stops, 3 of which would be underground stops. The new average distance between stops would be of 616 m.

Some discouraging importance has been previously given to these underground stops as they are not expected to attract the same number of users than their surface counterparts. This though, could be object of a revision as currently there are some underground stops (Sant Martí, Besòs, Espronceda) in the TRAMBESOS network, and no special attention has been paid to them.

This alternative would be capable of rolling faster which may probably involve a higher potential demand attraction as it might lower more the travel utility cost than the surface alternative.

Moreover, as faster travel time could be expected from this alternative, lower number of vehicles would be required to provide the same level of service than the surface alternative.

Despite that, the saved vehicle cost would not be able to justify by itself the cost of building a tunnel.

Alstom

The Tunnel – Alstom alternative does not include any increment in CAPEX costs as while rolling in the tunnel the vehicle might be feed by a rigid overhead line and, whenever exiting the tunnel no special buildings or places justify the over cost due to aesthetics reasons.

TRAMeBUS

The Tunnel – TRAMeBUS alternative would also implement a solid overhead line inside the tunnel leaving a unelectrified section of the network of just 1,9 Km.

6.3 Budgets

The material execution budget (from now on, PEM by the abbreviation in Catalan) to extend the current service nearly 4km more on surface in order to connect our two end stations adds up to 57.582.740,88 € according to [Roig, JM et al. 2017]. Considering General Expenses (13%), Industrial Profit (6%) and, on top of that, VAT (21%) the project reaches 82.913.388,59 €.

Tunnel option gets much more expensive. PEM adds to 205.6599.840,84 € and after adding the previous accounts 296.129.604,83€ are obtained. Main reason of this difference is the cost of building a tunnel in the middle of a city, which adds up to 97 MEUR. See Table 4: Budget Summary for budget details.

Budget Summary		
	Alternative 1	Tunnel
Required previous work and demolitions	539,410.56	395,721.45
Rail superstructure	8,252,353.27	8,232,206.88
Railway / road installations and operating systems	32,173,372.35	46,436,145.46
Traction alimentation system	9,240,000.00	6,635,000.00
Subestations and energy	10,013,027.82	10,013,027.82
Railway signaling	3,566,386.55	3,769,747.90
Road signaling (trafic lights)	2,752,100.84	1,588,235.29
Operation, control and telecomunications systems	5,782,857.14	6,462,134.45
Sattions auxiliar systems	819,000.00	468,000.00
Underground stations	0.00	17,500,000.00
Stations (civil and architectural works)	2,650,000.00	1,360,000.00
Stations (civil and architectural works)	1,304,925.00	1,304,925.00
Tunnel and stations(civil and architectural works)	0.00	97,661,819.11
Tunnel civil works	0.00	70,075,571.35
Stations civil worrks	0.00	21,111,744.96
Auscultation	0.00	1,749,502.80
Stations architechture	0.00	4,725,000.00
Urbanizations	1,306,903.14	1,635,209.45
Afectations (sewerage, public lights, trees, metro...)	1,298,809.15	18,182,072.58
Afefected services (Endesa, Agbar, Gas, Telecomunications)	869,580.00	1,333,470.00
Augmented accounts and other expenses	9,187,387.41	29,118,270.91
Health and Safety (2%)	1,140,000.00	4,000,000.00
Waste Management (1%)	570,000.00	2,000,000.00
Cultural Action (1%)	575,827.41	2,056,598.41
Others (10%)	5,700,000.00	20,000,000.00
Traffic diversions	1,201,560.00	1,061,672.50
Material Execution Budget (PEM)	**57,582,740.88**	**205,659,840.84**
General expenses (13%)	7,485,756.31	26,735,779.31
Industrial Profit (6%)	3,454,964.45	12,339,590.45
Execution Budget per Contract without VAT	**68,523,461.65**	**244,735,210.60**
VAT (21%)	14,389,926.95	51,394,394.23
Contract Execution Budget (PEC)	**82,913,388.59**	**296,129,604.83**

Table 4: Budget Summary.

When taking a closer look to them one can realise that the accounts "Rail superstructure" & "Railway / road installations and operating systems" accounts for the lion's share of the budget on the first alternative (70 % of the PEM) or an important part on the second one (26 % of the PEM).

For the first alternative the whole 8.252,353,27 € will not be taken because the concepts detailed on the accounts directly involves tram stock rolling exclusively on rails. See Table 5.

Analogous reductions could be made looking to the traction alimentation system but, pursuing the construction of a conservative approach and knowing that other costs that could have been considered there should also be considered. Taking into account these budgets will not violate the principle of the study.

Work		01	Budget Alternative 1		
Chapter		02	Rail superstructure		
Title 3		01	Rail superstructure and devices		
CODE	UA	DESCRIPTION	PRICE(€)	MESASUREMENT	IMPORT (€)
1 TT4SADGO	m	Trak superstructure of access to stop in layout in double track embedded in concrete and floors, and finished in grass (section type ST-ADG) (P - 27)	1,789.52	216.00	386,536.32
2 TT4SCDAO	m	Intersection track superstructure in double track layout embedded in concrete and asphalt concrete pavement (ST-CDA type section) (P-28)	1,960.35	1305.00	2,558,256.75
3 TT4SLDAO	m	Tram line superstructure in double track layout embedded in concrete and asphalt concrete pavement (type section ST-LDA) (P - 29)	1,839.08	251.00	461,609.08
4 TT4SLDGO	m	Superstructure of the tramway line in double-embedded layout in concrete and floors, and in grass (ST-LDG type section) (P - 30)	1,983.52	1386.00	2,749,158.72
5 TT4SPDGO	m	Superstructure of the track in the stop zone in a double track layout embedded in concrete and floors, and finished in grass (type section ST-PDG) (P - 32)	1,732.40	325.00	563,030.00
6 TT4SLUGO	m	Tram line superstructure in simple track layout embedded in concrete and floors, and finished in grass (type section ST-LUG) (P - 31)	1,075.80	678.00	729,392.40
7 TT4SPUGO	m	Superstructure of the track in the stop zone in a simple track layout embedded in concrete and floors, and finished in grass (type section ST-PUG) (P - 33)	1,023.00	190.00	194,370.00
8 TTA4VOOI	u	Track device mounted on concrete slab with tram Ri lane, crossing straight or in curves and radius equal to more than 30 m (P - 34)	90,000.00	6.00	540,000.00
9 TTA4V002	u	Simple junction mounted on concrete slab with Ri Tramvia rail. (P - 35)	70,000.00	1.00	70,000.00
TOTAL	Title 3	01.02.01			8,252,353.27

Table 5: Rail superstructure budget for alternative 1.

Making the same analysis for the second alternative (Tunnel), 8.176.656,65 € would be saved because it would be still needed to count accounts that involve dismantling of the current structure which add to 55.550,23 €. See Table 6

Work		01	Budget Alternative 2 - Tunnel		
Chapter		02	Rail superstructure		
Title 3		01	Rail superstructure and devices		
CODE	UA	DESCRIPTION	PRICE(€)	MESASUREMENT	IMPORT (€)
1 FT21VooA	m2	Dismantling of existing tram tracks, including dismantling of road superstructure (P -19)	58.69	175.00	10,270.75
2 FT21VOOB	u	Tram stop dismantling. Includes dismantling, superstructure, demolition of pavement and dismantling of marquee (P-20)	45,279.48	1.00	45,279.48
3 TT4SRDFO	m	Tramway line superstructure in double track layout on concrete slab ramp (ST-RDF type section) (P - 57)	1,647.60	275.00	453,090.00
4 TT4STDFO	m	Tramway line superstructure in double track layout rails on tunnel concrete slab (secció tipus ST-TDF) (P - 58)	1,671.60	1583.00	2,646,142.80
5 TT4SPDFO	m	Tram stop stop superstructure in double track layout on tunnel concrete slab (ST-PDF type section) (P - 54)	1,474.66	195.00	287,558.70
6 TT4SLDGO	m	Tram line superstructure in double track layout embedded in concrete and dirt, finished in grass (type section ST-LDG) (P - 52)	1,983.52	657.00	1,303,172.64
7 TT4SPDGO	m	Track superstructure in the stop zone in the layout of a double track embedded in concrete and dirt, finished in grass (section type ST-PDG) (P - 55)	1,732.40	130.00	225,212.00
8 TT4SADGO	m	Superstructure of track on access to stop in layout in double track embedded in concrete and floors, finished in grass (section type ST-ADG) (P - 50)	1,789.52	88.00	157,477.76
9 TT4SCDAO	m	Crossroad superstructure in double track layout embedded in concrete and asphalt concrete pavement (ST-CDA type section) (P -51)	1,960.35	801.00	1,570,240.35
10 TT4SLUGO	m	Tram line superstructure in simple track layout embedded in concrete and floors, finished in grass (type section ST-LUG) (P - 53)	1,075.80	678.00	729,392.40
11 TT4SPUGO	m	Superstructure of the track in the stop area in a simple track layout embedded in concrete and floors, and finished in grass (type section ST-PUG) (P - 56)	1,023.00	190.00	194,370.00
12 TTA4Vool	u	Track device mounted on concrete slab with tram Ri lane, crossing straight or in curves and radius equal or greater than 30 m (P - 59)	90,000.00	6.00	540,000.00
13 TTA4V002	u	Simple junction mounted on concrete slab with tram Ri tram rail. (P - 60)	70,000.00	1.00	70,000.00
TOTAL Title 3		01.02.01			8,232,206.88

Table 6: Rail superstructure budget for alternative 2.

Whenever looking to the accounts related to electrification and overhead lines, it is possible to see that the study made by GPO-SENER-TYPSA in 2017 did consider an alternative electrical alimentation system to be defined. That is the reason they added for the first alternative an over cost of 22 MEUR as an increment of OPEX and CAPEX.

That is the reason behind still considering the entire part of the budget devoted to electric and related accounts which includes building high-voltage transformers and other required systems.

As mentioned before the new trackless tram system would not be able to travel on top of a grass section. That is why an approximation to the cost of removing all the grass sections and paving them with an asphalt concrete pavement has been made.

To do so the TCQ2000 software and the ITeC 2019 price bank have been used and the detailed budget is presented in the following table. This budget considers taking all the earth extracted to the appropriate site, that is why these accounts do not cause a directly proportional waste management augment (taken as 1%) but it does so on the other augmented accounts.

Despite that and following the spirit of building a very conservative approach whenever incertitude about which pavement or antenna to choose the budget considers building a pavement better than the required one or more expensive antennas.

For the antennas case and given their actual working range that in a city with tall buildings if properly placed might be around 10 km, no more than 5 antennas should be needed for a 30 km network. The budget though, allocates resources to buy and install 10 at a reasonably high price so the real case scenario has no problems in building as much as necessary to provide the best possible service. Nonetheless the price of this systems does not have any impact on the final budget.

Even though, on the paper, this exceptional budget would not be necessary until 2032 it has been decided to incorporate it on the initial investments budget as it might allow to some interesting multimodal options and, in addition, it penalises the cases studies.

This budget needs only to be taken into account for the TTS alternatives and does not consider the removal of the current rail tracks as, it might only has sense to do it if it is economically profitable.

The detailed budget is presented in the next table and adds up to 2,9 MEUR. See Table 7.

Obra		01	PressupostTRAMeBUS Conditioning Budget		
Capítol		02	Pavement and required works		
Nmt. CODI	UA	DESCRIPCIÓ	PREU	AMIDAMENT	IMPORT
G222C423	m3	Excavació de rasa de més de 2 m d'amplària i fins a 2 m de fondària, en terreny de trànsit, amb pala excavadora i càrrega mecànica del material excavat	9.73	16,600.00	161,518.00
G2R35069	m3	Transport de terres a instal·lació autoritzada de gestió de residus, amb camió de 12 t i temps d'espera per a la càrrega amb mitjans mecànics, amb un recorregut de menys de 15 km	5.48	16,600.00	90,968.00
29512811	m2	Ferm flexible per a freqüència alta de trànsit pesat format per paviment de mescla bituminosa en calent de 6 cm, amb capa de trànsit de mescla bituminosa contínua AC de 6 cm, amb base de formigó HM--20/B/20/I i subbase de tot-u artificial	30.23	83,000.00	2,509,090.00
FBA14311	m	Pintat sobre paviment de marca vial longitudinal discontínua per a ús permanent i retrorreflectant en sec, tipus P-R, de 10 cm d'amplària i 3,5/1,5 de relació pintat/no pintat, amb pintura acrílica de color blanc i	0.50	132,288.00	66,144.00
TOTAL		01.02			2,827,720.00
Obra		01	PressupostTRAMeBUS Conditioning Budget		
Capítol		03	Self-driving aid systems		
Nmt. CODI	UA	DESCRIPCIÓ	PREU	AMIDAMENT	IMPORT
ANT3RTK	u	Compra e instalació Antena per a DGPS - RTK, rang >= 15 km	7,000.00	10.00	70,000.00
TOTAL		01.03			70,000.00

Table 7: TRAMeBUS Conditioning budget.

After these modifications of the different PEMs whenever adding the augmented accounts (which have direct relation to the PEM) big economic savings can be appreciated.

These accounts involve “cultural action” (1% established by law) or other accounts to be justified. So, after considering the reduction in the PEM a smaller Contract Execution budget (PEC) is obtained. Quantified savings reach 13,89 MEURs for the first alternative and 13,78 for the second one. See Table 8: Budget Summary.

Budget Summary	ALSTOM		TRAMeBUS	
	ALTERNATIVE 1	ALTERNATIVE 2	ALTERNATIVE 1	ALTERNATIVE 2
Required previous work and demolitions	539,410.56	395,721.45	539,410.56	395,721.45
Rail superstructure	8,252,353.27	8,232,206.88	0.00	55,550.23
Railway / road installations and operating systems	32,173,372.35	46,436,145.46	32,173,372.35	46,436,145.46
Stations (civil and architectural works)	2,650,000.00	1,360,000.00	2,650,000.00	1,360,000.00
Stations (civil and architectural works)	1,304,925.00	1,304,925.00	1,304,925.00	1,304,925.00
Tunnel and stations(civil and architectural works)	0.00	97,661,819.11	0.00	97,661,819.11
Urbanizations	1,306,903.14	1,635,209.45	1,306,903.14	1,635,209.45
Afectations (sewerage, public lights, trees, metro...)	1,298,809.15	18,182,072.58	1,298,809.15	18,182,072.58
Afefected services (Endesa, Agbar, Gas, Telecomunication:	869,580.00	1,333,470.00	869,580.00	1,333,470.00
TRAMeBUS Conditioning Budget	0.00	0.00	2,897,720.00	2,897,720.00
Augmented accounts and other expenses	9,187,387.41	29,118,270.91	8,254,512.33	28,974,039.23
Health and Safety (2%)	1,140,000.00	4,000,000.00	1,020,000.00	4,000,000.00
Waste Management (1%)	570,000.00	2,000,000.00	420,000.00	1,910,000.00
Cultural Action (1%)	575,827.41	2,056,598.41	512,952.33	2,002,366.73
Others (10%)	5,700,000.00	20,000,000.00	5,100,000.00	20,000,000.00
Traffic diversions	1,201,560.00	1,061,672.50	1,201,560.00	1,061,672.50
Material Execution Budget (PEM)	**57,582,740.88**	**205,659,840.84**	**51,295,232.53**	**200,236,672.51**
General expenses (13%)	7,485,756.31	26,735,779.31	6,668,380.23	26,030,767.43
Industrial Profit (6%)	3,454,964.45	12,339,590.45	3,077,713.95	12,014,200.35
Execution Budget per Contract without VAT	**68,523,461.65**	**244,735,210.60**	**61,041,326.71**	**238,281,640.28**
VAT (21%)	14,389,926.95	51,394,394.23	12,818,678.61	50,039,144.46
Contract Execution Budget (PEC)	**82,913,388.59**	**296,129,604.82**	**73,860,005.31**	**288,320,784.74**

Table 8: Budget Summary.

