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PROFITABILITY STUDY OF PERSONAL RAPID TRANSIT NETWORKS THROUGH MACROSCOPIC SIMULATION APPROACH

Dissertation in Sustainable Transport System Design

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1 Introduction

In the contemporary urban landscape, planners confront two significant challenges: the escalating emission of greenhouse gases (GHG) and other harmful pollutants, and the pervasive issue of car-centric urban environments. The emission of pollutants stems from various sources, but in densely populated cities, the transportation sector alone accounts for 51% of CO2 production (D. Y. Ahn, 2023). Addressing this issue requires a multifaceted approach: redesigning city environments to minimize inefficient travel plans, promoting a shift towards more sustainable modes of transportation, and enhancing the effectiveness of existing sustainable transportation options (Mårtensson, Larsen, & Höjer, 2023).

Conversely, cities heavily reliant on automobiles tend to allocate an imbalanced amount of public space towards road construction. This approach can initiate a detrimental feedback loop known also as Braess' Paradox: as more streets are built, cars become increasingly convenient for citizens, potentially leading to heightened traffic volumes (Braess, 1968) (Richard Steinberg, 1983). Eventually, this congestion culminates in frequent jams along major thoroughfares, prompting a political push for the construction of new or wider roads. Consequently, this process erodes valuable public space that could otherwise be utilized for pedestrian-friendly infrastructure or aesthetically pleasing urban landscapes.

These issues have been extensively debated since the 1950s, particularly in the United States, where car traffic proliferated at a faster rate than in other parts of the world. Today, many cities are actively investing in strategies to mitigate the impacts of car-centric mobility or to fundamentally reshape urban planning. Some proponents advocate for the adoption of electric fully automated car traffic as a solution. This approach holds the potential to significantly reduce pollution by shifting emissions outside city limits to where electricity is generated, plus enhancing the overall energy efficiency of this mode of transportation (Moro & Lonza, 2018). Additionally, it could enhance road safety by eliminating human-related factors such as reckless driving behaviours, impatience resulting from heavy traffic, or distractions that contribute to accidents (Almaskati, Kermanshachi, & Pamidimukkula, 2023).

However, the realization of fully automated driving remains a distant aspiration, given the considerable challenges in resolving liability issues in the event of accidents. Furthermore, transitioning to automated EVs places a significant financial burden on citizens, as these vehicles tend to be considerably more expensive. Consequently, such a transition may not be driven by public authorities and instead heavily relies on individual preferences.

Even if we hypothetically replaced current traffic with automated EVs, the issue of land use would persist, as cars whether automated or not need road and parking space. Additionally, it's plausible that the enhanced driving experience offered by automated vehicles would lead to a significant mode shift towards these new cars, exacerbating congestion issues (Lehtonen, et al., 2022). It's difficult to believe that increased driving efficiency alone would sufficiently offset the congestion resulting from this mode shift.

Private autonomous electric vehicles do not present a sustainable solution if solely deployed as replacements for traditional cars within existing road infrastructure. An alternative approach entails a deliberate transition towards more sustainable modes of transportation and soft mobilities, such as cycling and walking. Recent initiatives in cities like Paris, where capillary bike mobility schemes have been introduced to reclaim space from car traffic during the COVID-19 pandemic, and Barcelona's implementation of superblocks designed to minimize motorized traffic in residential areas, exemplify this vision. These solutions of *tactical urbanism* have the potential to yield significant impact in a relatively short timeframe, while also containing intervention costs (Nello-Deakin, 2022). Initially, implementation may involve reallocating existing space using vertical and horizontal signage. Subsequent development of the strategy can then occur gradually, allowing the population to acclimate to the changes over time.

Certainly, there are notable limitations to this approach, with one of the most significant being the inherent constraints of walking and cycling as modes of transportation. These options are primarily suitable for short-distance commuting or accessing nearby services. They are typically preferred by individuals in good health and of a younger demographic, which poses challenges in societies with an increasingly aging population. Furthermore, they are highly susceptible to weather changes and local climate variations. For these reasons modes similar to bike reach a hard cap in mode share, likely to be less or equal to 50%. (Schweizer & Rupi, 2014)

Let us focus particularly on the impact of adverse weather conditions. Assuming an urban centre where all trips are within a 2–4-kilometer range and all users are capable of walking or cycling such distances, weather becomes the primary concern. During rainfall, there would likely be a swift shift from soft mobility to motorized vehicles, such as cars and public transport. If cars are the predominant mode of choice, this leads to significant congestion in the city, making necessary an extensive proliferation of roads, thus exacerbating the issue of public space use.

Let us now assume that the city was virtuous and provided good public transport service designed on absorbing the current average share of people not able to move by feet or bike for their daily needs, and for this reason many citizens chose not to own a car. Even in this case reliance on such services during adverse weather could overwhelm the system. This scenario undermines the initial hypothesis, as even a well-designed public transport system may struggle to cope with excessive loading during inclement weather.

While a large-scale mass transit system could potentially address this demand, its implementation is both expensive and time-consuming. Furthermore, geological, morphological, or cultural heritage constraints may prevent the city from embarking on such projects. Consequently, while promoting a shift towards soft mobility is undoubtedly crucial, it cannot single-handedly bear the burden of effecting meaningful change. A comprehensive approach that integrates various transportation solutions is necessary to address the complexities of urban mobility.

Finally, one of the most widely discussed strategy for alleviating congestion through mode shift and public transport improvement revolves around promoting intermodality and mobility hubs. This approach targets the challenge of mode transition when utilizing public services, particularly addressing the "first mile" and "last mile" mobility and access to and egress from public transport services (Arnold, Dale, Timmis, Frost, & Ison, 2023). Currently, this aspect poses one of the most significant barriers to seamless public service experiences. The strategy aims to enhance the attractiveness and efficiency of sustainable services and should be a fundamental consideration in both urban and extra-urban mobility planning. However, there exists a significant limitation even within this strategy: the public transport modes themselves. Buses, trams, and rapid rail transit systems all demonstrate inefficiencies. With low load factors, especially during off-peak hours, they yield minimal revenues and thus require substantial public subsidies for construction and operation. A report by ASSTRA shows how in many European cities public transport can barely cover their expenses though ticket fare (Usai, 2014). In this scenario, the challenge lies not in the concept itself but rather in the limitations of the tools available to profitably implement such a strategy.

After examining these examples, it would be appealing a solution with electric powered vehicles, designed for decentralized pollution reduction, guided by an autonomous system to minimize driving errors and optimize efficiency, operated on a small, segregated guideway to preserve public space, accessible from numerous points within the city, and seamlessly connected to major destinations. Such a system exists in the form of Personal Rapid Transit (PRT), which serves as the focal point of analysis in this thesis. This document comprises three sections: an exploration of the state of the art and history of PRT to elucidate its characteristics, objectives, and evolution; a comprehensive study on the profitability of PRT systems, conducted through sensitivity analysis on key parameters defining the system; and a profitability assessment of a hypothetical PRT case study, based on the superblock model proposed for Bologna by Nguyen et al. (Nguyen, Schweizer, Rupi, Palese, & Posati, 2024)

2 State of the art of PRT: definition, technology, and history

Personal Rapid Transit (PRT) is a cutting-edge public transport system comprised of a fleet of small, lightweight, and fully automated vehicles operating on a segregated infrastructure. Commencing from designated stations, users embark on their journey and have the flexibility to disembark at any chosen station without the need for intermediate stops, as the station infrastructure remains independent of the main line. One of the defining characteristics setting PRT apart from conventional public transportation is its emphasis on privacy; passengers have the autonomy to ride solo or opt for shared travel.

In urban settings, Personal Rapid Transit (PRT) is typically conceived as a dense network comprising relatively compact stations spanning 10-30 meters in length, strategically spaced at intervals of 400-1000 meters. This spacing results in an average walking distance of 200-500 meters, equivalent to a travel time of 4-10 minutes on foot between stations. These stations are interconnected via a segregated mono-directional guideway system, which bifurcates prior to each station to facilitate seamless off-line boarding and alighting operations.

While PRT can accommodate various transport needs, its primary focus lies in passenger transportation, with freight transport often considered a supplementary function aimed at optimizing revenue, particularly during off-peak hours. In essence, PRT serves as a swiftly accessible network facilitating short to extended journeys within urban environments, offering distinct advantages over individual car mobility, including enhanced privacy, swift commercial speeds, and affordable fares.

However, the true strength of PRT emerges when it is integrated with other modes of transportation. Its inherent routing flexibility renders it an efficient feeder system for mass transit networks, thereby augmenting overall transportation efficiency.

Viewed from a societal perspective, PRT holds the potential to mitigate congestion, pollution, and noise pollution, while simultaneously fostering social equity by providing widespread, comfortable connectivity at minimal cost, facilitated by its efficient design.

2.1 Technology

Stations

Stations are pivotal components in the effective operation of a Personal Rapid Transit (PRT) system. Much like any other public transportation system, the network's capacity hinges on the efficiency of its stations, which act as the sole access and egress points for users. Understanding the intricacies of PRT design needs understanding of the various station layouts available. While this thesis will only explore some types, it's imperative to recognize that station operation is not solely dictated by geometric design; rather, it arises from the cohesive interplay between anticipated system usage, whether for passenger or freight transport, station geometry, guideway design, and vehicle specifications.

For instance, considerations such as whether the vehicles are suspended or supported, or if the guideway is captive or open, can significantly influence station design. Moreover, operational dynamics differ depending on whether vehicles possess lateral movement capabilities or are constrained to rigid, predetermined paths, akin to rail-like guides.

Stations within PRT systems are invariably conceived as off-line with respect to the guideway. This means that as a vehicle approaches a station, it encounters a diverging node, offering it the choice to either continue along the main route or divert into the station zone. This characteristic stands as one of PRT's primary advantages, allowing non-stop travel for passengers between any two stations.

According to O. Arslan, the simplest station design is the Serial station, characterized by a single lane where vehicles queue to board and alight passengers. Operationally, vehicles consistently occupy the foremost available position in the station in a FIFO (first in, first out) sequence. While this layout minimizes station costs by utilizing a single guideway span and reducing vehicle gaps, it is susceptible to delays in boarding and alighting, as vehicles must wait for the leading one to depart before progressing along the queue. Consequently, this design may encounter capacity limitations as the number of berths increases.

Another noteworthy design, termed the Loosened Serial station by O. Arslan, features two guideway spans, enabling vehicles to independently occupy and vacate berths without impeding each other. While this configuration offers potential capacity enhancements unaffected by berth increases, it entails doubled station guideway costs and requires larger gaps between vehicles to facilitate departing manoeuvres. Similarly, this station concept can be adapted for vehicles with lateral movement capabilities, reducing gaps between vehicles and consequently decreasing overall station costs at the expense of higher vehicle technology expenses. (Arslan, Reichert, Sellaouti, & Hoffmann, 2021)

Lastly, the Sawtooth station design involves vehicles entering separate berths and subsequently reversing to exit the boarding/alighting zone. Further insights and studies regarding this station type can be found in works by O. Arslan and J. Schweitzer (Schweizer, Mantecchini, & Greenwood, 2011)

Guideway

The guideway in one of the most critical elements of the PRT system when it comes to costs. We can design a guideway to be elevated from the ground, at grade with the road or under the ground level. Each option yields different costs and advantages. Elevated infrastructure allows for reduced soil consumption and contains costs, but severely hinders public acceptance due to visual obstruction, especially in historically relevant urban environments. At grade infrastructure would minimize infrastructure cost but comes with two significant drawbacks: larger soil consumption with space competition with existing transport modes, need of barriers to keep traffic to interfere with standard vehicle operation. Such barriers could become a huge obstacle in numerous situations from road crossing to intersections; such design would most likely just become a problem for general mobility in its environment. Last, we can design an underground guideway that would easily get rid of visual obstruction and soil consumption problems but would greatly increase the costs. Whatever the choice it is fundamental that the guideway is as small and lightweight as possible to minimize all negative effects that comes with its construction, though this depends heavily on vehicle size therefore on vehicle capacity. (Anderson, A Review of the State of the Art of Personal Rapid, 2000)

Another possible categorization depends on how the vehicles get in contact with the guideway, W.D. Cottrel offers three categories: Supported on Captive guideway, Supported on Open guideway, Suspended. In the first group, the vehicle remains confined to the guideway, rendering it "captive." Conversely, in the second group, the vehicle possesses the capability to operate off the guideway, potentially functioning as a dual-mode vehicle within a roadway setting. Finally, the third group involves vehicles suspended beneath the guideway; while in certain scenarios, the vehicle retains the ability to depart from the guideway, in other instances, it remains captive (Cottrell & Mikosza, New-Generation Personal Rapid Transit Technologies: Overview and Comparison, 2008). In general, it is preferable to utilize supported vehicles, meaning they are positioned on top of the guideway. This configuration allows for smaller vehicle designs and lighter guides. While certain suspended designs may be feasible for elevated guideways, they should be avoided for underground guides due to the significant increase in overall costs (Anderson, A Review of the State of the Art of Personal Rapid, 2000).

In the same review on PRT technology by W.D. Cottrel can be found information on maximum gradients and turning radii of tested or existing PRT designs. The maximum climbing gradients demonstrated by various PRT technologies varies significantly, ranging from 5% to 100%, with an average falling between 15% and 20%. It's noteworthy that in railroad engineering, gradients of 1.5% are considered restrictive for main-line tracks, with 2% to 3% gradients considered very steep. Light rail trains, along with heavy rail trains operating on rubber wheels, can manage grades of up to 10%. Nonetheless, the climbing capabilities of PRT generally surpass those of rail transit trains. Despite potentially lacking the tractive power of standard rail transit, PRT systems benefit from relatively lightweight vehicles, necessitating less tractive effort to traverse similar grades. Consequently, gradients of 15% to 20% can be accommodated within passenger service route profiles.

In terms of minimum turning radii, they varied from 4.5 to 26 meters, with an average of approximately 9 meters. By contrast, light rail trains are restricted to horizontal curve radii of 25 meters. The exceptional cornering capabilities of PRT vehicles provide a clear advantage, especially in manoeuvring through densely populated activity centre environments. Consequently, there exists potential for the establishment of densely interconnected guideway networks. However, it's crucial to acknowledge that vehicles must navigate small radius turns at significantly reduced speeds compared to traveling in straightaways at line speed (Cottrell & Mikosza, New-Generation Personal Rapid Transit Technologies: Overview and Comparison, 2008).

Vehicles and control

Vehicles in PRT systems exhibit significant design variation due to the diverse combinations of support and guidance mechanisms. Some utilize rubber tires on asphalt surfaces, while others adhere to the traditional yet less braking efficient steel wheel on steel support configuration. Additionally, certain systems employ rubber tires over steel and concrete guidance systems with external magnetic propulsion (Anderson, A Review of the State of the Art of Personal Rapid, 2000). While it would be impractical to enumerate all existing ideas and innovations here, it is notable that the prevailing design trend in recent years favours a car-like configuration: rubber tires on asphalt with internal electric propulsion. This design offers numerous advantages, including enhanced flexibility in steering, efficient braking on dry asphalt surfaces, and generally lighter vehicle weights compared to alternative proposals. However, the decision to rely on internal propulsion necessitates the use of batteries, which can increase costs in comparison to equivalent external propulsion vehicles. Moreover, it introduces new logistical challenges such as downtime for recharging and additional costs associated with integrating recharging capabilities into guideways or stations.

Minimum headways usually range from 0.5 to 4 seconds. Short headways are deemed crucial for the success of PRT, as the small size of vehicles necessitates a high throughput to accommodate heavy demand. However, a limiting factor is the "brick-wall" regulation, which mandates that a following vehicle must be able to stop without impacting an immediately upstream vehicle that comes to a sudden stop. The brick-wall headway varies with speed and system capabilities, with deceleration rate as main protagonist, which cannot exceed what is tolerable for passengers. All PRT concepts assume seated passengers; standing passengers would probably tolerate no more than 2-3 m/s^2, according to common emergency break acceleration in existing urban railway systems (Cottrell & Mikosza, New-Generation Personal Rapid Transit Technologies: Overview and Comparison, 2008). Though research from NASA highlighted that tolerance to decelerating G-forces in the transverse direction (Gx) diminishes with prolonged exposure. Individuals can endure a force of forward 4 Gx for up to at least 60 minutes and of 2 Gx for a whole day. Nonetheless, many PRT systems opt for more cautious braking rates ranging from 0.5 to 1 Gx. This suggests that deceleration forces of these magnitudes could be easily tolerated for several minutes. However, it's worth noting that

NASA's findings may primarily apply to young, healthy individuals with prior G-force training (Parker & West, 1973).

When discussing control in the context of PRT, it refers to the management of vehicles within the network. These strategies serve as the underlying framework of the PRT system, defining the efficient design requirements for stations, guideways, and vehicles. Here, I'll outline the two primary ideas governing fleet control, although other strategies have emerged from these foundational concepts. The first and simplest approach is known as "synchronous" control, wherein vehicles precisely follow pre-programmed virtual points along the guideway to avoid any conflicts at merge nodes. However, this system suffers from the drawback of increasing waiting times for vehicles departing from stations, as they must wait until their entire journey can be programmed to avoid conflicts in advance. Conversely, the "asynchronous" control strategy allows vehicles to flow freely within the network, dynamically adjusting their speed to accommodate merging needs. For completeness, I'll briefly mention other predominant strategies such as "quasi-synchronous," "point-synchronous," and "asynchronous point follower," with the latter being one of the most effective strategies to date (Anderson, A Review of the State of the Art of Personal Rapid, 2000).

2.2 History and development

Personal Rapid Transit first ideas were born in 1953 from Donn Fichter and Ed Hamilton, working independently on a new system made of small, automated vehicles that could carry users with no interruption from one to any other stop thanks to a separated guideway. The concept of such a system took a decade to appear in a paper: some sources consider of D. Fichter the first publisher of a PRT concept in 1964, although R.J. Bartells already expressed some PRT-like ideas in a 1962 paper. Whoever might be the first publisher we can clearly see that the PRT phenomenon appeared in the scientific community in 1964 with 21 publications in 6 years and it reached full bloom only in 1971 with 75 publications in 4 years. Such intense increase in productivity was determined by a large interest by U.S. government on the topic, which provided funds to the research and development of PRT prototypes. After 1975 changes in administration interests caused the number of publications to drop significantly. Stronger interest by the community arises again starting from 1990 and continuing today. (Cottrell, Critical Review of the Personal Rapid Transit Literature, 2005) (Anderson, A Review of the State of the Art of Personal Rapid, 2000)

From the beginning of the research several prototypes were created, they would be all worth mentioning as in absence of a manual our only chance to truly know PRT limits and opportunities is the careful examination of past cases. For the purposes of this dissertation, I will focus only on some PRT concepts that I think can offer interesting insight on the topic.

In 1953, Edward O. Haltom, a Dallas contractor, sought to build a monorail system but encountered challenges due to conventional design limitations. He envisioned a solution involving smaller, automated vehicles running at closer intervals to reduce costs and increase efficiency. This concept, initially named Monocab, saw advancements in switching mechanisms by the 1960s, leading to full-scale testing and subsequent sales to Rohr Corporation in 1971. Despite successful demonstrations, economic downturns, and technological diversions ultimately halted progress, signalling the end of the project by the 1980s. Despite innovative efforts, visual impact and cost concerns persisted, highlighting the complexities of PRT system development. (Anderson, Evolution of Personal Rapid Transit, 2009)

In the late 1950s and early 1960s, General Motors Research Laboratories developed air-suspended machines for military use, which later inspired transit applications due to the very low power consumption on paved roads. This led to the combination of air suspension and linear induction motor (LIM) propulsion. However, General Motors' involvement was hindered by antitrust laws, prompting the formation of Transportation Technology, Incorporated (TTI). TTI refined the concept into a leading PRT system candidate, conducting testing in Detroit in 1969 and moving operations to Denver in 1972. TTI became a subsidiary of Otis Elevator Company, demonstrating its system at Transpo72 and participating in the AGRT program until its funding ceased. Since the mid-1970s, TTI's Hovair+LIM system has been operational at Duke University Medical Centre, serving passengers between three points. Challenges included the visual impact and cost of the wide U-shaped guideway and susceptibility to snow accumulation. (Anderson, Evolution of Personal Rapid Transit, 2009)

In 1960, William Alden devised staRRcar, an early dual-mode system featuring small electric vehicles transitioning from road to guideway autonomously from home to destination. Alden formed Alden Self-Transit Systems Corporation, but the system faced challenges compared to captive-vehicle PRT, to which they shifted their attention and began development. Full-scale testing began in 1968 in Bedford, Massachusetts, with success in Morgantown. Alden's innovation included an on-board switch for short-interval operation. However, reliance on a U-shaped guideway with power rails hindered snow removal, necessitating costly guideway heating. These operational challenges, coupled with visual impact and guideway expenses, deterred customers post-Morgantown. (Anderson, Evolution of Personal Rapid Transit, 2009)

Until 1964, PRT initiatives operated relatively autonomously, with few influential figures knowledgeable about the concept of automating horizontal transportation with small vehicles. Congressman Henry S. Reuss of Milwaukee, Wisconsin, was an exception, having become acquainted with PRT and Dual Mode systems in the early 1960s. Recognizing the potential, Reuss advocated for political backing for new transit concepts through public speeches. His efforts led to his assignment to a subcommittee that crafted the Urban Mass Transportation Act of 1964. Through Reuss's endeavours, Section 6, titled Research, Development, and Demonstration Projects, was added to the Act, outlining provisions for advancing innovative transportation initiatives. The efforts of early inventors yielded a significant political outcome. In the absence of the U.S. Department of Transportation, the Urban Mass Transportation Act established the Urban Mass Transportation Administration (UMTA) under the Department of Housing and Urban Development (HUD). Responding to congressional directives, the new UMTA commenced a series of studies in 1966 to fulfil Section 6 of the Act. Dubbed the HUD studies, 17 projects were authorized, each funded at $500,000, and predominantly conducted in 1967. Then came a change in administration, which had regrettable repercussions for PRT system development in the United. The release of the HUD studies coincided closely with the arrival of President Nixon's new administration, which lacked a commitment or detailed understanding of the studies' implications. Under the new leadership, UMTA's focus shifted away from R&D toward stabilizing existing transit systems through capital grants for buses and rapid rail systems. (Anderson, Evolution of Personal Rapid Transit, 2009)

Developed in Japan from 1968, the Computer-Controlled Vehicle System (CVS) is a one-second-headway, four-passenger-vehicle PRT system. Extensive testing occurred by 1972 in Tokyo suburbs, featuring almost 5 km of guideway and 84 vehicles (Advanced Transit

Associations (ATRA), n.d.). The system went operative for public use in 1975 for six months, then closed in 1976 by Japan Ministry of Land, Infrastructure and Transport as it was not considered safe anymore and with challenges emerging, including traction issues, a rough ride experience, and inadequate station capacity understanding (Cottrell, Critical Review of the Personal Rapid Transit Literature, 2005). The size, cost, and visual impact of the guideway posed significant hurdles, while rushed design post-HUD studies left optimization opportunities unexplored. By 1983, Japanese engineers recognized the need for guideway optimization during a visit to the United States. However, the lack of market viability for the existing CVS model proved insurmountable within their organization. (Anderson, Evolution of Personal Rapid Transit, 2009)

In 1970, the German Ministry of Science and Technology facilitated a collaboration between Messerschmitt-Bölkow-Blohm (MBB) and DEMAG, prompting the formation of a joint venture, DEMAG+MBB, for PRT development. Their thorough analysis led to a configuration of three-passenger cabs propelled by linear induction motors, allowing one-second headways. They opted for analog, asynchronous control for its flexibility under practical conditions. Full-scale testing commenced in May 1973, demonstrating success by October 1974. Subsequent planning for deployment in cities, including studies in Freiberg and Hagen, bolstered confidence in the project's viability. In 1975, Raytheon Missile Systems Division explored licensing Cabintaxi for deployment in the United States, although the program was cancelled in July 1976. However, DEMAG+MBB continued marketing efforts in the US. The late 1970s witnessed Cabintaxi testing in Indianapolis, where support for AGT systems was strong across various vehicle sizes. Despite initial success, an economic crisis in 1980 halted plans for a 12-passenger Cabintaxi demonstration in Hamburg, underscoring missed opportunities for PRT advancement. (Anderson, Evolution of Personal Rapid Transit, 2009) (Advanced Transit Associations (ATRA), n.d.)

