POLITECNICO DI MILANO

Faculty of Industrial and Information Engineering

Master of Science in Mobility Engineering

Modal Shift in urban areas: State of the Art and Framework for policies assessment

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Abstract

The transport sector remains one of the most critical areas for achieving the climate neutrality targets set by the European Green Deal, accounting for roughly 25% of total CO_2 emissions, predominantly from road transport. Despite the proliferation of sustainability-oriented strategies, the misalignment between infrastructure planning and actual user behaviour has often limited the effectiveness of modal shift policies. This thesis aims to bridge the gap between decision-making theory and operational implementation through the development of an original predictive metamodel, configured as a Decision Support System (DSS) for evaluating the cost-effectiveness of mobility investments.

The work begins with a systematic analysis of the state of the art and international benchmarking, from which the empirical evidence necessary for the model's parametrization was extracted. Implemented in Excel, the metamodel follows an analytical-comparative logic based on a causal chain that transforms financial inputs into physical outputs and subsequently into modal share variations via differentiated elasticity coefficients. The methodological originality lies in integrating the concept of Functional Urban Areas (FUA) proposed by ISTAT, which allows the effectiveness of policies, divided into Push and Pull categories, to be weighted according to territorial context: Metropolitan Area, Urban Area, and Extra-Urban Area.

The analysis enabled the simulation of complex scenarios, comparing the marginal efficiency of 22 different policies, including heavy infrastructure projects, access regulations (LEZ/Congestion Charge), and active mobility solutions. Special emphasis was placed on the role of digital technologies and Artificial Intelligence: the metamodel demonstrates how integration under a Mobility as a Service (MaaS) framework and optimization through ITS systems act as efficiency catalysts, drastically reducing the cost required to achieve one percentage point of modal shift, especially in extra-urban contexts where Demand-Responsive Transport (DRT) emerges as the only competitive alternative to private cars.

In conclusion, the research provides policymakers with a quantitative tool for rational resource allocation, showing that an effective modal transition cannot ignore a granular

territorial perspective and pervasive digitalization of services, capable of overcoming the cognitive and physical barriers that still tie users to private car use.

Keywords: Modal Shift, Functional Urban Areas (FUA), Decision Support System (DDS), Meta-Model, Push and Pull Policies.

Abstract in italiano

Il settore dei trasporti si conferma come uno dei comparti più critici per il raggiungimento degli obiettivi di neutralità climatica fissati dal Green Deal europeo, essendo responsabile di circa il 25% delle emissioni totali di CO_2, con una predominanza del trasporto su gomma. Nonostante la proliferazione di strategie orientate alla sostenibilità, il disallineamento tra la pianificazione infrastrutturale e le reali dinamiche comportamentali dell'utenza ha spesso limitato l'efficacia delle politiche di *modal shift*. La presente tesi si propone di colmare il divario tra la teoria decisionale e l'implementazione operativa attraverso lo sviluppo di un metamodello predittivo originale, configurato come un *Decision Support System* (DSS) per la valutazione della *Cost-Effectiveness* degli investimenti in mobilità.

Il lavoro si articola in una prima fase di analisi sistematica dello stato dell'arte e di *benchmarking* internazionale, dalla quale sono state estratte le evidenze empiriche necessarie alla parametrizzazione del modello. Il metamodello, implementato in ambiente Excel, adotta una logica analitico-comparativa fondata su una catena di causalità che trasforma l'input finanziario in output fisici e, successivamente, in variazione della quota modale tramite coefficienti di elasticità differenziati. L'originalità metodologica risiede nell'integrazione del concetto di Functional Urban Areas (FUA) proposto dall'ISTAT, che permette di pesare l'efficacia delle politiche (suddivise in categorie *Push* e *Pull*) in funzione del contesto territoriale: Area Metropolitana, Area Urbana ed Area Extra-Urbana.

L'analisi ha permesso di simulare scenari complessi, confrontando l'efficienza marginale di 22 diverse politiche, tra cui interventi infrastrutturali pesanti, regolamentazioni d'accesso (LEZ/Congestion Charge) e soluzioni di mobilità attiva. Particolare enfasi è stata posta sul ruolo delle nuove tecnologie digitali e dell'Intelligenza Artificiale: il metamodello dimostra come l'integrazione in ottica *Mobility as a Service* (MaaS) e l'ottimizzazione tramite sistemi ITS agiscano come catalizzatori di efficienza, riducendo drasticamente il costo necessario per ottenere un'unità percentuale di *modal shift*, specialmente nei contesti extra-urbani dove il trasporto a chiamata (DRT) si rivela l'unica alternativa competitiva al mezzo privato.

In conclusione, la ricerca fornisce ai *policymakers* uno strumento quantitativo per l'allocazione razionale delle risorse, dimostrando che una transizione modale efficace non può prescindere da una visione territoriale granulare e da una digitalizzazione pervasiva dei servizi, capaci di abbattere le barriere cognitive e fisiche che ancora oggi vincolano l'utente all'utilizzo dell'auto privata.

Keywords: Cambiamento modale, Zone Urbane Funzionali (FUA), Sistemi di Supporto alle Decisioni (DDS), Meta-Modello, Politiche Push e Pull.

Summary

1. Introduction

1.1. Context and Research Motivations

The transport sector represents a strategic component for economic and social development, as it ensures access to goods, services, and opportunities. However, the dominant mobility model of the 20th and 21st centuries, strongly centred on private automobiles, has generated globally significant negative consequences. From an environmental perspective, transport is responsible for about one-quarter of total greenhouse gas emissions in the European Union (*Figure1-1*), with 71.7% attributable to road transport (*Figure 1-2*), mainly passenger cars and heavy commercial vehicles (European Environment Agency, 2023). Added to this are local air pollution, noise pollution, land fragmentation, and a high dependency on fossil fuels.

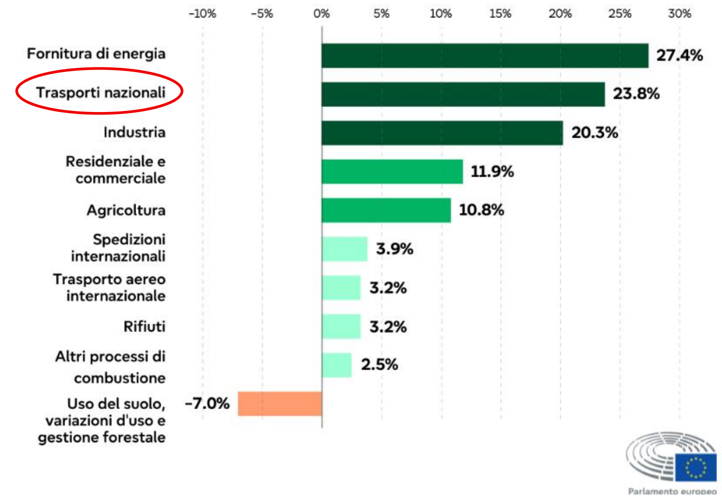


Figure 1-1: Greenhouse gas emissions in the EU by sector: total share of emissions estimated in CO_2 equivalent (2022).

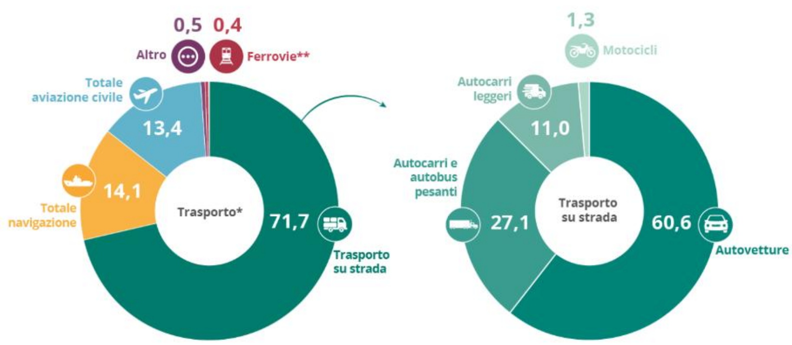


Figure 1-2: Greenhouse gas emissions from transport in the EU.

From an economic perspective, road congestion represents one of the main negative externalities: in several European cities, it is estimated to cause a productivity loss equal to 2% of GDP, with direct effects on citizens' travel times and indirect effects on the competitiveness of urban economic systems (OECD, 2022). Moreover, increasing urbanization, with over 70% of the European population living in urban areas by 2050, amplifies pressure on transport infrastructure, highlighting the urgency of more sustainable models.

From a social perspective, dependence on private cars generates inequalities in access to mobility, penalizing vulnerable groups such as the elderly, young people, and low-income families, who have fewer possibilities to bear the costs of vehicle ownership. In this sense, policies that enhance public transport and soft modes (cycling, walking, sharing mobility) take on a value of social equity, in addition to their environmental role.

In light of these challenges, the concept of modal shift emerges as a central tool to guide the transition toward a more sustainable mobility system. Analysing policies that have supported this shift and assessing the contribution that innovative technologies and artificial intelligence can bring is therefore a matter of significance not only for academic debate but also for the definition of concrete strategies at political and administrative levels.

1.2. The Concept of Modal Shift: Evolution Over Time

The concept of modal shift has undergone a profound transformation over the past three decades, evolving from a technical-descriptive approach to a strategic category within European transport policies. Whereas originally the term merely indicated changes in the modal distribution of passenger or freight flows, from the 1990s onwards it progressively entered the political and institutional vocabulary, acquiring a normative meaning and taking on an increasingly central role in strategies for sustainability and decarbonisation. Tracing its evolution through the European Commission's White

Papers on Transport makes it possible to clearly identify these semantic and functional shifts.