This budget keeps considering building a solid overhead line inside the tunnel on the tunnel alternative as no major disadvantage was found and the price was deemed logical (900.000€). This will leave the second alternative with no more than 2 Km without electrification against the 3,97 km of the first alternative. Although none of the two values poses a problem, the tiny drawbacks this option implies (just the price) do not arouse any significant change on the profitability, aesthetics, or any other considered field.

In addition to that all budgets consider a couple more inversions. According to [Roig, JM et al. 2017] in 2026 1,7 MEURS will have to be invested to amplify the electrical systems and new garages will be required 2029 so 32,8 MEURS have been allocated for that.

6.4 Potential demand

First thing to assess should be how many people will the system serve.

Taking the data of "TransMet Xifres" [ATM (2019c)] published by ATM the next table can be easily built. (see: Table 9: Users of Barcelona Light Rail System. Font: ATM & own elaboration.).

2019 figures are projected from the ones given by ATM for the first semester. Provided it can be extracted from the "TransMet Xifres" (since 2015) that the number of first semester users should represent, in average, less than the 51% of the annual users. This difference might be because the second semester has more holidays. In addition to that one might notice that most universities located all throughout three stops do not held normal activity during the months July and August.

	Milion of passengers			Length	Increment	
Year	Trambaix	Trambesos	Total	(km)	%	factor
2003	0	0	0	0		
2004	5.9	1.8	7.7	18.5		
2005	10.2	2.8	13	18.8	68.83%	1.6614
2006	12.8	4.1	16.9	23.8	30.00%	1.0269
2007	14.3	6.6	20.9	28.4	23.67%	1.0364
2008	15.7	7.5	23.2	29.1	11.00%	1.0833
2009	16.3	7.7	24	29.1	3.45%	1.0345
2010	15.8	8	23.8	29.1	-0.83%	0.9917
2011	16.1	8.1	24.2	29.1	1.68%	1.0168
2012	16	7.7	23.7	29.1	-2.07%	0.9793
2013	16.1	7.7	23.8	29.1	0.42%	1.0042
2014	16.3	8.2	24.5	29.1	2.94%	1.0294
2015	17	8.4	25.4	29.1	3.67%	1.0367
2016	17.7	9.1	26.8	29.1	5.51%	1.0551
2017	18.2	9.7	27.9	29.1	4.10%	1.0410
2018	19.1	10	29.1	29.1	4.30%	1.0430
2019	20.2*	9.7*	29.9*	29.1	2.75%*	1.0275*

Table 9: Users of Barcelona Light Rail System. Font: ATM & own elaboration.

In order to built a conservative approach, the increment tendency is expected to remain similar until the implementation of the new service. That is the reason why the study is taking the last four years and fits a simple regresion line to obtain the expected increments for the years 2020-2022. (see Table 10: Expected growth in demand.)

Expected Growth	
2020	2.14%
2021	1.33%
2022	0.52%

Table 10: Expected growth in demand.

The 10 firsts years after the implementation of the new service sustained annual grow of 1,5% is expected, from there on 1% without taking into account possible future prolongations of the network.

Except for the year 2024 that no growth is programmed as the central section of the metro line 9 should open then.

In a similar manner a decrement of 5% is programmed for the year 2028 as the prolongation of the metro line 8 might take some users from the tramway service.

The study [Lussich, M. et al. 2005] concludes that on 2005 under different transfer conditions and mainly analazyng the passangers taking other transportation modes to cover the section of study concludes that demand for the new tramway connection might range from 32,000 to 59,000 passangers per day. Stating that 44% of them will be induced demand.

That would, though, imply that between 28 % and 43 % will be passengers catched from other public transport options (bus and metro), and around 10% from the private vehicle.

The demand attracted from the bus and metro might decrease their specific revenue but it would be automatically translated to higher tramway revenue thus, leaving barcelona's public transport network treasury unchanged for that reason.

To actualise the potential demand value, it is possible to compare the values of total public transport use that the EMEF 2005 and EMEF 2018 ([ATM 2006] & [ATM 2019A]) give us for the Metropolitan Region of Barcelona. From there one might appreciate it has had a remarkable increase of 68 %. This value might be used to actualise the range to (53,800 – 99,120) for 2018. From there on potential demand will be actualised at the same rate of the light rail system (see Table 10) reaching a potential average value of more than 80,000 pax/day in 2022.

As the tunnel option it is thought to be 2,3% faster the author has chosen to augment the demand correspondingly as higher commercial speed will be able to attract more passengers.

As the new service cannot be expected to capture all the users from the very first day, a ramp-up of 85% for the first year and 95% for the second one has been considered.

With all this in mind the next demand tables are built. Please notice that values from 2018 are real values took from "Transmet Xifres", value for 2019 is extrapolated from the data of the first semester. From there on all values are computed with the aforementioned growing ratios.

Analogously, the studied demand for the TRAMeBUS alternatives has only to do with the expected demand of the corridor (Av. Diagonal), at least, until the year 2032 were the "new" and "old" services are planned to converge into a new one fully operated by TTS.

For the detailed expected demand see Table 12 & Table 13.

The study done by [Roig, JM et al. 2017] which has served for comparison other times might expect around 100 Million annual users for the last year as it is able to distinguish demand for working days. Whereas the proposed potential demand accounts for 80 Million annual users for the last year, a difference close to 20%.

Many other studies have been made in the past to study the demand and the social profitability of the project. It is interesting to notice that those made by the ATM obtained, on average 190.000 pax/working day (very close to [Roig, JM et al. 2017]).

As an indication the recompilation and actualisation of the values made by [Roig, JM et al. 2017] is presented here. (see Table 11)

Study - Alternative	Considered Investment	Working day demand	Time Savings	Return
	(M€)	(pax/day)	(h/day)	TIR (%)
PTP - Diagonal	168.1	130,000	9,300	11%
TM - Diagonal	175.8	140,000	9,678	17%
ATM PDI 2010 Diagonal	168.1	190,000	9,585	44%
ATM - Diagonal 1 (Tramway over actual bus lane)	142.3	177,857	8,570	56%
ATM - Diagonal 2 (Tramway over central boulevard)	181.8	213,216	8,570	47%
UPC Diagonal	101.0	163,000	9,642	14%
AB Diagonal Surface Tramway	175.0	222,000	3,416	11%
AB Diagonal Deep Underground Section	475.0	236,000	5,583	10%

Table 11: Other Previous Studies with actualised values. Font: [Roig, JM et al 2017]

All those studies considered though higher investments, from 101 MEUR for the on-surface alternative to 475 MEUR for the tunnel one. Some of them considered extra urbanization costs that others did not.

As a result, from the considered demand, and other monetized benefits, those studies also obtained high IRR for the on-surface connection (at least 10%), a couple of them were even capable to surpass a 40% theoretical IRR.

	Potential Demand - Alstom					
	Alt 1. / On-surface			Alt. 2 / Tunnel		
Year	Demand (pax/day)	Ramp-up ()	Demand' (pax/day)	Demand (pax/day)	Ramp-up ()	Demand' (pax/day)
2018	79,727	0	0	0	0	0
2019	81,918	0	0	0	0	0
2020	83,671	0	0	0	0	0
2021	84,784	0	0	0	0	0
2022	166,937	0.85	141,896	168,816	0.85	143,494
2023	169,441	0.95	160,968	171,349	0.95	162,782
2024	171,983	1	171,983	173,919	1	173,919
2025	171,983	1	171,983	173,919	1	173,919
2026	174,562	1	174,562	176,528	1	176,528
2027	177,181	1	177,181	179,175	1	179,175
2028	168,322	1	168,322	170,217	1	170,217
2029	170,847	1	170,847	172,770	1	172,770
2030	173,409	1	173,409	175,361	1	175,361
2031	176,010	1	176,010	177,992	1	177,992
2032	178,651	1	178,651	180,662	1	180,662
2033	180,437	1	180,437	182,468	1	182,468
2034	182,241	1	182,241	184,293	1	184,293
2035	184,064	1	184,064	186,136	1	186,136
2036	185,904	1	185,904	187,997	1	187,997
2037	187,763	1	187,763	189,877	1	189,877
2038	189,641	1	189,641	191,776	1	191,776
2039	191,538	1	191,538	193,694	1	193,694
2040	193,453	1	193,453	195,631	1	195,631
2041	195,387	1	195,387	197,587	1	197,587
2042	197,341	1	197,341	199,563	1	199,563
2043	199,315	1	199,315	201,559	1	201,559
2044	201,308	1	201,308	203,574	1	203,574
2045	203,321	1	203,321	205,610	1	205,610
2046	205,354	1	205,354	207,666	1	207,666
2047	207,408	1	207,408	209,743	1	209,743
2048	209,482	1	209,482	211,840	1	211,840
2049	211,577	1	211,577	213,958	1	213,958
2050	213,692	1	213,692	216,098	1	216,098
2051	215,829	1	215,829	218,259	1	218,259

Table 12: Expected demand for the Alstom study.

	Potential demand - TRAMeBUS					
	Alt 1. / On-surface			Alt. 2 / Tunnel		
Year	Demand (pax/day)	Ramp-up ()	Demand' (pax/day)	Demand (pax/day)	Ramp-up ()	Demand' (pax/day)
2018	0	0	0	0	0	0
2019	0	0	0	0	0	0
2020	0	0	0	0	0	0
2021	0	0	0	0	0	0
2022	81,712	0.85	69,455	83,592	0.85	71,053
2023	82,938	0.95	78,791	84,846	0.95	80,604
2024	84,182	1	84,182	86,118	1	86,118
2025	84,182	1	84,182	86,118	1	86,118
2026	85,445	1	85,445	87,410	1	87,410
2027	86,727	1	86,727	88,721	1	88,721
2028	82,390	1	82,390	84,285	1	84,285
2029	83,626	1	83,626	85,549	1	85,549
2030	84,880	1	84,880	86,833	1	86,833
2031	86,154	1	86,154	88,135	1	88,135
2032	178,651	1	178,651	180,662	1	180,662
2033	180,437	1	180,437	182,468	1	182,468
2034	182,241	1	182,241	184,293	1	184,293
2035	184,064	1	184,064	186,136	1	186,136
2036	185,904	1	185,904	187,997	1	187,997
2037	187,763	1	187,763	189,877	1	189,877
2038	189,641	1	189,641	191,776	1	191,776
2039	191,538	1	191,538	193,694	1	193,694
2040	193,453	1	193,453	195,631	1	195,631
2041	195,387	1	195,387	197,587	1	197,587
2042	197,341	1	197,341	199,563	1	199,563
2043	199,315	1	199,315	201,559	1	201,559
2044	201,308	1	201,308	203,574	1	203,574
2045	203,321	1	203,321	205,610	1	205,610
2046	205,354	1	205,354	207,666	1	207,666
2047	207,408	1	207,408	209,743	1	209,743
2048	209,482	1	209,482	211,840	1	211,840
2049	211,577	1	211,577	213,958	1	213,958
2050	213,692	1	213,692	216,098	1	216,098
2051	215,829	1	215,829	218,259	1	218,259

Table 13: Expected demand for the TRAMeBUS study.

6.5 Required cars

The study made by Ingerop (2017) studies the exploitation needs and quantifies the required number of convoys per year to be bought for the two Alstom Alternatives.

New Vehicles	Alt. 1	Alt. 2 -Tunnel
2022	18	17
2030	3	3
2032	41	41
2034	4	4
2040	3	3
2045	5	3
2050	3	4
TOT	77	75

Table 14: Number of vehicles to be bought each year. Font: [Ingérop 2017].

The two TRAMeBUS alternatives though, need to be assessed differently as it could be first though that, to properly serve a smaller corridor less vehicles might be needed, however, that might not be true.

For instance, analysing the on-surface case for the TRAMeBUS alternative at a 17,5 km/h commercial speed in order to achieve a 3-minute headway a total of 11 vehicles would be needed; 9 vehicles operating plus 2 in reserve in order to have a decent correction time when a vehicle malfunctions.

The problem arises whenever considering the mean passenger density at peak, 9 (or 11) vehicles are not enough to ensure a density smaller than 4 pax/m^2. As previously defined, theoretical maximum density due to comfort considerations has been defined at 2,9 pax/m^2 so the service would be worse than the offered standard and unable to serve some (non-negligible) demand at peak.

Pursuing the objective of serving at a decent comfort level all the capacity at peak the system would need, at least, 16 TRAMeBUS units to properly serve all the demand until 2030. In that sense, and considering the number of units that need to be in reserve to prevent any problem (2 or 3) the numbers obtained are the same from those of Ingerop. See Table 15.

From there on the number of vehicles to buy is mainly related to those units that get to the end of their service life.

That is the reason behind taking the required number of vehicles determined by Ingerop as true for the TRAMeBUS case.

This could potentially enable those alternatives to a couple of semi direct vehicles at peak hour from one point of the “ancient network” to las Glorias stop, going through Francesc Macià stop. For instance, the stop “Ernest Lluch” (see Figure 16) has currently

Confort Level (pax/m2)			
Vehicles→ ↓Year	9	16	19
2022	4.14	2.33	1.96
2023	4.71	2.65	2.23
2024	4.87	2.74	2.31
2025	4.95	2.79	2.35
2026	5.02	2.83	2.38
2027	5.10	2.87	2.42
2028	5.09	2.86	2.41
2029	5.16	2.90	2.44
2030	5.24	2.95	2.48

Table 15: Comfort level for the on-surface TRAMeBUS alternative.

three platforms and it is a point where the three Trambaix lines are already merged. This journey to glories through Francesc Macià would involve around 7'5 km.