Aramis, born from Frenchman Gerard Bardet in 1967, featured four-passenger vehicles propelled by a unique variable-reluctance motor and running on rubber-tired wheels. Engins Matra, a French aerospace firm, acquired the patents in May 1970, kickstarting their development efforts. By late 1970, Matra secured its first contract for Aramis from the French agency DATAR, leading to full-scale testing at Orly International Airport in April 1973. By summer 1974, the initial phase of proof testing was completed, paving the way for a public demonstration in a Paris suburb, backed by a contract from the Paris Metro Authority. Aramis distinguished itself by electronically training vehicles in platoons, maintaining close separation using ultrasonic and optical sensing. However, challenges arose, particularly with wet weather braking and the decision to increase vehicle capacity to ten, leading to concerns over personal security and station operations. In the end the project did not survive the trial phase in 1987, as inefficient braking and very close platoons of vehicles could cause collision beyond the required level of safety. Software and hardware of the time were not able to prevent such accidents to happen. (Advanced Transit Associations (ATRA), n.d.) (Anderson, Evolution of Personal Rapid Transit, 2009) (Cottrell, Critical Review of the Personal Rapid Transit Literature, 2005)

In 1967, the Canadian Ministry of Transport commissioned Norman D. Lea and Associates of Toronto to conduct a comparative study on transport alternatives for Canadian cities, exploring both conventional and PRT systems. Preferring the term "Programmed Modules" they envisioned a system for both freight and passenger transport. Studies suggested that freight movement could contribute significantly to system revenue. For Vancouver, they proposed a fare of 50¢, covering all costs if the system served both purposes. Subsequently, the formation of Urban Transportation Development Corporation in Ontario aimed to develop a PRT system. However, the influence of conventional rail proponents led to the adoption of 40-passenger steel-wheel, steel-rail vehicles propelled by linear induction motors, deterring market interest due to the large and costly guideway required. (Anderson, Evolution of Personal Rapid Transit, 2009)

The case for the Morgantown PRT by staRRcar now deserves some detailed description, as it represents a clear example of how political pressures are able to forage over-optimistic statements and deadlines in engineering teams. In the late 1960s, Professor Samy Elias, head of the Industrial Engineering Department at the University of West Virginia in Morgantown, recognized the potential of Personal Rapid Transit (PRT) systems, particularly for student transportation. With support from the University, city officials, and the West Virginia Congressional Delegation, Elias secured funding from the Urban Mass Transportation Administration (UMTA) for a comprehensive comparative study of PRT systems. The study, aimed at finding a suitable solution for Morgantown's transportation needs, evaluated several PRT concepts, ultimately favouring the Alden staRRcar. This preference led to serious consideration for its implementation in Morgantown's student transportation network. Political pressure from West Virginia bolstered plans for an operational PRT system, driven by a desire to showcase progress before the 1972 presidential election. Despite ambitious timelines and technical hurdles, UMTA appointed the Jet Propulsion Laboratory as the system manager and selected Boeing, Bendix Company, and F.R. Harris Engineering Company for various project roles. However, in the rush to meet deadlines, mistakes were made, resulting in cost overruns and negative media coverage. Despite setbacks, the Morgantown PRT system remained operational featuring 20 passenger vehicles and a flexible operation: when demand is low the system is operated like a proper PRT allowing for individual trips, when peak hours start the system behaves like a common Automated People Mover with trained vehicles to satisfy the greater flow of passengers. The Morgantown project's resilience had a lasting impact, influencing future PRT initiatives across the United States. Notably, Gayle Franzen, Chairman of the Northeastern Illinois Regional Transportation Authority, was inspired by Morgantown's success to recommend a new PRT program in 1990. While the Morgantown project faced challenges and criticism, its continuous operation underscored the potential of PRT systems to address urban transportation needs. (Advanced Transit Associations (ATRA), n.d.) (Anderson, Evolution of Personal Rapid Transit, 2009)

September 1974 marked a pivotal moment in Personal Rapid Transit (PRT) development. Despite the cessation of U.S. federal grants, interest in PRT persisted, driven by a recognition of unmet transportation needs and a belief in the feasibility of PRT solutions. The third international PRT conference was held in Denver in September 1975, resulting in the publication of PRT III, yet attendance had peaked earlier, indicating shifting dynamics in the field. City planners increasingly favoured proven systems over innovative ones, signalling a shift away from federal support for high-capacity PRT development. In response to these challenges, the organizing committee of the PRT conferences convened during the Denver conference to establish a permanent entity, leading to the formation of the Advanced Transit Association (ATRA) in 1976. ATRA held a successful conference in Indianapolis in April 1978, enriching the literature on PRT. One of the critical issues faced was the lack of a coherent theoretical framework guiding PRT design, resulting in a proliferation of ideas without robust cost-effectiveness analyses. Developers often failed to articulate the rationale behind design choices, such as vehicle capacity, undermining confidence in the viability of PRT solutions.

Comprehensive understanding and evaluation of factors like safety, cost, capacity, and user behaviour were crucial for informed decision-making, a necessity often overlooked in early PRT development endeavours. (Anderson, Evolution of Personal Rapid Transit, 2009)

The Northeastern Illinois Regional Transportation Authority (RTA) took large interest into PRT and set foot in April 1990 with a call for proposals, seeking two $1,500,000 preliminary PRT design studies. After reviewing twelve submissions, Taxi 2000 Corporation and Intamin, A.G., were chosen to develop two parallel PRT designs. In October 1993, the RTA opted for the Taxi 2000 system, with Raytheon Company as the prime contractor, to develop a test PRT system with a budget of $40,000,000. However, Raytheon's decision to deviate from prior designs, opting for wider guideways, heavier vehicles, and rotary motors instead of linear motors, led to escalated costs and technical concerns. By late 1998, the RTA shelved plans for further funding, and Raytheon eventually exited the PRT business in a disappointing turn of events. (Anderson, Evolution of Personal Rapid Transit, 2009)

Entering the 21st century, the concept of Personal Rapid Transit (PRT) began to find more widespread applications in niche markets globally, notably spearheaded by ULTra Global PRT and 2getthere. ULTra, conceived in 1995 in collaboration with the University of Bristol, initiated its journey with a modest test track, subsequently expanding to a significant trial in Cardiff with a one-kilometre guideway. Securing a pivotal contract in 2005, ULTra commenced operations in London, linking Heathrow Airport's Terminal 5 with a designated parking facility. Upholding the core tenets of PRT, ULTra's system features low-capacity pods and remains operational since its inauguration in 2011, currently featuring a fleet of 21 vehicles (Advanced Transit Associations (ATRA), n.d.) (Lawson, 2002). On the other hand, 2getthere embarked on several projects with varying degrees of success. Their inaugural endeavour, the Parking Hopper system launched in 1995, connected Schiphol Airport in the Netherlands with a parking area but was discontinued in 2004 due to perceived inefficiency. Subsequently, the Rivium Park Shuttle commenced operations in 1999, undergoing an upgrade in 2008 with the introduction of second-generation vehicles, and continuing until ConneXXion assumed management in 2016, persisting to this day (Advanced Transit Associations (ATRA), n.d.). Notably, 2getthere's most prominent achievement is the Masdar project, linking Masdar City in Abu Dhabi with the Masdar Institute of Science and Technology through a fleet of 13 vehicles, including standard, VIP, and freight transport variants; although it is currently limited to a 1.2-kilometer network with five stations, three of which are exclusive to freight transport. (Graaf & Lohmann, 2011)

2.3 Personal comment

I would like to end this state-of-the-art section with some personal considerations on the topic. When embarking on new implementations, we encounter a multitude of challenges, ranging from technological hurdles to socio-economic and political considerations. Typically, the larger the project we undertake, the more formidable these challenges become, commensurate with the stakes involved. The examples provided earlier aptly illustrate this point: initially, projects often faltered before or during real testing phases due to significant disparities between technological aspirations and practical capabilities. Many systems, while theoretically feasible as small and lightweight, proved impractical. Additionally, control systems often exhibited response times that were inadequate for achieving short headways with the necessary safety standards.

As time progressed, some projects managed to enter public service, only to be swiftly dismantled thereafter. At this juncture, the challenges extend beyond technological limitations; the viability of PRT systems hinges on social and political acceptance. Given that PRT systems are still in their infancy within the realm of public transportation, their development necessitates tailored approaches for each case study. Such processes demand dedicated researchers, adequate funding, and significant time investment. However, the protracted development timelines can easily outlast shifts in political administrations' visions, leading to setbacks and sudden withdrawals of funding, as observed in the 1970s. (Anderson, A Review of the State of the Art of Personal Rapid, 2000)

Since the 2000s, some PRT systems have managed to endure, albeit in simplified forms connecting strategic locations. However, none of these systems constitute a comprehensive urban network. This approach, in my view, represents an attempt to mitigate the challenges posed by lengthy development times. By scaling down project sizes and timelines, we can address a narrower range of challenges and establish functioning systems. Nevertheless, this approach comes with inherent limitations; these systems do not represent transformative advancements in the transportation sector, nor do they serve as compelling case studies to persuade public authorities to implement full-scale urban PRT networks.

In conclusion, I believe this incremental approach is the most pragmatic course of action. Society is unlikely to readily accept sudden, drastic changes to their urban environments. Instead, progress must be gradual but steadfast. As more examples of successful systems emerge, there is greater potential for the exploration of more innovative designs, thereby inching towards the realization of full-scale urban networks. We must acknowledge that effecting change within the complex ecosystem of a large city requires a generational effort.

3 Profitability Evaluation

The core of the thesis lies in the next pages. Here will be shown that estimation of PRT cash flow is rather simple and does not need too many simplifying assumptions. This comes with the closed nature of PRT networks: absence of interaction with the traffic makes it more predictable and simpler to design with respect to traditional bus or tram lines.

The following chapter is divided into 2 parts. The first features a study on the correlation between profitability and PRT system characteristics and is conducted by studying classes of PRT with different network saturation. The second part is the economic feasibility of a hypothetical case study in Bologna, Italy.

The tool, a python script, is meant to be very flexible in its use. It can be used to study whole classes of PRT systems characterized by common parameters to make sensitivity analysis at the change of other determining factors, therefore a more research oriented approach; but it perfectly suits also the role of a designing tool to simulate a great number of different scenarios when some parameters are preliminarily fixed, as well as a verification tool to be paired with detailed micro-simulations where the user can take the extremely detailed output of the simulation to verify the commercial feasibility of its design.

3.1 Methodology

The following chapter focuses on the methodology used for the analysis shown in this dissertation. Following, an exhaustive explanation of all operations starting from the initial inputs.

Inputs

Defining the Vehicles requires us to input:

Average line speed:

$$V_{line} = \left[\frac{m}{s}\right]$$

Emergency braking deceleration:

$$a_e = \left[\frac{m}{s^2}\right]$$

Braking time of reaction:

$$t_{react} = [s]$$

Number of passenger places in the vehicle:

$$N_{places} = [-]$$

Vehicle length:

$$L_{veh} = [m]$$

Commercial speed:

$$V_{comm} = \left[\frac{m}{s}\right]$$

Occupation factor of vehicle:

$$Occup_{veh} = [-]$$

Fraction of empty vehicle circulating:

$$Share_{empty} = [-]$$

Defining the Guideway requires us to input:

Guideway length

Or

Maximum Saturation (used in the following description)

We have 2 alternative ways to define guideway. The most intuitive is to directly give the guideway length, which will work in most cases when applying the tool to specific study cases; in this case the saturation will be calculated later as mentioned in paragraph 3.2. But when performing analysis on classes of PRT systems varying the value of Saturation we need to freely set this value; in this case the guideway length will become function of saturation and all revenues and costs will be evaluated in terms of Euro/kilometre, therefore normalizing with respect to the guideway length. In this explanation I will use Maximum saturation, as it is the less intuitive way of working with the tool and to fully support the method used for the analysis in paragraph 3.2.

Guideway length:

$$L_{guide} = [m]$$

Maximum Saturation:

$$Sat = [-]$$

Defining the Stations requires us to input:

Number of stations

Or

Average station distance (used in the following description)

For the stations we have 2 different ways of accounting for them. As for the guideway, the most intuitive way is to give the exact number of stations in the network, which will work in all specific case studies applications. When performing analysis on classes of PRT can be more important to study the linear density of stations. In this case all costs should then be normalized with respect to guideway length as number of stations will become function of it. In this explanation I will use Average station distance, as it is the less intuitive way of working with the tool and to fully support the method used for the analysis in paragraph 3.2.

Number of stations:

$$N_{stat}$$

Average station distance along the guideway, measured in $[m]$:

$$D_{stat,av}$$

Defining the demand requires us to input:

Trips per day on the PRT system:

$$N_{trips,day}$$

Days in a year of working system:

$$N_{days,yr}$$

Share of daily trips performed in one rush hour:

$$Share_{trips,day,1h,rush}$$

Average trip length, measured in $[m]$:

$$L_{trip,av}$$

Fraction of daily rush hours:

$$Share_{peak}$$

Fraction of daily off-peak hours:

$$Share_{off}$$

Ratio between demand of off-peak hours w.r.t. rush hours:

$$Ratio_{off}$$

Defining the financial aspects of our design requires us to input:

Capital cost of guideway per meter, measured in $[€/m]$:

$$Cost_{cap,guide,m}$$

Capital cost of a single station, measured in $[€]$:

$$Cost_{cap,stat}$$

Capital cost of a single vehicle, measured in $[€]$:

$$Cost_{cap,veh}$$

Operation and Maintenance cost of vehicles per km, measured in $[€/km]$:

$$Cost_{om,veh,km}$$

Time of mortgage of guideway, measured in $[years]$:

$$t_{am,guide}$$

Time of mortgage of station, measured in $[years]$:

$$t_{am,stat}$$

Time of mortgage of vehicles, measured in $[years]$:

$$t_{am,veh}$$

Interest rate for capital borrowing:

$$r$$

Ticket fare, measured in [€]:

$$Price_{ticket}$$

Process

Given these inputs the software calculates all values necessary to reach the estimated profit. The process develops as follows:

First, the software calculates the Share of full vehicles in the network from the estimated Share of empty vehicles in the network given as input.

Share of full vehicles in the network:

$$Share_{full} = 1 - Share_{empty} \in [0, 1]$$

Then the script needs to evaluate the Cost of Operation and Maintenance for a single vehicle moving a kilometre. This will be fundamental when estimating the total costs of infrastructure and of single vehicle trips to compare them with total and vehicle trip revenues.

Cost of Operation and Maintenance per vehicle kilometre:

$$Cost_{om,ve\ \ ,km} = Cost_{om,pax,km}\left(Occup_{veh} * N_{places}\right) = Cost_{om,pax,km}N_{pax}\ \frac{\text{€}}{veh * km}$$

Now it finds the values of capacity both in terms of vehicles per hour per direction and of passengers per hour per direction or, more precisely for our case, as vehicle/passenger per hour on a link as we work only on single lane networks. To perform this calculation we need the time of reaction to brake the vehicle, the emergency braking deceleration and the average line speed to calculate the average safety distance for braking under the hypothesis that the front vehicles stops at infinite deceleration; we need the length of the vehicle and the average line speed to add the time needed for the vehicle to cover its own length's distance and finally obtain an average minimum time headway to calculate capacity. In the case of Passenger capacity, it simply multiplies for the average number of passengers given as number of places in the vehicle times the occupancy rate.

Capacity as Vehicles per second on a single link, in $[veh/s]$*:*

$$Cap_{ve} \quad = \frac{1}{H_{time}} = \frac{1}{\left(t_{react} + \frac{V_{line}}{2 * a_e}\right) + \frac{L_{veh}}{V_{line}}}$$

Capacity as Passengers per second on a single link, in $[pax/s]$*:*

$$Cap_{pax} = \frac{N_{pax}}{H_{time}} = \frac{N_{places} Occup_{veh}}{\left(t_{react} + \frac{V_{line}}{2 * a_e}\right) + \frac{L_{ve}}{V_{line}}}$$

Where:

- N_{places} is the number of passenger places in the vehicle
- $Occup_{veh}$ is the occupancy rate as number of passengers over number of places
- t_{react} $[s]$ is the reaction time to start vehicle braking manoeuvre
- V_{line} $[m/s]$ is the average line speed of the vehicle
- a_e $[m/s\hat{}2\ ]$ is the emergency braking deceleration
- L_{veh} $[m]$ is the vehicle length

To estimate the number of vehicles that are going to be needed in the system it is fundamental to know the average trip time, as it directly influences the time needed before a vehicle is available to accommodate a new customer. This value is calculated as the ratio between average trip length and commercial speed, both given as inputs at the beginning of the code.

Average trip time, in $[s]$*:*

$$t_{trip,av} = \frac{L_{trip,av}}{V_{com}}$$

Where:

- $L_{trip,av}\ [m]$ is the average trip length
- $V_{com}\ [m/s]$ is the vehicles commercial speed

Now are evaluated a number of parameters describing the demand and the service that must be offered. The first variable is the number of PRT user trips undertaken during a whole year. This value is simply calculated by multiplying the number of daily trips for the number of days in a year, both given as input at the beginning of the script. Please note that the days in a year are to be intended as the expected days of operation in a year.

Number of trips per year:

$$N_{trips,yr} = N_{days,yr} * N_{trips,day}$$

Where:

- $N_{days,yr}$ is the number of days in a year
- $N_{trips,day}$ is the number of daily trips

To run the system and to evaluate the operations costs and revenues, we are much interested in the number of vehicle trips performed during the days of operation and over the year. For that the script calculates the number of vehicle trips per day as the number of user trips over the average vehicle occupation. The number of vehicle trips per year is then calculate multiplying the daily value for the number of days per year. Also in this case the number of day per year is to be intended as the expected days of operation in a year.

Number of vehicle trips per day:

$$N_{trips,veh,day} = \frac{N_{trips,day}}{N_{places} * Occup_{veh}}$$

Number of vehicle trips per year:

$$N_{trips,veh,yr} = N_{trips,veh,day} * N_{days,yr}$$

Where:

- $N_{trips,day}$ is the number of daily trips of users
- N_{places} is the number of passenger places on a vehicle
- $Occup_{veh}$ is the occupancy rate as number of passengers over number of places
- $N_{days,yr}$ is the number of days in a year

Dimensioning the PRT requires it to sustain the demand of the most stressful hours of the day. The first step is to calculate the number of trips performed in a single rush hour as the share of trips performed in such hour for the total number of daily trips, both given as inputs in the script.

Number of trips during one rush hour:

$$N_{trips,peak,1h} = Share_{peak} * N_{trips,day}$$

Where:

- $Share_{peak}$ is the share of trips in one rush hour w.r.t the total daily trips
- $N_{trips,day}$ is the number of daily trips undertaken by users

From the capacity evaluated before can be derived the minimum time headway to satisfy said demand of the links that reached capacity limit. This value not only allows to verify is the headway requirements in reachable between present technological boundaries, but more importantly is fundamental to calculate the guideway length. As explained in paragraph 3.2, for this analysis we are interested especially in fixing values of maximum network saturation and observing all costs and revenues normalized over the guideway length. To do that we need to define guideway length as function of saturation and other parameters, as the minimum time headway. So, it can be obtained as the ratio of one over the capacity.

Time headway reached in links at capacity, in $[s]$*:*

$$H_{time,min} = \frac{1}{Cap_{veh}}$$

Now we can finally define some of the most important aspects of the PRT system: guideway length, number of stations and number of vehicles. The software starts form the required number of vehicles as it is fundamental on later calculations. This value is obtained on the assumption that the minimum number of full vehicles required in a general network is like the ones required in a network with a single loop between two stations connected by equal length guideways and symmetrical transport demand. In this case a vehicle starting from station "1" is ready to serve another customer right after ending its trip in station "2", meaning that it can serve users every trip time on average. Under such circumstance the total number of vehicles would be the number of trips in one second, calculated as trips in one hour over 3600 seconds, times the average trip time in seconds. Then to account for the fact that we are in a general network where inefficiencies in empty vehicle management will occur and demand might be strongly asymmetric, we increase the amount by the ratio of one over the share of full vehicles. Please note that this value might be given directly as input if already known or part of design boundary conditions, in this case the user should manually deactivate the line and add one where it states the exact the number of vehicles. (Please refer to the appendix 6.1)

Required number of vehicles to satisfy demand:

$$N_{ve} \quad = \frac{N_{trips,veh,peak,1h}}{3600[s]} * \frac{1}{Share_{full}} * t_{trip,av}$$

Where:

- $N_{trips,veh,peak,1h}$	is the number of vehicle trips in one rush hour
- $Share_{full}$	is the share of full circulating vehicle
- $t_{trip,av}$ $[s]$	is the average trip time

The guideway length is obtained by rewriting the equation in paragraph 3.2, resulting in the time headway times the number of vehicles times the average line speed divided by the maximum saturation. Please note that the user might give this value directly as input, in that case the user would need to manually deactivate this line and state the value of guideway length in meters. It is fundamental that the value for saturation is calculated after the definition of the guideway length, and the formula for saturation manually input after it. The relation between saturation and guideway length can be found at paragraph 3.2.