The 1992 White Paper, The Future Development of the Common Transport Policy, marks the turning point at which the notion of modal shift was formally introduced into the European agenda. At this stage, the concept was employed to address the imbalance caused by the growing predominance of road transport, considered a source of congestion, accidents and environmental degradation. Modal shift was defined primarily as a technical tool to transfer significant shares of freight traffic to rail and inland waterways, seen as more energy-efficient and less environmentally damaging. Its role was essentially corrective, aiming to reduce inefficiencies and restore fair competition between transport modes (European Commission, 1992).

A first conceptual evolution occurred with the 2001 White Paper, European Transport Policy for 2010: Time to Decide. Here, modal shift ceased to be an accessory measure and became an explicit political objective within a long-term vision. The Commission acknowledged that mobility growth was not in itself negative, but its concentration in a single mode was unsustainable. Modal rebalancing was therefore linked to a broader project: reducing pressure on road transport, increasing safety, cutting greenhouse gas emissions, and improving urban quality of life. In this context, modal shift acquired a normative and proactive meaning: not only describing trends but actively orienting policy choices to induce behavioural change (European Commission, 2001).

A further development came with the 2006 Communication, Freight Transport Logistics in Europe – the key to sustainable mobility. In contrast with previous documents, which mainly associated the concept with the direct transfer of traffic volumes from road to rail or waterways, the Commission now placed it within a broader perspective of logistics and intermodality. Modal shift was no longer conceived as a mere quantitative shift but as part of a qualitative process aimed at integrating transport modes into efficient logistics chains, reducing costs and negative externalities. The focus thus shifted from single modes to the design of interconnected systems, where modal shift became possible only through the optimisation of entire supply chains (European Commission, 2006).

A decisive redefinition was provided by the 2011 White Paper, Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. This document consolidated modal shift as a cornerstone of European sustainability strategies, by setting binding quantitative targets: by 2030, 30% of road freight over distances greater than 300 km should shift to rail or waterways, increasing to 50% by 2050. Modal shift was thus reframed not simply as a tool to reduce congestion and accidents, but as a structural component of the EU's climate roadmap, tightly connected with greenhouse gas reduction strategies. From this point on, the concept became a key driver of decarbonisation policy (European Commission, 2011).

Finally, in more recent strategies such as the 2020 Sustainable and Smart Mobility Strategy, developed within the framework of the European Green Deal, the concept of modal shift has been embedded in a broader vision that combines sustainability, digitalisation and resilience. Although the expression is not always explicitly used, the idea of "shift to sustainable modes" remains a central priority, now linked to technological innovation, automation and the digitalisation of both logistics and mobility services. In this context, modal shift evolves once more: it is no longer limited to the physical transfer of flows between modes but extends to systemic transformations involving travel behaviour, multimodal integration, and the diffusion of digital solutions such as Mobility as a Service and e-logistics platforms. It thus emerges as a strategic concept that integrates efficiency, equity, ecological transition and technological innovation (European Commission, 2020).

Viewed historically, the European White Papers reveal how modal shift has moved from a technical and corrective notion in the 1990s, to a political priority in the 2000s, and finally to a strategic category underpinning the sustainable and digital transition of European transport systems in the last decade. This trajectory reflects the progressive broadening of its functions: from a quantitative measure of modal rebalancing to a strategic lever for redesigning mobility systems in a resilient, integrated, and low-carbon direction.

1.3. Objectives of the thesis and research questions

This thesis aims to investigate the dynamics of modal shift through a systemic approach that combines the historical analysis of transport policies with the development of an original analytical tool. The originality of the research lies in the design and implementation of a decision metamodel intended to quantify the effectiveness of investments in sustainable mobility, integrating the role of digital innovations and artificial intelligence as catalysts for ecological transition.

The specific objectives of the research are structured along three main directions:

1) Systematization of Modal Shift Policies: mapping the state of the art of European and international strategies, distinguishing between deterrence (push) and incentive (pull) measures, to identify the critical success factors and causes of ineffectiveness in traditional models.

2) Development of a Parameterized Decision Metamodel: designing a logical-mathematical architecture capable of converting financial inputs into physical outputs and, subsequently, into modal shift percentages, based on elasticity coefficients derived from empirical evidence and global case studies.

3) Assessment of Differential Effectiveness Across Functional Urban Areas (FUA): applying the metamodel to the various functional geographies proposed by Istat (Metropolitan, Urban, and Extra-Urban areas) to demonstrate how system sensitivity to different policies varies significantly depending on territorial morphology and density.

In light of these objectives, the thesis seeks to answer the following research questions:

- How does the proper integration of push and pull policies influence a territorial system's ability to generate a genuine modal shift?
- What is the estimated return, in terms of modal shift, for each unit of investment allocated across infrastructure, regulatory, and digital intervention categories?
- To what extent can new technologies and artificial intelligence act as efficiency multipliers, especially in complex or low-density contexts where traditional policies are less effective?

The ultimate goal is to provide a Decision Support System (DSS) capable of offering concrete recommendations to planners and policymakers, enabling a more informed, efficient, and resilient allocation of resources in response to the climate and social challenges of contemporary mobility.

2. State of the art

2.1. Approaches and Tools for Modal Shift Policies

Strategies aimed at promoting modal shift are traditionally classified into two main conceptual categories, reflecting complementary approaches to managing mobility demand: "Push" policies and "Pull" policies (Butty et al., 2015).

Before applying them to the transport context, it is useful to define these two approaches in general terms. A "push" approach involves introducing measures that actively discourage a specific behaviour by making it more costly, difficult, or less desirable. Conversely, a "pull" approach is based on incentivizing a preferred alternative, working to make it more accessible, convenient, and attractive than the first.

Translating this dichotomy into the mobility sector, "push" policies are those that disincentivize the use of less sustainable transport modes, particularly the private car. "Pull" policies, in contrast, aim to make greener alternative (such as public transport, cycling, and walking) more attractive, efficient, and competitive.

It is now well-established in the literature (May et al., 2006) that the effectiveness of modal rebalancing policies does not lie in the application of a single instrument. Success depends on the ability to orchestrate an integrated package of measures, where "push" and "pull" interventions not only coexist but mutually reinforce each other. This creates an urban ecosystem in which choosing sustainable mobility becomes the most logical and advantageous option, stimulating a structural and lasting change in citizens' behaviour.

"Push" Policies: Intervening in Private Car Use

"Push" policies aim to reduce the attractiveness of the private car. As emphasized in the literature (Butty et al., 2015), their strategic objective is to internalize the numerous negative externalities associated with road transport: congestion, air and noise pollution, accidents, and land consumption.

However, in analysing these tools, it is crucial to adopt the distinction suggested by academic critique between the primary intent of the measure and its final effect. Some policies are specifically designed to disincentivize cars (e.g congestion charge), while others, despite having different primary objectives (e.g., road safety, urban liveability), generate a powerful "push effect" as a consequence.

Adopting a categorization based on the type of intervention (Butty et al., 2015), we can distinguish three main approaches.

1. *Economic Measures (Direct Push)*

These represent the most direct form of "push" policy, acting on the marginal cost of each car trip to make the user aware of the social costs.

Parking Pricing: The tariffed and dynamic management of parking, combined with the reduction of on-street parking supply, transforms parking from a perceived free good into a limited resource, the cost of which directly impacts modal choice (Butty et al., 2015).

Road Pricing: Instruments like congestion charges or variable tolls impose a fee for accessing specific urban areas, often differentiated by time of day or emission class, directly disincentivizing access.

2. *Regulatory and Access Measures (Mixed Approach)*

These policies impose regulatory limits on circulation. The intent may be a direct "push" or aimed at other objectives (such as environmental ones), but they generate a clear disincentivizing effect.

Limited Traffic Zones (LTZ): These represent a direct limitation on vehicle access in specific areas (e.g., historic centres) to reduce pressure, constituting a clear "push" policy.

Low Emission Zones (LEZ): These measures have a primarily environmental objective (internalizing the externality of pollution). Their effect is a powerful "push" that disincentivizes the use and ownership of more polluting vehicles.

3. ***Infrastructural and Urban Planning Measures (Mainly "Push Effect")***

This approach physically modifies the street space. In this case, the primary intent is often not to disincentivize cars, but to improve safety, liveability, or rebalance space in favour of active mobility. The "push effect" is a consequence of these choices.

Traffic Calming: Measures such as creating "30 km/h Zones," installing speed bumps, speed cushions, or redesigning intersections. The primary objective is safety (internalizing the externality of accidents). The consequence is an increase in travel time for cars, which makes them less competitive.

Road Space Reallocation (Road Diet): Interventions that reduce the space dedicated to motor vehicles (e.g., reducing lanes, removing parking) to create space for cycle lanes, wider sidewalks, or green corridors.

Pedestrianization: The total closure of streets to private traffic, with the objective of improving quality of life and supporting commercial activities, has the effect of the strongest possible disincentive for car use in that area (Butty et al., 2015).

"Pull" Policies: Attracting Users to Sustainable Alternatives

"Pull" policies work in a complementary way, acting to improve the quality, accessibility, reliability, and convenience of sustainable transport modes. The goal is to offer an alternative to the private car that is superior not only economically or environmentally, but also in terms of efficiency and comfort.

As highlighted by the literature (e.g., Butty et al., 2015), the attractiveness of public transport (PT) and other alternatives depends on a complex set of quality attributes perceived by the user. "Pull" policies can be grouped based on how they intervene on these factors.

1. ***Improving Service Quality Attributes***

This is the primary lever, acting directly on the user's perception and experience.

Cost and Fare Policies: Measures such as reducing the cost of tickets and passes (including cases of fare-free PT), or introducing integrated fares that allow the use of multiple modes with a single travel card.

Speed, Frequency, and Reliability: Interventions to increase the time-competitiveness of PT, through increasing service frequency, creating protected bus lanes, traffic signal priority systems, and extending service hours.