All vehicles have been assumed to have a 5% residual value at the end of their service life (30 years). To properly account their value at the end of the project (year 2051) a lineal depreciation has been considered.

6.6 Other costs

The studied alternatives would need additional investments to perform under the required level of service.

These costs (expressed in euros) and their concepts are detailed in the next table (see: Table 16).

Except for the investment required to adapt Alstom Citadis Units to cover a section without overhead lines, and additional expenses related to the tunnel alternatives, all the other costs have been understood as common for the four alternatives.

Others	TRAM Alt 1	TRAM Tunel	eBUS Alt 1	eBus Tunel	
2026	1,745,900	1,745,900	1,745,900	1,745,900	Ampliation Electric system
2029	32,790,678	32,790,678	32,790,678	32,790,678	Workshops
2032	2,616,600	3,323,940	2,616,600	3,323,940	Installation Comunications and ticked control
2037	4,261,000	4,351,000	4,261,000	4,351,000	Installation Signals, auxiliars & others
2042	24,267,103	42,001,153	24,267,103	42,001,153	Fixed installations, Electrifica tion + auxiliars tunel & undergorund stations
2051	22,000,000	0	0	0	No catenary costs

Table 16: Other Costs.

7. Cost-Benefit Analysis

For the cost-benefit analysis aforementioned variables will be taken and added to the monetised savings of time (as a benefit), the time loses and the externalities generated to the private vehicle and the cost of maintaining the infrastructure.

As explained on the beginning of the section 6 (6. The study) shadow price coefficients will be used whenever requiring reflecting the social opportunity cost of each value.

7.1 Value of time

In order to properly assess the socio-economic gains of the project a value of time or perceived value needs to be considered.

As a matter of fact, this variable depends on a lot of other variables (salary, age, education etc…) and in addition to that people do not value equally huge than little time savings.

The study follows the methodology introduced by [Garola À. Et al. 2019] trough which a perceived value of time is determined throughout the ponderation of an hourly reference cost by means of trip reason and expected trip reasons.

Where the determination of the hourly reference cost is made by means of the average gross salary times the proportion of employed active population plus the average dole times the percentage of unemployed active population.

The required figures can be easily extracted from IDESCAT[4]:

- Average annual gross salary for Catalonia in 2017 (25.180,45 €).
- Unemployment benefit for Catalonia in 2017 (2.160.797.000 €).
- Active population for Barcelona in 2017 (2.802.500 pax).
- Number of workers for Barcelona in 2017 (2.453.300 pax).

Then, understanding that workers will be working for 1764 h/year and assigning unemployed 1250 h/year (ass suggested [Garola À. Et al. 2019]) it is possible to translate annual wages into hourly rates.

Then, through the next formula it is possible to obtain our hourly reference cost (C):

[4] Institut D'Estadística de Catalunya (Catalonia's Institute of Statistics) in: <www.idescat.cat> consulted the 24th of May 2020

$$C = \%_{Employed} * C_{Employed} + \%_{Unemployed} * C_{Unemployed}$$

Where:

- $\%_{Employed}$ is the ratio of workers divided by Barcelona's active population.
- C_i in €/h obtained by dividing the annual retribution by worked hours.
- $\%_{Unemployed}$ is simply 1 - $\%_{Employed}$.

After that it is important to know why the expected user will be travelling for. From the values published in [ATM 2014], neglecting "empty answers", correcting the percentage and grouping the reasons to travel, the next table can be elaborated: (see: Table 17)

	Trambaix			Trambesós		
	2011	2012	2013	2011	2012	2013
Work (%)	62.30	56.54	64.32	59.68	64.13	66.53
Groceries (%)	7.26	3.04	2.51	14.54	6.11	7.46
Leisure (%)	8.37	15.78	7.44	6.52	10.72	12.60
Duties (%)	22.08	24.64	25.73	19.26	19.04	13.41
Sum (%)	100.00	100.00	100.00	100.00	100.00	100.00

Table 17: Distribution of user trips. font: [ATM 2014] & own elaboration.

Knowing the number of passengers each network has transported that year is easy to build a weighted mean to know why the average user would be travelling for. The project is considering our expected user will have the same profile. (Table 18).

Mean values	TRAM
Work (%)	61.84
Groceries (%)	5.94
Leisure (%)	10.34
Duties (%)	21.88
Sum (%)	100.00

Table 18: Distribution of mean user trips. font: [ATM] & own elaboration.

From there and knowing the percentage of the value of time (VoT) chargeable to each trip type the perceived value of time from the expected customer can be determined as follows:

$$VoT = \sum_{i=1}^{n} \%_i * f_i * C$$

Where:

- $\%_i$ is the percentage of workers travelling by the reason i.
- f_i is the chargeable cost factor for the reason i. See: Table 19: Chargeable cost factor. Font: [Garola, À. Et al. 2019.]

Chargable cost factor (%)	
Work & studies	69.00
Groceries/shopping	59.00
Leisure	47.00
Duties	100.00

Table 19: Chargeable cost factor. Font: [Garola, À. Et al. 2019.]

From there it is obtained an average value of time of 9,486 €/h.

7.2 Time savings

For the socioeconomic analysis it is crucial to have a good approximation to the time saved per user and per trip.

To make that it is assumed that access time to the new public transport infrastructure remains the same, this involves assuming the average distance you will need to walk to the stop will not change. So, the study might be neglecting the difference this may involve.

In addition to that, it is assumed that the user is perfectly aware of the schedule of the transport system he might be boarding so he will arrive at the stop and have no need to wait for the vehicle.

Average passenger boarding and alighting times of the different transportation modes have been understood equal, so no difference is introduced by this variable.

Today, the normal user taking the best public transport alternative to go from Francesc Macià to Glories (or vice versa) will need to invest 30mins by bus. Due to the lack of precise information the project assumes this time varies linearly with the distance the user needs to cover i.e. that at half the distance the user will need to devote half the time.

After the implementation of the future transport mode times will be drastically reduced. To cover the same distance (3.972 km) at the expected average commercial speed (17,6 km/h) they will only need to invest 13’33”.

If demand is equally distributed all along the line the average user will need to travel only half the line to arrive to their destination. For the normal users accessing the line in the studied stops might be true as no major difference in population density has been found close to the studied section. In addition, there is no abnormal distribution of offices, museums, shops, restaurants, or places of interests if it was not for “Passeig de gracia” situated close to the midpoint of the infrastructure.

In a similar manner the destinations will be equally distributed all along the line, so the average user might will to descend at halfway. This might also be close to the final situation thanks to the fact that “Passeig the gracia” is situated close to the midpoint.

So, both hypothesis combined lead to the assumption that the average studied user will travel only one fourth of the length. This immediately leads to a saved time value equal to 4,11 mins / (trip & user).

$$\frac{1}{4} * \left(30\ mins - \frac{3{,}972\ km}{17{,}6\ {}^{km}/_{h}} * \frac{60\ mins}{1\ h}\right) = 4{,}11\ mins$$

Analogously performing the same operations for the tunnel alternative with its corresponding reference commercial speed (18 km/h), the saved tame value of 4,19 mins / (trip & user) is reached.

This obtained values through a simplified methodology get very close to those obtained by [Roig, JM et al. 2017] (4,10 & 4,13 mins / (trip & user)) with relative percentual differences of 0,24 % & 1,45 %.

This time saving will be compatibilized only for the users captured from other public transport means, which get around 27,5% of the total users.

There is though, another type of new user considered, the ones belonging to the group of the induced demand. These users did not travel in the studied section but, thanks to the implementation of a new transportation mean they started using it.

It is impossible then to know which was their previous utility cost but, thanks to the demand curves an estimation on the willingness to pay can be done. [Flores, X. et al 2015].

The most common approximation to this value is the “rule of half” which involves considering half the benefit for induced users than for captured ones.

So, for induced users (close to 22% of the total demand) the study will be considering their time savings per trip as: 2.057 & 2.095 mins / (trip & user).

The implementation of this alternatives also considers the subtraction of a lane for the private car owners and consequently implies some extra congestion in the section of study which is directly translated into time loses by the driver and occupants.

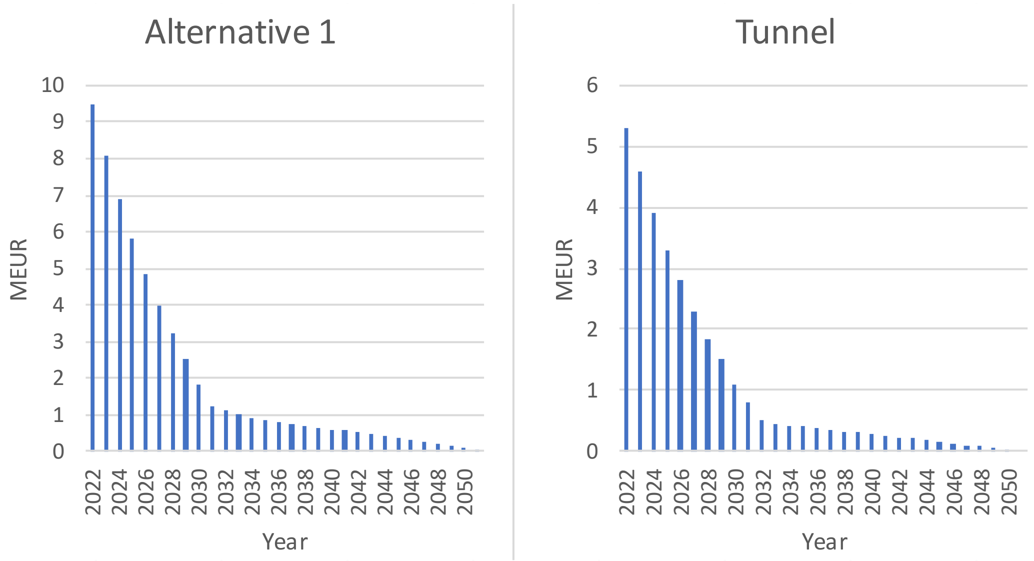


Figure 28: Congestion costs. Font : [Roig, JM et al. 2017].

Due to the impossibility to obtain satisfactory results from our simplified congestion simulation throughout the years. The values determined by the study made by [Roig, JM et al. 2017]) have been taken and replicated in Figure 28 (notice the different scales).

This study differentiated congestion costs in externalities and time loses by driver and passengers. To properly count these costs in the study the time loses has been converted to euros with our value of time, as a way to actualise them and keep concordance with the other parts of the study.

As expected, tunnel alternative has a minor congestion cost as while it runs underneath the surface keeps three lanes per direction on top of it.

7.3 Maintenance Costs

In order to properly perform the cost benefit analysis, it is not only important to quantify the benefits or the required investment but also the required maintenance costs.

To do so, it is possible to take advantage from the infrastructure maintenance costs published by [Flores, X. et al 2015]

From there it is possible to extract that maintenance costs for a tramway system are around 40.000 €/km-year and 140.000 €/km-year for the metro lines.

In a similar manner maintenance costs for road infrastructures are also detailed (see: Table 20.)

From there it has been decided to evaluate the tramway kilometres as suggested in SAIT 2015 [Flores, X. et al 2015] and those that run inside the tunnel as if they were kilometres from a metro line.

Maintenance		Conventional (€/km-year)	Extraordinary (€/km-10 year)
Road	Highway	33,000.00 €	130,000.00 €
	Conventional	16,500.00 €	65,000.00 €
	Local	7,100.00 €	65,000.00 €
	Increments		
	Tunnel	398,231.00 €	/

Maintenance		Conventional (€/km-year)	Extraordinary (€/km-10 year)
RailRoad	Tramway	40,000.00 €	/
	Metro	140,000.00 €	/

Table 20: Maintenance costs. Font : [Flores, X. et al 2015]

The increment of cost quantified by [Flores, X. et al 2015] in SAIT 2015 for roads it is thought to be conceived for big road infrastructures going through mountains or complicated environments that require really expensive techniques and have to be conceived to withstand different geotechnical derived problems.

That is the main reason why, for the trackless alternatives the maintenance cost of the tunnel has been taken equal to the one suggested for metro in SAIT 2015 [Flores, X. et al 2015] despite, probably, overestimating the real cost.

For the on-surface trackless sections as the vehicles that transit the section have a max loaded weight of 9tn/axe [Newman, P. et al. 2019] (not surpassing never 13tn/axe which can involve a quicker road degradation). So the conventional road reference cost is taken and has been augmented 20% to take into account any other unforeseen special needs the trackless tram system might have (19.800,00€) or the expected rutting of the pavement as the vehicle will be making exactly same path day after day.

CCRC though, claims that its light construction means that it can be implemented very rapidly in most urban road system without change and that after three years of trials there is no sign of road damage. [Newman, P. et al. 2019]

All the maintenance costs to make the analysis are presented in Table 21.

Maintenance	Conventional (€/km-year)	Extraordinary (€/km-10 year)
Alstom	40,000.00 €	/
TRAMeBUS	20,000.00 €	65,000.00 €
Tunnel	140,000.00 €	/

Table 21: Expected maintenance costs.

7.4 Results Cost-Benefit Analysis

As explained before all the computations for the cash flows of the different periods (2022 – 2051) are made, these results can be seen on the annex.

From them it is possible to extract the value of the four tools that have been presented at the beginning of the section (NPV, IRR, NPV/Investments, payback). The detailed results are presented in the next table. See: Table 22: Cost-Benefit Analysis Results.

The option that gets the best overall results is: Alternative 1 –TRAMeBUS.

This alternative obtains nearly a 9% internal rate of return which involves a good social value of the investment made. This implies that, under a social scope, the alternative is very recommendable.

In addition is the alternative which pays-back the inversion made faster.

The second TRAMeBUS alternative also awards a mention as despite the astronomical inversion required it manages to achieve a positive NPV.

Alt. 1 Alstom	
NPV (€)	69,158,620.64
IRR	6.24%
Payback	2041
NPV/Investment	0.1650

Alt. 2 -Tunnel Alstom	
NPV (€)	(22,177,987.07)
IRR	2.41%
Payback	2048
NPV/Investment	-0.0356

Alt 1 TRAMeBUs	
NPV (€)	109,738,725.37
IRR	8.99%
Payback	2037
NPV/Investment	0.3305

Tunel TRAMeBUs	
NPV (€)	11,151,782.93
IRR	3.32%
Payback	2045
NPV/Investment	0.0199

Table 22: Cost-Benefit Analysis Results.

7.5 Sensitivity analysis

For this analysis, the study asses how changes in three crucial variables impact the result of the study.