Length of the Guideway, in $[m]$*:*

$$L_{guide} = \frac{H_{time}}{Sat} N_{veh} V_{line}$$

Where:

- H_{time} $[s]$	is the minimum time headway
- N_{veh}	is the number of circulating vehicles
- V_{line} $[m/s]$	is the average line speed
- Sat	is the maximum achievable network saturation

Finally, the number of stations is calculated as the guideway length over the average distance between stations. Please note that the user might give this value directly as input, in that case the user would need to manually deactivate this line and state the value of stations number (Please refer to the appendix 6.1). It is usually common to give exact station number for verification of specific study cases, while its useful to keep it function of the station density when studying general classes of PRT systems.

Number of stations:

$$N_{stat} = \frac{L_{guide}}{D_{stat,av}}$$

Where:

- L_{guide} $[m]$	is the guideway length
- $D_{stat,av}$ $[m]$	is the average distance between stations

Now that all physical parameters are fixed, we can proceed with the financial aspects of the analysis. The first thing the script evaluates is the capital cost of a single kilometre of the system under the assumption that it is entirely paid at day one, with no mortgage i.e. no interest rate applies. The value is calculated as 1000 over the guideway length, to get per-kilometre results, times the sum of guideway length in meters times the guideway cost per meter, the number of stations times the cost per station, the number of vehicles times the cost per vehicle.

Capital cost per kilometre of the whole system, in $[€/km]$*:*

$$Cost_{cap,sys,km} = \frac{1000}{L_{guide}}\left(L_{guide}Cost_{cap,guide,m} + N_{stat}Cost_{cap,stat} + N_{veh}Cost_{cap,veh}\right)$$

Where:

- L_{guide} $[m]$	is the guideway length
- N_{stat}	is the number of stations
- N_{veh}	is the number of vehicles
- $Cost_{cap,guide,m}[€/m]$	is the capital cost of one meter of guideway
- $Cost_{cap,stat}$ $[€]$	is the capital cost of one station
- $Cost_{cap,veh}$ $[€]$	is the cost of one vehicle

Finally, the first important output of the whole process emerges. The fixed yearly capital cost of a single vehicle comprehensive of the interest matured over the mortgage time. Note that the following equation considers that the debt is gradually extinguished year by year.

Yearly Cost of one Vehicle, net of Operation and Maintenance, in $[€/year]$*:*

$$Cost_{cap,veh,yr} = Cost_{place}N_{places,veh}\frac{r}{1-(1+r)^{-t_{am,ve}}}$$

Where:

- $Cost_{place}$ $[€]$	is the capital cost of a single vehicle seat/place
- $N_{places,ve}$	is the vehicle passenger capacity

- r	is the interest rate of borrowed capital
- $t_{am,veh}$ $[year]$	is the amortization time for vehicle capital investment

Now it calculates the fixed yearly capital cost of a single station comprehensive of the interest matured over the mortgage time. Note that the following equation considers that the debt is gradually extinguished year by year.

Yearly cost of one Station, in $[€/year]$*:*

$$Cost_{cap,stat,yr} = Cost_{cap,stat} \frac{r}{1-(1+r)^{-t_{am,stat}}}$$

Where:

- $Cost_{cap,stat}$ $[€]$	is the capital cost of a single station
- r	is the interest rate of borrowed capital
- $t_{am,stat}$ $[year]$	is the amortization time for station capital investment

Now it calculates the fixed yearly capital cost of a single meter of guideway comprehensive of the interest matured over the mortgage time. Note that the following equation considers that the debt is gradually extinguished year by year.

Yearly cost of one meter of Guideway, in $[€/(m\ year)]$*:*

$$Cost_{cap,guide,m,yr} = Cost_{cap,guide,m} \frac{r}{1-(1+r)^{-t_{am,guide}}}$$

Where:

- $Cost_{cap,guide,m}$ $[€/m]$	is the capital cost of a meter of guideway
- r	is the interest rate of borrowed capital
- $t_{am,guide}$ $[year]$	is the amortization time for guideway capital investment

Yearly cost of Infrastructure, in $[€/year]$*:*

$$Cost_{cap,inf,yr} = Cost_{cap,stat,yr}\, N_{stat} + Cost_{cap,guide,yr}\, L_{guide}$$

Where:

- $Cost_{cap,stat,yr}$ $[€/year]$ is the fixed yearly payment of a station
- N_{stat} is the number of stations
- $Cost_{cap,guide,yr}$ $[€/year]$ is the fixed yearly payment of a meter of guideway
- L_{guide} $[m]$ is the length of the guideway

Yearly cost of System, net of Operation and Maintenance, in $[€/year]$*:*

$$Cost_{cap,sys,yr} = Cost_{cap,stat,yr}\, N_{stat} + Cost_{cap,guide,yr}\, L_{guide} + Cost_{cap,veh,yr}\, N_{veh}$$

Where:

- $Cost_{cap,stat,yr}$ $[€/year]$ is the fixed yearly payment of a station
- N_{stat} is the number of stations
- $Cost_{cap,guide,yr}$ $[€/year]$ is the fixed yearly payment of a meter of guideway
- L_{guide} $[m]$ is the length of the guideway
- $Cost_{cap,veh,yr}$ $[€/year]$ is the fixed yearly payment of a vehicle
- N_{veh} is the number of vehicles

Cost of a single vehicle trip, in $[€]$*:*

$$Cost_{trip,veh} = \frac{Cost_{cap,sys,yr} + \left(Cost_{om,veh,km} \frac{L_{trip,av}}{1000}\, N_{trips,veh,yr}\right)}{N_{trips,veh,yr}}$$

Where:

- $Cost_{cap,sys,yr}$ $[€/year]$ is the fixed yearly payment of the whole network
- $Cost_{om,veh,km}$ $[€/km]$ is the operation and maintenance cost per kilometre
- $L_{trip,av}$ $[m]$ is the average trip length
- $N_{trips,veh,yr}$ is the number of yearly vehicle trips

Profit of a single vehicle trip, in $[€]$*:*

$$Profit_{trip,veh} = Occup_{veh}\, N_{places}\, Price_{ticket} - Cost_{trip,veh}$$

Where:

- $Occup_{veh}$ is the occupancy rate as number of passengers over number of places
- N_{places} is the number of passenger places on a vehicle
- $Price_{ticket}$ is the ticket price
- $Cost_{trip,veh}$ is the aggregated cost of a single vehicle trip

Yearly Revenues, in $[€/year]$*:*

$$Revenue_{yr} = N_{trips,veh,yr}\, Occup_{veh}\, N_{places}\, Price_{ticket}$$

Where:

- $N_{trips,veh,yr}$ is the number of yearly vehicle trips
- $Occup_{veh}$ is the occupancy rate as number of passengers over number of place
- N_{places} is the number of passenger places on a vehicle
- $Price_{ticket}$ is the ticket price

Yearly Profit, in $[€/year]$*:*

$$Profit_{yr} = Revenue_{yr} - Cost_{trip,ve}\;\; N_{trips,veh,yr}$$

Where:

- $Revenue_{yr}$ $[€]$ is the yearly revenues from ticket fares
- $Cost_{trip,veh}$ $[€]$ is the aggregated cost of a vehicle trip
- $N_{trips,veh,yr}$ is the number of yearly vehicle trips

3.2 Profitability correlation with network Saturation

This thesis starts by showing how economic feasibility in PRT systems greatly depends on vehicle density in the network, especially during peak hours. To do so the concept of network saturation will be used; a parameter that describes a class of PRT systems with similar proportion between number of vehicles and guideway length. As the method of this work closely bonds the number of vehicles to the transport demand, this parameter aggregates crucial information about network geometry, vehicle circulation, and demand characteristics.

$$Saturation = \frac{Number\ of\ vehicles\ in\ the\ network}{Maximum\ number\ of\ vehicles}\ or\ Sat = \frac{N_{ve}}{N_{ve\ \ ,max}}$$

Where the Maximum number of vehicles is the maximum number that can physically fit inside the guideway for a given safety space headway.

$$N_{ve\ \ ,max} = \frac{L_{guide}}{H_{space}} = \frac{L_{guide}}{H_{time} * V_{line}}$$

Where L_{guide} is the length of the guideway, H_{space} is the space headway, H_{time} is the time headway, V_{line} is the average line speed. Following, the fundamental relation between saturation and some key parameters that define the system:

$$Sat = \frac{N_{ve}}{L_{guide}}\ H_{time} V_{line}$$

This value is the maximum saturation achievable by the system, and it will be most likely reached during rush hours.

The value for space headway is calculated considering the brick wall criteria for emergency braking i.e. the front vehicle stops with infinite deceleration and the following vehicle must have enough space to safely stop with an emergency deceleration.

$$H_{space} = D_{safe\ decel} + L_{veh} = \frac{V_{line}^2}{2a_e} + L_{ve}$$

Why is saturation so important for revenues? Under the assumption that the system is properly dimensioned for the demand, therefore no jamming will occur due to traffic, the higher the number or vehicles circulating the higher the number of tickets paid; if then the network is rather compact the cost for its construction will be lower which, given fixed tickets sold, will provide higher profits. From a different point of view, we can see the saturation as an index of efficient usage of the network: if the peak saturation is low it means that during rush hours only some links of the network are producing useful mobility for the users, while a greater portion of the system is being passive; high saturation will be associated instead to a network utilized to its maximum capabilities. Of course, we cannot expect the saturation to grow close to 1, as it would imply that vehicles interactions due to acceleration/deceleration manoeuvres would propagate throughout the network hindering the system's correct functioning. Realistic values of saturation are in the range of $S = [0.4; 0.6\ ]$. The maximum saturation is a simple, but meaningful parameter.

Through a python script implementing a static simulation it is possible to study a PRT network, and derive estimate costs and revenues. By changing iteratively the saturation along with one other parameter is possible to derive a profit and loss plot showing correlation between saturation and profit as function of the third parameter. To cover different aspects of the system I chose to study three distinct features: guideway cost per meter to consider the value most related to construction costs, average vehicle trip length to account for different network topologies, maximum emergency deceleration to account for a circulation aspect that heavily influences the time headway.

Vehicle, guideway, and station parameters	
$V_{line}\ [m/s]$	11.11 (=40 km/h)
$a_e\ [m/s^2]$	5.00
$t_{react}\ [s]$	0.50
N_{places}	6.00
$L_{veh}\ [m]$	3.00
$V_{comm}\ [m/s]$	6.94 (=25 km/h)
$Occup_{veh}$	1.30
$Share_{empty}$	0.30
Sat	From 0.1 to 0.7
$D_{stat,av}\ [m]$	1000

Demand characteristics parameters	
$N_{trips,day}$	*Any*, this value does not influence this analysis
$N_{days,yr}$	350, conservatively accounts for lost days due to maintenance

$L_{trip,av}$ $[m]$	2500
$Share_{peak}$	0.25 (=6/24)
$Share_{off}$	0.42 (=10/24)
$Ratio_{off}$	0.60

Financial parameters	
$Cost_{cap,guide,m}$ $[€/m]$	5000
$Cost_{cap,stat}$ $[€]$	750000
$Cost_{cap,veh}$ $[€]$	50000
$Cost_{om,pax,km}$ $[€/km]$	0.19
$t_{am,guide}$ $[years]$	40
$t_{am,stat}[years]$	25
$t_{am,veh}[years]$	25
r	0.04
$Price_{ticket}$ $[€]$	1.50

Table 1: Input System, Demand, and Financial parameters for the sensitivity analysis of PRT systems profitability

Saturation vs Guideway cost

The first sensitivity analysis is performed over the guideway cost per meter as a value directly connected to the overall cost of the system. It is crucial to have a good range of profitability over a range of guideway costs as it is the most expensive element. A reasonable value for guideway cost is 5000 €/m, even though it depends on many local characteristics and restrictions; sometimes there might be the necessity to create some part of the network underground to avoid visual obstruction in historically relevant areas or to avoid conflicts with already existing suspended infrastructures. In case of underground construction, the cost might increase dramatically so I considered that observing profitability in cases of extreme costs would have a great significance.

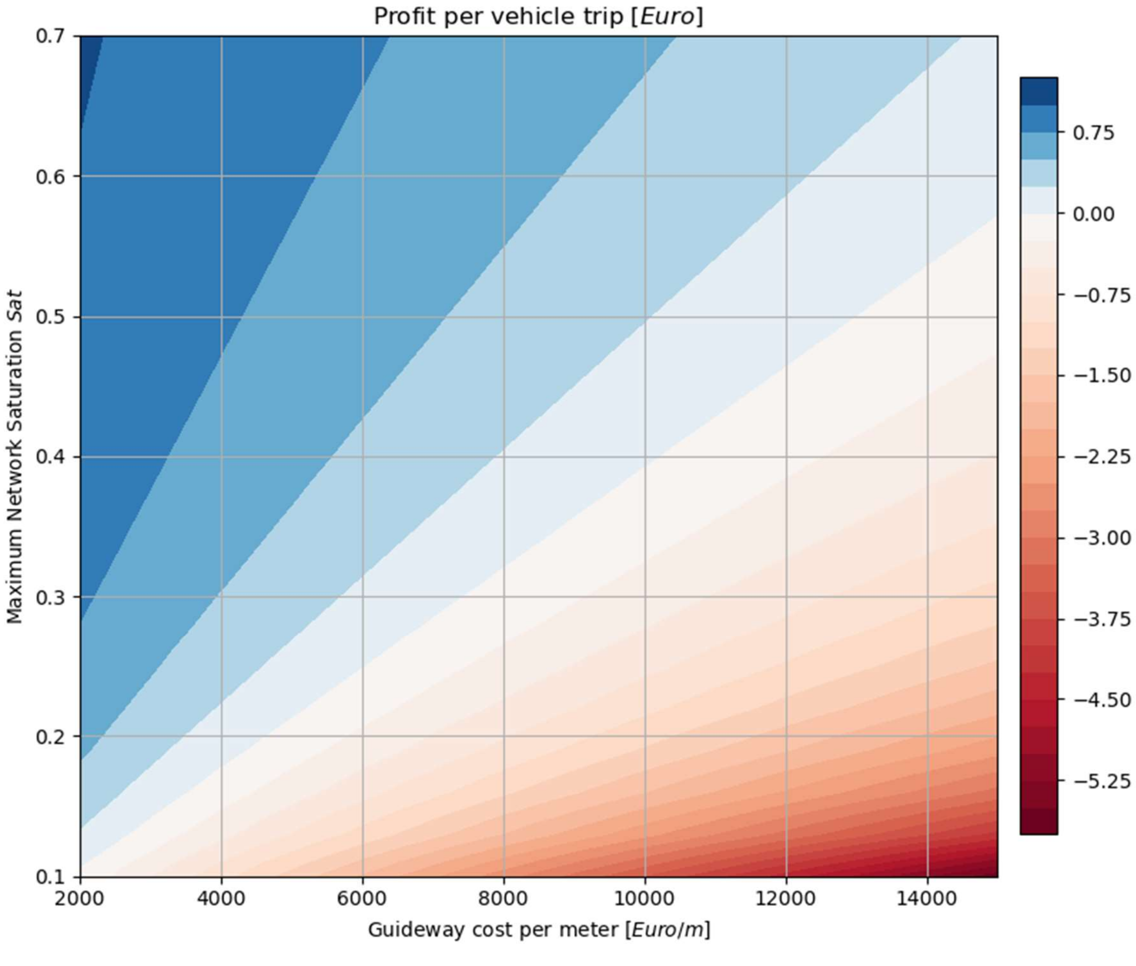

Figure 1: Plot showing the profit in Euros of each full vehicle trip. The maximum network saturation in the y-axis, the guideway cost per metre in the x-axis, the profits are shown in with a red (loss) and blue (profit) colormap.

The results show two expected trends: the profit per vehicle trip is directly proportional to the saturation and inversely proportional to the guideway cost. As the increase in guideway cost is a linear operation with respect to the increase of general capital costs, also the plot show that the points of constant profit lay on almost straight lines. Be aware that such simple behaviour is guaranteed only for reasonable values of the parameters, for example in the vicinity of saturation equal to 1 we can appreciate some non-linear behaviours. Every slight change in parameters can indirectly alter all the others, this very simple yet fundamental example shows an intuitive almost linear correlation between guideway cost and saturation needed to maintain profitability positive.

The plot shows a wide range of possible profitable designs. Assuming that we can achieve a saturation of 0.5, which is totally realistic for any well designed PRT network, we break even at 13000 €/m, which is 160% more costly than average. From this I can conclude that the cost of guideway for normal cases is not critical as the designers have a wide range of profitability and the system would remain self-sustainable even if the costs were to be doubled due to unexpected events. As the guideway is the heaviest element financially, PRT systems can be considered to be very resilient to capital costs increases.

On the other hand, for expected guideway cost of 5000 €/m the break even for saturation is 0.21, this is another huge result. It means that the system is also resilient to very slow build-ups of demand. The PRT needs a certain quantity of users to be interested to become truly sustainable and the initial moments of life of a PRT can be critical as it still needs to earn people's trust and attention. From this result can be concluded that in case of systems built in areas without great challenges to overcome, i.e. the guideway cost can be safely estimated to be the average of 5000 €/m, the system has all the time to build-up demand and trust. So, planners can rely on less accurate or less optimistic estimations of mode shift towards PRT to design the system.

Saturation vs Average trip length

The second sensitivity analysis is performed changing the value of average trip length, as it is a value directly connected to the topology and shape of the network. The crucial aspect of this parameter arises when expansions of the network are proposed. Every time the network is modified also the opportunities to move of the users are deeply impacted, and it is reasonable to expect an inflation of average trip lengths when providing new destinations that are further away from the main net or that prefer a less circular and symmetrical shape pf the network. The distance inflation is a phenomenon well known in transportation engineering and always occurred whenever new driving technology of better roads were available to the users, so it is only reasonable that the same would happen in a PRT system. So, I consider very important to make a sensitivity analysis on this parameter so that planners may have a better perception of the incoming costs of expanding and adding new modules to an existing system.

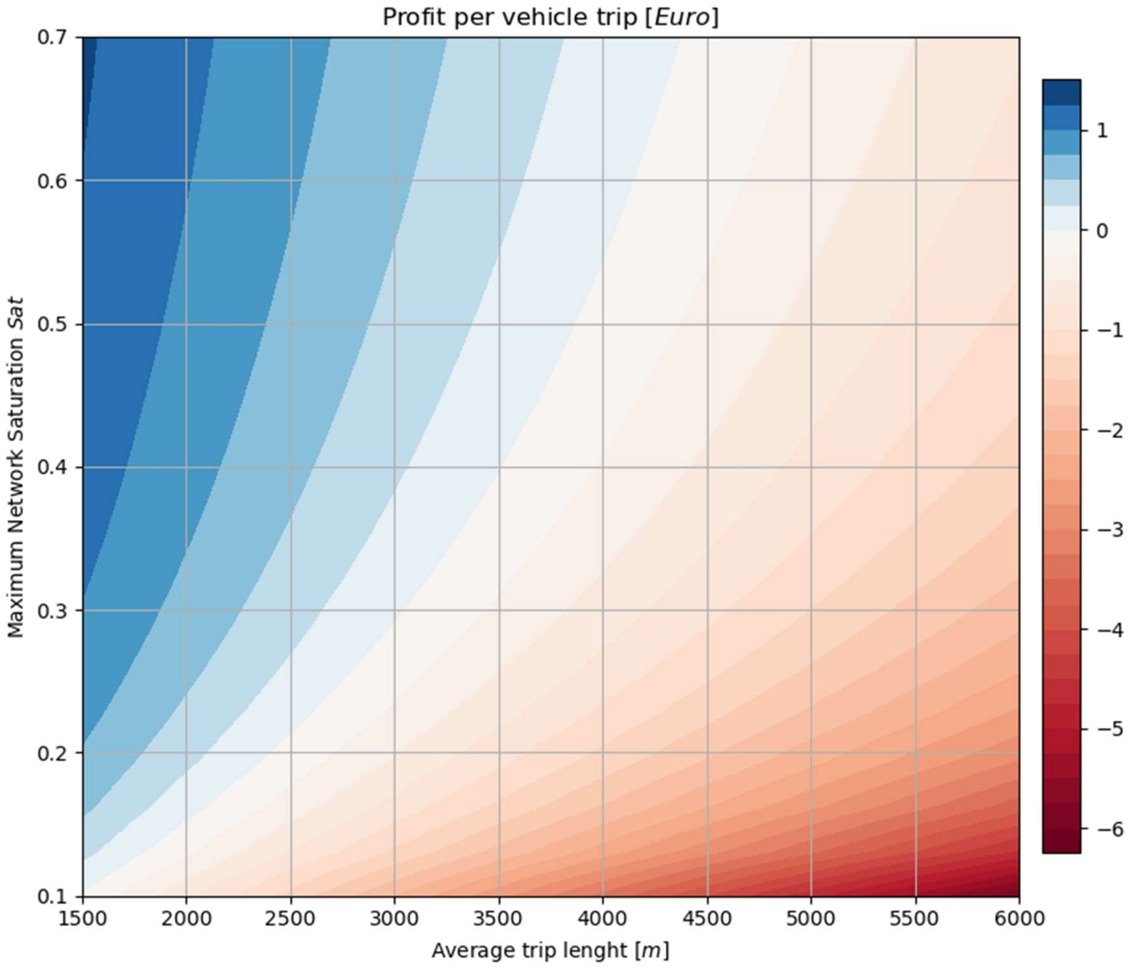

Figure 2: Plot showing the profit in Euros of each full vehicle trip. The maximum network saturation in the y-axis, the average trip length in the x-axis, the profits are shown in with a red (loss) and blue (profit) colormap.