Comfort, Safety, and Information: This includes renewing the fleet with modern and accessible vehicles, cleaning vehicles and stations, increasing perceived safety (lighting, staff, CCTV), and enhancing real-time information (pre-trip and on-board), which reduces uncertainty.

2. ***Developing Intermodality and Integration***

The most innovative "pull" policies focus on seamless integration between different services to offer a competitive door-to-door travel experience (Butty et al., 2015).

Physical Integration (Networks and Interchanges): Development of dense, safe, and continuous cycling and pedestrian networks that are not fragmented but constitute a coherent system. This also includes the creation of high-quality interchange nodes (e.g., Park & Ride at stations) and secure bicycle parking facilities.

Digital and Service Integration (MaaS): The development of Mobility as a Service (MaaS) platforms represents a paradigm shift. The user does not purchase a ticket, but rather a personalized mobility plan that allows them to plan, book, and pay for multimodal journeys (train, bus, bike-sharing, etc.) through a single interface. This, combined with the promotion of sharing mobility services, makes the sustainable ecosystem flexible and competitive without the need to own a car.

2.2. Modal Shift Policies

The evolution of urban transport policies in recent decades has marked a clear departure from a single-sector approach, focused on vehicle traffic fluidity, to embrace a systemic vision. The primary objective of many administrations has become the modal shift, the transfer of mobility shares from private cars to more sustainable modes such as public transport (PT), cycling, and walking. The international state of the art shows that the success of this transition stems not from individual measures, however effective, but from complex and integrated strategies.

As highlighted by Dijk, Givoni & Diederiks (2018), success is not achieved by a simple "accumulation" of interventions (policy piling up), but by the design of coherent "policy packages". In these packages, the tools reinforce each other synergistically. This approach is supported by extensive literature reviews on congestion (Policy measures to reduce road congestion, 2019), which confirm that while supply-side policies (e.g., building new roads) prove ineffective in the long term due to "induced demand," demand-side measures combining disincentives and incentives are the only ones that have demonstrated real and lasting effectiveness.

The ineffectiveness of a non-synergistic approach is demonstrated by the Rotterdam case study (Attia et al., 2023). The introduction of a Low-Emission Zone (LEZ) in 2016, a "Push" measure aimed at banning older passenger vehicles, did not produce a significant modal shift towards public transport. The analysis by Attia et al. (2023) reveals the reasons: first, the "Push" measure was intrinsically weak, affecting less than 2% of the total vehicle fleet. Second, and more critically, the policy package was contradictory. The scrapping program, intended to act as a "Pull" measure, effectively incentivized fleet replacement: 72% of users who scrapped their old car used the incentive to buy a new one, predominantly petrol or diesel, and only 5% shifted to alternative modes. Similarly, the investment in "Pull" infrastructure like Park-and-Ride (P+R) facilities showed no correlation with an increase in metro passengers, effectively being used as "extra parking" that ultimately fed car traffic, failing the package's objective.

The failure of Rotterdam and the success of other cities, such as Freiburg and Copenhagen, demonstrate that the effectiveness of modal shift lies in the architecture of the policy package. It is therefore necessary to analyse "Push" and "Pull" intervention types separately to understand how they must be integrated.

2.2.1. “Push" Policies: Disincentivizing Car Use

"Push" policies are designed to increase the perceived monetary, time, and convenience costs of private vehicle use. Although often unpopular initially, they have proven essential for creating the market conditions that make "Pull" alternatives competitive.

2.2.1.1. Congestion and Access Charging (Road Pricing)

Urban access charging is one of the most powerful "Push" measures, enabled by monitoring and payment technologies. As confirmed by several analyses (Policy measures to reduce road congestion, 2019), congestion pricing is the tool with the highest impact on traffic reduction.

The Singapore case study is considered the global "gold standard" for its integration (Lam & Toan, 2006; Tan & Leong, 2013). Forced by extreme land scarcity, the city-state implemented a two-tiered "Push" package. The first is a control on vehicle ownership through the Vehicle Quota System (VQS), an auction mechanism to obtain a 10-year "Certificate of Entitlement" (COE) required to purchase a car. This tool limits the total number of vehicles in circulation a priori. The second level is a control on use: as early as 1998, Singapore replaced its manual system (ALS) with Electronic Road Pricing (ERP), a technological urban toll system. Through electronic gantries and an in-vehicle unit (IU), the ERP charges a "pay-per-use" toll that varies dynamically based on time, location, and traffic conditions, managing demand in real-time.

A key European model is Sweden's, with the Congestion Charges in Stockholm and Gothenburg. The introduction of the tax in Stockholm in 2006, initially as an experiment (the "Stockholm Trial"), produced an immediate and lasting reduction in traffic in the central area (about -22% in the first year, stabilizing at -20% in subsequent years) (Eliasson, 2008; Börjesson et al., 2018). The most relevant aspect of this case is the phenomenon of "policy learning": public acceptance, initially very low (36%), grew dramatically to over 65% after implementation, once citizens could personally experience the benefits (less traffic, cleaner air) (Becker, 2008). This shows that the initial unpopularity of a "Push" measure can be overcome if the benefits are tangible. However, the comparison with Gothenburg, where the traffic reduction was more limited (12-14%), highlighted the criticality of the "package": Stockholm's success also depended on the presence of a high-quality, capillary "Pull" network of public transport, in which the revenues were reinvested, capable of absorbing the demand shifted from cars (Börjesson et al., 2018).

Milan also represents a significant European case study with its congestion charge (Area C). The introduction of Area C in 2012 was an immediate success, reducing vehicle entries by 28.3% and road accidents by 23.8% (Croci et al., 2017). The analysis of subsequent policy modifications offers important insights: an increase in the fee produced a further, albeit modest, traffic reduction. Conversely, introducing a ban on the most polluting vehicles (another "Push" lever) proved very effective in reducing specific emissions (like PM10 and NH3) but had no statistically significant impact on the total number of vehicles entering, demonstrating how different levers achieve different results (Croci et al., 2017).

2.2.1.2. Parking Management and Pricing (Parking Pricing)

Less drastic than road pricing, but equally effective and politically easier to implement (Litman, 2024), is parking pricing. The analysis by the Victoria Transport Policy Institute (VTPI) provides the theoretical basis: "free parking" is an illusion, a hidden subsidy that generates induced traffic (including cruising, the search for parking) and regressively favours motorists at the expense of those using other modes (Litman, 2024). Modern parking pricing policies do not aim to maximize revenue, but to manage demand to maintain an optimal occupancy rate (e.g., 85-90%) that ensures turnover and eliminates cruising. This approach is enabled by new technologies, such as smart meters, mobile payment apps, and dynamic pricing (prices that vary with demand) (Litman, 2024).

The effectiveness of this "Push" policy is visible in the success of cities like Vienna and Freiburg. The celebrated Viennese model (Buehler et al., 2016) is based not only on the "Pull" incentive of the €365 annual pass but on its synergistic combination with a strict "Push" policy of parking management and pricing, and the progressive elimination of free parking in the centre, which increased the opportunity cost of car use. Similarly, Freiburg (Buehler & Pucher, 2009) built its decades-long success not only by investing in public transport and cycle paths but also by implementing extensive car-free zones and aggressive traffic calming (30 km/h zones and even 7 km/h, or "walking speed" zones) which includes strict residential parking regulation.

2.3. "Pull" Policies: Attracting Users to Alternatives

If "Push" measures create the need for an alternative, "Pull" measures must ensure this alternative is not just available, but also desirable. The state of the art shows that the competition with the private car is played on a complex field that includes psychology, convenience, and time, even before cost.

2.3.1.1. The Barriers: Cost vs. Convenience and Psychology

Before analysing "Pull" solutions, it is essential to understand the barriers preventing modal shift. The study by Urbanek (2021) on Poland offers a crucial analysis of psychological and emotional barriers. The research shows that many drivers do not act as purely rational, economic actors. The car maintains a powerful "symbolic" function (status, self-expression) and "affective" function (driving pleasure, sense of freedom and control).

This "psychological dependence" translates into very low price elasticity. The study found that drivers are willing to pay much more for fuel before considering an alternative (over 33% are willing to spend up to €233 more per month), and nearly 35% stated that the price of fuel is not an important factor. Consequently, even "Pull" policies based exclusively on price, such as free public transport, have limited effectiveness: studies cited by Urbanek (2021) (Baum, 1973; De Witte et al., 2008) indicate that only 10-13% of drivers would switch modes.

The true identified barriers are convenience and travel time. The car is chosen because it is perceived as faster (25.8%) and more convenient (16.7%). Concurrently, the main obstacles for public transport are "lack of adequate connections," "excessive travel time," and "insufficient frequency." A further convenience barrier, which emerged powerfully in the Asian context, is "trip-chaining" (Vu Anh Tuan, 2023). In the Hanoi study, it was seen that the motorcycle dominates because it allows users to easily chain multiple trips (e.g., home -> kids' school -> shopping -> work), a level of flexibility that linear public transport (bus or metro) cannot offer.

Successful "Pull" policies, therefore, must not only be economical; they must be faster, more convenient, and more flexible than the car/motorcycle.

2.3.1.2. The Price "Pull": The Power and Limits of Pricing

The economic incentive remains a powerful "Pull" tool for recruiting new users and overcoming the initial cost barrier. The German €9 ticket experiment (Loder et al., 2023) was an emblematic case. Valid nationwide from June to August 2022, it generated a mass modal shift: 52 million tickets sold, a 25-30% increase in public transport users, and an estimated reduction of 1.8 million tons of CO_2.