The assessed variables are: Value of time, Capital Expenditures (CAPEX) and Maintenance.

The reasons of not doing the same with Demand or Saved Time per user and trip is because their results might be extrapolated to the changes in the value of time. I.e. a decrement in the served demand would imply a decrement in the monetised time savings of the users, the same happens with value of time, or the saved time per trip.

This analysis could be understood as a proof of robustness of the alternative. For instance, if a small variation in CAPEX implies that it is not socially profitable anymore the authorities should be pretty aware of that and be cautious with their decision. This would imply that the social benefit is not important enough, or at least, not important enough to compensate small deviations.

The next plots have been constructed varying a parameter ± 5%. This way different scenarios where the parameter changes from – 45% to + 50% its original value have been built.

7.5.1 Value of time

Value of time should be understood as a crucial parameter as it is responsible for the lion's share of the obtained social benefits.

The consequences of varying the original parameter (9,48€/h) can be understood as directly related to demand or the time saved per trip and user.

The sensibility analysis shows that the alternative can withstand a decrement of up to 35% (6,17 €/h) and keep being socially profitable.

This implies that even in the case that the alternative is not able to attract all the users it is expected to it will kept being profitable for the society.

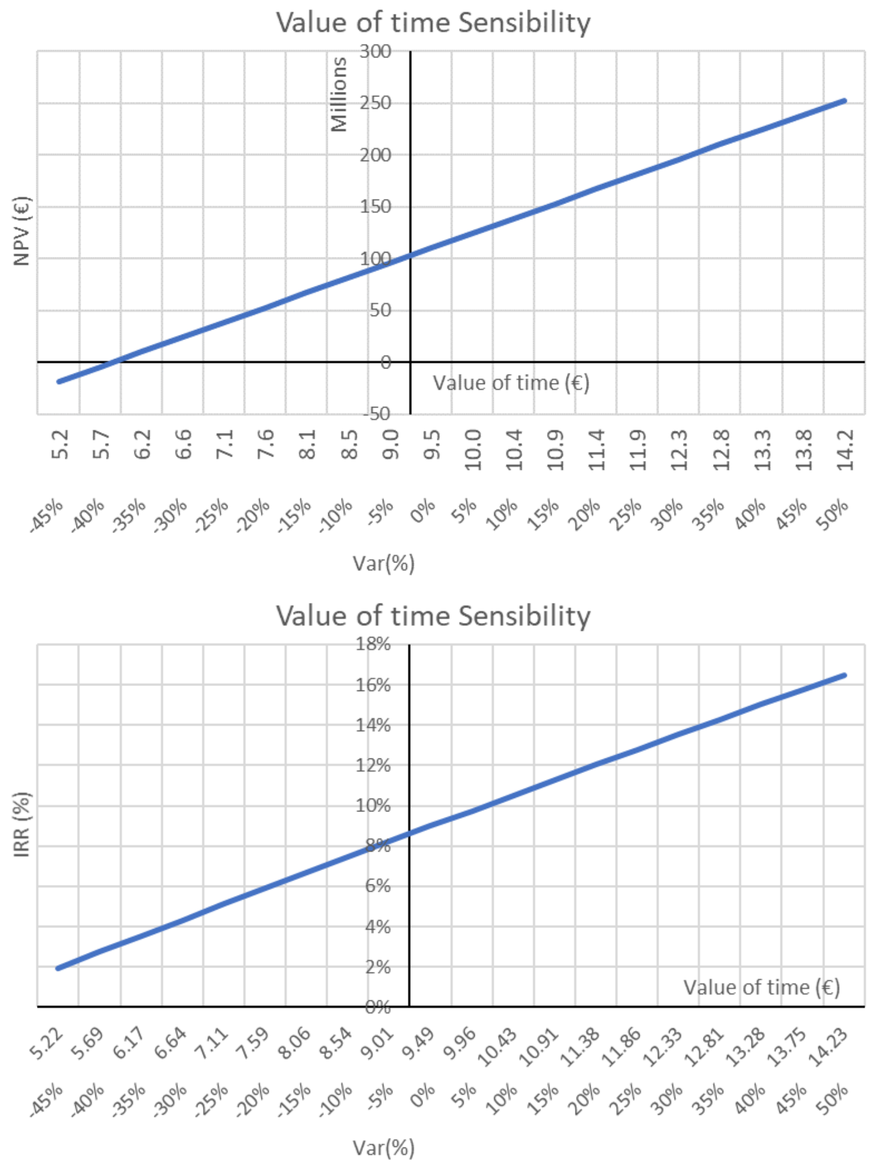


Figure 29: Value of time Senstivity.

7.5.2 CAPEX

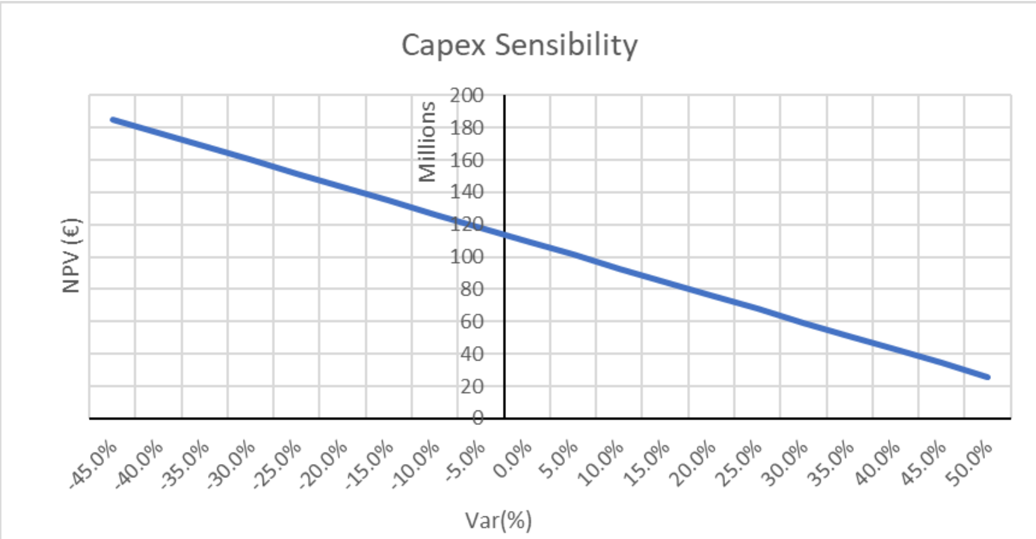
The sensibility to CAPEX variations is another key parameter to assess the likelihood of delivering social benefits after being built.

Despite enterprises might try to adjust to the budget as close as possible over costs are a normal thing. Taking a close look to the city of Barcelona and that the last two major projects (building two new metro lines or the upgrade of Plaça les Glories) are suffering over costs or big delays (which might be also understood as an over coast).

Supplier instability or demand of different important pieces being higher in the future causing to rise their price can also be considered through this sensibility analysis.

The alternative though proves to be quite robust to high CAPEX variations while maintaining a good social profitability.

From the analysis made it is clear that an overall over cost of 25% wouldn't involve a major social profitability decrement as this will be kept higher than 7%.



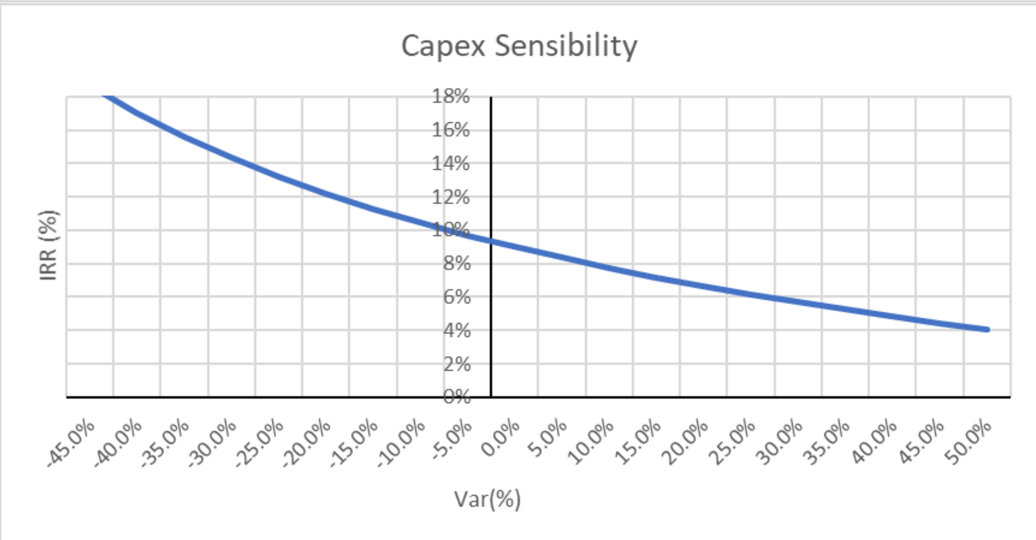


Figure 30: CAPEX Sensitivity..

7.5.3 Maintenance

After performing the required iterations to assess the alternative sensitivity to changes on maintenance cost one can state that the alternative is insensitive to this parameter.

This should not come up as a surprise because it never adds more than 2 MEUR for a single period and all the required maintenance cost over all periods equals no more than 15 MEUR.

This happens in a project were total CAPEX surpass 330 MEUR or were social benefits are clearly bigger than that. So, as defined, maintenance variable has no relative importance or decision value.

Figure 31: Maintenance Sensitivity..

8. Financial study

8.1 Fare

Whenever trying to maximise social benefit, one might incur in major economical drawbacks as all those benefits might never turn into actual cash.

That ought to be one of the arguments behind public transport having deficit as, if that is not the case, it will not be serving a fair share of the population or all the users it should.

So, whenever exploiting a public transport concession it is not only normal but logical to expect a public grant. Data given in grants to operators is largely available on public transport and town council webs.

Combining that data with revenue and the number of passengers for the different public transport systems one can obtain the mean technical rate for the public transport in Barcelona, 1,86€ in 2014.

The study will be assuming that Barcelona tramway system will be receiving a similar quantity per passenger.

Nonetheless it should be logical to assume technical fare will be renegotiated and lowered as the 4-km ampliation is able to attract a high number of passengers without augmenting the cost proportionally.

8.2 OPEX

In order to take into account not only the cost of maintaining the infrastructure but also the cost of operating, Operation Expenditures need to be determined.

It is possible to look at the operating income and gross profit from TRAMVIA METROPOLITA SA society, the concessionaire that operates the tramway service in Barcelona.

All expenses (found as the difference between income and gross profit) are around 24 MEUR for the past 4 years (2015-2018).

With this information and knowing the number of veh-km made each year by the all the vehicle feet it is possible to find an operating cost per veh-km.

Then, subtracting the industrial profit (6%) give indicative values to use as whenever building the model.

TRAMVIA METROPOLITA SA	31/12/2018EUR	31/12/2017EUR	31/12/2016EUR	31/12/2015EUR
Income (€)	37,302,043.00	36,855,266.00	36,112,565.00	35,865,674.00
Gross Profit (€)	12,677,421.00	12,363,073.00	12,418,237.00	12,029,448.00
Expenses (€)	24,624,622.00	24,492,193.00	23,694,328.00	23,836,226.00
veh-km (milions)	2.6	2.6	2.5	2.5
Cost €/veh-km	9.47	9.42	9.48	9.53
Basic cost (€)	8.93	8.89	8.94	8.99
Industrial profit (0.06) (€)	0.54	0.53	0.54	0.54

Table 23: OPEX Cost. Font: ATM & own elaboration.

The averaged value is 8,94 € / veh-km, other mean values have been considered but no significant difference was found.

This value gets close to the 9 €/veh-km determined by [Roig, JM et al. 2017]. This is the reason why the model would be taking 9 €/veh-km as the reference value. The same study proposed a value of 9,5 €/ vehicle-km for the tunnel alternative as it ill imply higher maintenance and exploitation costs.

Despite working with this value assumes all direct cost have turned into variable its use delivers really good results by comparison with the study "PROJECTE DE SISTEMES I AVANTPROJECTE D'EXPLOTACIÓ D'UNA XARXA TRAMVIÀRIA UNIFICADA" (2017). At the end, the total cost difference does not surpass 2'5% for the tunnel alternative and gets close to 3,5% on the on-surface one.

From the "*INFORME DE GESTIÓ*" [TMB 2018] one can extrapolate the cost of running the urban bus public transport system in Barcelona, reaching the value of 6,57 €/veh-km.

As the TRAMeBUS might be similar at the same time to a bus and a tramway the highest value is taken to perform the study despite, probably, overestimating its cost.

Understanding that rubber-tyred vehicles might require more energy the account of electric power requirements determined for the light-rail system in [Roig, JM et al. 2017] will be increased by 50% which will involve adding 0,35 €/veh-km.

It is expected that the increased OPEX cost taken as reference will account for problems that may arise that could not be foreseen due to lack of experience with the system. The considered extra cost would account for the required formation of employees, hiring some new specialised personal etc.

Thus, the study is taking 9,35€ / vehicle-km for the TRAMeBUS surface alternative and 9,95 €/veh-km for the tunnel alternative.

This method requires properly estimating the commercial speed and schedule of the tramway system.

The current commercial schedule is:

- Sunday to Thursday from 5:00 to 24:00h.
- Friday, Saturday, and days before public holidays from 5:00 to 2:00h.

Which involves an average of 19h35 per day.

Considering bank holidays had no major affection on the average working hours per day.

Whereas, considering the time it took to the vehicles to get back to the garages made us add up to 21mins for the surface alternative.

The study made by [Rosell, F. et al. 2017] declares that exploiting the corridor at frequencies of 4mins lowers the possibility of tram-bunching and gives an average commercial speed of 17,6 km/h. As the speed obtained nowadays on the “Trambaix” (18.3 km/h) and “Trambesos” (18.4 km/h) [Via Libre (2008)] the slowest speed is took and it is understood that the whole infrastructure will to adapt to it.

For the tunnel alternative higher speeds might be expected, as the full studied section will not run completely inside the tunnel, the study will not expect a much higher one. 18 km/h has been took as the reference commercial speed as it is still lower to the commercial speed obtained until now by the two other tram sections.

It should be kept in mind that despite 17,5 km/h might look as “relatively slow” buses in Barcelona struggle to reach 12km/h as mean commercial speed at the end of the day [TMB 2020]. So, a surface public transport system being capable to travel at 17,5 km/h is quite fast.

8.3 Results Financial Analysis

The obtained results go beyond what could have been expected. The obtained values are very desirable from an economical point of view.

All four alternatives can pay-back the initial investment in less than 10 years and obtain very interesting IRR from the point of view of a private investor.