The plot shows again a trend of positive correlation between profit and saturation, as expected, and then a negative correlation between average trip length and profit. This can be simply explained as for a fixed saturation the system has a fixed number of vehicles, or better “density” of vehicles, so if the average trip length also increases the average trip time increases reducing the maximum number of trips that a single vehicle can perform in a given time span. This is extremely important to consider as the shorter the trips the higher the performance, but the PRT has two fundamental characteristics that go against this behaviour:

first of all it is meant to substitute the car for all urban and peri-urban movements, so the trip length will hardly decrease below 1500-2500 meters as for such travels a bike or walking can be valid substitutes, then one of PRT's strengths is the ability to scale-up and add new modules connecting new areas and innervating the whole urban structure. So as planners it is fundamental to keep in mind that PRT trips can vary their characteristics as demand needs change over time. This is very different with respect to traditional public transport, where a line is fixed a-priori by the planner, so that any extension of the general network of transport can happen without necessarily changing the public transport lines. Here every new destination can have relevant impacts on both trip lengths and demand distribution.

On the trip length side, assuming a saturation value of 0.5, the break-even lies at 3850 m. From this result I can conclude that if the ticket price if fixed a PRT system might have limitations on its range, probably a network could not be sustainable anymore past 6-8 km of diameter (assuming a circular, symmetrical shape of the network). An immediate solution to this problem would be to have a variable price depending on space travelled, the solution could be similar to current metro systems where the network is divided into zones, where outer zones have higher prices with respect to central zones. Otherwise, as the PRT is a fully on demand service where the user can individually pay the single run and there is no possibility to buy a ticket for a shorter distance and then dwell inside the vehicle waiting to get to an outer station, the operator could make the customer pay for the exact distance in advance.

On the maximum network side, assuming an average trip distance of 2500m, we break even at saturation 0.21, which again is a very positive result as explained in the *saturation vs guideway cost* analysis.

Saturation vs Emergency deceleration

In this third and last sensitivity analysis the maximum emergency deceleration is studied, which is strictly related to circulation aspects of the network. As the maximum deceleration increases the safety distance decreases, allowing for shorter headways that directly lead to higher capacity and higher number of vehicles for a fixed saturation value. More vehicles and capacity mean more demand the system is able to satisfy and the more profit it is able to give back. The range for deceleration has been given between 1 and 10 m/s^2 to represent possible comfortable decelerations in different vehicles. In case of vehicles with standing passengers, highly discouraged in every PRT systems as comfort is key to its success, the maximum deceleration that can be sustained without starting to fall is in the order of 2 m/s2, while in case of seated passengers without seatbelt, as happens commonly in all urban public transport, the maximum deceleration that can be sustained before risking to fall from the seat is in the order of 5 m/s^2 . In the case of seat belted passengers the maximum deceleration can be far higher, but to avoid any discomfort even in emergency situations, a maximum value of 5 m/s^2 can be safely considered.

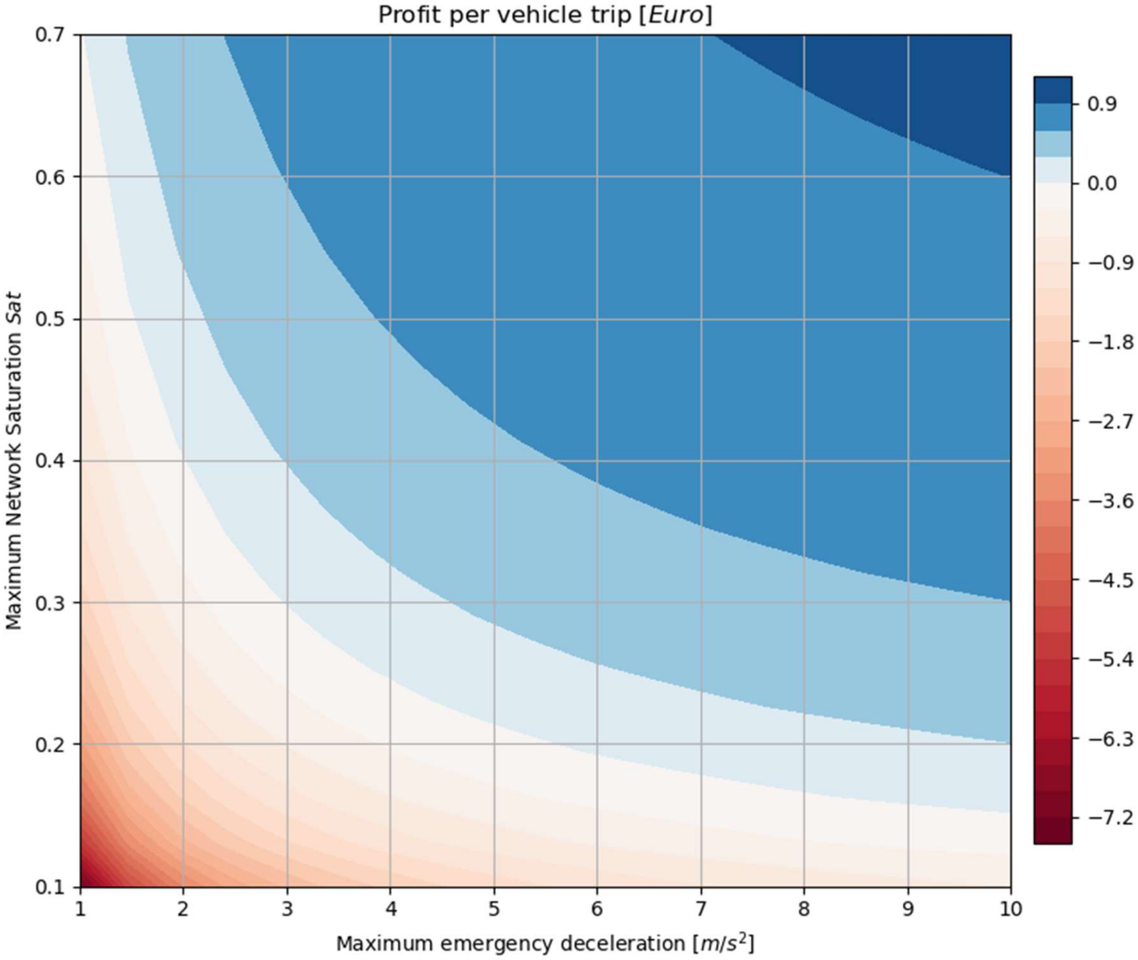

Figure 3: Plot showing the profit in Euros of each full vehicle trip. The maximum network saturation in the y-axis, the maximum emergency deceleration in the x-axis, the profits are shown in with a red (loss) and blue (profit) colormap.

From the side of maximum emergency deceleration we can observe that fixed the usual saturation at 0.5 we break even at 1.5 m/s^2 meaning that the service could be run with very high time headways and give the passengers the chance not to wear a seatbelt, which would significantly increase the comfort for all users and would alleviate from the operator the need to check if the user is wearing a seatbelt at all times during the ride. The debate about whether the seatbelt is to eliminate or not in PRT systems is still open, as many valid argumentations arise defending both sides. Favouring the seatbelt is usually defended by arguing that this allows for greater safety in any condition, not only for vehicle-to-vehicle collision; moreover, it allows to accelerate and decelerate much faster, which reduces dimension of the deceleration and acceleration lanes before and after stations and reduces time headways with significant increase in revenues and level of service. The side favouring the elimination of seatbelts argue that it reduces the comfort of the ride with respect to private car, especially when considering that the user might feel more anxious about risks, i.e. getting stuck after a collision or under normal circumstances, as there is no other person inside the vehicle that might help them; then there the problem of making sure that the user keeps the seatbelt fastened at all times. We can imagine that the user might refuse to fasten the belt at all before the trip starts, therefore slowing the whole station down by occupying indefinitely the berth, or that the user might fasten the belt at first and then loosening it when the ride started. In Italy the driver of the vehicle is to be considered responsible for the injuries of other passengers, even if caused by their irresponsible behaviours; so who would it be to blame in the case of a driverless vehicle? Who is to blame among all the passengers? Can the law assign individual responsibility in these cases? These questions do not have easy answers, nor I will cover them in this dissertation. I personally think that the seatbelt problem is a challenge to be overcome for the sake of greater efficiency and safety, that is why in all my simulations is assumed a value for deceleration of 0.5 m/s^2 with the hypothesis of a fastened seatbelt.

Looking now on the saturation side, assuming a deceleration of 0.5, the break-even lies at 0.21 saturation. This means that if our vehicles where to mount seatbelts on them the system would be extremely resilient against periods of low affluence or during the build-up phase of the users. Moreover, I would like to notice that due to the quasi-hyperbolic shape of the constant profit curves we can observe that the higher the acceleration the quicker the profit raises with the rise of saturation, which makes me think that the derivative of the profitability with respect to the saturation might be strongly positively correlated with the value of acceleration.

3.3 The case of Bologna, Italy.

The following chapter analyse a hypothetical case study located in the city of Bologna, Italy. The scenario is an original design of a PRT network based on a concept and model of Bologna developed by Nguyen et al. In their research the authors tried to fit the idea of superblocks as seen in the city of to the urban environment of Bologna. First, the concept of superblocks will be briefly introduced, then will follow a sensitivity and construction phase interface analyses on the PRT network.

The Superblocks

As environmental issues are becoming a priority, city planners are trying to consider new solutions to mitigate air and noise pollution as well as decongestion the city streets towards a more “human-sized” urban environment. Among these new concepts emerges the superblock design. It consists of a grid of zones of various shape and size where circulation is partially or totally limited to soft mobility i.e. not motorized vehicles. Iside the areas can be installed traffic calming structures, and the road design must clearly prioritize and incentivize the pedestrian use, whether the car traffic is forbidden or just strongly limited. The areas are delimited by roads where car traffic is allowed, fundamental to allow medium to long distance travel by car or, preferably, public transport. Barcelona superblock design is a great example of this concept: residential square blocks of 400m sides where internal traffic is limited to walking, biking, and driving of resident vehicles and, of course, urban services and emergency vehicles (López, 2020). In this example car traffic is only partially retracted to allow residents to retain easy access to their own car, but the design is a clear mobility statement that in such area the cars are the guests, in opposition to the traditional design of roads where cars are the main scope of planning. Please note that similar concepts are not new in the transportation field: *woonerfs* in the Netherlands (Schepel, 2005) and *shared spaces* in the United Kingdom (Luca, Gaman, & Singueranu, 2012) are very close concepts, with the fundamental difference that the superblock design is meant to completely restructure a city’s way to mobility in a strategic and systematic manner. Finally, implementation of superblock comes at relatively low investment as it consists mainly of repurposing of existing infrastructure with minor structural changes (López, 2020).

A change that big comes of course with its own problems and challenges. First of all planners must completely re-design the public transport network to ensure all citizen accessible transport for everyday demand; this operation is most complex as now the public services wil have less roads that will need to be shared with the circulating cars. The public transport must be provided preferential paths to ensure its attractivity, once the users will leave the car mode the streets will be enough for all the remaining motorized transport. The second crucial aspect is that it must be a radical change to city scale. If applied to limited portions of the urban environment it could lead to both inefficient mobility, as the system works when synergizing with the rest of the city, and stronger social inequality due to the appreciation of the renewed districts with respect to the old ones, a consequence that cannot be accepted as the superblock design should help level mobility and transport inequalities. Finally, it is likely that the project will face strong political and social opposition (López, 2020), so it is important that the purposes and advantages of the new design are stated clearly and brought to the population.

Bologna superblock model

The model developed by Nguyen et al. is based on a digital twin of the city of Bologna made by J. Schweitzer. The authors then adopted a multistage process to identify potential

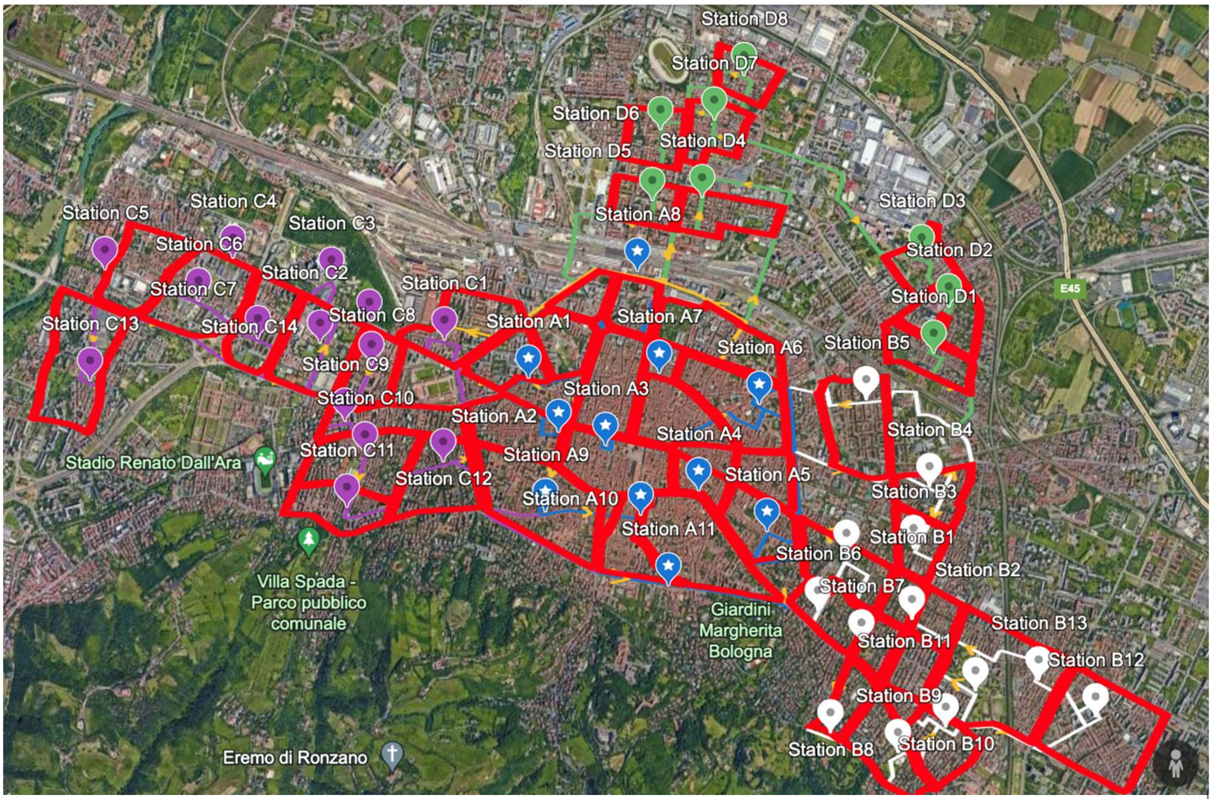

Figure 4: The superblock design by Nguyen et al. (in red) and the PRT stations location.

superblocks, based on the following criteria: Road network hierarchy, population density, building footprint and public transport network. At the end of the process the authors propose 49 superblocks distributed all over the metropolitan area of Bologna.

The PRT network

My PRT design for the Bologna superblock scenario is born by the idea that a superblock-oriented city could greatly benefit from PRT network. The system allows to connect all superblocks with a unique network easily accessible by the population. Considering that the service provided would be equivalent to that of a car as far comfort, on demand service and speed are concerned it could be an excellent tool in the hands of the planners to replace all the comforts that the private cars ensured, while keeping the block free from traffic. To verify this hypothesis, a digital model on SUMO was realised to study in detail the interactions that would occur between the PRT implementation with the original superblock design. As also the model from Nguyen et al. was built to run on SUMO micro-simulation engine, the two designs can seamlessly interact inside the micro-simulator.

The base idea is to provide each superblock its own PRT station, that way all trips inside the urban area could be undertaken with public transport only. The PRT would also connect the users to Bologna Centrale train station to provide 24h access to long distance transport modes and, vice-versa, distribute in the whole metropolitan area the flows of residents and travellers coming by train. Moreover, the network places station as close as possible to some of the centralized parking that come along with the superblocks, so that users may easily access their car if ever needed and would help public acceptance. Once the preliminary position of the station is set, the last step was the design of the guideway that would connect them. To minimize the travel time between any pair of stations it is fundamental to carefully design the direction of motion and the exact sequence with which the stations are connected, it is important to create just enough extra loops so that a vehicle can quickly access nearby stations without the need to wander through kilometres of network; at the same time every extra connection means extra guideway costs and extra merge nodes that make the system more complex and more susceptible to heavy traffic, as one of the main congestion causes in a PRT system are merging nodes overcrowdings, where vehicle must time their entrance to avoid collisions while keeping satisfying speed. The balance is very subtle at this point of the design process, that is why systems like PRT are to be simulated with micro-simulation techniques that allow for extremely precise and congestion sensitive analysis. In such environments is also possible to artificially create demand loads to stress the system in critical points and evaluate its resilience to unexpected demand events. Though, unfortunately, in this thesis the simulation of this network will not be covered; only preliminary design and profitability analysis will be addressed.

To summarize, the criteria where: try giving every superblock at least one station, try connecting stations with centralized parking and key transport nodes, maximize redundancy of path between stations, minimize travel distance between stations, minimize overall guideway length.

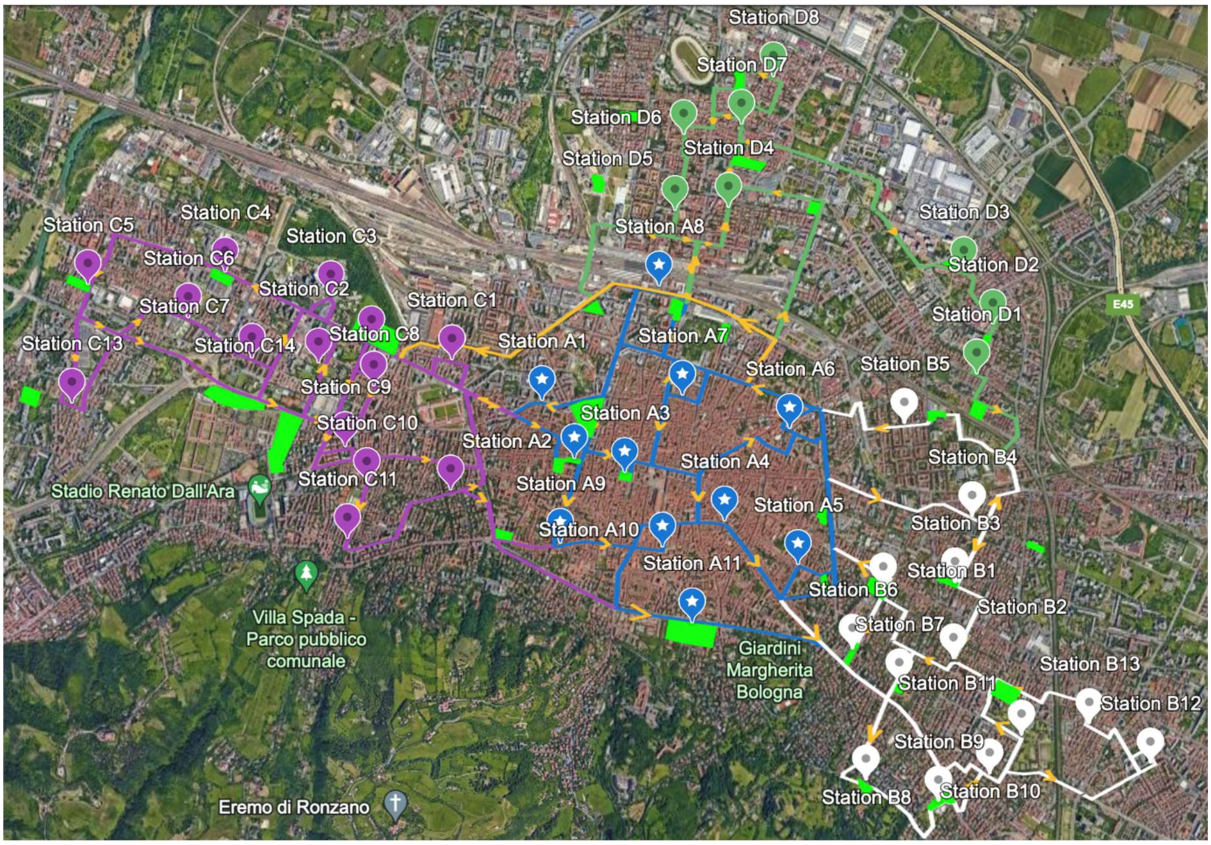

Figure 5: The centralized parking designed by Nguyen et al. (in green), and the PRT stations location.

As shown in Figure 4 the network covers the whole metropolitan area of Bologna and provides a PRT station to almost every superblock. The network was arbitrarily divided into 4 zones called the Blue Line, White Line, Green Line and Purple Line following the same colour in Figure 5. Please note that the distinction is for orientation purposes only and the network is completely connected as a whole: every station of a Line can reach every other in any other

Line. The Lines do differ in something, due to the very different population distribution and the very different shape of the area to be served they feature different approaches to the guideway design, especially in the way the loops are conceived.

The PRT design comes also with a proposal for construction phasing. It is important to notice that such a huge network would probably cost too much to be completed in one single instance, on the other hand the PRT network works only if all present stations present at any given time work harmonically with one another. So, another important aspect I had to keep in mind when preparing the design was to divide the network in three phases. As public and political acceptance are key factors each phase must provide a satisfactory service and be economically sustainable. While evaluating the service efficiency will be done in future research trough detailed micro-simulation, the economic feasibility can be assessed with the same methodology shown in the previous part of this chapter.