A similar study on Bonn's "Climate Ticket" initiative (Hahn et al., 2024), a €365 annual pass, confirmed this dynamic: 76% of users increased their public transport use, and 62% admitted to buying it exclusively for the price advantage.

However, both experiments revealed the limits of a price-only approach. In Germany, the initiative highlighted the infrastructure's capacity limits, leading to drastic overcrowding. In Bonn, the temporary nature of the effect emerged: 74% of respondents stated that, without the discount, they would return to using public transport less, and 49% would use their car more. The lesson is clear: the price "Pull" is an exceptional "marketing campaign" that fails if the "product" (the service and infrastructure) is insufficient to meet the generated demand.

2.3.1.3. The Infrastructural "Pull": Competing on Time, Safety, and Quality

The most durable "Pull" policies are those that have invested for decades in infrastructure quality, making sustainable alternatives better than the private car, thereby attacking the barriers of time and convenience.

- Public Transport and Urban Integration: The Freiburg model (Buehler & Pucher, 2009) is the primary example of a long-term "Pull" strategy initiated in the 1970s. The city made its tram system (Stadtbahn) the "backbone" of its urban development. Instead of bringing public transport to existing neighbourhoods, Freiburg built new neighbourhoods (like Rieselfeld and Vauban) around new tram lines, applying a rigorous Transit-Oriented Development (TOD) model. This, combined with strong "Push" measures (car-free zones and traffic calming), produced a structural modal shift: between 1982 and 2007, the cycling share rose from 15% to 27% and public transport from 11% to 18%, while the car's share fell from 38% to 32%.

  Likewise, Vienna's success (Buehler et al., 2016) is not just due to the €365 ticket, but to decades of consistent investment in network expansion (U-Bahn, S-Bahn) and fare integration. The Viennese model is based on a package that combines: accessible "Pull" fares (the €365 ticket), a dense, high-quality "Pull" public transport network, and "Push" measures on parking and integrated urban planning (Buehler et al., 2016). Vienna also anticipated the times in technological integration with the "WienMobil" platform, which functions as an ante-litteram Mobility as a Service (MaaS), allowing users to plan and pay for public transport, bike-sharing, and car-sharing from a single app.
- Active Mobility and Cycling: For active mobility, Copenhagen is the global benchmark (Ruggieri, 2017). The city's "Pull" strategy has evolved: from promoting cycling for environmental reasons, to promoting it because it is "the fastest and most convenient way to get around." This was achieved through an infrastructure package that addresses key barriers:

- Safety: The adoption of "Copenhagen-style cycle tracks" is fundamental: unidirectional and, crucially, physically separated from car traffic by a curb, and also separate from the sidewalk.
- Convenience and Speed: The creation of a primary network of "Cycle Superhighways" (the Cykelsuperstier) and the "PlusNet" connects suburbs to urban centres with high standards of width (allowing for overtaking and "conversational cycling"), pavement, and lighting, making cycling competitive even over medium and long distances.
- Technology: The use of "Green Waves" (Grøn Bølge) is a perfect example of a technological "Pull": traffic lights along main arteries are synchronized for cyclists traveling at a constant speed (e.g., 20 km/h), minimizing stops and drastically reducing travel time (Ruggieri, 2017).
- Integration: The construction of new bridges dedicated exclusively to cyclists and pedestrians (like the Cykelslangen, or "Cycle Snake") creates strategic shortcuts over physical barriers like canals and railways, making the cycling route more direct than the car route.

This approach is not static; it is in continuous evolution thanks to the "Bicycle Account". This is a biennial report that, since 1996, has collected objective data (km travelled, accidents) and subjective surveys (perceived safety, satisfaction with maintenance) from citizens. This data-driven governance tool makes it possible to monitor progress, identify problems (e.g., congestion on paths, lack of parking), and guide future investments in a transparent and iterative way.

- The Technological "Pull": Micromobility and Integration with Public Transport
  New digital technologies have not only improved existing "Pull" policies but have created entire new categories of services. Bike-Sharing and micromobility (e.g., e-scooters) have become central players in the modal shift. The study by Ma et al. (2019) in the city of Delft is illuminating, as it analyses the impact of three different business models enabled by technology:

- OV-fiets (Docked): This is the bike-sharing system of the Dutch railways (NS), tied to stations. Its role is clear: it is a "Pull" for public transport. It solves the first/last mile problem, and data shows it increases train usage.
- Mobike (Dockless): Enabled by GPS and apps, this is a free-floating system. Its impact is ambivalent: while it reduces car use (37% of users), it also replaces public transport on some routes (16% of users use PT less) and, to a large extent (34%), replaces trips on foot or by private bike.
- Swapfiets (Lease): A long-term rental/subscription model. This "Pull" model attacks a purely psychological and convenience barrier: the fear of theft and the cost/hassle of maintenance. The main motivations for choosing it are indeed "Less worry about theft/damage" (55.7%) and "Good quality bike" (52.7%).

The emergence of this multitude of actors (bike-sharing, e-scooters, ride-sourcing, car-sharing) has made managing the "policy package" exponentially more complex. To govern this ecosystem and prevent new "Pull" services from conflicting with each other or with public transport (as seen in Delft), the state of the art is moving toward data-driven management.

As documented by the International Transport Forum (ITF, 2024), the most advanced cities (like Berlin, New York, Brussels, Stockholm) are adopting common data standards to manage private operators. Standards like MDS (Mobility Data Specification) and GBFS (General Bikeshare Feed Specification) are APIs that allow cities to receive real-time data from fleets. This data is not just descriptive, but enabling: it allows cities to implement digital "Push" policies (e.g., geofenced parking bans, automatic speed limits for e-scooters in pedestrian areas) and "Pull" policies (e.g., incentives for parking in designated mobility hubs, like Berlin's "Jelbi Stations"). This data management is the technological prerequisite for a truly integrated Mobility as a Service (MaaS), in which "Push" and "Pull" policies are no longer static, but dynamically managed to optimize the entire mobility system.

2.4. Technologies implementation

The successful implementation of modal shift policies increasingly depends on the deployment of a robust technological infrastructure capable of supporting real-time data collection, processing, and decision-making (Katrakazas et al., 2019). Modern urban mobility systems can no longer rely solely on static regulations or isolated transport services; instead, they require a network of interconnected technologies that operate as an integrated ecosystem (Torre-Bastida et al., 2018), enabling dynamic and adaptive management of mobility flows.

From this perspective, enabling technologies can be categorized according to their position within the mobility data value chain: Data Acquisition Technologies, which capture information from the physical environment through sensors, Automatic Number Plate Recognition (ANPR) systems, and Global Positioning System (GPS) devices.

Data Management and Analytical Technologies, including Intelligent Transport Systems (ITS), Big Data analytics, and Artificial Intelligence (AI), which transform raw data into actionable insights for policy design, traffic optimization, and behavioural modelling.

Integration and Interaction Technologies, such as Mobility as a Service (MaaS) platforms, Digital Twins, 5G communication, Edge Computing, and Vehicle-to-Everything (V2X) systems, which ensure seamless coordination among users, vehicles, and infrastructures.

Together, these technologies form a digital backbone for sustainable mobility: they enable continuous monitoring of transport networks, predictive modelling of demand, and personalized service delivery. The integration of high-resolution data, low-latency communication, and intelligent algorithms allows for mobility systems that are not only reactive but also proactive and self-optimizing, ultimately enhancing the effectiveness of both push and pull modal shift policies.

In the following sections, each enabling technology will be analysed in detail, focusing on its technical functioning, its role in the modal shift framework, and real-world applications that demonstrate its transformative potential in achieving sustainable urban mobility.

2.4.1. Data Acquisition Technologies

The foundation of any intelligent and sustainable mobility system lies in its ability to capture accurate, high-frequency, and spatially distributed data (Torre-Bastida et al., 2018). Data acquisition technologies represent the first layer of the technological infrastructure that enables modal shift policies to transition from static regulation to dynamic data-driven management (Katrakazas et al., 2019). These technologies operate at the interface between the physical and digital domains (International Transport Forum, 2015), converting real-world phenomena, vehicle movements, occupancy levels, environmental conditions, into digital information that can be stored, processed, and analysed.

Automatic Number Plate Recognition (ANPR)

Among the most established tools for large-scale traffic monitoring is Automatic Number Plate Recognition (ANPR) technology. ANPR systems employ high-resolution cameras coupled with optical character recognition (OCR) algorithms to automatically detect and identify vehicle license plates (*Figure 2-1*). The technology relies on infrared illumination to ensure reliable performance under varying light and weather conditions, and modern systems achieve recognition accuracies exceeding 95% in real-world deployments (Tang et al., 2022; Yasin et al., 2010).

In the context of modal shift policies, ANPR represents a crucial enabler for “push” measures, particularly congestion charging, low-emission zones, and access control schemes (Tang et al., 2022). The successful implementation of systems such as the Stockholm Congestion Charge or London’s Ultra Low Emission Zone would not be feasible without automated vehicle identification technologies. By allowing vehicles to be detected, categorized, and billed in real time, without physical toll booths, ANPR enables efficient and scalable enforcement (Tang et al., 2022). The elimination of manual processes minimizes operational costs and maximizes compliance, transforming congestion charging from an administrative burden into a fluid, technology-driven solution.

Beyond fiscal applications, ANPR data also provide valuable inputs for traffic modelling, origin-destination (O/D) analysis, and travel time estimation. When integrated with other sensor networks, plate recognition contributes to constructing high-resolution mobility maps that support policy evaluation and simulation (Tang et al., 2022; Yasin et al., 2010; Du et al., 2021).