Alstom alternatives rank considerably better than in the Cost-Benefit analysis, this it easily understood looking to the demand tables (Table 12 & Table 13) as they are able to merge the two networks from the first day thus obtaining revenue from both of them whereas TRAMeBUS alternatives are expected to wait until 2032.

Results might label alternative as excessively profitable; they are but, there is a reason behind that. To build the study efforts have been centred in analysing and taking the data available of the current Tramway network. This network is 29,1 km in total length and has a demand of 1 Million passengers / (km * year). The central section of the network (less than 4km), that would unify the two ancient ones it is expected to attract more than 7,45 Million passengers / (km * year) while it would only represent the 12% of the new network.

So, whenever the two tramway networks are unified, total demand nearly doubles and the network gets a 1.86 Million passengers / (km * year) ratio without proportionally augmenting the network.

From the merely financial point of view all four alternatives are recommendable to a private investor. See Table 24: Financial study results. For the detailed results.

To further understand how the alternatives behave and in order to compare them a limit-case analysis is made. The value of the Fare is iterated until an IRR of 7,5% is reached. This IRR in an investment backed up by the public authorities would make the inversion very desirable for a private investor.

Alt. 1 Alstom	
NPV (€)	1,344,146,293.79
IRR	51.29%
Payback	2024
NPV/Investmen	3.2062

Alt. 2 -Tunnel Alstom	
NPV (€)	1,158,057,043.03
IRR	19.91%
Payback	2026
NPV/Investmen	1.8603

Alt 1 TRAMeBUs	
NPV (€)	1,093,480,511.14
IRR	35.28%
Payback	2024
NPV/Investmen	3.2932

Alt. 2 - Tunel TRAMeBUs	
NPV (€)	904,489,761.14
IRR	14.29%
Payback	2029
NPV/Investmen	1.6151

Table 24: Financial study results.

Once all the cases are generated, it is possible to appreciate that the alternative that requires the smallest fare to give an IRR of 7,5% is Alternative 1 TRAMeBUS.

This implies that at this given theoretical profitability level is the alternative that needs the smallest public grant.

Despite that Alt.1 Alstom needs a fare just a 1.5% higher and is has a smaller payback. Nevertheless, the TTS alternative, obtains a 17% higher NPV/Investment ratio.

From the obtained results (see: Table 25) it can be extracted that this study is not useful to make the decision on which alternative to build as all four alternatives require a small subvention by comparison of the one given nowadays.

Alternative	Fare (€)	NPV (€)	IRR (%)	Payback	NPV/Investment
Alt. 1 Alstom	0.8619	111,216,819.08	7.50%	2031	0.2653
Alt. 2 -Tunnel Alstom	1.1450	264,901,924.15	7.50%	2036	0.4255
Alt 1 TRAMeBUs	0.8529	103,139,711.28	7.50%	2039	0.3106
Alt. 2 - Tunel TRAMeBUs	1.2411	287,291,918.75	7.50%	2036	0.5130

Table 25: Required fare at IRR = 7,5%

In an analogous manner, to compare alternatives between them a concession fee due to pay on the first year is analysed. Results are also iterated to find the value of the fee that gives an IRR close to 7,50%.

Results though, get similar. Alstom on-surface alternative is capable to bear the highest fee while TRAMeBUS alternatives manage to obtain a higher NPV/Investment ration despite paying-back two years further in time (2032).

See Table 26 for detailed results notice that as canon fee would be an expenditure for the concession owner is market as a negative value in the table.

Alternative	Canon (€)	Fare (€)	NPV (€)	IRR (%)	Payback	NPV/Investment
Alt. 1 Alstom	(709,462,279.92)	1.8600	655,347,963.77	7.52%	2034	0.5806
Alt. 2 -Tunnel Alstom	(513,876,425.57)	1.8600	659,147,892.00	7.51%	2034	0.5800
Alt 1 TRAMeBUS	(516,704,338.49)	1.8600	591,825,813.57	7.51%	2036	0.6973
Alt. 2 - Tunel TRAMeBUS	(320,676,295.80)	1.8600	593,153,551.62	7.52%	2036	0.6735

Table 26: Bearable Canon fee at IRR = 7,5%

9. Multicriteria analysis

In order to further assess the suitability of each project another comparative analysis is made.

This analysis is made to complement the project and see how alternatives rank among the others in a quantitative manner.

To properly compare the alternatives previously assessed or monetized items (i.e. time savings) are not considered.

To accurately do this analysis one should ask different experts to measure as precisely as possible each indicator (for instance CO2 absorption by trees) and meticulously decide all the ponderations and weights of the considered indicators.

This study though, has been dealing with the different constraints as seamlessly as it possible could, following the same idea a simplified methodology is presented.

Still and all, meaningful results are expected that will give the reader a precise conjecture of what a legitimate rock-solid multicriteria analysis will deliver.

For this the important comparison fields are defined. After an extensive review and to avoid making a lengthy analysis, those variables that do not introduce major difference between alternatives have not been taken into account.

To name a few the study has discarded the number of users serviced, the intermodally and the easiness of changing transportation modes as all alternatives make the connexion within the same path.

In a similar manner, noise and greenhouse gases have not been considered as both systems would be rolling on electric motors.

Nonetheless a penalisation has been accounted for the tunnel alternatives as underground stops are expected to cause discomfort and have a smaller potential of attraction. This, as all the other indicators, will be discussed in the next pages.

The multicriteria analysis will compare the alternatives in the following fields:

Comfort

As different vehicles and underground stations might imply a perceived difference from the user's point of view and even a decrement in the expected demand

As vehicles are expected to have similar lateral and vertical accelerations (both follow a route that would be carefully built), higher importance has been given to the discomfort introduced by underground stations.

Vehicle comfort has been ranked as perceived in users from EMEF 2017 [ATM 2017] understanding that, in the worst case, TRAMeBUS comfort level will be that from the urban bus.

The discomfort generated by underground stations has been assessed by the ratio of newly built underground stations by newly built stations.

Similarly, it has been assessed the discomfort caused by the need of changing vehicle in the TRAMeBUS alternatives, at least, for the first ten years. As Francesc Macià platform would be long enough to fit two vehicles in double composition (a total of 4 simple units). It is expected for the average user to walk less than 30 m from one vehicle to another (or less than 60m for two vehicles in double composition).

The tiny distance to be walked and the short duration of the discomfort (less than 10 years) by comparison with the project service life, has awarded them a small relative importance.

Environment & Aesthetics

Many different initiatives, studies and organisations endorse cities should be building greener spaces in the cities. Moreover, they defend their importance in different fields (conservation of flora and fauna, cleaner air, less noise, shadow obtained from trees etc..) and citizens also value them from an aesthetic point of view. This makes the field difficult to be split.

Consequently, it has been measured the square meters of grass on platform each alternative has together with an indicator built by means of the number of trees that need to be removed.

Given that Barcelona benchmarks as a nice city full of different architectural monuments and pretty streets the study is assessing the importance of lacking overhead lines as it is considered a form of "visual pollution"

Accidents

Interaction between pedestrians and faster-rolling vehicles always causes problems. There are though some mechanisms that dissuade pedestrians from crossing without looking such as rails or grass platforms.

Despite considering that the TRAMeBUS alternatives might require smaller distance to break and fully stop the vehicle they are penalised proportionally to the number of kilometres without rails. Tunnel alternatives as they run underground for nearly 50% of the track are awarded a bonus.

These problems could be mitigated by differentiating the Tram platform from the normal street asphalt. The city of Castellon chose to paint it in a different colour and made it run some centimetres higher than the car street. This approach has been taken by different public transport operators, for instance, Toulouse public transport buses also run in a higher reddish platform.

Line exploitation

This field tries to quantify the major non-monetizable difference between the TRAMeBUS and Alstom alternatives, some of them have been expressed in the course of this study.

Basically, it is measured based on the delays that rolling on rails might cause when you cannot surpass the vehicles (i.e. Barcelona Tramway service averages nearly two incidences per week), the flexibility that a system has to change its normal route when a major event or any strange circumstance might advise to change do so.

It is also measuring the easiness to expand the route as different city council plans state that expanding the current network might be worth it. In this sense an alternative that does not require a major intervention (and its associated cost) might prove itself valuable.

In addition to those three criteria a last one is added measuring the possibility to implement direct and semi direct lines introducing a new mode of exploitation that few services around the world have. This feature might be comparable to the New York subway but demand a much smaller inversion as, instead of requiring building 3 or 4 tracks with just a couple would be more than enough (as vehicles would be able to surpass each other at virtually any point of the track).

Macroeconomics

Despite all alternatives might enable a similar zoned development the manufacturer of the vehicles are different enterprises. It should be noted then that Alstom has a fabric and officers nearby Barcelona whereas CCRC is established in China and no other supplier with similar technological development has been found. That is why Alstom alternatives will be better ranked in this field.

The study also considers here the potential overseas impact of building an innovative public transport service in a city that works to attract technological talent and holds a big number of important IT events as the “Mobile World Congress” or the “Smart City Expo”.

Works

In this category it is ranked the disruptions when building the infrastructure and their duration. As citizens might be able to bear an important disruption for a short period of time or a lighter one for a longer period.

In this sense building a tunnel might cause higher disruptions and require more time whereas alternatives without rails might be completed faster as the constructive process would be less demanding.

In the end the field measures the expected citizen's discomfort but accurately measuring greenhouse gasses emissions our sound pollution would deliver a similar result.

9.1 Normalised Indicators

All introduced indicators are normalised on 0 to 10 scale to facilitate its interpretation. In this scale 10 is the highest possible positive impact and 0 would imply a negative impact, lacking the assessed feature or being the worst alternative in the considered item.

The marks obtained by each project in each field and item are presented in the next table: (Table 27).

Normalised marks		Alstom		TRAMeBUS	
		Alt. 1	Tunnel	Alt. 1	Tunnel
Comfort	Vehicles	7,7	7,7	7,1	7,1
	Stops	10,0	5,0	10,0	5,0
	Transfer	10,0	10,0	0,0	0,0
Environment & Aesthetics	Grass on platform	10,0	6,3	0,0	0,0
	Trees	10,0	6,8	10,0	6,8
	Overhead Lines	0,0	0,0	10,0	10,0
Accidents	Lack of rails	10,0	10,0	0,0	4,7
	Tunnel	0,0	10,0	0,0	10,0
Line exploitation	Incidence driven delays	0,0	0,0	10,0	10,0
	Flexibility / Day-day route changes	0,0	0,0	10,0	5,3
	Easiness of route expansion	0,0	0,0	10,0	10,0
	Direct & semi-direct lines	0,0	0,0	10,0	9,3
Macroeconomics	Workplaces in the region	10,0	10,0	0,0	0,0
	Positioning BCN as an innovative hub	0,0	0,0	10,0	10,0
Works	Disruptions	8,8	0,0	10,0	0,0
	Duration	6,7	0,0	10,0	3,3

Table 27: Normalised marks for the different indicators.

9.2 Proposal of weights

To achieve a real consistent mark reflecting the pros and cons of each alternative to compare them it is though convenient to establish ponderations (weights) of each field to reflect their relative importance.

Following this method, the "final mark" will be computed as a weighted mean according to the next formula:

$$M = \sum_{f=1}^{8} \sum_{i=0}^{n} \%_f * \%_i * m_i$$

Where:

- M is the final mark on scale 0-10.
- $\%_f$ is the assigned weight of the considered field.
- $\%_i$ is the assigned weight of the considered item within the field.
- m_i is the mark obtained in the item i on scale 0 - 10.

That is the reason behind of first ranking fields and assigning a value to them.

It is understood that the most important field is environment and aesthetics as society's concern on their well-being and their desire to live in better cities with more greener spaces and better air quality drives important city-planning changes on planification. That is why it accounts for $1/4^{th}$ of the total final mark.

Line exploitation field introduces some though-to-be interesting changes on the current paradigm. So, a $1/5^{th}$ of the total final mark is given to this field.

After that, the next fields have been considered as important and understood they should have a similar weight in the total final mark. So, Comfort and Accidents fields account for the 17% and 18% of the total final mark.

Comfort and Works have been considered to be similar in importance but, as comfort might have an implication in the number of users attracted and it is considered to last for all the service life whereas works is a transitive field (just two years); it has been decided to assign lower relative importance to the works field. Moreover, provided it has been difficult to access to a precise software or find a precise methodology to approximate works impact the study has mainly assessed that in terms of "potential discomfort caused" (Disruptions & Duration).

Finally, it has been given a 10% to "aesthetics Macroeconomics field "macroeconomics" as to properly quantify it a specialised study might also be required but, despite that, it is expected to deliver a pretty good approximation.

Similar methodology has been used to determine the weights of the different items.

All weights are exposed in the next table: (See Table 28: Proposal of weights.).

Weights		%f	%i
Comfort	Vehicles	17%	35%
	Stops		40%
	Transfer		25%
Environment & Aesthetics	Grass on platform	25%	35%
	Trees		30%
	Overhead Lines		35%
Accidents	Lack of rails	18%	70%
	Tunnel		30%
Line exploitation	Incidence driven delays	20%	40%
	Flexibility / Day-day route changes		18%
	Easiness of route expansion		25%
	Direct & semi-direct lines		18%
Macroeconomics	Workplaces in the region	10%	70%
	Positioning BCN as an innovative hub		30%
Works	Disruptions	10%	30%
	Duration		70%

Table 28: Proposal of weights.

9.3 Results Multicriteria Analysis

Considering the relative weight of each item inside the field it is possible to build a table where comparison of each field might be made to determine where each one ranks best (See Table 29: Field and final mark for each alternative.).

The results of the multicriteria analysis show that the alternative which fits best the analysed items is TRAMeBUS – Alt. 1.

Ponderated Mark		Alstom		TRAMeBUS	
Field	%f	Alt 1	Tunnel	Alt 1	Tunnel
Comfort	17%	9,20	7,20	6,49	4,49
ronment & Aesthetics	25%	6,50	4,25	6,50	5,54
Accidents	18%	7,00	10,00	0,00	6,29
Line exploitation	20%	0,00	0,00	10,00	9,06
Macroeconomics	10%	7,00	7,00	3,00	3,00
Works	10%	7,29	0,00	10,00	2,33
Ponderated Mark		5,88	4,78	6,03	5,62

Table 29: Field and final mark for each alternative.

One can see from the analysis that there is no alternative capable of standing out in all items, it is important to see that the second best ranked alternative (Alstom – Alt. 1) gets better punctuation in some important fields.

That is why results have been analysed to see if there is any major bias in the assigned weights of each field. So, different step-by step simulations changing weights $\pm 0.1\%$ up to $\pm 10\%$ have been made. Results though kept mainly unchanged and TRAMeBUS – Alt. 1 kept being the best ranked alternative for most cases (83%).