The first phase consists of a corridor connecting 6 stations from the Purple Line, 8 stations form the Blue Line and 6 stations from the White Line, for a total of 20 stations. The corridor stretches west to east to catch the very high transport demand concerning these areas. The

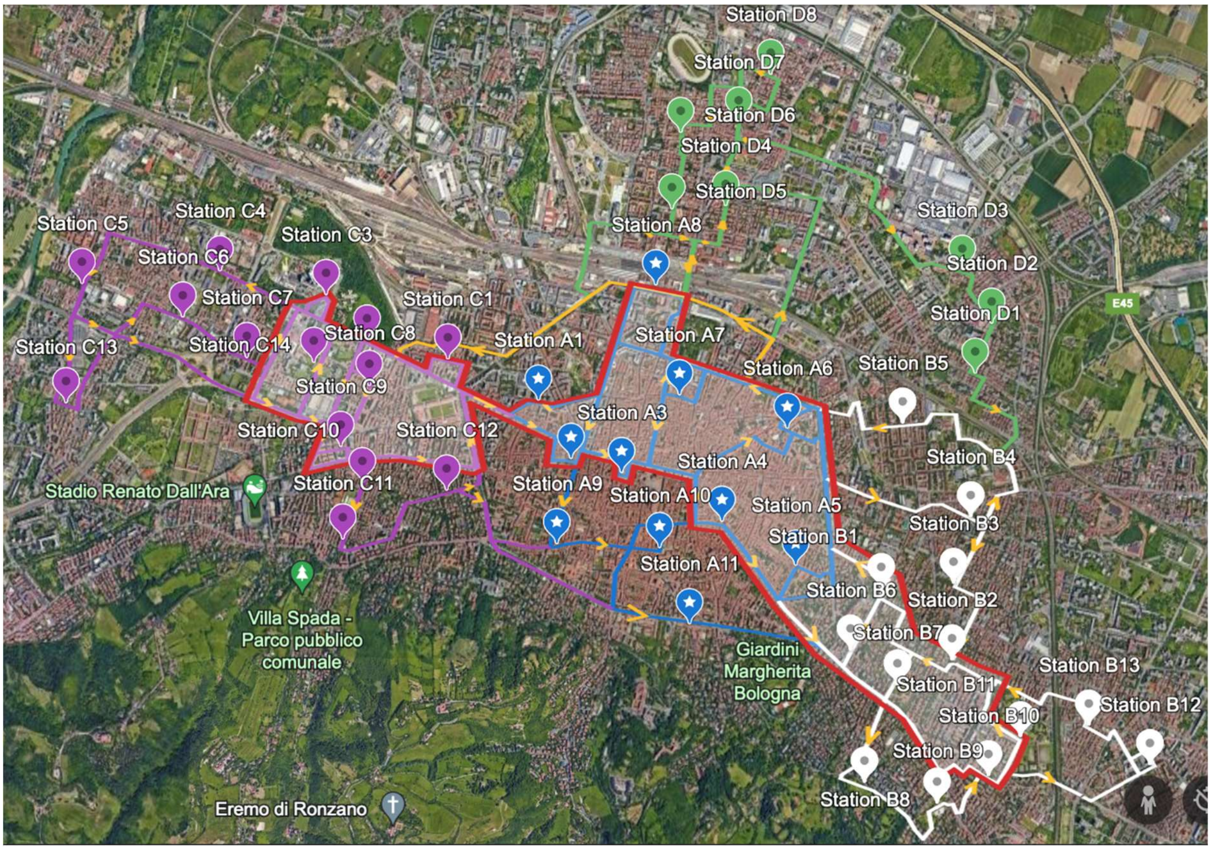

Figure 6: Construction Phase 1 of the Bologna PRT network (in red).

benefits of starting from this area are the catchment of car traffic both passing through the city centre both directed to the city centre, and the creation of a medium size network with high expected demand. This would correspond in our model to a high saturation of the network with corresponding high profitability. With the Blue line we would cover the upper half of the historical centre and Bologna Centrale train station, while the Purple line would stretch up until the Ospedale Maggiore hospital and the white line reaching in the most dense urban area of Murri. It is important to provide immediately a service that feature several benefits to the city as proof of work to support the construction of the full-size network.

The second phase of construction adds 3 stations from the Purple Line, 3 stations from the Blue Line and 3 stations from the White Line, for a total of 29 stations in the network. This phase basically strengthens the original corridor as its geometry keep being quite horizontal and stretched from west to east. With this phase the whole historical centre is covered with stations and the zones of Murri and Cirenaica would now be substantially covered, at least in some of the most dense and close residential areas. With this construction phase also arises the need of adding a bypass guideway that directly connects the White Line with the Purple Line passing above the Bologna Centrale train station and skipping it. This bypass is

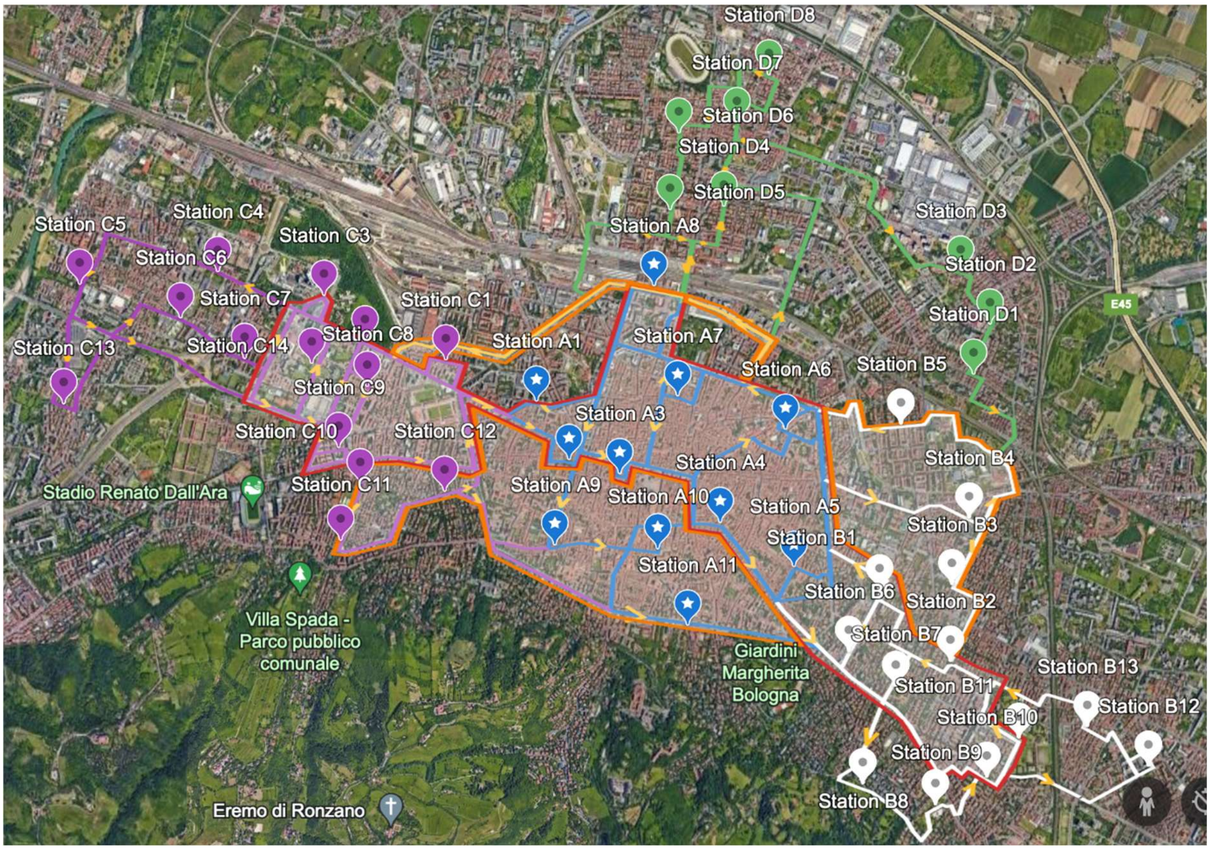

Figure 7: Construction Phase 2 (in orange) of the Bologna PRT network.

fundamental to allow fast travels for commuters passing through that would have their trip hindered by the high traffic in the train station direction.

The third and last phase of construction is completing the system with 5 stations in the Purple Line, 4 stations in the White Line and all 8 stations of the Green Line. Only in this third phase the Green Line enters in action, connecting the zone of Bolognina. The construction of this side of the network probably needs to wait until the third phase as the population density, but most importantly the PRT transport demand in this area is expected to be lower. The newbuilt Green Line will now connect to the Blue Line near the Bologna Centrale station by means of a bit more complex disposition of guideways, to The White Line with a bypass that skips the city centre, to the Purple Line through the bypass already built in the second phase.

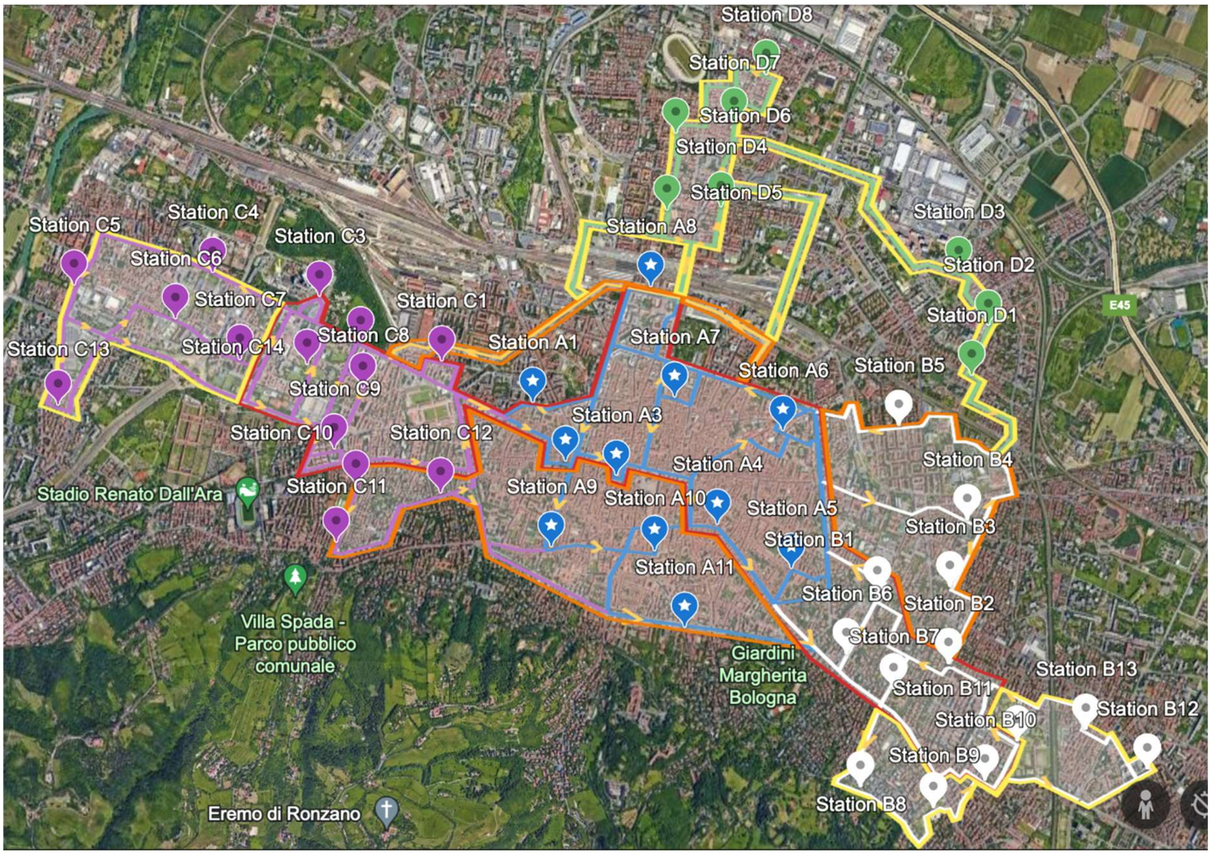

Figure 8: Construction Phase 3 (in yellow) of the Bologna PRT network.

The Profitability analysis

On this case will be provided four analyses:

1) First Phase considered as a standalone with no future development.
2) Second Phase considered as built in a single instance.
3) Third Phase considered as built in a single instance.
4) The process of building the three phases in succession giving each some time to generate cashflow, positive or negative, to support the next steps.

The first analysis will verify if a small dense network could sustain itself. If the system is to succeed, we first need to ascertain that the initial corridor is sustainable and highly profitable to guarantee a cashflow and finance the successive two phases of construction. It is also important to evaluate if such system could work effectively as a standalone in the unfortunate case of political change of vision that might block future development.

The second analysis is the same as the first, with the difference that the second phase of construction is realised in a single instance and then no future development is considered. This analysis is useful to understand if it might be possible to skip entirely the first phase and proceed immediately with a slightly larger network.

The third analysis is a challenge for the network, I am interested in verifying if a large-scale system can sustain itself even with strongly reduced profit efficiency due to lower network saturation, under the quite unrealistic assumption that the whole network can be built in short times and start a cashflow almost immediately. If this analysis proves that the large network can sustain itself then the chances of it surviving the whole step by step process can be considered high.

Finally, the fourth analysis considers a more realistic scenario where the first part of system is built, it produces some profit or loss, then the second and third part are built with the same idea. This process better represents the actual phasing of the project and can better help identify its most critical points. Of course, this analysis will take the strong hypothesis that each phase can be built in zero time and immediately start to function and produce income.

Performing this case study analysis requires a slightly different methodology with respect to the one shown in paragraph 3.1. This time I work directly with known values for number of stations and guideway length and assuming a realistic value for saturation the exact number of vehicles is also defined. I need to further explain how the value of saturation is considered realistic. Saturation values above $Sat = 0.7$ are considered unrealistic, especially if the objective is to maintain a high circulation speed, as the vehicle start having little manoeuvring space for deceleration and acceleration in proximity of the stations. In the saturation was set to $Sat = 0.6$ which gives vehicles enough room, later the script evaluates the number of passenger trips associated with this value of saturation and the results is compared to real demand data to estimate a hypothetical mode share for PRT. If this share is consistent with expected mode shift from public and private transport, then the initial hypothesis is considered valid. In case the mode shift required to reach the calculated mode share is too high, the simulation will be repeated with a slightly lower value of saturation until verification of the condition.

To validate the number of trips hypothesized the benchmark will be based on real measurements. In (Nguyen, Schweizer, Rupi, Palese, & Posati, 2024) the authors derive an estimation of the number of trips form the disaggregation of OD matrix from population census. Based on this data they create a virtual population of 167062 people in the whole area of their study area, coincident with the area of influence of the third phase of my design. These people are then assigned trip plans, for a total of 448597 planned trips in two rush hours, the modes are assigned and the mode share for car resulted being 19.29% equivalent to 43267 trips by car in a single rush hour. As in this superblock scenario the PRT network is mainly meant to substitute the car, the resulting values of PRT trips will be checked against the values of car trips found by Nguyen et al. To adapt the numbers to first and second phase the comparison value will be scaled down proportionally to the number of stations; in the last phase there are a total of 46 stations, 29 in phase 2 and 20 in phase 1, so the car trips will be reduced in phase 2 to 29/46 * 43267=27277 and in phase 1 to 20/46*43267=18812.

Analysis on the First Phase alone

On this analysis the following assumptions are used:

- t_{am}, the mortgage time, is considered the same for every element in this analysis. equal to the useful life of the element when proper maintenance, both ordinary and extra-ordinary, is done on the element. For $t_{am,veh}$, the mortgage time of the vehicles, I assumed a time of 25 $[years]$. For $t_{am,station}$, the mortgage time of the stations, I assumed a time of 25 $[years]$. For $t_{am,guide}$, the mortgage time of the guideway, I assumed a time of 40 $[years]$.

- r, the fixed interest rate for the mortgage, is taken equal to the Internal Rate of Return of present year (2024) corporate bonds expiring in more than 15 years from the current year; $r = 0.04$ can be assumed as a realistic average value.
- a_{emerge}, the emergency deceleration value, is considered equal to 0.5 $[m/s]$, under the hypothesis that seatbelts are mandatory on the vehicle.

Vehicle, guideway, and station parameters	
$V_{line}\ [m/s]$	11.11 (=40 km/h)
$a_e\ [m/s^2]$	5.00
$t_{react}\ [s]$	0.50
N_{places}	6.00
$L_{veh}\ [m]$	3.00
$V_{comm}\ [m/s]$	6.94 (=25 km/h)
$Occup_{veh}$	1.30
$Share_{empty}$	0.30
Sat	0.6
N_{stat}	20
$L_{guide}\ [m]$	24376

Demand characteristics parameters	
$N_{days,yr}$	350, conservatively accounts for lost days due to maintenance
$L_{trip,av}\ [m]$	2500
$Share_{peak}$	0.25 (=6/24)
$Share_{off}$	0.42 (=10/24)
$Ratio_{off}$	0.60

Financial parameters	
$Cost_{cap,guide,m}\ [€/m]$	5000
$Cost_{cap,stat}\ [€]$	750000
$Cost_{cap,veh}\ [€]$	50000
$Cost_{om,pax,km}\ [€/km]$	0.19
$t_{am,guide}\ [years]$	40
$t_{am,stat}[years]$	25

$t_{am,veh}[years]$	25
r	0.04
$Price_{ticket}$ [€]	1.50

Table 2: Input System, Demand, and Financial parameters for analysis of profitability of Phase I alone

Methodology differences

Originally the process takes as input the daily demand for PRT trips along with station density, saturation, average trips length etc… to evaluate other parameters live vehicles and total vehicle trips, now I need to start from a value of saturation and known number of stations and guideway length to reach number of vehicles and total vehicle trips, while verifying that the total number of daily trips of users is realistic. First, I can derive:

Number of vehicles:

$$N_{veh} = \frac{Sat\ L_{guide}}{H_{time}\ V_{line}}$$

Where:

- Sat	is the maximum achievable network saturation
- $L_{guide}\ [m]$	is the guideway length
- $H_{time}\ [s]$	is the minimum time headway
- $V_{line}\ [m/s]$	is the line speed

The number of vehicles is now derived directly from the definition of saturation, while before it was obtained by knowing the number of passenger trips and the average trip length to assign exactly the minimum required number of vehicles to satisfy that demand.

Number of vehicle trips in one rush hour:

$$N_{trips,veh,peak,1h} = \frac{3600[s]\ N_{veh}\ Share_{full}}{t_{trip,av}}$$

Where:

- N_{veh} is the number of vehicles in circulation
- $Share_{full}$ is the share of full vehicles circulating
- $t_{trip,av}$ $[s]$ is the average trip time

From the definition of N_{veh} given in paragraph 3.1 we can derive the inverse formulation for the number of vehicle trips.

Number of vehicle trips in one day:

$$N_{trip,veh,day} = N_{trip,veh,peak,1h}\, 24\, Share_{peak} + N_{trip,veh,peak,1h}\, 24\, Share_{off}\, Ratio_{off}$$

Where:

- $N_{trip,veh,peak,1h}$ is the number of vehicle trips done in one rush hour
- $Share_{peak}$ is the share of rush hours w.r.t. the whole day
- $Share_{off}$ is the share of off-peak hours w.r.t. the whole day
- $Ratio_{off}$ is the ratio between the trips done in rush hours w.r.t off-peak hours

Number of passenger trips in one day

$$N_{trips,day} = N_{trip,veh,day}\, Share_{full}\, Occup_{veh}\, N_{places}$$

Where:

- $N_{trip,veh,day}$ is the number of vehicle trips in one day
- $Share_{full}$ is the share of full vehicles circulating
- $Occup_{veh}$ is the occupancy rate as number of passengers over number of places
- N_{places} is the number of passenger places on a vehicle

Number of passengers trips in one year:

$$N_{trips,yr} = N_{trips,day}\, N_{days,yr}$$

Where:

- $N_{trips,day}$ is the number of daily trips
- $N_{days,yr}$ is the number of days in a year

A planner willing to build this first phase of the network faces two main assumptions: the sum of all costs concerning the guideway construction and the mode share attracted from the system that will determine the revenues. For this reason, the following sensitivity analysis revolves around these two parameters. I will show how the gross profit change iterating through the values of guideway cost per meter and network saturation. I chose a scale of saturation starting from 0.1, which would mean a total refusal of the mode from the users, up to 0.7 which is the upper bound for service disruption, reasonable high values are 0.5-0.6. For the guideway cost I chose a range going from 2500 €/m, which would be equivalent to half of the average cost for this type of infrastructures, up to 15000 €/m, three times higher than the

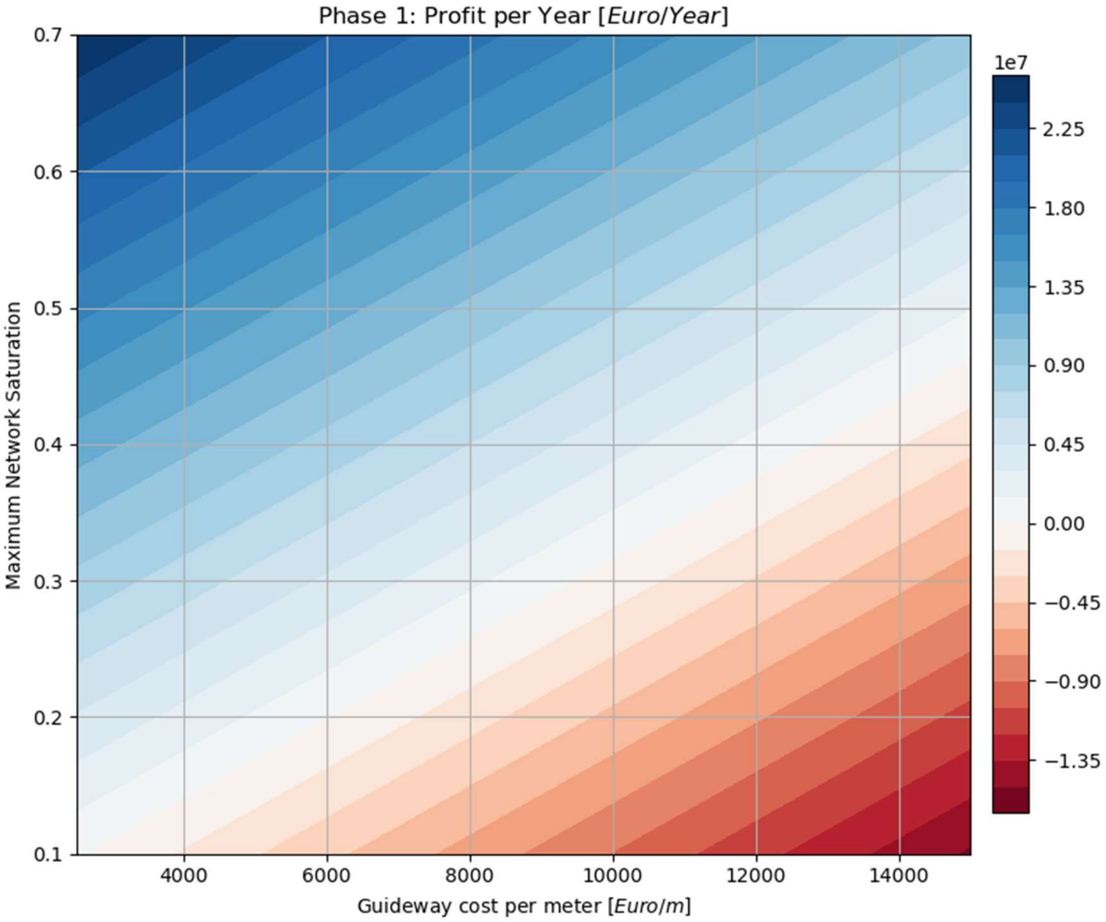

Figure 9: Plot showing the profit in 10^7 Euros (tens of millions of Euros) for a year of operation. The maximum network saturation in the y-axis, the guideway cost per meter in the x-axis, the profits are shown in with a red (loss) and blue (profit) colormap.

average value that could occur in case of extraordinary complex sites of construction with the need for special interventions like building an underground guideway.