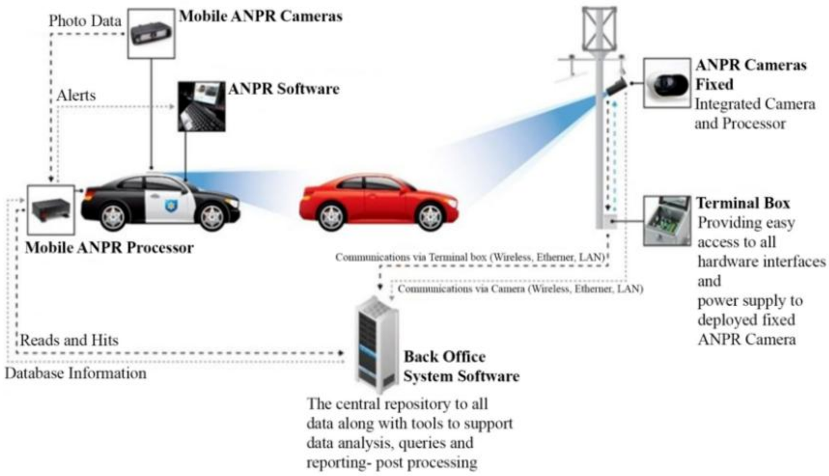


Figure 2-1: Typical ANPR System Diagram of a Fixed ANPR System (right) and a Mobile ANPR System (left)

Urban Sensing and Environmental Sensors

Complementing camera-based systems, urban sensors collect a wide range of data related to both mobility and environmental performance (Babu et al., 2023). Inductive loops, magnetometers, radar detectors, and ultrasonic sensors are traditionally deployed for vehicle counting and speed detection (Yasin et al., 2010; International Transport Forum, 2015). More recent innovations include smart pavement sensors capable of detecting vehicle presence, type, and weight, as well as acoustic and vibration sensors that capture qualitative aspects of road use.

Environmental sensors play an increasingly strategic role in linking modal shift policies with sustainability goals. Air quality monitoring stations measure concentrations of pollutants such as NO_2, $PM_{2.5}$, and CO_2, enabling policymakers to correlate traffic flows with environmental impacts. These datasets support the development of data-informed regulatory strategies, such as adaptive low-emission zones where restrictions vary dynamically according to real-time air quality indicators (Katrakazas et al., 2019).

The integration of these sensing technologies contributes to the development of urban data lakes, where multi-source information, traffic counts (Kušić et al., 2023), emissions, weather conditions, noise levels, is aggregated to provide a comprehensive representation of urban mobility ecosystems (Torre-Bastida et al., 2018).

Global Positioning System (GPS) and Mobile Data

The Global Positioning System (GPS) and its European counterpart Galileo form the backbone of individual and fleet-level mobility tracking (Harrison et al., 2020). GPS devices embedded in vehicles, smartphones or public transport fleets generate continuous streams of spatial-temporal data describing trip origins, destinations, routes and speeds (Zheng et al., 2008). The precision and ubiquity of GPS make it indispensable for both operational and strategic mobility management (Harrison et al., 2020).

At the operational level, real-time GPS tracking enables dynamic fleet management, public transport punctuality monitoring, and route optimization. For example, GPS-based data are used to adjust headways and dispatching frequencies in real time, aligning service supply with observed demand (Urbano et al., 2025). At the strategic level, aggregated and anonymized GPS traces provide insights into travel behaviour patterns, helping to identify potential modal shift opportunities, such as corridors where latent demand for cycling or public transport exists but remains under-served (Chen et al., 2016).

Furthermore, the fusion of GPS data with mobile network information (cell-ID or triangulation data) has expanded the analytical scope to a truly population-wide scale. This synergy allows for near-real-time estimation of origin-destination matrices , crucial for evaluating the impacts of policies like fare integration, parking restrictions, or new public transport lines (Chen et al., 2016; Urbano et al., 2025).

Role in Modal Shift Policies

Collectively, ANPR, environmental sensors, and GPS technologies form the data acquisition backbone that underpins modern modal shift strategies. Their ability to deliver continuous, high-resolution information enables cities to move from reactive to proactive management. Through automated monitoring, it becomes possible to:

- Quantify the behavioral impact of specific policies (e.g., reduction in car trips following a congestion charge) (Tang et al., 2022);
- Identify underutilized transport modes and optimize service allocation (Urbano et al., 2025);
- Calibrate traffic simulation models and Digital Twins with real-world data (Kušić et al., 2023);
- Support adaptive and evidence-based policymaking through real-time feedback loops (International Transport Forum, 2015).

In this sense, data acquisition technologies not only provide visibility over the mobility system but also act as catalysts for behavioural change (Harrison et al., 2020). By enabling transparent, responsive, and data-informed governance, they lay the groundwork for the intelligent, user-centred transport ecosystems required to achieve lasting modal shifts.

2.4.2. Data Management and Analytical Technologies

While data acquisition technologies capture the raw signals of urban mobility, the true intelligence of a transport system emerges in its capacity to manage, integrate and interpret that information effectively. Data management and analytical technologies form the second layer of the mobility technology stack, transforming fragmented datasets into structured knowledge that supports strategic decision-making. Within this domain, Intelligent Transport Systems (ITS), Big Data analytics, and Artificial Intelligence (AI) are the primary enablers that convert passive data collection into active system optimization.

Intelligent Transport Systems (ITS)

Intelligent Transport Systems (ITS) encompass a broad spectrum of technologies that apply information and communication systems (ICT) to improve the efficiency, safety, and sustainability of transport networks. ITSs are designed to improve transportation operations through the integration of sensors, communication networks, data centres, and user interfaces (Torre-Bastida et al., 2018).

ITS applications range from real-time traffic monitoring and adaptive signal control to public transport fleet management and traveller information systems (Katrakazas et al., 2019). For instance, Advanced Traffic Management Systems (ATMS) use data from loop detectors, cameras, and probe vehicles to optimize signal timings and reroute flows during congestion or incidents (Torre-Bastida et al., 2018). Similarly, Advanced Public Transport Systems (APTS) rely on GPS (come AVL, Automatic Vehicle Location) and APC (Automatic Passenger Counting) to dynamically adjust schedules, improving service reliability and reducing passenger waiting times (Urbano et al., 2025).

From a modal shift perspective, ITS provide the operational intelligence required to make sustainable modes, such as public transport, cycling, or walking, more reliable and competitive (Katrakazas et al., 2019). By minimizing uncertainty, improving punctuality, and delivering real-time travel information to users, ITS reduce perceived travel costs and strengthen user confidence in alternatives to private cars. In *Figure 2-2*, an example of an ITS is presented.

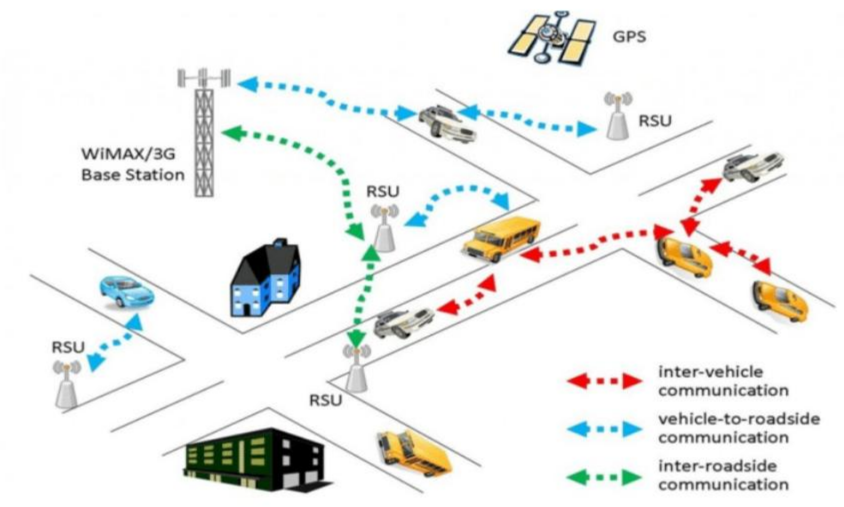


Figure 2-2: Example of an Intelligent Transport System (ITS) scenario

Big Data Analytics

The digitalization of mobility systems has generated unprecedented volumes of heterogeneous data, originating from ticketing systems, GPS traces, mobile networks, social media, and IoT devices. Big Data analytics enables transport authorities to handle this "data deluge" by applying advanced processing frameworks and algorithms capable of uncovering latent patterns and correlations (Torre-Bastida et al., 2018).

In transport planning, Big Data allows for fine-grained demand modelling that surpasses the limitations of traditional survey-based approaches. By analysing millions of travel records in real time, planners can detect spatial-temporal mobility trends, identify under-served routes, and evaluate behavioural responses to policy measures (Urbano et al., 2025). For example, integrating fare collection data (Smart Card) with smart card transactions provides insights into peak-period crowding, enabling dynamic adjustments to public transport supply (Urbano et al., 2025).

Big Data also plays a pivotal role in impact evaluation. Machine learning algorithms applied to Big Data streams can automatically detect mode-switching behaviours, distinguishing between car, bus, tram, or cycling trips based on trajectory features. This analytical capability allows decision-makers to evaluate not only the direct traffic effects but also the broader behavioural dynamics triggered by policy interventions (Zheng et al., 2008; Chen et al., 2016).

A critical aspect of Big Data management is data governance: ensuring interoperability, privacy, and ethical use of mobility data (International Transport Forum, 2015). The development of urban data platforms represents a paradigm shift toward shared, standardized data ecosystems where public and private stakeholders collaborate to manage and exploit mobility data for collective benefit (Katrakazas et al., 2019).

Artificial Intelligence (AI)

At the top of the analytical hierarchy, Artificial Intelligence (AI) introduces a transformative leap from descriptive analytics to predictive and prescriptive intelligence (Torre-Bastida et al., 2018). Machine learning (ML) and deep learning (DL) algorithms enable transport systems to autonomously recognize complex mobility patterns, predict future demand, and optimize operations accordingly (Babu et al., 2023).