It is interesting to point out that whenever works field weighted less than 4,75% TRAMeBUS – Tunnel alternative was the chosen one.

It is not much of a surprise though that when line exploitation weight decreased to 13,3% Alstom – Alt.1 started being the best ranked alternative as when line exploitation started losing importance.

Results are presented in the next figure. See Figure 32.

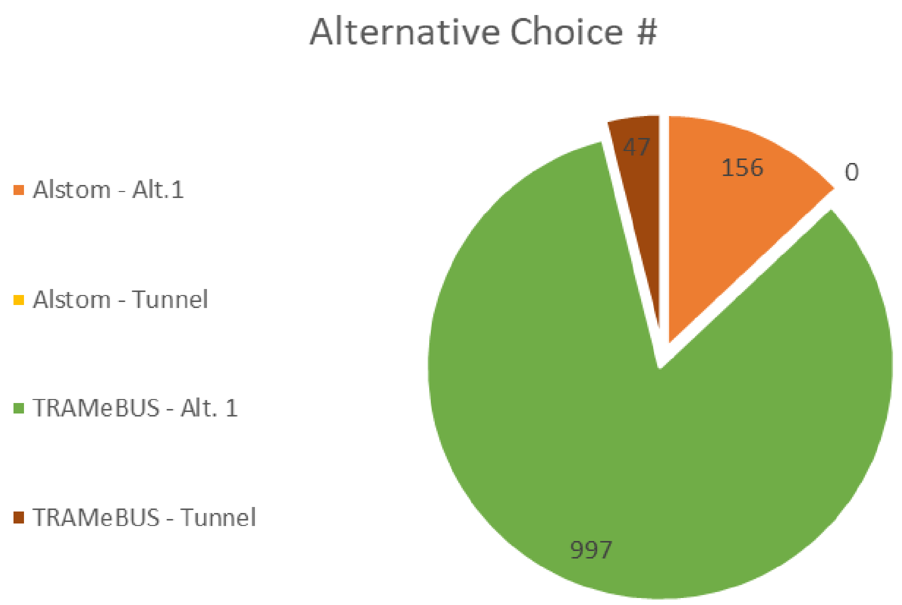


Figure 32: Times each alternative is chosen on the built scenarios

10. Summary of Results

The first analysis made, the cost benefit analysis, is capable to recommend by itself both surface alternatives and the TRAMeBUS Tunnel one.

TRAMeBUS – Alt. 1 ranks best in all the analysed items.

Alt. 1 Alstom	
NPV (€)	69,158,620.64
IRR	6.24%
Payback	2041
NPV/Investment	0.1650

Alt. 2 -Tunnel Alstom	
NPV (€)	(22,177,987.07)
IRR	2.41%
Payback	2048
NPV/Investment	-0.0356

Alt 1 TRAMeBUs	
NPV (€)	109,738,725.37
IRR	8.99%
Payback	2037
NPV/Investment	0.3305

Tunel TRAMeBUs	
NPV (€)	11,151,782.93
IRR	3.32%
Payback	2045
NPV/Investment	0.0199

Table 30: Cost-Benefit Analysis Results.

The merely financial study made states that at the current fare all four alternatives would be profitable for a private investor.

Despite that we have analysed which alternative can bear a lower fare while maintaining a good IRR. The simulations made give similar values to both on-surface alternatives without none of them both clearly standing out. However, the Alstom alternative was able to pay a 30% higher concession fee for the current fare (1,86 €).

Alternative	Fare (€)	NPV (€)	IRR (%)	Payback	NPV/Investment
Alt. 1 Alstom	0.8619	111,216,819.08	7.50%	2031	0.2653
Alt. 2 -Tunnel Alstom	1.1450	264,901,924.15	7.50%	2036	0.4255
Alt 1 TRAMeBUs	0.8529	103,139,711.28	7.50%	2039	0.3106
Alt. 2 - Tunel TRAMeBUs	1.2411	287,291,918.75	7.50%	2036	0.5130

Table 31: Required fare at IRR = 7,5%

Finally, the Multicriteria analysis awards the highest mark to TRAMeBUS – Alt.1 (6,03/10) but, the second best ranked alternative (Alstom – Alt.1) obtains a 5,88/10.

Notwithstanding, when a sensitivity analysis is made changing the chosen weights up to $\pm$ 10% the TRAMeBUS – Alternative 1 is chosen on the 83% of the cases.

11. Conclusions

As it is been proved on the first part of this thesis the current state of development of technology is enough to ensure the required reliability needed for a public transport system.

This technology is not new, the French city of ROUEN implemented the first rolling vehicles able to follow a virtual path on 2001 and the network has been growing since then.

Neither it is DGPS guidance which was proven useful for farming utilities in 1996 and since then technology has been improved by lots of suppliers that nowadays deliver enhanced auto-guiding systems based on the same technology all over the world.

Moreover, electric batteries are nothing new and lots of vehicles (and urban bus) suppliers produce vehicles with enough energy storing capabilities to assure that, in combination with the efficiency of the electric motor, these vehicles can travel great distances without recharging.

It is then understood that merging these technologies would result in a fully automated electric vehicle. CCRC Corporation has been able to prove so and different public transport lines have been built taking advantage of the technology.

Many major cities are nowadays slaves of the car layout they have been built during years, that is the case of the Diagonal avenue of Barcelona where cars and unsustainable development has jeopardized citizen's space leaving them in the background.

This car-centrist heritage prevents the capital becoming a 21^{st} century city.

It is then clear that it needs to be rethought and rearranged. Moreover, there is a high unserved demand for public transport in the studied section.

So, whenever analysing how a Trackless Tram System might be able to solve these problems, it is possible to see from the cost-benefit analysis that it easily beats its more conventional counterparts.

Despite aiming to build an over-conservative study due to the incertitude a new technology might come with, the TRAMeBUS on-surface alternative is the one that scores best in the analysed fields.

The Alternative 1 – TRAMeBUS obtains a much higher IRR than its conventional light rail counterpart (8,99% vs 6,24%).

This alternative would still be socially profitable (IRR > 3%) as long as:

- The value of time does not decrease more than a 35 %
- CAPEX (Investment costs) do not augment more than 60 %

This implies a high likelihood of the infrastructure being socially profitable even in the worst case.

In addition, the study built has always augmented the cost of the alternative whenever a slight incertitude was introduced in detriment, always, of the TRAMeBUS alternatives. So actual costs could be expected to be lower thus, profitability higher than computed.

The results of the financial study make all four studied alternatives advisable as they are all capable of achieving high merely economical profitability. This might make the town council push to further develop the network and serve a greater share of the population.

Both on-surface alternatives required a similar fee to obtain a merely economical profitability of IRR = 7,5 %. The TTS was 1% cheaper.

The results of the Multicriteria Analysis also drive this study to recommend the Alt.1 – TRAMeBUS option as it is the one with the overall higher mark.

This study then concludes that that the best option for the city of Barcelona is to build a TTS.

It also recommends any other developed city planning to build a conventional tramway to rethink the project and consider implementing a TTS as it is the foreseeable future.

11.1 Comments

As a stress proof it has also been computed to see how the chosen alternative (Alt 1. – TRAMeBUS) behaves if it is capable of completely replacing the current light rail service since the day one.

For that, the alternative should be buying 59 vehicles the first year of exploitation.

This also makes the option advisable from the cost benefit analysis as it pays back in 2038 or it has a high IRR. (See Table 32)

The scenario also obtains good results from the financial point of view (it is also able to obtain a high merely economic profitability) and requires a fare equal to 0,9 €/pax to obtain an economic IRR = 7,5%.

This scenario has not been considered in the main part of the thesis as it would involve discarding Alstom vehicles that are not in the end of their service life. Which is socially unacceptable.

Nevertheless this scenario can be understood as the possibility to converge faster to a unique tramway network or opens the possibility to exploit circular lines in the already built conventional rails while the major part of the network is operated with TRAMeBUS vehicles.

This interesting scenario could be object of another study focused on management of mixed in-city rail-lines of TTS and conventional light rail. Results might encourage cities to slowly replace obsolete vehicles with new TRAMeBUS units until fully replacing them.

Alt. 1 - TRAMeBUs v2	
NPV (€)	77,055,068.65
IRR	6.04%
Payback	2038
NPV/Investment	0.2321

Table 32: TRAMeBUS Hypothetical Scenario.

Annex

In this annex the detailed cash flow results are presented in the same order that has been used in the study:

- Alternative 1 – Alstom
- Alternative 2 Tunnel – Alstom
- Alternative 1 – TRAMeBUS
- Alternative 2 Tunnel – TRAMeBUS

The results presented are those obtained after the application of the shadow price coefficient (Table 3: Shadow Price coefficients- Font: SAIT (2015) & ADIF (2013)).

These results have been presented as detailed as possible for all the studied time periods (2020 – 2051) in other to let the readers observe all the number required and generated for the study.

Numbers between brackets and in red (example) are negative values, negative quantities to be subtracted.

They might indicate a payment to make (i.e. buying new units) or a social prejudice (congestion costs).

As a recall of the results Table 22: Cost-Benefit Analysis Results. Is reproduced here:

Alt. 1 Alstom	
NPV (€)	69,158,620.64
IRR	6.24%
Payback	2041
NPV/Investment	0.1650

Alt. 2 -Tunnel Alstom	
NPV (€)	(22,177,987.07)
IRR	2.41%
Payback	2048
NPV/Investment	-0.0356

Alt 1 TRAMeBUs	
NPV (€)	109,738,725.37
IRR	8.99%
Payback	2037
NPV/Investment	0.3305

Tunel TRAMeBUs	
NPV (€)	11,151,782.93
IRR	3.32%
Payback	2045
NPV/Investment	0.0199

Table 22: Cost-Benefit Analysis Results.

		Alt. 1 Alstom					Cost-Benefit Analysis					Alt. 1 Alstom				
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
New Users (pax/day)			69,456	78,791	84,182	84,182	85,445	86,726	82,390	83,626	84,881	86,154	87,446	88,321	89,204	90,096
Catched users			38,895	44,123	47,142	47,142	47,849	48,567	46,138	46,831	47,533	48,246	48,970	49,460	49,954	50,454
Induced Users			30,560	34,668	37,040	37,040	37,596	38,160	36,252	36,795	37,347	37,908	38,476	38,861	39,250	39,642
Time saved h/day			3,711	4,210	4,498	4,498	4,565	4,634	4,402	4,468	4,535	4,603	4,672	4,719	4,766	4,814
h/year			1,354,520	1,536,587	1,641,715	1,641,715	1,666,343	1,691,334	1,606,767	1,630,871	1,655,337	1,680,165	1,705,366	1,722,424	1,739,645	1,757,047
Monetised time savings			12,848,975	14,576,062	15,573,305	15,573,305	15,806,928	16,043,991	15,241,796	15,470,439	15,702,522	15,938,046	16,177,102	16,338,917	16,502,272	16,667,347
Congestion			(9,703,333)	(8,271,667)	(7,046,667)	(5,926,667)	(4,900,000)	(4,033,333)	(3,211,667)	(2,500,000)	(1,800,000)	(1,200,000)	(1,100,000)	(1,000,000)	(900,000)	(850,000)
Investments	(25,175,174)	(25,175,174)	0	0	0	0	(1,222,130)	0	0	(22,953,475)	0	0	(1,831,620)	0	0	0
Regular maintenance			(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)
Tunnel Maintenance			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extraordinary maintenance			0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Uts			18	0	0	0	0	0	0	0	3	0	41	0	4	0
Price(€)			(40,685,400)	0	0	0	0	0	0	0	(6,780,900)	0	(92,672,300)	0	(9,041,200)	0
TOT	(25,175,174)	(25,175,174)	(38,465,765)	5,378,388	7,600,630	8,720,628	8,758,787	11,084,646	11,104,117	(10,909,049)	6,195,608	13,812,032	(80,352,833)	14,412,902	5,635,057	14,891,332

		Alt. 1 Alstom					Cost-Benefit Analysis					Alt. 1 Alstom				
Year	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051
New Users (pax/day)	90,997	91,907	92,826	93,754	94,692	95,638	96,595	97,561	98,537	99,522	100,517	101,522	102,538	103,563	104,598	105,644
Catched users	50,958	51,468	51,982	52,502	53,027	53,557	54,093	54,634	55,180	55,732	56,290	56,853	57,421	57,995	58,575	59,161
Induced Users	40,039	40,439	40,843	41,252	41,664	42,081	42,502	42,927	43,356	43,790	44,227	44,670	45,117	45,568	46,023	46,483
Time saved h/day	4,862	4,911	4,960	5,009	5,059	5,110	5,161	5,213	5,265	5,317	5,371	5,424	5,479	5,533	5,589	5,645
h/year	1,774,611	1,792,357	1,810,284	1,828,383	1,846,672	1,865,134	1,883,786	1,902,630	1,921,655	1,940,870	1,960,277	1,979,884	1,999,682	2,019,671	2,039,870	2,060,269
Monetised time saving	16,833,962	17,002,297	17,172,353	17,344,038	17,517,535	17,692,661	17,869,599	18,048,347	18,228,816	18,411,096	18,595,187	18,781,180	18,968,984	19,158,598	19,350,205	19,543,713
Congestion	(800,000)	(750,000)	(700,000)	(650,000)	(600,000)	(550,000)	(500,000)	(450,000)	(400,000)	(350,000)	(300,000)	(250,000)	(200,000)	(150,000)	(100,000)	(50,000)
Investments	0	(2,982,700)	0	0	0	0	(16,986,972)	0	0	0	0	0	0	0	0	(15,400,000)
Regular maintenance	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)
Tunnel Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extraordinary maintena	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Uts	0	0	0	0	3	0	0	0	0	5	0	0	0	0	3	0
Price(€)	0	0	0	0	(6,780,900)	0	0	0	0	(11,301,500)	0	0	0	0	(6,780,900)	0
TOT	15,107,947	12,343,582	15,546,337	15,768,023	9,210,619	16,216,646	(543,389)	16,672,332	16,902,801	5,833,581	17,369,172	17,605,164	17,842,968	18,082,582	11,543,289	90,754,322

Table 33: Alt.1 - Alstom Cost Benefit Analysis Detailed Cash Flows.