In Figure 9 we can appreciate the results of profit per vehicle trip, If we assume that the guideway will cost 5000 €/m as expected we require a saturation of 0.17 to reach profitability, while in the case of guideway cost three times higher, 15000 €/m, we require a minimum saturation of 0.46. If the guideway is expected to have great issues being built, then we also need to make sure a large share of users will use the system.

My conclusions on the first phase analysis are very positive, the investment is expected to give back great profits to operator and city, plus the system would prove profitable even in case of cost exceedance by a factor of 3 or in case of slow response from the users in mode shifting. This means that the project can be interrupted beforehand if any unexpected event was to block it from further development. The corridor would be a great helper for mobility in the new superblock city arrangement and thanks to its efficiency it would also benefit local economy and city profit, while keeping unchanged the costs for mobility of local users as the ticket fare was considered equal to the current bus ticket price.

Finally, I need to validate the values of trips in a single rush hour. The simulation finds that 7641 trips are performed while the comparison value is 18812 trips in one hours, so the hypothesis of the analysis is confirmed. The share of PRT estimated for this phase would be of 7.84%, covering just less than half of the precedent car demand.

Analysis on the Second Phase alone

On this analysis the following assumptions are used:

- t_{am}, the mortgage time, is considered the same for every element in this analysis. equal to the useful life of the element when proper maintenance, both ordinary and extra-ordinary, is done on the element. For $t_{am,veh}$, the mortgage time of the vehicles, I assumed a time of 25 $[years]$. For $t_{am,station}$, the mortgage time of the stations, I assumed a time of 25 $[years]$. For $t_{am,guide}$, the mortgage time of the guideway, I assumed a time of 40 $[years]$.

- r, the fixed interest rate for the mortgage, is taken equal to the Internal Rate of Return of present year (2024) corporate bonds expiring in more than 15 years from the current year; $r = 0.04$ can be assumed as a realistic average value.
- a_{emerge}, the emergency deceleration value, is considered equal to 0.5 $[m/s]$, under the hypothesis that seatbelts are mandatory on the vehicle.

Vehicle, guideway and station parameters	
V_{line} $[m/s]$	11.11 (=40 km/h)
a_e $[m/s^2]$	5.00
t_{react} $[s]$	0.50
N_{places}	6.00
L_{veh} $[m]$	3.00
V_{comm} $[m/s]$	6.94 (=25 km/h)
$Occup_{veh}$	1.30
$Share_{empty}$	0.30
Sat	0.6
N_{stat}	29
L_{guide} $[m]$	38869

Demand characteristics parameters	
$N_{days,yr}$	350, conservatively accounts for lost days due to maintenance
$L_{trip,av}$ $[m]$	2500
$Share_{peak}$	0.25 (=6/24)
$Share_{off}$	0.42 (=10/24)
$Ratio_{off}$	0.60

Financial parameters	
$Cost_{cap,guide,m}$ $[€/m]$	5000
$Cost_{cap,stat}$ $[€]$	750000
$Cost_{cap,veh}$ $[€]$	50000
$Cost_{om,pax,km}$ $[€/km]$	0.19
$t_{am,guide}$ $[years]$	40
$t_{am,stat}[years]$	25
$t_{am,veh}[years]$	25
r	0.04
$Price_{ticket}$ $[€]$	1.50

Table 3: Input System, Demand, and Financial parameters for analysis of profitability of Phase II alone

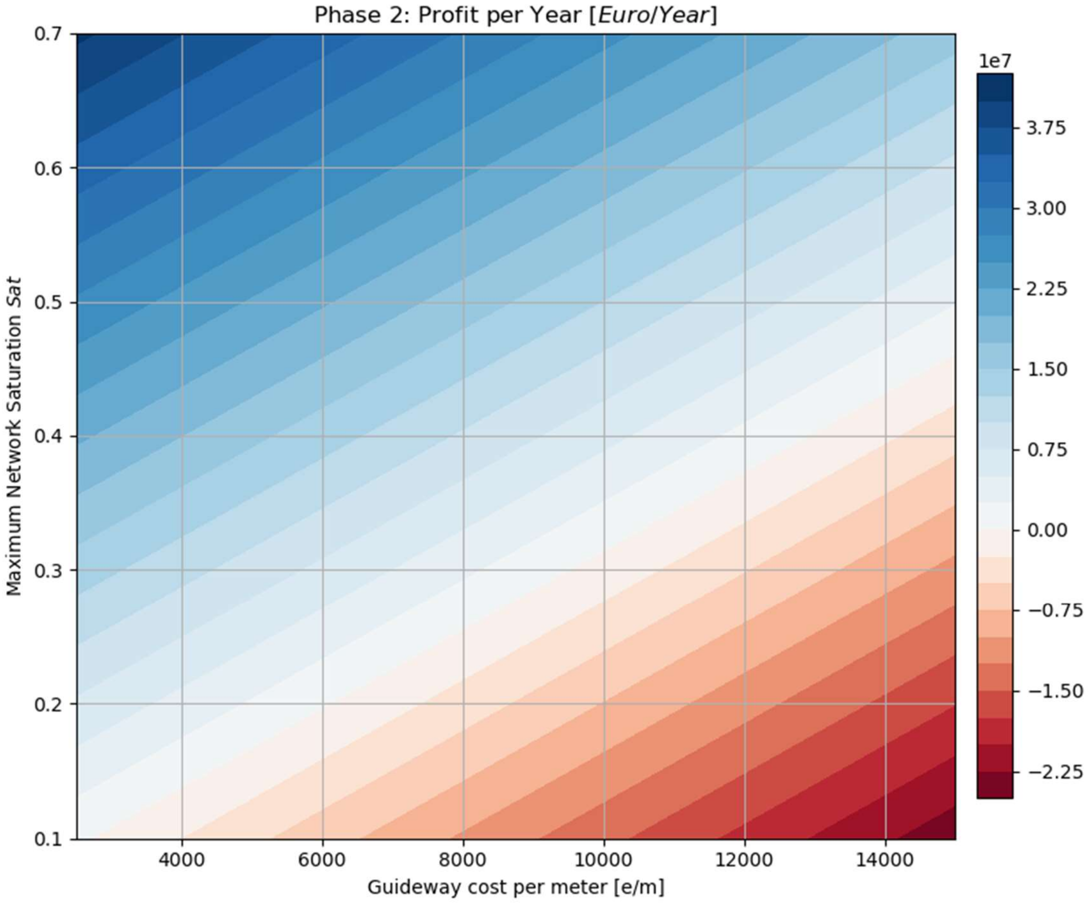

Figure 10: Plot showing the profit in 10^7 Euros (tens of millions of Euros) for a year of operation. The maximum network saturation in the y-axis, the guideway cost per meter in the x-axis, the profits are shown in with a red (loss) and blue (profit) colormap.

Also, in this case it is interesting to observe the behaviour of profitability when changing the cost of the guideway. In Figure 10 we can look at the results of profit per vehicle trip; if the guideway will cost 5000 €/m we require a saturation of 0.16 to reach profitability, while in the case of guideway cost three times higher, 15000 €/m, we require a minimum saturation of 0.46. As for phase 1 the system looks very promising, which could be expected as it is quite a proportionate scaling with respect to the first phase while the average trip length does not increase as the shape of the network is basically the same, only adding some station around the existing network without stretching the overall shape of the network.

My conclusions on the second phase analysis are very positive, the investment is expected to give back great profits to operator and city, plus the system would prove profitable even in case of cost exceedance by a factor of 3 or in case of slow response from the users in mode shifting, all analogue to phase 1.

Finally, the simulation finds that 12184 trips are performed while the comparison value is 27277 trips in one hours, so the hypothesis of the analysis is confirmed. The share of PRT estimated for this phase would be of 8.62%, covering just less than half of the precedent car demand.

Analysis on the Third Phase alone

On this analysis the following assumptions are used:

- t_{am}, the mortgage time, is considered the same for every element in this analysis. equal to the useful life of the element when proper maintenance, both ordinary and extra-ordinary, is done on the element. For $t_{am,veh}$, the mortgage time of the vehicles, I assumed a time of 25 $[years]$. For $t_{am,station}$, the mortgage time of the stations, I assumed a time of 25 $[years]$. For $t_{am,guide}$, the mortgage time of the guideway, I assumed a time of 40 $[years]$.
- r, the fixed interest rate for the mortgage, is taken equal to the Internal Rate of Return of present year (2024) corporate bonds expiring in more than 15 years from the current year; $r = 0.04$ can be assumed as a realistic average value.
- a_{emerge}, the emergency deceleration value, is considered equal to 0.5 $[m/s]$, under the hypothesis that seatbelts are mandatory on the vehicle.

Vehicle, guideway, and station parameters	
$V_{line}\ [m/s]$	11.11 (=40 km/h)
$a_e\ [m/s^2]$	5.00
$t_{react}\ [s]$	0.50
N_{places}	6.00
$L_{veh}\ [m]$	3.00
$V_{comm}\ [m/s]$	6.94 (=25 km/h)
$Occup_{veh}$	1.30
$Share_{empty}$	0.30
Sat	0.6
N_{stat}	46
$L_{guide}\ [m]$	59885

Demand characteristics parameters

$N_{days,yr}$	350, conservatively accounts for lost days due to maintenance
$L_{trip,av}$ $[m]$	4000
$Share_{peak}$	0.25 (=6/24)
$Share_{off}$	0.42 (=10/24)
$Ratio_{off}$	0.60

Financial parameters	
$Cost_{cap,guide,m}$ $[€/m]$	5000
$Cost_{cap,stat}$ $[€]$	750000
$Cost_{cap,veh}$ $[€]$	50000
$Cost_{om,pax,km}$ $[€/km]$	0.19
$t_{am,guide}$ $[years]$	40
$t_{am,stat}[years]$	25
$t_{am,veh}[years]$	25
r	0.04
$Price_{ticket}$ $[€]$	1.50

Table 4: Input System, Demand, and Financial parameters for analysis of profitability of Phase III alone

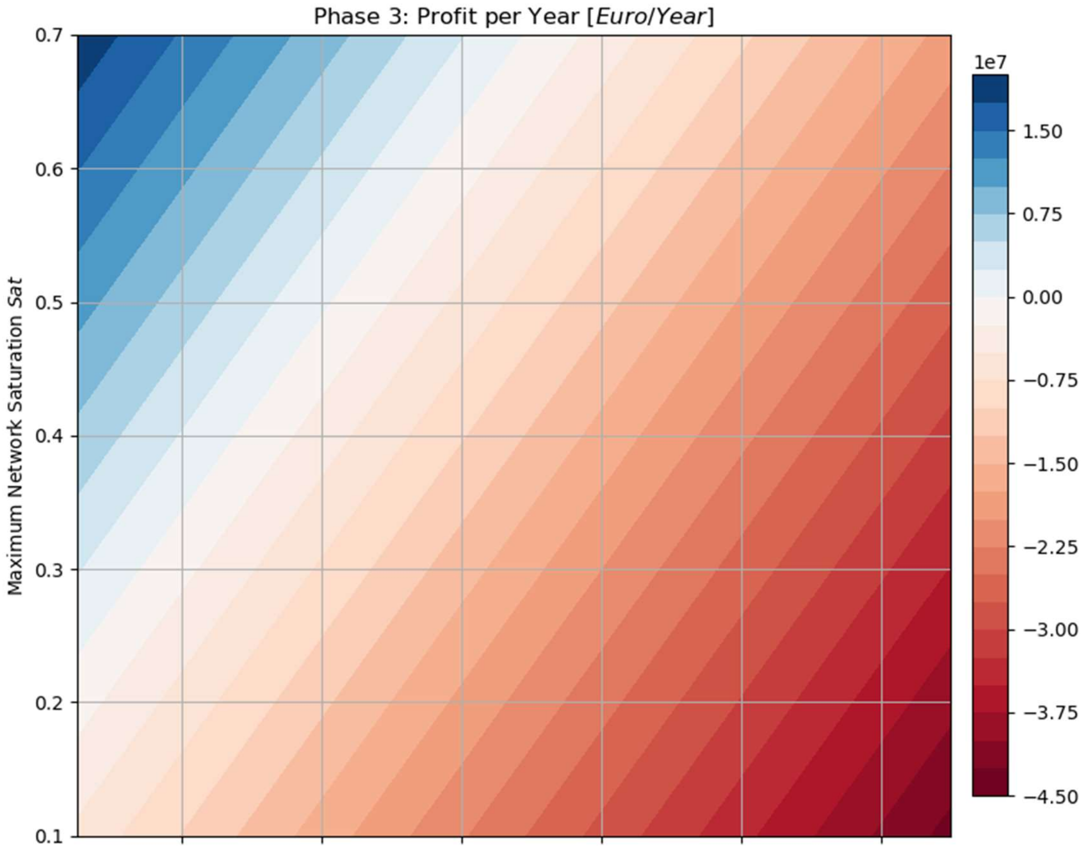

Figure 11: Plot showing the profit in 10^7 Euros (tens of millions of Euros) for a year of operation. The maximum network saturation in the y-axis, the guideway cost per meter in the x-axis, the profits are shown in with a red (loss) and blue (profit) colormap.

Also in this case it is interesting to observe the behaviour of profitability when changing the cost of the guideway. In Figure 11 we can look at the results of profit per vehicle trip and immediately see a very different behaviour with respect to phase 1 and 2. If the guideway costs 5000 €/m we require a saturation of 0.42 to reach profitability, more than 2 times higher compared to precedent phases. While in the case of guideway costs being three times higher, 15000 €/m, we cannot reach profitability for values of saturation below 0.7. For saturation 0.6, the maximum I would recommend, the maximum guideway cost we can sustain is 7500 €/m, only 50% uncertainty whit respect to the average value of 5000 €/m. The system in this condition is much less economically sustainable and uncertainties play a greater and more dangerous role. This could be due to the increased average trip length caused by the major change in shape of the network now that it has been stretched along the east-west direction.

My conclusions on the third phase analysis are sceptic, the investment is expected to give back profits to operator and city only if the costs we expect are matched by real conditions and the demand proves quite high right from the opening of the system.

Finally the simulation finds that only 11732 trips are performed in one rush hour, less than phase 2. This means that the great increase in average trip length was significantly higher than the increase of number of vehicles. Even if the system now covers a larger area, therefore providing a better service, it also serves less users per hour, which in my opinion is a failure given the objective of helping to substitute the car traffic after the superblock application. The comparison value is 43267 trips in one hours, so the hypothesis of the analysis is confirmed. The share of PRT estimated for this phase would be of 5.23%, covering less than a third of the precedent car demand.

Analysis on the whole construction process

Now that each phase has been studied, we have gathered important data to proceed with the main core of this chapter: studying the whole process keeping phase interfaces into account. No civil engineering process can be understood without unravelling all steps that cooperate to its completion, so I consider fundamental to introduce in this problem the variable of time. For the scope of this thesis, I will take some simplification hypothesis; the first is simple and meant to facilitate calculations with minor changes of the results: all mortgage times are changed to 36 years. The value was calibrated so that on the first phase of construction the overall yearly fixed payment would remain substantially unchanged, and as expected the value is very close to 40 years, the mortgage time related to the guideway because it is so relevant in the total capital expenses. The second hypothesis is much stronger and is adequate only in the context of a preliminary analysis to assess the weakest joints in the project unravelling: all phases are assumed to be built instantly, so that the revenues start in conjunction with the payment of the mortgage. Each phase is let producing profits, or losses, for 5 years and the successive phase will bear the consequences of these years of functioning, positive or negative.

Methodology differences

To achieve these results the methodology was slightly changed to take the precedent phase performance, follows a description of the parts interested by the adjustments.

In the original methodology the capital costs per year were calculated singularly for each cost item in the following manner:

Yearly Cost of one Vehicle, net of Operation and Maintenance, in $[€/year]$*:*

$$Cost_{cap,veh,yr} = Cost_{place} N_{places,veh} \frac{r}{1-(1+r)^{-t_{am,ve}}}$$

Where:

- $Cost_{place}$ $[€]$ is the capital cost of a single vehicle seat/place
- $N_{places,veh}$ is the vehicle passenger capacity
- r is the interest rate of borrowed capital
- $t_{am,veh}$ $[year]$ is the amortization time for vehicle capital investment

Yearly cost of one Station, in $[€/year]$*:*

$$Cost_{cap,stat,yr} = Cost_{cap,stat} \frac{r}{1-(1+r)^{-t_{am,stat}}}$$

Where:

- $Cost_{cap,stat}$ $[€]$ is the capital cost of a single station
- r is the interest rate of borrowed capital

- $t_{am,stat}\ [year]$	is the amortization time for station capital investment

Yearly cost of one meter of Guideway, in $[€/(m\ year)]$*:*

$$Cost_{cap,guide,m,yr} = Cost_{cap,guide,m} \frac{r}{1-(1+r)^{-t_{am,guide}}}$$

Where:

- $Cost_{cap,guide,m}\ [€/m]$	is the capital cost of a meter of guideway
- r	is the interest rate of borrowed capital
- $t_{am,guide}\ [year]$	is the amortization time for guideway capital investment

While now the *capital investments* are grouped inside a single cost item, in [€]:

$$Cost_{cap,sys} = \left(L_{guide}\ Cost_{cap,guide,m} + N_{stat}\ Cost_{cap,stat} + N_{veh}\ Cost_{place}\ N_{places,veh}\right)$$

Where:

- $L_{guide}\ [m]$	is the length of the guideway
- $Cost_{cap,guide,m}[€]$	is the capital cost of a meter of guideway
- N_{stat}	is the number of stations
- $Cost_{cap,stat}\ [€]$	is the capital cost of a station
- N_{veh}	is the number of vehicles
- $Cost_{place\ [€]}$	is the cost of a single passenger place in a vehicle
- $N_{places,veh}$	is the number of passenger places in a vehicle

Then a new input is added, the *profit or loss, matured over the last phase life, in* $[€]$:

$$Profit_{last\ phase}$$

Finally, the *fixed yearly payment* is calculated as follows*, in* $[€/year]$*:*

$$Cost_{cap,sys,yr} = \left(Cost_{cap,sys} - Profit_{last\ phase}\right)\frac{r}{1-(1+r)^{-t_{am}}}$$

Where:

- $Cost_{cap,sys}$ [€]	is the overall capital cost of the system, net of interests
- $Profit_{last\ phase}$ [€]	is the overall profit matured over the last phase's life
- r	is the interest rate of borrowing
- t_{am} $[years]$	is the mortgage time

The *cost per vehicle trip* is calculated as, in [€]*:*

$$Cost_{trip,veh} = \frac{Cost_{cap,sys,yr} + \left(Cost_{om,veh,km}\frac{L_{trip,av}}{1000}\ N_{trips,ve\ \ ,yr}\right)}{N_{trips,veh,yr}} = \left[\frac{€}{trip}\right]$$

Where:

- $Cost_{cap,sys,yr}$ $[€/year]$	is the fixed yearly payment of the whole network
- $Cost_{om,veh,km}$ $[€/km]$	is the operation and maintenance cost per kilometre
- $L_{trip,av}$ $[m]$	is the average trip length
- $N_{trips,veh,yr}$	is the number of yearly vehicle trips

1) First phase

Vehicle, guideway, and station parameters	
V_{line} $[m/s]$	11.11 (=40 km/h)
a_e $[m/s^2]$	5.00
t_{react} $[s]$	0.50
N_{places}	6.00
L_{veh} $[m]$	3.00
V_{comm} $[m/s]$	6.94 (=25 km/h)
$Occup_{veh}$	1.30
$Share_{empty}$	0.30
Sat	0.6
N_{stat}	20
L_{guide} $[m]$	24376

Demand characteristics parameters	
$N_{days,yr}$	350, conservatively accounts for lost days due to maintenance
$L_{trip,av}\ [m]$	2500
$Share_{peak}$	0.25 (=6/24)
$Share_{off}$	0.42 (=10/24)
$Ratio_{off}$	0.60

Financial parameters	
$Cost_{cap,guide,m}\ [€/m]$	5000
$Cost_{cap,stat}\ [€]$	750000
$Cost_{cap,veh}\ [€]$	50000
$Cost_{om,pax,km}\ [€/km]$	0.19
$t_{am}\ [years]$	36
r	0.04
$Price_{ticket}\ [€]$	1.50
$Profit_{last\ phase}\ [mln\ €]$	N/A

Table 5: Input System, Demand, and Financial parameters for analysis of profitability of Phase I for the study of phases interfacing.

Phase I Results	
$Daily\ Trips\ [trips/day]$	76412
$Number\ of\ Staions$	20
$Guideway\ Lenght\ [m]$	24376
$Vehicles\ circulating$	700
$Time\ Headway\ Required\ [s]$	1.88
$Capital\ Cost - Only\ Phase\ I\ [€]$	171867406
$Capital\ Cost - with\ last\ phase\ profits\ [€]$	171867406
$Capital\ Cost\ per\ kilometre\ [€/km]$	7070681
$Revenue\ per\ vehicle\ trip\ [€]$	1.95 (=1.5 x 1.3)
$Cost\ per\ vehicle\ trip\ [€]$	1.06
$Yearly\ Revenue\ [mln€/year]$	40.12
$Yearly\ Capital\ Cost - interest\ [mln€/year]$	9.09
$Yearly\ Operation\ Cost\ [mln€/year]$	12.71
$Yearly\ Profit\ [mln€/year]$	18.32

Table 6: Results of Phase I for the study of phases interfacing

This first evaluation is totally equivalent to the one at page 53. The system is able to produce 18.3 million Euros each year, if let work for 5 years that would correspond to 91.6 million Euros to invest in the next phase of construction.

2) Second phase

Vehicle, guideway, and station parameters	
$V_{line}\ [m/s]$	11.11 (=40 km/h)
$a_e\ [m/s^2]$	5.00
$t_{react}\ [s]$	0.50
N_{places}	6.00
$L_{veh}\ [m]$	3.00
$V_{comm}\ [m/s]$	6.94 (=25 km/h)
$Occup_{veh}$	1.30
$Share_{empty}$	0.30
Sat	0.6
N_{stat}	29
$L_{guide}\ [m]$	38869

Demand characteristics parameters	
$N_{days,yr}$	350, conservatively accounts for lost days due to maintenance
$L_{trip,av}\ [m]$	2500
$Share_{peak}$	0.25 (=6/24)
$Share_{off}$	0.42 (=10/24)
$Ratio_{off}$	0.60

Financial parameters	
$Cost_{cap,guide,m}\ [€/m]$	5000
$Cost_{cap,stat}\ [€]$	750000
$Cost_{cap,veh}\ [€]$	50000
$Cost_{om,pax,km}\ [€/km]$	0.19
$t_{am}\ [years]$	36
r	0.04
$Price_{ticket}\ [€]$	1.50
$Profit_{last\ phase}\ [mln\ €]$	91.62

Table 7: Input System, Demand, and Financial parameters for analysis of profitability of Phase II for the study of phases interfacing.