In the context of modal shift, AI supports three major applications:

- Predictive Demand Modelling: AI models forecast short and long-term transport demand, enabling proactive adjustments to service frequency, vehicle allocation, or pricing schemes.
- Traffic Control and Optimization: reinforcement learning algorithms and other AI-driven optimization techniques are increasingly used to manage signal timings adaptively, coordinating entire traffic networks to minimize delays and emissions.
- User Behaviour and Personalization: AI-driven recommendation systems power Mobility as a Service (MaaS) platforms by suggesting multimodal routes tailored to user preferences, habits, and environmental conditions.

By processing data streams in real time, AI systems transform the transport network into an adaptive organism, capable of responding autonomously to disruptions, congestion, or demand peaks (Torre-Bastida et al., 2018). This continuous feedback loop between data, analysis, and control closes the gap between policy design and operational implementation, allowing modal shift strategies to evolve from static planning instruments to self-learning ecosystems.

Role in Modal Shift

Data management and analytical technologies act as the intelligence core of sustainable mobility ecosystems (Torre-Bastida et al., 2018). They provide the analytical capability to:

- Identify and quantify opportunities for modal rebalancing (Chen et al., 2016);
- Predict the impacts of policy measures before implementation (Kušić et al., 2023);
- Continuously monitor behavioural responses and adapt interventions dynamically (Urbano et al., 2025);
- Integrate technological and human dimensions of mobility planning (International Transport Forum, 2015).

Together, ITS, Big Data analytics, and AI enable a transition from reactive governance to predictive, data-driven policymaking. They represent the "brain" of the digital mobility infrastructure, translating raw data into insights, insights into actions, and actions into sustainable modal outcomes.

2.4.3. Integration and Interaction Technologies

If data acquisition and analytical systems represent the senses and brain of an intelligent mobility ecosystem, integration and interaction technologies constitute its nervous system, the set of digital infrastructures that enable communication, synchronization and interaction among users, vehicles, and infrastructures. These technologies ensure that information generated at the sensing and analytical levels can be transmitted, processed, and acted upon in real time. Their collective purpose is to create a seamless, user-centred, and adaptive mobility experience, capable of supporting large-scale modal shifts through integration rather than fragmentation.

Mobility as a Service (MaaS)

Mobility as a Service (MaaS) represents a paradigm shift in the organization and consumption of transport services. Instead of relying on fragmented and mode-specific systems, MaaS integrates various mobility services, public transport, car sharing, bike sharing, e-scooters, taxis and on-demand shuttles into a single digital platform. Through a unified application interface, users can plan, book and pay for multimodal trips in one transaction, while receiving real-time updates and dynamic suggestions based on system conditions.

From a technical perspective MaaS relies on Application Programming Interfaces (APIs) that allow interoperability among multiple service providers and data platforms (*Figure 2-3*). However, effective integration is hindered by barriers such as the "lack of cooperation" among stakeholders. As identified by Caiati et al. (2025), the success of MaaS depends on resolving the tension between an "Open Ecosystem," based on standardized APIs that promote innovation, and a "Walled Garden," in which dominant operators restrict access to data and APIs, leading to market fragmentation.

In terms of modal shift, MaaS is considered one of the most effective "pull" technologies. By reducing cognitive, temporal, and logistical barriers between modes, it makes public and shared transport options as convenient as private car use. Empirical evidence from pilot projects shows that MaaS adoption can reduce private car trips, especially among commuters with access to high-quality public transport and reliable digital infrastructure (Caiati et al., 2025).

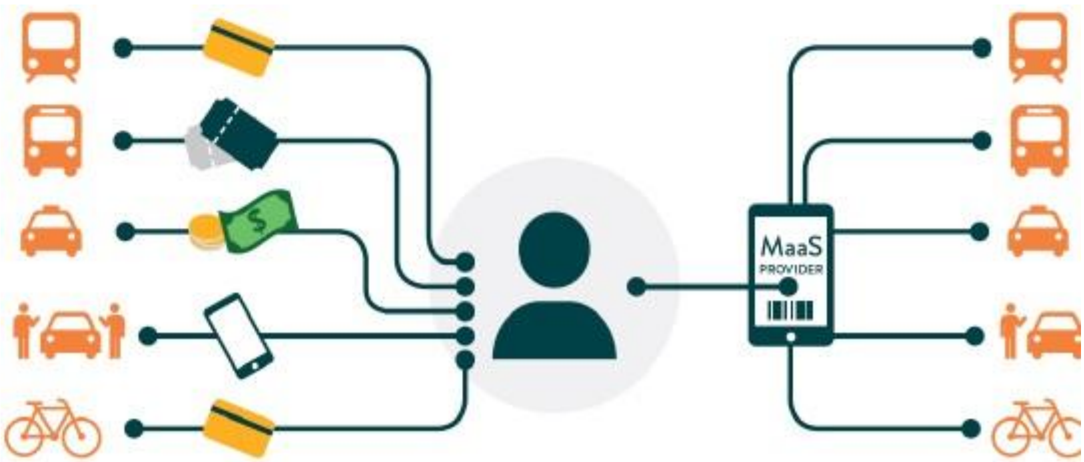


Figure 2-3: MaaS System Scheme

Digital Twins

The concept of Digital Twins (DTs) introduces an unprecedented level of intelligence into urban mobility management. A Digital Twin is a virtual, continuously updated replica of a physical system, such as a transport network or an entire city, fed by real-time sensor data and representing a real-time synergy between traffic data flows and simulation (Kušić et al., 2023) (*Figure 2-4*).

In the context of modal shift, Digital Twins provide a decision-support environment where scenarios like new bike lane deployment, dynamic tolling schemes, or parking policy changes can be virtually tested. Using data-driven simulations, often microscopic, such as SUMO, Digital Twins enable authorities to assess environmental, social, and economic impacts under multiple conditions, thereby reducing implementation risks. Advanced models integrate agent-based simulations and AI to predict behavioural responses at individual and collective levels (Kušić et al., 2023).

Moreover, DTs facilitate cross-domain integration, linking transport data with urban planning, energy management, and environmental monitoring systems. This systemic view aligns with the "Avoid–Shift–Improve" framework of sustainable mobility, supporting more holistic and resilient policy design.

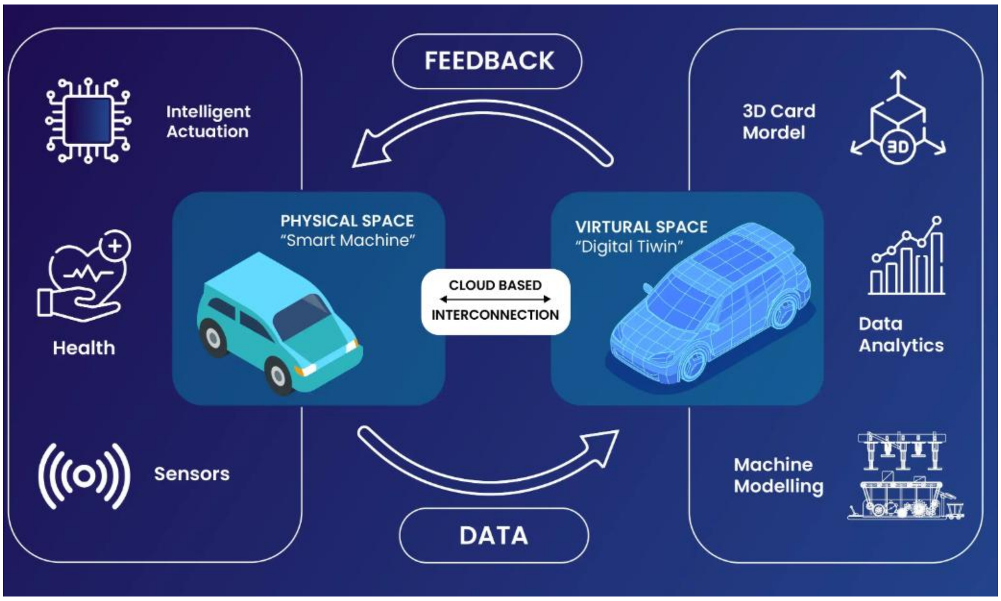


Figure 2-4: Digital Twin Functional Scheme

5G and Edge Computing

The transition to real-time, high-resolution mobility management is underpinned by next-generation communication networks, particularly 5G and Edge Computing. While 4G technologies provided sufficient bandwidth for data transfer, 5G introduces ultra-low latency (URLLC) e massive connectivity (mMTC)capable of supporting thousands of connected devices per square kilometres. This enables instantaneous communication among vehicles, sensors, and control centres, essential for safety-critical and time-sensitive applications (Kononova et al., 2020; Almeida et al., 2025).

Edge Computing complements 5G by decentralizing computational resources. Instead of sending all data to distant cloud servers, processing occurs at the network "edge", closer to where data are generated. This architecture reduces transmission delays, enhances privacy, and enables real-time decision-making in mobility systems (Torre-Bastida et al., 2018). For instance, in traffic management, Edge Computing nodes can process sensor data locally to adapt traffic light cycles or provide immediate hazard alerts to vehicles without waiting for central validation.

Together, 5G and Edge Computing form the communication backbone of future mobility, supporting distributed intelligence across the network. There is a "dynamic symbiosis" between mobility and 5G, where the network is not just a channel, but mobility data can be used to dynamically allocate network resources. (Almeida et al., 2025). In *Figure 2-5*, the scheme of the Edge Computing is presented.