		Alt. 2 -Tunnel Alstom					Cost-Benefit Analysis					Alt. 2 -Tunnel Alstom				
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
New Users (pax/day)			71,053	80,603	86,118	86,118	87,410	88,721	84,285	85,550	86,833	88,135	89,458	90,352	91,255	92,168
Catched users			39,790	45,138	48,226	48,226	48,950	49,684	47,200	47,908	48,626	49,356	50,096	50,597	51,103	51,614
Induced Users			31,263	35,465	37,892	37,892	38,460	39,037	37,085	37,642	38,206	38,780	39,361	39,755	40,152	40,554
Time saved h/day			3,870	4,390	4,691	4,691	4,761	4,833	4,591	4,660	4,730	4,801	4,873	4,921	4,971	5,020
h/year			1,412,641	1,602,514	1,712,163	1,712,163	1,737,847	1,763,916	1,675,718	1,700,861	1,726,368	1,752,270	1,778,555	1,796,334	1,814,300	1,832,444
Monetised time savings			13,400,311	15,201,444	16,241,576	16,241,576	16,485,219	16,732,505	15,895,861	16,134,369	16,376,332	16,622,030	16,871,370	17,040,025	17,210,454	17,382,564
Congestion			(5,426,667)	(4,703,333)	(3,990,000)	(3,370,000)	(2,860,000)	(2,348,333)	(1,885,667)	(1,523,333)	(1,105,667)	(800,000)	(500,000)	(450,000)	(425,000)	(400,000)
Investments	(89,914,482)	(89,914,482)	0	0	0	0	(1,222,130)	0	0	(22,953,475)	0	0	(2,326,758)	0	0	0
Regular maintenance			(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)
Tunnel Maintenance			(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)
Extraordinary maintenance			0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Uts			17	0	0	0	0	0	0	0	3	0	41	0	4	0
Price(€)			(38,425,100)	0	0	0	0	0	0	0	(6,780,900)	0	(92,672,300)	0	(9,041,200)	0
TOT	(89,914,482)	(89,914,482)	(31,583,070)	9,366,495	11,119,960	11,739,959	11,271,472	13,252,554	12,878,576	(9,474,058)	7,358,146	14,690,411	(79,759,308)	15,458,405	6,612,634	15,850,945

		Alt. 2 -Tunnel Alstom					Cost-Benefit Analysis					Alt. 2 -Tunnel Alstom				
Year	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051
New Users (pax/day)	93,090	94,020	94,961	95,911	96,870	97,838	98,817	99,805	100,803	101,811	102,829	103,857	104,896	105,944	107,004	108,074
Catched users	52,130	52,651	53,178	53,710	54,247	54,789	55,337	55,891	56,450	57,014	57,584	58,160	58,742	59,329	59,922	60,522
Induced Users	40,959	41,369	41,783	42,201	42,623	43,049	43,479	43,914	44,353	44,797	45,245	45,697	46,154	46,616	47,082	47,553
Time saved h/day	5,071	5,121	5,173	5,224	5,276	5,329	5,383	5,436	5,491	5,546	5,601	5,657	5,714	5,771	5,829	5,887
h/year	1,850,765	1,869,273	1,887,968	1,906,850	1,925,919	1,945,175	1,964,627	1,984,277	2,004,114	2,024,158	2,044,398	2,064,845	2,085,490	2,106,340	2,127,408	2,148,682
Monetised time saving	17,556,355	17,731,921	17,909,260	18,088,375	18,269,263	18,451,926	18,636,456	18,822,854	19,011,027	19,201,160	19,393,162	19,587,124	19,782,954	19,980,746	20,180,591	20,382,398
Congestion	(375,000)	(350,000)	(325,000)	(300,000)	(275,000)	(250,000)	(225,000)	(200,000)	(175,000)	(150,000)	(125,000)	(100,000)	(75,000)	(50,000)	(25,000)	(25,000)
Investments	0	(3,045,700)	0	0	0	0	(29,400,807)	0	0	0	0	0	0	0	0	0
Regular maintenance	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)	(926,016)
Tunnel Maintenance	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)
Extraordinary maintena	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
New Uts	0	0	0	0	3	0	0	0	0	3	0	0	0	0	4	0
Price(€)	0	0	0	0	(6,780,900)	0	0	0	0	(6,780,900)	0	0	0	0	(9,041,200)	0
TOT	16,049,736	13,204,601	16,452,641	16,656,755	10,081,743	17,070,306	(12,120,971)	17,491,235	17,704,407	11,138,641	18,136,542	18,355,504	18,576,334	18,799,126	9,982,771	104,648,973

Table 34: Alt.2 Tunnel - Alstom Cost Benefit Analysis Detailed Cash Flows.

			Alt 1 TRAMeBUs					Cost-Benefit Analysis					Alt 1 TRAMeBUs			
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
New Users (pax/day)			69,456	78,791	84,182	84,182	85,445	86,727	82,390	83,626	84,880	86,154	87,446	88,320	89,203	90,095
Catched users			38,895	44,123	47,142	47,142	47,849	48,567	46,138	46,831	47,533	48,246	48,970	49,459	49,954	50,453
Induced Users			30,561	34,668	37,040	37,040	37,596	38,160	36,252	36,795	37,347	37,908	38,476	38,861	39,249	39,642
Time saved h/day			3,711	4,210	4,498	4,498	4,565	4,634	4,402	4,468	4,535	4,603	4,672	4,719	4,766	4,814
h/year			1,354,527	1,536,578	1,641,713	1,641,713	1,666,344	1,691,346	1,606,766	1,630,870	1,655,326	1,680,171	1,705,366	1,722,415	1,739,635	1,757,037
Monetised time savings			12,849,047	14,575,980	15,573,291	15,573,291	15,806,940	16,044,105	15,241,779	15,470,433	15,702,418	15,938,102	16,177,102	16,338,827	16,502,182	16,667,257
Congestion (€)			(9,703,333)	(8,271,667)	(7,046,667)	(5,926,667)	(4,900,000)	(4,033,333)	(3,211,667)	(2,500,000)	(1,800,000)	(1,200,000)	(1,100,000)	(1,000,000)	(900,000)	(850,000)
Investments	(22,426,276)	(22,426,276)	0	0	0	0	(1,222,130)	0	0	(22,953,475)	0	0	(1,831,620)	0	0	0
Regular maintenance			(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(463,008)	(463,008)	(463,008)	(463,008)
Tunnel Maintenance			0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extraordinary maintenance			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(1,504,776.00)	0.00	0.00	0.00	0.00	0.00
New Uts			18	0	0	0	0	0	0	0	3	0	41	0	4	0
Price(€)			(31,500,000)	0	0	0	0	0	0	0	(5,250,000)	0	(71,750,000)	0	(7,000,000)	0
TOT	(22,426,276)	(22,426,276)	(28,409,884)	6,248,714	8,471,023	9,591,022	9,629,207	11,955,167	11,974,508	(10,038,647)	7,092,036	14,682,495	(58,967,525)	14,875,820	8,139,175	15,354,250

			Alt 1 TRAMeBUs					Cost-Benefit Analysis					Alt 1 TRAMeBUs			
Year	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051
New Users (pax/day)	90,996	91,906	92,825	93,754	94,691	95,638	96,594	97,561	98,536	99,521	100,516	101,522	102,537	103,563	104,598	105,644
Catched users	50,958	51,467	51,982	52,502	53,027	53,557	54,093	54,634	55,180	55,732	56,289	56,852	57,421	57,995	58,575	59,161
Induced Users	40,038	40,439	40,843	41,252	41,664	42,081	42,501	42,927	43,356	43,789	44,227	44,670	45,116	45,568	46,023	46,483
Time saved h/day	4,862	4,911	4,960	5,009	5,059	5,110	5,161	5,213	5,265	5,317	5,371	5,424	5,479	5,533	5,589	5,645
h/year	1,774,602	1,792,347	1,810,274	1,828,383	1,846,663	1,865,124	1,883,777	1,902,620	1,921,645	1,940,861	1,960,267	1,979,874	1,999,672	2,019,671	2,039,860	2,060,260
Monetised time saving	16,833,871.55	17,002,206.64	17,172,262.21	17,344,038.26	17,517,444.23	17,692,570.68	17,869,508.16	18,048,256.67	18,228,725.65	18,411,005.67	18,595,096.71	18,781,089.33	18,968,892.98	19,158,598.21	19,350,114.46	19,543,622.85
Congestion (€)	(800,000.00)	(750,000.00)	(700,000.00)	(650,000.00)	(600,000.00)	(550,000.00)	(500,000.00)	(450,000.00)	(400,000.00)	(350,000.00)	(300,000.00)	(250,000.00)	(200,000.00)	(150,000.00)	(100,000.00)	(50,000.00)
Investments	0	(2,982,700)	0	0	0	0	(16,986,972)	0	0	0	0	0	0	0	0	0
Regular maintenance	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)
Tunnel Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Extraordinary maintena	0	0	0	0	(1,504,776)	0	0	0	0	0	0	0	0	0	(1,504,776)	0
New Uts	0	0	0	0	3	0	0	0	0	5	0	0	0	0	3	0
Price(€)	0	0	0	0	(5,250,000)	0	0	0	0	(8,750,000)	0	0	0	0	(5,250,000)	0
TOT	15,570,864	12,806,499	16,009,255	16,231,031	9,699,661	16,679,563	(80,471)	17,135,249	17,365,718	8,847,998	17,832,089	18,068,082	18,305,885	18,545,590	12,032,331	86,843,115

Table 35: Alt. 1 - TRAMeBUS Cost Benefit Analysis Detailed Cash Flows.

		Alt. 2 - Tunel TRAMeBUs						Cost-Benefit Analysis				Alt. 2 - Tunel TRAMeBUs				
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
New Users (pax/day)			71,053	80,603	86,118	86,118	87,410	88,721	84,285	85,549	86,833	88,135	89,457	90,351	91,255	92,168
Catched users			39,790	45,138	48,226	48,226	48,950	49,684	47,200	47,907	48,626	49,356	50,096	50,597	51,103	51,614
Induced Users			31,263	35,465	37,892	37,892	38,460	39,037	37,085	37,642	38,207	38,779	39,361	39,755	40,152	40,554
Time saved h/day			3,870	4,390	4,691	4,691	4,761	4,833	4,591	4,660	4,730	4,801	4,873	4,921	4,971	5,020
h/year			1,412,644	1,602,513	1,712,159	1,712,159	1,737,846	1,763,911	1,675,716	1,700,847	1,726,375	1,752,260	1,778,545	1,796,324	1,814,291	1,832,434
Monetised time savings			13,400,339	15,201,434	16,241,543	16,241,543	16,485,210	16,732,460	15,895,846	16,134,232	16,376,390	16,621,942	16,871,277	17,039,931	17,210,361	17,382,471
Congestion (€)			(5,426,667)	(4,703,333)	(3,990,000)	(3,370,000)	(2,860,000)	(2,348,333)	(1,885,667)	(1,523,333)	(1,105,667)	(800,000)	(500,000)	(450,000)	(425,000)	(400,000)
Investments	(87,543,473)	(87,543,473)	0	0	0	0	(1,222,130)	0	0	(22,953,475)	0	0	(2,326,758)	0	0	0
Regular maintenance			(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(55,608)	(463,008)	(463,008)	(463,008)	(463,008)
Tunnel Maintenance			(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)
Extraordinary maintenance			0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(1,504,776.00)	0.00	0.00	0.00	0.00	0.00
New Uts			17	0	0	0	0	0	0	0	3	0	41	0	4	0
Price(€)			(29,750,000)	0	0	0	0	0	0	0	(5,250,000)	0	(71,750,000)	0	(7,000,000)	0
TOT	(87,543,473)	(87,543,473)	(22,037,534)	10,236,894	11,990,335	12,610,335	12,141,871	14,122,917	13,748,969	(8,603,786)	8,254,736	15,560,731	(58,374,093)	15,921,320	9,116,749	16,313,859

		Alt. 2 - Tunel TRAMeBUs						Cost-Benefit Analysis				Alt. 2 - Tunel TRAMeBUs				
Year	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051
New Users (pax/day)	93,089	94,020	94,960	95,910	96,869	97,838	98,816	99,804	100,802	101,810	102,828	103,857	104,895	105,944	107,004	108,074
Catched users	52,130	52,651	53,178	53,710	54,247	54,789	55,337	55,890	56,449	57,014	57,584	58,160	58,741	59,329	59,922	60,521
Induced Users	40,959	41,369	41,783	42,200	42,622	43,049	43,479	43,914	44,353	44,797	45,245	45,697	46,154	46,615	47,082	47,552
Time saved h/day	5,071	5,121	5,172	5,224	5,276	5,329	5,383	5,436	5,491	5,546	5,601	5,657	5,714	5,771	5,828	5,887
h/year	1,850,755	1,869,263	1,887,958	1,906,840	1,925,909	1,945,165	1,964,618	1,984,267	2,004,104	2,024,148	2,044,388	2,064,836	2,085,480	2,106,331	2,127,398	2,148,672
Monetised time saving	17,556,261.87	17,731,827.29	17,909,167.04	18,088,281.13	18,269,169.54	18,451,832.29	18,636,362.75	18,822,760.93	19,010,933.44	19,201,067.06	19,393,068.39	19,587,030.82	19,782,860.98	19,980,652.23	20,180,497.98	20,382,304.82
Congestion (€)	(375,000.00)	(350,000.00)	(325,000.00)	(300,000.00)	(275,000.00)	(250,000.00)	(225,000.00)	(200,000.00)	(175,000.00)	(150,000.00)	(125,000.00)	(100,000.00)	(75,000.00)	(50,000.00)	(25,000.00)	(25,000.00)
Investments	0	(3,045,700)	0	0	0	0	(29,400,807)	0	0	0	0	0	0	0	0	0
Regular maintenance	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)	(463,008)
Tunnel Maintenance	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)	(205,604)
Extraordinary maintena	0	0	0	0	(1,504,776)	0	0	0	0	0	0	0	0	0	(1,504,776)	0
New Uts	0	0	0	0	3	0	0	0	0	3	0	0	0	0	4	0
Price(€)	0	0	0	0	(5,250,000)	0	0	0	0	(5,250,000)	0	0	0	0	(7,000,000)	0
TOT	16,512,650	13,667,516	16,915,555	17,119,669	10,570,782	17,533,221	(11,658,056)	17,954,149	18,167,322	13,132,455	18,599,457	18,818,419	19,039,249	19,262,040	10,982,110	85,826,193

Table 36: Alt. 2 Tunnel - TRAMeBUS Cost Benefit Analysis Detailed Cash Flows.

In an analogous manner to that from the cost benefit analysis the results from the financial study are presented in this section in the same order.

As a recall of the results Table 24: Financial study results.is reproduced here:

Alt. 1 Alstom	
NPV (€)	1,344,146,293.79
IRR	51.29%
Payback	2024
NPV/Investmen	3.2062

Alt. 2 -Tunnel Alstom	
NPV (€)	1,158,057,043.03
IRR	19.91%
Payback	2026
NPV/Investmen	1.8603

Alt 1 TRAMeBUs	
NPV (€)	1,093,480,511.14
IRR	35.28%
Payback	2024
NPV/Investmen	3.2932

Alt. 2 - Tunel TRAMeBUs	
NPV (€)	904,489,761.14
IRR	14.29%
Payback	2029
NPV/Investmen	1.6151

Table 24: Financial study results.