Phase II Results	
$Daily\ Trips\ [trips/day]$	121844
$Number\ of\ Staions$	29
$Guideway\ Lenght\ [m]$	38869
$Vehicles\ circulating$	1116
$Time\ Headway\ Required\ [s]$	1.88
$Capital\ Cost - Only\ Phase\ II\ [€]$	100002121
$Capital\ Cost - with\ last\ phase\ profits\ [€]$	180269527
$Capital\ Cost\ per\ kilometre\ [€/km]$	4637874
$Revenue\ per\ vehicle\ trip\ [€]$	1.95 (=1.5 x 1.3)
$Cost\ per\ vehicle\ trip\ [€]$	1.06
$Yearly\ Revenue\ [mln€/year]$	63.97
$Yearly\ Capital\ Cost - interest\ [mln€/year]$	9.53
$Yearly\ Operation\ Cost\ [mln€/year]$	20.26
$Yearly\ Profit\ [mln€/year]$	34.18

Table 8: Results of Phase II for the study of phases interfacing

Now we can appreciate the main differences with the analysis performed with the different phases considered as standalones. The first phase is very profitable and letting it produce capital can help in two different directions: lowering the net cost of the next investment phase, appreciable in the yearly cost increase of only 0.5 million Euros equivalent to a 4.89% increase, while we added 59.4% more vehicles, 59.5% more guideway and 45.0% more stations; on the other hand the planners are able to adapt changes while the system is running, increasing the reliability of the project as a whole, though this factor was not discounted in my calculations.

The system can produce 34.18 million Euros each year, if let work for 5 years that would correspond to 170.89 million Euros to invest in the next phase of construction.

3) *Third phase*

Vehicle, guideway, and station parameters	
$V_{line}\ [m/s]$	11.11 (=40 km/h)
$a_e\ [m/s^2]$	5.00
$t_{react}\ [s]$	0.50
N_{places}	6.00
$L_{veh}\ [m]$	3.00
$V_{comm}\ [m/s]$	6.94 (=25 km/h)

$Occup_{veh}$	1.30
$Share_{empty}$	0.30
Sat	0.6
N_{stat}	46
$L_{guide}\ [m]$	59885

Demand characteristics parameters	
$N_{days,yr}$	350, conservatively accounts for lost days due to maintenance
$L_{trip,av}\ [m]$	4000
$Share_{peak}$	0.25 (=6/24)
$Share_{off}$	0.42 (=10/24)
$Ratio_{off}$	0.60

Financial parameters	
$Cost_{cap,guide,m}\ [€/m]$	5000
$Cost_{cap,stat}\ [€]$	750000
$Cost_{cap,veh}\ [€]$	50000
$Cost_{om,pax,km}\ [€/km]$	0.19
$t_{am}\ [years]$	36
r	0.04
$Price_{ticket}\ [€]$	1.50
$Profit_{last\ phase}\ [mln\ €]$	170.89

Table 9: Input System, Demand, and Financial parameters for analysis of profitability of Phase III for the study of phases interfacing.

Phase III Results	
$Daily\ Trips\ [trips/day]$	117327
$Number\ of\ Staions$	46
$Guideway\ Lenght\ [m]$	59885
$Vehicles\ circulating$	1719
$Time\ Headway\ Required\ [s]$	1.88
$Capital\ Cost - only\ Phase\ III [€]$	148013525
$Capital\ Cost - with\ last\ phase\ profits\ [€]$	248994252
$Overall\ Capital\ Cost\ per\ kilometre\ [€/km]$	4157873
$Revenue\ per\ vehicle\ trip\ [€]$	1.95 (=1.5 x 1.3)
$Cost\ per\ vehicle\ trip\ [€]$	1.40

$Yearly\ Revenue\ [mln€/year]$	63.97
$Yearly\ Capital\ Cost - interest\ [mln€/year]$	9.53
$Yearly\ Operation\ Cost\ [mln€/year]$	20.26
$Yearly\ Profit\ [mln€/year]$	34.18

Table 10: Results of Phase III for the study of phases interfacing

In the analysis shown at page 63 we saw how the third phase was critical if created immediately. It both had low margin for guideway construction costs and for system usage, meaning that if only one of the two where to be heavily different from expectations the project would probably run onto severe losses. On that considerations I would feel very sceptical on building this phase of the network, but the scope of this PRT system is to also support the superblock structure of the city so it is important to make it capillary. The solution to the financial problem could lie in the phasing itself. As we can see in Table 10 the system in this phase is perfectly able to produce positive cash flows due to the existing profit raised in the past decade. The yearly fixed costs see an increase of 38.12% with respect to phase 2, while 54.03% vehicles, 54.07% more guideway and 58.62% more stations were added to the system and considering that the average trip length was considered 60.00% higher compared to phase 2. This means that the system could be profitable in this scenario. Though the problem of reduced overall capacity caused by the average trip time increase remains and cannot be ignored, it would be a great challenge to face as a planner to find solutions both on the technological, circulation and operation sides.

4 Conclusions

In this thesis, I illustrate the fundamental relationship between network saturation and the profitability of Personal Rapid Transit (PRT) systems. Through multivariable sensitivity analyses, I explore critical components of transport systems: infrastructure costs, maximum emergency deceleration rates, and average trip lengths.

Initially, I examine the cost of infrastructure, which serves as a representative for the correlation between costs and civil works. The analysis reveals that PRT systems exhibit considerable resilience when confronted with escalating civil works costs. For instance, with a saturation level of 0.5, the system can accommodate cost increases of up to 2.6 times the average expected cost of €5000/m, as depicted in Figure 1.

Secondly, I investigate the significant influence of maximum emergency deceleration on system profitability, which is intricately linked to circulation features and vehicle technology, particularly in relation to minimum time headways and maximum vehicle density within the network. Existing literature already underscores the importance of minimum time headways for PRT system performance, and my research confirms that deceleration rates in the range of 0.2-0.3 G can suffice for profitability in many average cases. However, minimum values of 0.5 G significantly enhance the likelihood of positive cash flows, especially in scenarios of slow public acceptance i.e. with initial low network saturation. It is important to note that decelerations of 0.5 G, while beneficial for profitability, still result in time headways exceeding 1 second which strongly limits, from a capacity perspective, the system's ability to attract a significant share of private car users. From the results obtained and the literature reviewed I feel confident in suggesting deceleration values of at least 1 G.

In conclusion, the sensitivity analysis conducted on average trip length reveals that under the specified parameters, the system maintains positive cash flows until trip lengths reach approximately 4000-4500 meters. This finding stands out as particularly intriguing, shedding new light on the expandability and modularity of PRT systems. The dimensions and layout of a PRT network, along with demand characteristics, distinctly shape average trip length, resulting in significant variations across different applications, even when seemingly similar. As depicted in Figure 2, the break-even curve exhibits a super-linear growth pattern with increasing average trip length. This phenomenon imposes a substantial constraint on the expandability of PRT networks. While technological advancements can optimize vehicle management and reduce headways to a certain extent, the potential for network extension remains limitless. This behaviour of the break-even curve raises questions about the existence of a hard cap on network size, potentially restricting applications primarily to medium-large urban environments and impeding large-scale territorial interconnections between distant areas. It's important to note that while increasing fares for longer travels may address profitability concerns, it fails to resolve the underlying issue of reduced system capacity, a key objective of PRT systems in mitigating urban car traffic. While these results serve as preliminary indications rather than conclusive evidence, they serve as a catalyst for further research aimed at accurately defining the extension limit of PRT networks in relation to network shape and achievable average minimum time headway. In my view, the logical progression involves replicating the analysis on High Capacity PRT (HCPRT) systems equipped with platooning technology and specialized passenger group operations for extended trips. For instance, permitting trips exceeding 7000-8000 meters exclusively for passenger groups of at least three individuals could offset the reduced number of trips a vehicle can perform, thereby optimizing system efficiency and performance.

To conclude my analysis, I would like to address observations from the Bologna case study. Here, we find substantiation of my concerns regarding the scalability of PRT networks, particularly evident in the disappointing outcomes observed during Phase III construction. This holds true for both instances: single instance construction and deferred building processes with phase interface analysis.

In the former scenario, the system displayed insufficient resilience to unforeseen construction complications or inaccuracies in estimating demand parameters. Such shortcomings are too significant to justify the construction of a very innovative system with little prior validation. Conversely, in the latter scenario, the system did yield positive profits, thanks in part to mortgage costs being offset by past cash flows. However, profitability values witnessed a sharp decline alongside transport capacity with respect to Phase II, indicating an overall failure to meet initial objectives, albeit retaining economic viability.

In contrast, the analysis of Phases I and II presents a more promising outlook. Both phases demonstrated favourable results during sensitivity analysis and exhibited exceptional profits during the construction phases. In Phase I, the success can be attributed to a compact network with short average trip lengths, ideal for attracting a significant user base in a densely populated urban environment. Phase II saw an expansion primarily in a circular shape around the initial corridor, facilitating an increase in overall network traffic without a proportional increase in average trip length.

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6 Appendix

6.1 Python implementation for sensitivity analyses

```
from pylab import *
from sys import exit

import capa_20240207 as capa
import plotter
import matplotlib.pyplot as plt
import numpy as np


def get_cost_per_year(c,t_am,r_dis):
  """Calculates cost  per year of an item based on
  c = invested capital of item
  t_am = ammortization time of respective item
  r_dis = discount rate (interrest for borrowing money)
  """
  return c*r_dis/(1-((1+r_dis)**-t_am))


def
get_cost_trip(n_tpa=0,len_trip_av=0.0,cost_veh_pa=0.0,n_pax=6,n_veh=0,cost_
guidew_pa=0.0,len_guidew=0.0,cost_station_pa=0.0,n_station=0,cost_inter_pa=
0.0,n_inter=0,cost_om_pkm_pa=0.0):
  return ( cost_veh_pa*n_veh \
           +cost_guidew_pa*len_guidew\
       +cost_station_pa*n_station\
       +cost_inter_pa*n_inter\
       +cost_om_pkm_pa/1000.0*n_tpa*len_trip_av)/n_tpa


def
get_cost_vehtrip_test(n_vtpa=0,len_trip_av=0.0,cost_veh_pa=0.0,n_pax=6,n_ve
h=0,cost_guidew_pa=0.0,len_guidew=0.0,cost_station_pa=0.0,n_station=0,cost_
inter_pa=0.0,n_inter=0,cost_vom_pkm_pa=0.0):
  print '\n\n----------------------------------------'
  print 'get_cost_vehtrip_test with n_vtpa=',n_vtpa
  print 'n_veh=',n_veh
  print 'cost_veh_pa*n_veh/n_vtpa=',cost_veh_pa*n_veh/n_vtpa
  #print 'len_guidew=',len_guidew
  print
'cost_guidew_pa*len_guidew/n_vtpa=',cost_guidew_pa*len_guidew/n_vtpa
  print
'cost_station_pa*n_station/n_vtpa=',cost_station_pa*n_station/n_vtpa
  #print 'len_trip_av=',len_trip_av
  #print 'cost_vom_pkm_pa=',cost_vom_pkm_pa
  print
'cost_vom_pkm_pa/1000.0*n_vtpa*len_trip_av/n_vtpa=',cost_vom_pkm_pa/1000.0*
n_vtpa*len_trip_av/n_vtpa
  print '\n'
  return ( cost_veh_pa*n_veh \
           +cost_guidew_pa*len_guidew\
       +cost_station_pa*n_station\
       +cost_inter_pa*n_inter\
       +cost_vom_pkm_pa/1000.0*n_vtpa*len_trip_av)/n_vtpa
```

```
NN=20
x_var = np.linspace(1500, 6000, num=NN)
y_var = np.linspace(0.1, 0.7, num=NN)
z_var = np.zeros((NN, NN), dtype=float)

ky=0

for sat_max_pat in y_var: #start loop for y variable

    kx=0

    for len_trip_av in x_var: #start loop for x variable

        # downwriting times in years
        t_am_inf=40.0       # in years
        t_am_station=25.0   # in years
        t_am_veh=25.0       # in years
        r_inter=0.04        # discount rate [AATS05]
        dpa=350             # days per year
        price_ind = 1.5 # ticket price of individual ticket
        price_group = 1.0 # ticket price of group ticket
        price_freight=2.0 # ticket price of freight movement


###########################################################################
###
        if True: #__name__ == '__main__':

###########################################################################
###
          a_emerge=5.0          # maximum emergency brake deceleration in
m/s^2
          t_emerge=0.5          # emergency brake actuation time in s
          v_line=40/3.6         # average line speed in m/s

            ###[ITERATE]###len_trip_av=2500.0 # average trip length in m
          c_empties_pat=0.3# coefficient of empty vehicles

          c_veh_full=1.0-c_empties_pat           # fraction of full
vehicles

          print
'\n########################################################'
          print 'PAT with 6 passenger vehicles\n'

          n_pax_pat=6       # number places of places to sit/stand
          len_veh_pat= 3.0  # vehicle length in m
          v_com_pat=25.0/3.6    # commercial speed in m/s
            ###[ITERATE]###sat_max_pat = 0.5 # maximum allowed network
saturation
          occup_indiv_pat=1.3/n_pax_pat # occupation rate of individually
controlled vehicles
          r_indiv_pat=1.0       # 100% individual vehicles, no trains

          # not influential here, no trains
          occup_train_pat=-1.0       # occupation rate of vehicles in train
formation
          n_chain_pat=-1.0           # number of vehicles chained together
in a train
```

```
          len_square_pat= 1000        # grid length of PAT network,in m
                                      # gives also average distance between
stations
          #system costs
          cost_pax_cap_pat=50000.0/n_pax_pat # capital cost per place in
EUR [ULTra ATRA]
          cost_pax_om_pkm_pat=0.19  # operating and maintenance 0.17EUR/km
with 70000km/a [WSP]

cost_veh_om_pkm_pat=cost_pax_om_pkm_pat*(occup_indiv_pat*n_pax_pat)

          cost_guidew_cap_pat=5000.0      # >track per meter in EUR
[AATS05]
          cost_station_cap_pat=0.75*10**6  # >costs per station

          # specific demand characteristics
          n_trip_pd_pat=25000    # number of trips per day
          c_trips_peak_day_pat=0.1  # ratio trips during one peak hour and
trips per day

          # demand distribution
          tau_peak_pat=6.0/24.0;beta_peak_pat=1;
          tau_off_pat=10.0/24.0;beta_off_pat=0.6;


          print 'n_trip_pd_pat=',n_trip_pd_pat,'\n'

          # capacity calcs at line speed

capa_veh_pat=capa.capa_mix_veh(r_indiv_pat,n_chain_pat,len_veh_pat,v_line,t
_emerge,a_emerge)

capa_pax_pat=capa.capa_mix_pax(n_pax_pat,occup_indiv_pat,occup_train_pat,r_
indiv_pat,n_chain_pat,len_veh_pat,v_line,t_emerge,a_emerge)
          print 'capa_veh_pat=',capa_veh_pat*3600,'veh/h
at',v_line*3.6,'km/h'
          print 'capa_pax_pat=',capa_pax_pat*3600,'pax/h
at',v_line*3.6,'km/h'
          #n_pax_ind=n_pax_pat*occup_indiv_pat
          t_trip_av_pat=len_trip_av/v_com_pat   # average trip time in s

          n_trips_pa_pat=dpa*n_trip_pd_pat      # number of trips per year
          n_vehtrips_pd_pat=n_trip_pd_pat/(n_pax_pat*occup_indiv_pat)
          n_vehtrips_pa_pat= dpa*n_vehtrips_pd_pat

          n_trips_peak_pat=c_trips_peak_day_pat*n_trip_pd_pat # trips per
hour during pear time
          t_headway_pat=1/capa_veh_pat
          n_veh_pat=c_trips_peak_day_pat*n_vehtrips_pd_pat/3600.0/(1-
c_empties_pat)*t_trip_av_pat

          #print 'check
n_veh_pat=',n_trips_peak_pat/3600.0/(n_pax_pat*occup_indiv_pat*c_veh_full)*
t_trip_av_pat
          print 'n_veh_pat=',n_veh_pat

          print 't_headway_pat=', t_headway_pat
          len_guidew_pat=t_headway_pat/sat_max_pat*n_veh_pat*v_line
          #len_guidew_pat=30942.0 #10000.0# assumption fixed track length
in m
          n_station_pat=len_guidew_pat/len_square_pat
```

```
     print 't_trip_av_pat=',t_trip_av_pat
     print 'len_guidew_pat=',len_guidew_pat
     print 'n_station_pat=',n_station_pat
     print 'n_veh_pat=',n_veh_pat
     print 'n_trips_peak_pat=',n_trips_peak_pat
     print '=',


cost_pat_cap_pkm=1000.0/len_guidew_pat*(cost_guidew_cap_pat*len_guidew_pat+
n_station_pat*cost_station_cap_pat+n_veh_pat*cost_pax_cap_pat*n_pax_pat)
     # = approx 7MEUR/km OK with WSP estimategamma_veh
     print '\ncost_pat_cap_pkm=',cost_pat_cap_pkm,'\n'

     cost_veh_pa_pat=
get_cost_per_year(cost_pax_cap_pat*n_pax_pat,t_am_veh,r_inter)

cost_guidew_pa_pat=get_cost_per_year(cost_guidew_cap_pat,t_am_inf,r_inter)

cost_station_pa_pat=get_cost_per_year(cost_station_cap_pat,t_am_station,r_i
nter)

#cost_inter_pa_pat=get_cost_per_year(cost_inter_cap_pat,t_am_inf,r_inter)


costs_inf_pa_pat=cost_guidew_pa_pat*len_guidew_pat+cost_station_pa_pat*n_st
ation_pat
     print 'costs_inf_pa_pat per
km=',1000.0*costs_inf_pa_pat/len_guidew_pat
     #print '=',
     #print '=',
     costs_cap_pa_pat=costs_inf_pa_pat+cost_veh_pa_pat*n_veh_pat
     print 'costs_cap_pa_pat=',costs_cap_pa_pat

     cost_vehtrip_pat=get_cost_vehtrip_test(\
      n_vtpa=n_vehtrips_pa_pat,\
      len_trip_av=len_trip_av,\
      cost_veh_pa=cost_veh_pa_pat,\
      n_pax=n_pax_pat,\
      n_veh=n_veh_pat,\
      cost_guidew_pa=cost_guidew_pa_pat,\
      len_guidew=len_guidew_pat,\
      cost_station_pa=cost_station_pa_pat,\
      n_station=n_station_pat,\
      cost_inter_pa=0.0,\
      n_inter=0,\
      cost_vom_pkm_pa=cost_veh_om_pkm_pat)


     print '\n\ncost_vehtrip_pat=',cost_vehtrip_pat,'EUR/trip'
     #print
'cost_pkm_pat=',cost_trip_pat/(len_trip_av/1000.0),'EUR/km'

     profit_vehtrip_pat = (n_pax_pat*occup_indiv_pat *price_ind)-
cost_vehtrip_pat #the profit made on each vehicle trip

     return_pa_pat= n_vehtrips_pa_pat*n_pax_pat*occup_indiv_pat
*price_ind #Assumes the price is per passenger
     #return_pa_pat = n_vehtrips_pa_pat*price_ind #Assuming the price
is per vehicle
     print 'return_pat=',return_pa_pat,'EUR/a'
```

```
          profit_pa_pat=return_pa_pat-cost_vehtrip_pat*n_vehtrips_pa_pat
          print 'profit_pa_pat=',profit_pa_pat,'EUR/a'

          z_var[ky, kx] = profit_pa_pat #Insert here the variable to
colormap.

          kx = kx + 1

    ky = ky + 1

plotter.plot_cashflow('Yearly Profit [$Euro/year$]', x_var, y_var, z_var,
ylabel='Maximum Network Saturation $Sat$', xlabel='Average trip lenght
[$m$]') #create the plot
plt.show()
```