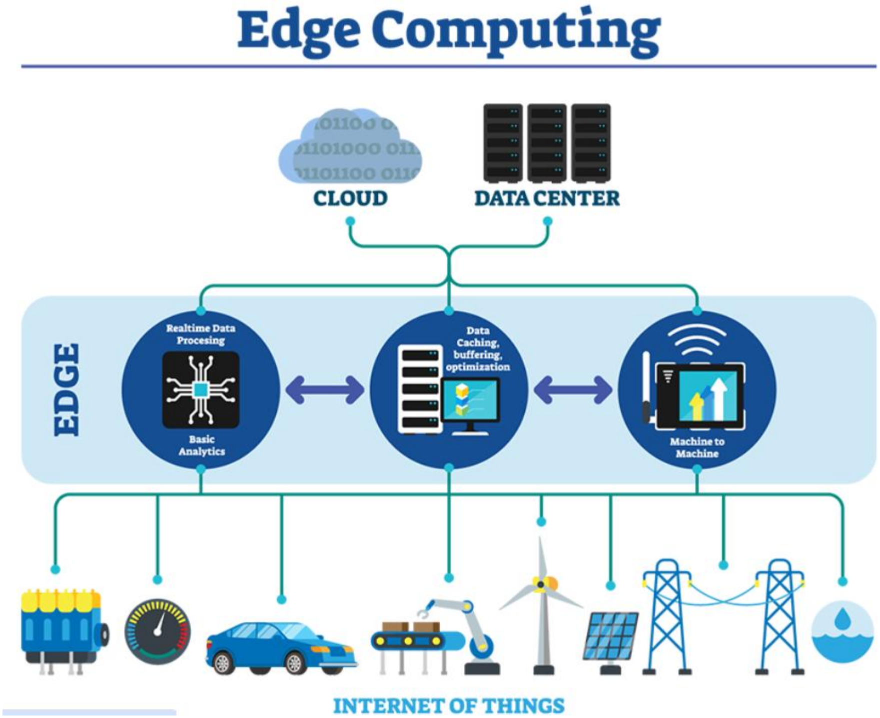


Figure 2-5: Edge Computing Functional Scheme

Vehicle-to-Everything (V2X) Communication

At the interface between communication networks and mobility operations lies Vehicle-to-Everything (V2X) technology, a framework enabling direct communication among vehicles (V2V), between vehicles and infrastructure (V2I), and with other road users like pedestrians (V2P) (Zohir et al., 2025). V2X operates through Dedicated Short Range Communications (DSRC) or, more recently, through Cellular-V2X (C-V2X), which leverages the 5G network (Sadeeq & Ajao, 2024).

In practical terms, V2X systems enable cooperative awareness: vehicles can anticipate traffic events, coordinate manoeuvres, and adjust speeds to avoid congestion or collisions (Zohir et al., 2025). To manage the high volume of data, C-V2X protocols prioritize message transmission based on the level of risk (e.g., “collision risk probability”), ensuring that critical safety alerts take precedence (Sadeeq & Ajao, 2024). For public transport, V2X allows priority signalling, where buses or trams communicate directly with traffic lights to request green phases, reducing delays and increasing service reliability.

By fostering coordination and safety, V2X technologies strengthen the systemic efficiency of the transport network, creating conditions in which shared and active modes become more viable and competitive. Furthermore, V2X encompasses the integration with energy grids, such as V2G (Vehicle-to-Grid), enabling electric vehicles to act as storage units to stabilize the grid (Safari & Rahimi, 2025). In *Figure 2-6*, an example of a V2X scenario is presented.

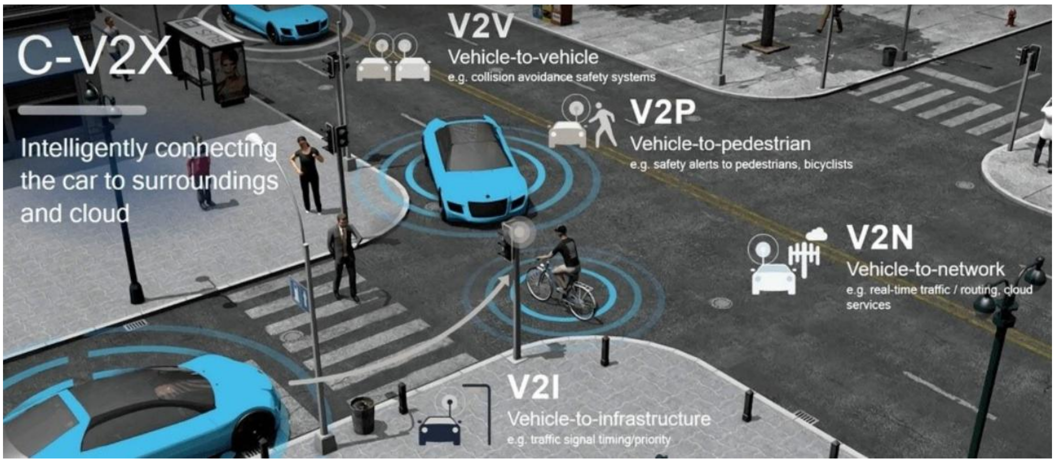


Figure 2-6: V2X Functional Scheme

Role in Modal Shift

Integration and interaction technologies collectively act as the connective tissue of sustainable mobility (Torre-Bastida et al., 2018). They close the loop between users, services, and infrastructures, enabling transport systems that are interoperable, predictive, and user-centric. Through data integration (Maas), virtual simulation (Digital Twins), low-latency communication (5G, Edge Computing), and cooperative coordination (V2X), these technologies transform fragmented urban mobility landscapes into cohesive, adaptive ecosystems.

From a policy standpoint, their value lies not only in technological innovation but also in institutional integration (Caiati et al., 2025), aligning transport operators, digital providers, and public authorities under a shared governance framework (International Transport Forum, 2015). Ultimately, these technologies enable the scalability, personalization, and resilience required to achieve lasting modal shifts toward sustainable, connected, and intelligent mobility systems.

3. Development of a Predictive Metamodel for Modal Shift

This chapter aims to illustrate the methodological and analytical process that led to the design, calibration, and implementation of the predictive metamodel for modal shift, the core instrument of this study. While the scientific literature has widely demonstrated the necessity of transitioning toward sustainable mobility paradigms (Banister, 2005; Pucher & Buehler, 2017), an operational gap still remains for public decision-makers in translating financial resources into quantifiable behavioural impacts. The metamodel presented here emerges as a response to this strategic planning need, positioning itself as a Decision Support System capable of estimating the relative effectiveness of different transport policies across heterogeneous territorial contexts.

Specifically, the methodological narrative will unfold through a sequential path beginning with the definition of the model's functional logic and objectives, grounded in the principle of causality between investment, physical output, and demand variation. This will be followed by a rigorous examination of the data collection and processing methodology, based on a comparative analysis of international best-practice case studies, which provided the empirical foundation for defining the calculation parameters.

A crucial section will be devoted to the model's parameterization, outlining the criteria for determining unit costs and elasticity coefficients, key variables influencing system sensitivity. Subsequently, the concept of territorial differentiation based on the Functional Urban Areas (FUA) model (OECD, 2012) will be introduced, which is essential for adapting the metamodel's outputs to specific urban, metropolitan, or extra-urban morphologies. The chapter will conclude with a technical description of the metamodel's architecture in Excel, detailing the structure of the calculation matrices, the management of synergies between Push and Pull policies, and the configuration of simulation scenarios that ultimately enable the identification of the most efficient investment trajectories for achieving modal rebalancing objectives.

3.1. Territorial Characterization: The Functional Urban Areas (FUA) Model

Before proceeding with the technical examination of the metamodel, it is essential to precisely frame the territorial and statistical context in which it is applied. The effectiveness of a modal shift policy cannot be separated from the morphology and functional dynamics of the territory in which it is implemented. To this end, this work adopts the classification of Functional Urban Areas (FUA) proposed by Istat, in accordance with Regulation (EU) 2017/2391, to define the macro-intervention areas within Italy.

The adoption of FUAs allows overcoming the limitations of purely administrative divisions by identifying territorial units based on actual population concentration and commuting flows for work purposes. The metamodel incorporates this classification by making a fundamental distinction between three types of areas, for each of which specific efficiency parameters have been calibrated:

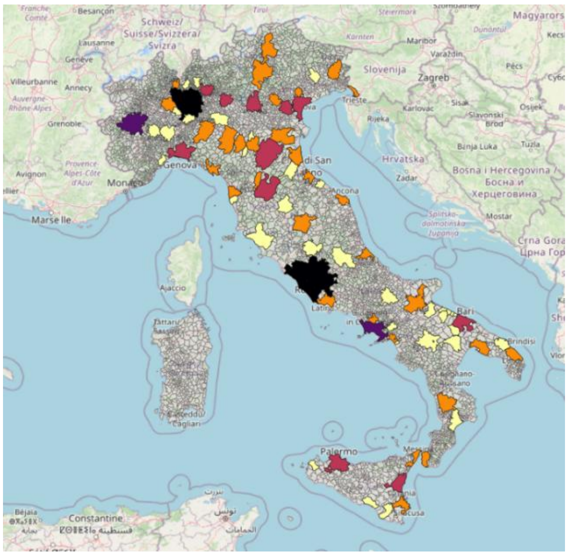
- **Metropolitan Area (Cities or Densely Populated Zones):** Corresponds to high-density agglomerations (large urban areas or Greater Cities) where complex economic functions are concentrated. In these contexts, the metamodel assigns the highest elasticities to heavy infrastructure (Metro, Tram) and Road Pricing policies, leveraging the high demand density and the presence of structured alternatives that make private car disincentives extremely effective.
- **Urban Area (Small Cities and Suburbs or Intermediate-Density Zones):** Identifies areas where the population primarily resides in medium-density urban agglomerations. Within the metamodel, this zone is characterized by strong sensitivity to active mobility policies (Cycling, Pedestrianization) and local regulation measures (30 km/h Zones, LEZs), reflecting typically intra-urban travel distances where public space redevelopment serves as the main driver for modal shift.
- **Extra-Urban Area (Rural or Sparsely Populated Zones):** Includes commuter zones and rural areas where over 50% of the population resides in low-density

cells. In this context, the model's logic changes significantly: the elasticity of fixed-route systems is set to zero in favour of flexible solutions such as DRT (Demand Responsive Transport). The metamodel recognizes the strategic role of multimodal hubs and Park & Ride facilities as interception nodes for vehicle flows directed toward urban centres.