		Alt. 1 Alstom				Financial Study					Alt. 1 Alstom				
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Pax/day	0	0	141,897	160,970	171,983	171,983	174,563	177,181	168,322	170,847	173,410	176,011	178,651	180,438	182,242	184,065
Income (€)	0	0	96,333,873	109,282,533	116,759,259	116,759,259	118,510,821	120,288,181	114,273,806	115,988,028	117,728,049	119,493,868	121,286,164	122,499,358	123,724,094	124,961,729
New Uts	0	0	18	0	0	0	0	0	0	0	3	0	41	0	4	0
Price (€)	0.00	0.00	(58,122,000.00)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(9,687,000.00)	0.00	(132,389,000.00)	0.00	(12,916,000.00)	0.00
Final Value (€))																
Uts	0	41	59	59	59	59	59	59	59	59	62	62	62	62	66	66
OPEX (€)	0.00	0.00	(33,653,627.17)	(33,653,627.17)	(33,653,627.17)	(33,653,627.17)	(33,653,627.17)	(33,653,627.17)	(33,653,627.17)	(33,653,627.17)	(35,364,828.55)	(35,364,828.55)	(35,364,828.55)	(35,364,828.55)	(37,646,430.39)	(37,646,430.39)
Others (€)	(41,456,694.30)	(41,456,694.30)	0.00	0.00	0.00	0.00	(1,745,900.00)	0.00	0.00	(32,790,678.00)	0.00	0.00	(2,616,600.00)	0.00	0.00	0.00
TOT	(25,175,174.31)	(25,175,174.31)	(38,465,764.51)	5,378,388.00	7,600,629.58	8,720,628.46	8,758,786.77	11,084,646.20	11,104,116.99	(10,909,049.31)	6,195,607.88	13,812,031.53	(80,352,832.81)	14,412,902.48	5,635,057.14	14,891,332.33

		Alt. 1 Alstom				Financial Study					Alt. 1 Alstom				
Year	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051
Pax/day	185,905.00	187,764.00	189,642.00	191,538.00	193,454.00	195,388.00	197,342.00	199,316.00	201,309.00	203,322.00	205,355.00	207,409.00	209,483.00	211,577.00	213,693.00	215,830.00
Income (€)	126,210,904.50	127,472,979.60	128,747,953.80	130,035,148.20	131,335,920.60	132,648,913.20	133,975,483.80	135,315,632.40	136,668,680.10	138,035,305.80	139,415,509.50	140,809,970.10	142,218,008.70	143,639,625.30	145,076,177.70	146,526,987.00
New Uts	0	0	0	0	3	0	0	0	0	5	0	0	0	0	3	0
Price (€)	0.00	0.00	0.00	0.00	(9,687,000.00)	0.00	0.00	0.00	0.00	(16,145,000.00)	0.00	0.00	0.00	0.00	(9,687,000.00)	0.00
Final Value (€))																87,586,625.00
Uts	66	66	66	66	69	69	69	69	69	74	74	74	74	74	77	77
OPEX (€)	(37,646,430.39)	(37,646,430.39)	(37,646,430.39)	(37,646,430.39)	(39,357,631.77)	(39,357,631.77)	(39,357,631.77)	(39,357,631.77)	(39,357,631.77)	(42,209,634.07)	(42,209,634.07)	(42,209,634.07)	(42,209,634.07)	(42,209,634.07)	(43,920,835.45)	(43,920,835.45)
Others (€)	0.00	(4,261,000.00)	0.00	0.00	0.00	0.00	(24,267,103.00)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(22,000,000.00)
TOT	15,107,946.90	12,343,581.94	15,546,337.47	15,768,022.91	9,210,619.39	16,216,645.79	(543,388.89)	16,672,331.67	16,902,800.61	5,833,580.57	17,369,171.56	17,605,164.13	17,842,967.73	18,082,582.36	11,543,289.11	90,754,322.45

Table 37: Alt. 1 – Alstom Detailed Cash Flows for the Financial study.

		Alt. 2 -Tunnel Alstom						Financial Study				Alt. 2 -Tunnel Alstom				
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Pax/day	0	0	143,494	162,781	173,919	173,919	176,528	179,176	170,217	172,771	175,362	177,993	180,663	182,469	184,294	186,137
Income (€)	0	0	97,418,077	110,512,021	118,073,609	118,073,609	119,844,859	121,642,586	115,560,321	117,294,232	119,053,262	120,839,448	122,652,111	123,878,204	125,117,197	126,368,409
New Uts	0	0	17	0	0	0	0	0	0	0	3	0	41	0	4	0
Price (€)	0.00	0.00	(54,893,000.00)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	(9,687,000.00)	0.00	(132,389,000.00)	0.00	(12,916,000.00)	0.00
Final Value (€))																
Uts	0	41	58	58	58	58	58	58	58	58	61	61	61	61	65	65
OPEX (€)	0.00	0.00	(34,285,125.48)	(34,285,125.48)	(34,285,125.48)	(34,285,125.48)	(34,285,125.48)	(34,285,125.48)	(34,285,125.48)	(34,285,125.48)	(36,058,494.04)	(36,058,494.04)	(36,058,494.04)	(36,058,494.04)	(38,422,985.45)	(38,422,985.45)
Others (€)	(148,064,802.42)	(148,064,802.42)	0.00	0.00	0.00	0.00	(1,745,900.00)	0.00	0.00	(32,790,678.00)	0.00	0.00	(3,323,940.00)	0.00	0.00	0.00
TOT	(89,914,482.41)	(89,914,482.41)	(31,583,070.38)	9,366,495.35	11,119,959.70	11,739,959.08	11,271,472.28	13,252,554.20	12,878,576.47	(9,474,057.67)	7,358,145.95	14,690,410.51	(79,759,307.54)	15,458,405.28	6,612,634.45	15,850,944.57

		Alt. 2 -Tunnel Alstom						Financial Study				Alt. 2 -Tunnel Alstom				
Year	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051
Pax/day	187,998.00	189,878.00	191,777.00	193,695.00	195,632.00	197,588.00	199,564.00	201,560.00	203,575.00	205,611.00	207,667.00	209,744.00	211,841.00	213,959.00	216,099.00	218,260.00
Income (€)	127,631,842.20	128,908,174.20	130,197,405.30	131,499,535.50	132,814,564.80	134,142,493.20	135,483,999.60	136,839,084.00	138,207,067.50	139,589,307.90	140,985,126.30	142,395,201.60	143,818,854.90	145,256,765.10	146,709,611.10	148,176,714.00
New Uts	0	0	0	0	3	0	0	0	0	3	0	0	0	0	4	0
Price (€)	0.00	0.00	0.00	0.00	(9,687,000.00)	0.00	0.00	0.00	0.00	(9,687,000.00)	0.00	0.00	0.00	0.00	(12,916,000.00)	0.00
Final Value (€))																85,423,195.00
Uts	65	65	65	65	68	68	68	68	68	71	71	71	71	71	75	75
OPEX (€)	(38,422,985.45)	(38,422,985.45)	(38,422,985.45)	(38,422,985.45)	(40,196,354.01)	(40,196,354.01)	(40,196,354.01)	(40,196,354.01)	(40,196,354.01)	(41,969,722.57)	(41,969,722.57)	(41,969,722.57)	(41,969,722.57)	(41,969,722.57)	(44,334,213.98)	(44,334,213.98)
Others (€)	0.00	(4,351,000.00)	0.00	0.00	0.00	0.00	(42,001,153.00)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOT	16,049,735.63	13,204,601.03	16,452,640.75	16,656,754.81	10,081,743.20	17,070,305.92	(12,120,970.74)	17,491,234.52	17,704,407.00	11,138,640.59	18,136,541.90	18,355,504.31	18,576,334.44	18,799,125.67	9,982,771.39	104,648,973.23

Table 38: Alt. 2 Tunnel - Alstom Detailed Cash Flows for the Financial study.

		Alt 1 TRAMeBUs					Financial Study					Alt 1 TRAMeBUs				
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Pax/day	0	0	69,456	78,791	84,182	84,182	85,445	86,727	82,390	83,626	84,880	86,154	178,651	180,437	182,241	184,064
Income (€)	0	0	47,153,678	53,491,210	57,151,160	57,151,160	58,008,611	58,878,960	55,934,571	56,773,691	57,625,032	58,489,951	121,286,164	122,498,679	123,723,415	124,961,050
New Uts	0	0	18	0	0	0	0	0	0	0	3	0	41	0	4	0
Price (€)	0	0	(45,000,000)	0	0	0	0	0	0	0	(7,500,000)	0	(102,500,000)	0	(10,000,000)	0
Final Value																
Uts	0	0	18	18	18	18	18	18	18	18	21	21	62	62	66	66
OPEX (€)	0	0	(10,666,489)	(10,666,489)	(10,666,489)	(10,666,489)	(10,666,489)	(10,666,489)	(10,666,489)	(10,666,489)	(12,444,237)	(12,444,237)	(36,740,127)	(36,740,127)	(39,110,458)	(39,110,458)
Others (€)	(36,930,003)	(36,930,003)	0	0	0	0	(1,745,900)	0	0	(32,790,678)	0	0	(2,616,600)	0	0	0
Total (€)	(36,930,003)	(36,930,003)	(8,512,810)	42,824,721	46,484,671	46,484,671	45,596,222	48,212,472	45,268,082	13,316,525	37,680,795	46,045,714	(20,570,564)	85,758,552	74,612,957	85,850,591

		Alt 1 TRAMeBUs					Financial Study					Alt 1 TRAMeBUs				
Year	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051
Pax/day	185,904	187,763	189,641	191,538	193,453	195,387	197,341	199,315	201,308	203,321	205,354	207,408	209,482	211,577	213,692	215,829
Income (€)	126,210,226	127,472,301	128,747,275	130,035,148	131,335,242	132,648,234	133,974,805	135,314,954	136,668,001	138,034,627	139,414,831	140,809,291	142,217,330	143,639,625	145,075,499	146,526,308
New Uts	0	0	0	0	3	0	0	0	0	5	0	0	0	0	3	0
Price (€)	0	0	0	0	(7,500,000)	0	0	0	0	(12,500,000)	0	0	0	0	(7,500,000)	0
Final Value																67,812,500
Uts	66	66	66	66	69	69	69	69	69	74	74	74	74	74	77	77
OPEX (€)	(39,110,458)	(39,110,458)	(39,110,458)	(39,110,458)	(40,888,206)	(40,888,206)	(40,888,206)	(40,888,206)	(40,888,206)	(43,851,120)	(43,851,120)	(43,851,120)	(43,851,120)	(43,851,120)	(45,628,868)	(45,628,868)
Others (€)	0	(4,261,000)	0	0	0	0	(24,267,103)	0	0	0	0	0	0	0	0	0
Total (€)	87,099,767	84,100,842	89,636,817	90,924,690	82,947,035	91,760,028	68,819,496	94,426,747	95,779,795	81,683,507	95,563,711	96,958,171	98,366,210	99,788,505	91,946,631	168,709,940

Table 39: Alt. 1 –TRAMeBUS Detailed Cash Flows for the Financial study.

		Alt. 2 - Tunel TRAMeBUs					Financial Study					Alt. 2 - Tunel TRAMeBUs				
Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Pax/day	0	0	71,053	80,603	86,118	86,118	87,410	88,721	84,285	85,549	86,833	88,135	180,662	182,468	184,293	186,136
Income (€)	0	0	48,237,882	54,721,377	58,465,510	58,465,510	59,342,649	60,232,687	57,221,087	58,079,216	58,950,924	59,834,852	122,651,432	123,877,525	125,116,518	126,367,730
New Uts	0	0	17	0	0	0	0	0	0	0	3	0	41	0	4	0
Price (€)	0	0	(42,500,000)	0	0	0	0	0	0	0	(7,500,000)	0	(102,500,000)	0	(10,000,000)	0
Final Value																
Uts	0	0	17	17	17	17	17	17	17	17	20	20	61	61	65	65
OPEX (€)	0	0	(10,419,318)	(10,419,318)	(10,419,318)	(10,419,318)	(10,419,318)	(10,419,318)	(10,419,318)	(10,419,318)	(12,258,021)	(12,258,021)	(37,386,965)	(37,386,965)	(39,838,569)	(39,838,569)
Others (€)	(144,160,392)	(144,160,392)	0	0	0	0	(1,745,900)	0	0	(32,790,678)	0	0	(3,323,940)	0	0	0
Total (€)	(144,160,392)	(144,160,392)	(4,681,436)	44,302,059	48,046,192	48,046,192	47,177,431	49,813,369	46,801,768	14,869,220	39,192,902	47,576,830	(20,559,473)	86,490,560	75,277,949	86,529,161

		Alt. 2 - Tunel TRAMeBUs					Financial Study					Alt. 2 - Tunel TRAMeBUs				
Year	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051
Pax/day	187,997	189,877	191,776	193,694	195,631	197,587	199,563	201,559	203,574	205,610	207,666	209,743	211,840	213,958	216,098	218,259
Income (€)	127,631,163	128,907,495	130,196,726	131,498,857	132,813,886	134,141,814	135,483,321	136,838,405	138,206,389	139,588,629	140,984,447	142,394,523	143,818,176	145,256,086	146,708,932	148,176,035
New Uts	0	0	0	0	3	0	0	0	0	3	0	0	0	0	4	0
Price (€)	0	0	0	0	(7,500,000)	0	0	0	0	(7,500,000)	0	0	0	0	(10,000,000)	0
Final Value																66,137,500
Uts	65	65	65	65	68	68	68	68	68	71	71	71	71	71	75	75
OPEX (€)	(39,838,569)	(39,838,569)	(39,838,569)	(39,838,569)	(41,677,272)	(41,677,272)	(41,677,272)	(41,677,272)	(41,677,272)	(43,515,976)	(43,515,976)	(43,515,976)	(43,515,976)	(43,515,976)	(45,967,580)	(45,967,580)
Others (€)	0	(4,351,000)	0	0	0	0	(42,001,153)	0	0	0	0	0	0	0	0	0
Total (€)	87,792,594	84,717,926	90,358,157	91,660,287	83,636,614	92,464,542	51,804,895	95,161,133	96,529,116	88,572,653	97,468,472	98,878,547	100,302,200	101,740,111	90,741,352	168,345,955

Table 40: Alt. 2 Tunnel - Alstom Detailed Cash Flows for the Financial study.

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