6.2 Python implementation for Bologna case study sensitivity analysis

```
from pylab import *
from sys import exit

import capa_20240207 as capa
import plotter
import matplotlib.pyplot as plt
import numpy as np



def get_cost_per_year(c,t_am,r_dis):
  """Calculates cost  per year of an item based on
  c = invested capital of item
  t_am = ammortization time of respective item
  r_dis = discount rate (interrest for borrowing money)
  """

  return c*r_dis/(1-((1+r_dis)**-t_am))


def
get_cost_trip(n_tpa=0,len_trip_av=0.0,cost_veh_pa=0.0,n_pax=6,n_veh=0,cost_
guidew_pa=0.0,len_guidew=0.0,cost_station_pa=0.0,n_station=0,cost_inter_pa=
0.0,n_inter=0,cost_om_pkm_pa=0.0):
  return ( cost_veh_pa*n_veh \
           +cost_guidew_pa*len_guidew\
       +cost_station_pa*n_station\
       +cost_inter_pa*n_inter\
       +cost_om_pkm_pa/1000.0*n_tpa*len_trip_av)/n_tpa


def
get_cost_vehtrip_test(n_vtpa=0,len_trip_av=0.0,cost_veh_pa=0.0,n_pax=6,n_ve
h=0,cost_guidew_pa=0.0,len_guidew=0.0,cost_station_pa=0.0,n_station=0,cost_
inter_pa=0.0,n_inter=0,cost_vom_pkm_pa=0.0):
  print '\n\n----------------------------------------'
  print 'get_cost_vehtrip_test with n_vtpa=',n_vtpa
```

```
  print 'n_veh=',n_veh
  print 'cost_veh_pa*n_veh/n_vtpa=',cost_veh_pa*n_veh/n_vtpa
  #print 'len_guidew=',len_guidew
  print
'cost_guidew_pa*len_guidew/n_vtpa=',cost_guidew_pa*len_guidew/n_vtpa
  print
'cost_station_pa*n_station/n_vtpa=',cost_station_pa*n_station/n_vtpa
  #print 'len_trip_av=',len_trip_av
  #print 'cost_vom_pkm_pa=',cost_vom_pkm_pa
  print
'cost_vom_pkm_pa/1000.0*n_vtpa*len_trip_av/n_vtpa=',cost_vom_pkm_pa/1000.0*
n_vtpa*len_trip_av/n_vtpa
  print '\n'
  return ( cost_veh_pa*n_veh \
           +cost_guidew_pa*len_guidew\
       +cost_station_pa*n_station\
       +cost_inter_pa*n_inter\
       +cost_vom_pkm_pa/1000.0*n_vtpa*len_trip_av)/n_vtpa


NN=20           ###To run a single scenario NN=2 and lower bound = upper
bound for the variables: output gives 4 identical iterations and useless
plot, but it works and you do not need to chage the code
x_var = np.linspace(2500, 15000, num=NN)
y_var = np.linspace(0.1, 0.7, num=NN)
z_var = np.zeros((NN, NN), dtype=float)

ky=0

for sat_max_pat in y_var: #start loop for y variable

    kx=0

    for cost_guidew_cap_pat in x_var: #start loop for x variable

                # downwriting times in years
        t_am_inf=40.0       # in years
        t_am_station=25.0   # in years
        t_am_veh=25.0       # in years
        r_inter=0.04        # discount rate [AATS05]
        dpa=350             # days per year
        price_ind = 1.5 # ticket price of individual ticket
        price_group = 1.0 # ticket price of group ticket
        price_freight=2.0 # ticket price of freight movement


###########################################################################
###
        if True: #__name__ == '__main__':

###########################################################################
###

            len_guidew_pat=59885.0  #fixed track length in m #[BERNIERI]
            n_station_pat = 46      #fix the number of station

            a_emerge=5.0          # maximum emergency brake deceleration in
m/s^2
            t_emerge=0.5          # emergency brake actuation time in s
            v_line=40/3.6         # average line speed in m/s
```

```
            len_trip_av=4000.0 # average trip length in m
            c_empties_pat=0.3# coefficient of empty vehicles

            c_veh_full=1.0-c_empties_pat           # fraction of full
vehicles

            print
'\n############################################################'
            print 'PAT with 6 passenger vehicles\n'

            n_pax_pat=6             # number places of places to sit/stand
            len_veh_pat= 3.0        # vehicle length in m
            v_com_pat=25.0/3.6      # commercial speed in m/s
            #t_headway_pat=3        # in s....get it from capacity
                ###ITERATE###sat_max_pat = 0.6      # maximum allowed
network saturation
            occup_indiv_pat=1.3/n_pax_pat # occupation rate of individually
controlled vehicles
            r_indiv_pat=1.0         # 100% individual vehicles, no trains

            # not influential here, no trains
            occup_train_pat=-1.0       # occupation rate of vehicles in
train formation
            n_chain_pat=-1.0           # number of vehicles chained
together in a train

            #system costs
            cost_pax_cap_pat=50000.0/n_pax_pat # capital cost per place in
EUR [ULTra ATRA]
            cost_pax_om_pkm_pat=0.19  # operating and maintenance
0.17EUR/km with 70000km/a [WSP]

cost_veh_om_pkm_pat=cost_pax_om_pkm_pat*(occup_indiv_pat*n_pax_pat)

                ###[ITERATE]###cost_guidew_cap_pat=5000.0      # >track per
meter in EUR [AATS05]
            cost_station_cap_pat=0.75*10**6  # >costs per station

            # specific demand characteristics
            c_trips_peak_day_pat=0.1  # ratio trips during one peak hour
and trips per day

            # demand distribution
            tau_peak_pat=6.0/24.0;beta_peak_pat=1;
            tau_off_pat=10.0/24.0;beta_off_pat=0.6;

            # capacity calcs at line speed

capa_veh_pat=capa.capa_mix_veh(r_indiv_pat,n_chain_pat,len_veh_pat,v_line,t
_emerge,a_emerge)

capa_pax_pat=capa.capa_mix_pax(n_pax_pat,occup_indiv_pat,occup_train_pat,r_
indiv_pat,n_chain_pat,len_veh_pat,v_line,t_emerge,a_emerge)
            print 'capa_veh_pat=',capa_veh_pat*3600,'veh/h
at',v_line*3.6,'km/h'
            print 'capa_pax_pat=',capa_pax_pat*3600,'pax/h
at',v_line*3.6,'km/h'

            ##calculating the demand that can be satisfied
```

```
            t_headway_pat=1/capa_veh_pat
#time headway
            n_veh_pat=(sat_max_pat*len_guidew_pat)/(t_headway_pat*v_line)
#number of needed vehicles to match saturation
            t_trip_av_pat=len_trip_av/v_com_pat
#average trip time in s
            print 'nimber of vehicles =',n_veh_pat
            n_vehtrips_rush_1h=(3600*n_veh_pat*c_veh_full)/t_trip_av_pat
#number of vehicletrips in one rush hour
            print 'vehicletrips in 1 rush h=',n_vehtrips_rush_1h
            n_vehtrips_pd_pat=
(n_vehtrips_rush_1h*24*tau_peak_pat*beta_peak_pat)+(n_vehtrips_rush_1h*24*t
au_off_pat*beta_off_pat) #[BERNIERI] number of daily vehicle trips
            print 'vehicletrips in 1 day=',n_vehtrips_pd_pat
            n_trip_pd_pat=n_vehtrips_pd_pat*occup_indiv_pat*n_pax_pat
#number of daily trips
            print 'daily demand=',n_trip_pd_pat
            n_trips_pa_pat=dpa*n_trip_pd_pat
#number of trips per year
            n_vehtrips_pa_pat= dpa*n_vehtrips_pd_pat
#vehicletrips in one year
            print 'vehicle trips in 1 year=',n_vehtrips_pa_pat

            print 't_headway_pat=', t_headway_pat

            print 't_trip_av_pat=',t_trip_av_pat
            print 'len_guidew_pat=',len_guidew_pat
            print 'n_station_pat=',n_station_pat
            print 'n_veh_pat=',n_veh_pat
            print 'trips in one rush
hour=',n_trip_pd_pat*c_trips_peak_day_pat
            print '=',


cost_pat_cap_pkm=1000.0/len_guidew_pat*(cost_guidew_cap_pat*len_guidew_pat+
n_station_pat*cost_station_cap_pat+n_veh_pat*cost_pax_cap_pat*n_pax_pat)
            print '\ncost_pat_cap_pkm=',cost_pat_cap_pkm,'\n'

            cost_veh_pa_pat=
get_cost_per_year(cost_pax_cap_pat*n_pax_pat,t_am_veh,r_inter)

cost_guidew_pa_pat=get_cost_per_year(cost_guidew_cap_pat,t_am_inf,r_inter)

cost_station_pa_pat=get_cost_per_year(cost_station_cap_pat,t_am_station,r_i
nter)


costs_inf_pa_pat=cost_guidew_pa_pat*len_guidew_pat+cost_station_pa_pat*n_st
ation_pat
            print 'costs_inf_pa_pat per
km=',1000.0*costs_inf_pa_pat/len_guidew_pat
            #print '=',
            #print '=',
            costs_cap_pa_pat=costs_inf_pa_pat+cost_veh_pa_pat*n_veh_pat
            print 'costs_cap_pa_pat=',costs_cap_pa_pat

            cost_vehtrip_pat=get_cost_vehtrip_test(\
            n_vtpa=n_vehtrips_pa_pat,\
            len_trip_av=len_trip_av,\
            cost_veh_pa=cost_veh_pa_pat,\
            n_pax=n_pax_pat,\
```

```
            n_veh=n_veh_pat,\
            cost_guidew_pa=cost_guidew_pa_pat,\
            len_guidew=len_guidew_pat,\
            cost_station_pa=cost_station_pa_pat,\
            n_station=n_station_pat,\
            cost_inter_pa=0.0,\
            n_inter=0,\
            cost_vom_pkm_pa=cost_veh_om_pkm_pat) #the costs are referred to
full vehicles trips


            print '\n\ncost_vehtrip_pat=',cost_vehtrip_pat,'EUR/trip'

            profit_vehtrip_pat = (n_pax_pat*occup_indiv_pat *price_ind)-
cost_vehtrip_pat #the profit made on each full vehicle trip

            return_pa_pat= n_vehtrips_pa_pat*n_pax_pat*occup_indiv_pat
*price_ind #Assumes the price is per passenger
            #return_pa_pat = n_vehtrips_pa_pat*price_ind #Assuming the
price is per vehicle
            print 'return_pat=',return_pa_pat,'EUR/a'

            profit_pa_pat=return_pa_pat-cost_vehtrip_pat*n_vehtrips_pa_pat
            print 'profit_pa_pat=',profit_pa_pat,'EUR/a'

            z_var[ky, kx] = profit_vehtrip_pat #Insert here the variable to
colormap.

            kx = kx + 1

    ky = ky + 1

plotter.plot_cashflow('Phase 3: Profit per Vehicle Trip [$Euro$]', x_var,
y_var, z_var, ylabel='Maximum Network Saturation $Sat$', xlabel='Guideway
cost per meter [e/m]') #create the plot
plt.show()
```

6.3 Python implementation for Bologna case study with phase interface analysis

```
from pylab import *
from sys import exit

import capa_20240207 as capa
import plotter
import matplotlib.pyplot as plt
import numpy as np


def get_cost_per_year(c,t_am,r_dis):
  """Calculates cost  per year of an item based on
  c = invested capital of item
  t_am = ammortization time of respective item
  r_dis = discount rate (interrest for borrowing money)
  """

  return c*r_dis/(1-((1+r_dis)**-t_am))
```

```
def
get_cost_trip(n_tpa=0,len_trip_av=0.0,cost_veh_pa=0.0,n_pax=6,n_veh=0,cost_
guidew_pa=0.0,len_guidew=0.0,cost_station_pa=0.0,n_station=0,cost_inter_pa=
0.0,n_inter=0,cost_om_pkm_pa=0.0):
  return ( cost_veh_pa*n_veh \
           +cost_guidew_pa*len_guidew\
       +cost_station_pa*n_station\
       +cost_inter_pa*n_inter\
       +cost_om_pkm_pa/1000.0*n_tpa*len_trip_av)/n_tpa


def
get_cost_vehtrip(cost_system_cap=0,n_vtpa=0,len_trip_av=0.0,cost_vom_pkm_pa
=0.0): #[BERNIERI] get the cost per vehicle trip from an aggregated capital
cost
    return (cost_system_cap +
cost_vom_pkm_pa/1000.0*n_vtpa*len_trip_av)/n_vtpa


NN=2    ###To run a single scenario NN=2 and lower bound = upper bound for
the variables: gives 4 identical iterations and useless plot, but it works
and you do not need to chage the code
x_var = np.linspace(4000, 4000, num=NN)
y_var = np.linspace(5.0, 5.0, num=NN)
z_var = np.zeros((NN, NN), dtype=float)

ky=0

for a_emerge in y_var: #start loop for y variable

    kx=0

    for len_trip_av in x_var: #start loop for x variable

                # downwriting times in years
        t_am_inf=36.0       # in years
        t_am_station=25.0   # in years
        t_am_veh=25.0       # in years
        r_inter=0.04        # discount rate [AATS05]
        dpa=350             # days per year
        price_ind = 1.5 # ticket price of individual ticket
        price_group = 1.0 # ticket price of group ticket
        price_freight=2.0 # ticket price of freight movement

        capital_saved = 5*34.177*1e6 # starting capital saved from profits
of last construction phase [hp. 5 years of accumulation]


############################################################################
###
        if True: #__name__ == '__main__':

############################################################################
###

            len_guidew_pat=59885.0   #fixed track length in m
            n_station_pat = 46      #fix the number of station
```

```
                ###[ITERATE]###a_emerge=2.0          # maximum emergency
brake deceleration in m/s^2
            t_emerge=0.5          # emergency brake actuation time in s
            v_line=40/3.6         # average line speed in m/s


                ###ITERATE###len_trip_av=2500.0 # average trip length in m
            c_empties_pat=0.3# coefficient of empty vehicles

            c_veh_full=1.0-c_empties_pat           # fraction of full
vehicles

            print
'\n########################################################'
            print 'PAT with 6 passenger vehicles\n'

            n_pax_pat=6              # number places of places to sit/stand
            len_veh_pat= 3.0         # vehicle length in m
            v_com_pat=25.0/3.6       # commercial speed in m/s
            #t_headway_pat=3         # in s....get it from capacity
            sat_max_pat = 0.6        # maximum allowed network saturation
            occup_indiv_pat=1.3/n_pax_pat # occupation rate of individually
controlled vehicles
            r_indiv_pat=1.0          # 100% individual vehicles, no trains

            # not influential here, no trains
            occup_train_pat=-1.0       # occupation rate of vehicles in
train formation
            n_chain_pat=-1.0           # number of vehicles chained
together in a train

            #len_square_pat= 1000        # grid length of PAT network,in m
                                      # gives also distance between
stations
            #system costs
            cost_pax_cap_pat=50000.0/n_pax_pat # capital cost per place in
EUR [ULTra ATRA]
            cost_pax_om_pkm_pat=0.19  # operating and maintenance
0.17EUR/km with 70000km/a [WSP]

cost_veh_om_pkm_pat=cost_pax_om_pkm_pat*(occup_indiv_pat*n_pax_pat)

            cost_guidew_cap_pat=5000.0      # >track per meter in EUR
[AATS05]
            cost_station_cap_pat=0.75*10**6  # >costs per station

            # specific demand characteristics
            c_trips_peak_day_pat=0.1  # ratio trips during one peak hour
and trips per day

            # demand distribution
            tau_peak_pat=6.0/24.0;beta_peak_pat=1;
            tau_off_pat=10.0/24.0;beta_off_pat=0.6;

            # capacity calcs at line speed

capa_veh_pat=capa.capa_mix_veh(r_indiv_pat,n_chain_pat,len_veh_pat,v_line,t
_emerge,a_emerge)

capa_pax_pat=capa.capa_mix_pax(n_pax_pat,occup_indiv_pat,occup_train_pat,r_
indiv_pat,n_chain_pat,len_veh_pat,v_line,t_emerge,a_emerge)
```

```
            print 'capa_veh_pat=',capa_veh_pat*3600,'veh/h
at',v_line*3.6,'km/h'
            print 'capa_pax_pat=',capa_pax_pat*3600,'pax/h
at',v_line*3.6,'km/h'
            #n_pax_ind=n_pax_pat*occup_indiv_pat

            ##calculating the demand that can be satisfied

            t_headway_pat=1/capa_veh_pat
#time headway
            n_veh_pat=(sat_max_pat*len_guidew_pat)/(t_headway_pat*v_line)
#number of needed vehicles to match saturation
            t_trip_av_pat=len_trip_av/v_com_pat
#average trip time in s
            print 'nimber of vehicles =',n_veh_pat
            n_vehtrips_rush_1h=(3600*n_veh_pat*c_veh_full)/t_trip_av_pat
#number of vehicletrips in one rush hour
            print 'vehicletrips in 1 rush h=',n_vehtrips_rush_1h
            n_vehtrips_pd_pat=
(n_vehtrips_rush_1h*24*tau_peak_pat*beta_peak_pat)+(n_vehtrips_rush_1h*24*t
au_off_pat*beta_off_pat) #[BERNIERI] number of daily vehicle trips
            print 'vehicletrips in 1 day=',n_vehtrips_pd_pat
            n_trip_pd_pat=n_vehtrips_pd_pat*occup_indiv_pat*n_pax_pat
#number of daily trips
            print 'daily demand=',n_trip_pd_pat
#
            n_trips_pa_pat=dpa*n_trip_pd_pat
#number of trips per year
            #n_vehtrips_pd_pat=n_trip_pd_pat/(n_pax_pat*occup_indiv_pat)
#
            n_vehtrips_pa_pat= dpa*n_vehtrips_pd_pat
#vehicletrips in one year
            print 'vehicle trips in 1 year=',n_vehtrips_pa_pat

            print 't_headway_pat=', t_headway_pat

            print 't_trip_av_pat=',t_trip_av_pat
            print 'len_guidew_pat=',len_guidew_pat
            print 'n_station_pat=',n_station_pat
            print 'n_veh_pat=',n_veh_pat
            print '=',

            cost_pat_cap
=(cost_guidew_cap_pat*len_guidew_pat+n_station_pat*cost_station_cap_pat+n_v
eh_pat*cost_pax_cap_pat*n_pax_pat)-capital_saved #[BERNIERI] total capital
cost of whole system, changed to take into account profits from last phases
            print 'cost_pat_cap=',cost_pat_cap
            cost_pat_cap_pkm=1000.0/len_guidew_pat*(cost_pat_cap)

            print '\ncost_pat_cap_pkm=',cost_pat_cap_pkm,'\n'

            cost_veh_pa_pat=
get_cost_per_year(cost_pax_cap_pat*n_pax_pat,t_am_veh,r_inter)

cost_guidew_pa_pat=get_cost_per_year(cost_guidew_cap_pat,t_am_inf,r_inter)

cost_station_pa_pat=get_cost_per_year(cost_station_cap_pat,t_am_station,r_i
nter)
```

```
costs_inf_pa_pat=cost_guidew_pa_pat*len_guidew_pat+cost_station_pa_pat*n_st
ation_pat
            print 'costs_inf_pa_pat per
km=',1000.0*costs_inf_pa_pat/len_guidew_pat
            #print '=',
            #print '=',

costs_cap_pa_pat=get_cost_per_year(cost_pat_cap,t_am_inf,r_inter) #costs
per year of whole system also taking into accocunt past profits, all
brought to the guideway mortagage time as it is the heaviest.

            print 'costs_cap_pa_pat=',costs_cap_pa_pat

            cost_vehtrip_pat=get_cost_vehtrip(\
            n_vtpa=n_vehtrips_pa_pat,\
            len_trip_av=len_trip_av,\
            cost_vom_pkm_pa=cost_veh_om_pkm_pat,\
            cost_system_cap=costs_cap_pa_pat) #the costs are referred to
full vehicles trips (full and empty costs are all aggregated inside full
veh trips)


            print '\n\ncost_vehtrip_pat=',cost_vehtrip_pat,'EUR/trip'

            profit_vehtrip_pat = (n_pax_pat*occup_indiv_pat *price_ind)-
cost_vehtrip_pat #[BERNIERI] the profit made on each full vehicle trip

            return_pa_pat= n_vehtrips_pa_pat*n_pax_pat*occup_indiv_pat
*price_ind #Assumes the price is per passenger
            #return_pa_pat = n_vehtrips_pa_pat*price_ind #Assuming the
price is per vehicle
            print 'return_pat=',return_pa_pat,'EUR/a'

            profit_pa_pat=return_pa_pat-
(cost_vehtrip_pat*n_vehtrips_pa_pat)
            print 'profit_pa_pat=',profit_pa_pat,'EUR/a'

            z_var[ky, kx] = profit_pa_pat #Insert here the variable to
colormap. Remember that python calls the y axis variable first and the x
variable then (rows [y] first, colums [x] later)

            kx = kx + 1

    ky = ky + 1

plotter.plot_cashflow('title', x_var, y_var, z_var, ylabel='Maximum Network
Saturation $Sat$', xlabel='Guideway cost per meter [e/m]') #[BERNIERI]
create the plot
plt.show()
```

6.4 Python implementation to calculate line capacity

```
#capa_20240207
from sys import exit

def t_safety(v_line,t_emerge,a_emerge):
  return t_emerge+v_line/(2.0*a_emerge)
```

```
def t_veh(len_veh,v_line):
  return len_veh/v_line

def t_train(n_train,len_veh,v_line,t_emerge,a_emerge):
  return t_safety(v_line,t_emerge,a_emerge)+n_train*t_veh(len_veh,v_line)

def t_indiv(len_veh,v_line,t_emerge,a_emerge):
  return t_safety(v_line,t_emerge,a_emerge)+t_veh(len_veh,v_line)

def capa_mix_veh(ratio_indiv,n_chain,len_veh,v_line,t_emerge,a_emerge):
  ts=t_safety(v_line,t_emerge,a_emerge)
  tv=t_veh(len_veh,v_line)
  return 1.0/( (1.0-ratio_indiv)*(ts/n_chain+tv) + ratio_indiv*(ts+tv) )

def
capa_mix_pax(n_pax,occup_indiv,occup_train,ratio_indiv,n_chain,len_veh,v_li
ne,t_emerge,a_emerge):
  ts=t_safety(v_line,t_emerge,a_emerge)
  tv=t_veh(len_veh,v_line)
  return 1.0*n_pax*((1.0-
ratio_indiv)*occup_train+ratio_indiv*occup_indiv)/( (1.0-
ratio_indiv)*(ts/n_chain+tv) + ratio_indiv*(ts+tv) )

def capa_veh(len_veh,v_line,t_emerge,a_emerge):
  ts=t_safety(v_line,t_emerge,a_emerge)
  tv=t_veh(len_veh,v_line)
  return 1.0/(ts+tv)
```

6.5 Python implementation to plot the results

```
import matplotlib as mpl
import matplotlib.pyplot as plt
import numpy as np
from numpy import ma
from matplotlib import colors, ticker, cm
#from pyplot_hatch import plot_hatch [deactivated for debug]

from sys import exit

def plot_cashflow(title, SAT, MSIP,  CASHFLOW, figname = None, v_min =
None, v_max=None,
                  cmap=cm.RdBu, padding = 0.02, shrink_cbar = 0.9,n_levels
= 30,
                  ylabel = r'Individual mode share ($IMS$)',
                  xlabel = '',
                  ytickspos = None, ytickstext = None):
    #http://matplotlib.org/examples/color/colormaps_reference.html

    global figformat
    global dpi
    global figsize

    figsize = [10, 8]

    fig = mpl.pyplot.gcf()
    ax1 = fig.add_subplot(111)
```

```
    fig.set_size_inches(figsize[0], figsize[1], forward=True)

    #extends = ["neither", "both", "min", "max"]
    extend = 'neither'

    cs = ax1.contourf(SAT, MSIP, CASHFLOW,n_levels,
norm=MidpointNormalize(midpoint=0.,vmin = v_min, vmax=v_max), cmap = cmap,
extend=extend)


    if ytickspos != None:
        plt.yticks(ytickspos,ytickstext)

    ax1.set_xlabel(xlabel)
    ax1.set_ylabel(ylabel)

    fig.colorbar(cs, ax=ax1, shrink=shrink_cbar,pad = padding)

    plt.title(title)
    plt.grid()


    if figname!= None:
        plt.savefig("%s.%s"%(figname, figformat), format=figformat,dpi=dpi,
                        #orientation='landscape',
                        orientation='portrait',
                        transparent=True)
```