The construction of FUAs is based on a dual criterion: population concentration and economic attraction. A FUA consists of a City (the densely populated urban core) and its commuting zone, defined as the set of surrounding municipalities where at least 15% of the employed population commutes to the central city for work. This functional distinction is crucial for calibrating the model's elasticities: for example, a Maas policy or fare integration measure assumes higher efficiency in extra-urban areas if aimed at connecting with the metropolitan hub, reducing interchange barriers for commuters.

Adopting this non-administrative geography ensures the metamodel's precision in evaluating the cost-effectiveness of investments. By assigning specific elasticity values for Metropolitan, Urban, and Extra-Urban Areas, the tool overcomes "blind" planning relative to territorial morphology, directing resources toward the technologies and policies that best align with the intrinsic density and mobility characteristics of each zone.

In *Figure 3-1*, the Italian Functional Urban Areas Map, made on QGIS, is presented, with the legend in *Figure 3-2*.



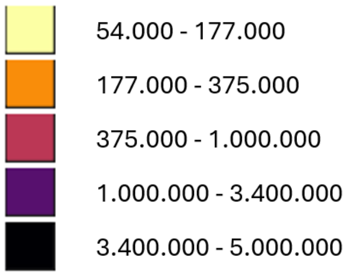


Figure 3-1: Italian Functional Urban Areas Map Legend (Population)

Figure 3-2: Italian Functional Urban Areas Map on QGIS

3.2. Objectives and Functional Logic of the Model

The primary objective of the metamodel is to create an analytical tool capable of overcoming the fragmentation of qualitative assessments by providing a quantitative and comparative estimate of the effectiveness of sustainable mobility policies. In a context characterized by the need to allocate limited public resources, the model is conceived as a Decision Support System (DSS) designed to identify which investments ensure the highest return in terms of modal rebalancing for each monetary unit spent.

However, it is essential to clarify that the objective of the metamodel is not to create a self-adjusting systemic simulator, but rather to provide a comparative framework that enables the precise isolation of the effectiveness of each individual policy lever. The functional logic is therefore analytical and comparative in nature: the model processes each policy separately in order to allow planners to compare, under equal investment levels or target objectives, which measure ensures the highest marginal return. In this architecture, the approach oriented toward "policy packages" is not an automatic function of the model, but rather represents the strategic purpose of the evaluation, which is left to the decision-maker.

The functional logic of the model is structured around a linear yet rigorous causal chain that transforms economic input into behavioural impact. This architecture unfolds through the following logical-mathematical stages:

- **Financial Input (€):** Represents the total volume of investment allocated to the implementation of a specific policy.
- **Determination of Physical Output:** Financial resources are converted into a physical dimension through the application of a Unit Cost (€/unit). This parameter, normalized for the specific type of intervention (e.g., cost per kilometre of cycling lane, cost per new bus), makes it possible to define the tangible scale of the implemented policy.
- **Supply Elasticity Coefficient:** The physical output is multiplied by an elasticity factor, which expresses the intrinsic capacity of a given measure to

attract users away from private modes. Elasticity is defined as the percentage of modal shift generated per unit of physical output delivered.

- **Modal Shift (%):** The final result is the estimated share of mobility that effectively transfers from private vehicles to sustainable modes.

This analytical decomposition responds to three fundamental requirements for strategic planning:

- **Performance isolation**: By analysing policies separately, the model allows for the precise identification of the specific contribution of each measure. This prevents the benefits of an efficient policy from masking the inefficiencies of another within an aggregated calculation, enabling a clear distinction, for example, between the impact of a DRT system and that of a tram line.
- **Support for manual composition of the mix**: The model provides the quantitative "building blocks" (costs and elasticity); it is then up to the decision-maker, based on the separate results, to compose the ideal mix of interventions. The development of an integrated mobility plan therefore occurs through a critical analysis of the outcomes, promoting the creation of coordinated policy packages.
- **Data transparency**: The separation of analyses ensures that each modal shift value is directly attributable to a specific investment and elasticity. This eliminates statistical "noise" arising from complex interactions that could obscure the understanding of individual causal links between public expenditure and environmental impact.

In summary, the functional logic of the metamodel is that of a parameterized efficiency catalogue: a tool that clearly shows how much a single percentage point of modal shift "costs" for each technological, infrastructural, or regulatory option available.

3.3. Data Collection Methodology and Case Study Analysis

The scientific validity of a decision-making metamodel intrinsically depends on the quality and heterogeneity of the data used for its calibration. For this reason, the data collection phase was structured as a rigorous international benchmarking exercise, aimed at mapping the state of the art of modal shift policies implemented over the past three decades. The adopted methodological approach allowed for moving beyond simple descriptive analysis, extracting quantitative parameters, in terms of economic investments and percentage changes in modal share, necessary to feed the metamodel's computational engine.

The selection of case studies was guided by criteria of geographic relevance, demographic diversity, and informational completeness, focusing on contexts that have demonstrated a proven ability to reduce dependence on private vehicles.
Specifically, the information extraction process focused on the previously mapped deterrence (Push) and incentive (Pull) policies, analysing demand responses to economic, regulatory, and infrastructural interventions. Through the study of established experiences such as Singapore, Stockholm, and Milan, it was possible to precisely calibrate the elasticities related to congestion pricing and parking management, observing how the internalization of negative externalities directly affects modal choices. At the same time, the analysis of the Vienna and Freiburg models provided the data needed to quantify the effectiveness of investments in service quality and rail-oriented planning (Transit-Oriented Development), while the cases of Copenhagen and Vancouver enabled the parameterization of the performance of cycling infrastructure and ITS technologies applied to active mobility.

However, the investigation highlighted that the availability of granular and uniform data is not consistent across the full spectrum of policies integrated into the metamodel. While the literature provides comprehensive case studies for major public transport infrastructure or road pricing systems, for some emerging or softer measures, such as the development of Maas platforms, the creation of multimodal hubs, or specific micromobility interventions, obtaining historical series relating physical investment to the resulting modal shift proved to be more challenging.

In these cases, the methodology involved integrating empirical evidence with a hypothetical-analytical approach. For policies lacking direct reference in the analysed case studies, parameters were derived through logical inference, based on market averages for unit costs and calibrating elasticities according to the functional hierarchy of similar measures already validated. This procedure ensured the internal consistency of the model, allowing for a complete efficiency catalogue despite the partial fragmentation of historical data, while ensuring that each entry in the catalogue remained anchored to a structured and coherent logic consistent with the principles of transport engineering.
Below, in *Table 3-1*, it is shown which indicators were found/calculated from the case studies (and by which ones) and which ones were instead assumed (in grey).

INDICATORS ORIGIN		CITIES OF THE CASE STUDIES																					
		Vienna	Stockholm	Goteburg	Germany	Perth	Paris	Singapore	Rotterdam	Milan	Hanoi	Bonn	Bruges	Copenhagen	Freiburg	Lucknow	Katmandu	Barcelona	Lisbon	Tallin	Cina	Seoul	Vancouver
INDICATORS OF: (Unit costs, Elasticities)	Parking pricing					X	X																
	Road pricing		X	X				X															
	LTZ							X		X													
	LEZ								X	X													
	30 km/h																						
	Pedestrianisation							X					X										X
	Construction of cycle paths	X											X	X	X								X
	Fare reduction	X			X							X											
	Fare free																			X			
	Subway construction	X													X	X							
	Bus fleet renewal							X															
	Train fleet renewal																						
	Increase in bus frequency																						
	Increase in train frequency																						
	Tram Costruction																						
	DRT																						
	BRT																X						
	Park & ride																						
	Bike sharing																						
	Car sharing																						
	Hub multimodale																						
	MaaS																						

Table 3-1: Indicators Origin Table

3.4. Model Parameterization: Unit Costs and Elasticities

The parameterization phase represents the analytical core of the metamodel, as it determines the tool's sensitivity and its ability to translate macroeconomic variables into behavioural changes. The construction of the numerical dataset required a bimodal calibration process, rigorously distinguishing between empirically derived parameters and those determined through a hypothetical-analytical procedure.

Within the Excel software architecture, this distinction is visually represented through colour coding to ensure methodological transparency: white cells identify data extracted directly from scientific literature and case studies, while grey cells indicate assumptions calibrated by the author based on logical inference and sector benchmarks.

Unit Costs: Translating Investment into Physical Output

The first pillar of parameterization concerns the definition of unit costs (*Table 3-2*), which are necessary to convert financial input into a measurable physical entity, normalized by policy type.

- **Empirical Data (Market Benchmarks):** For heavy transport infrastructure and consolidated deterrence policies, unit costs were derived from the analysis of public budgets and technical reports of international projects. The costs per kilometre of metro, tram, and BRT were aligned with values observed in dense contexts such as Vienna, including expenditure items related to civil works and technological systems. Similarly, the implementation costs of ANPR gateways for Road Pricing and LEZ systems were calibrated based on the operational experiences of Milan and Stockholm.
- **Analytical Estimates (Sector Averages):** For measures where the literature did not provide a single or clearly isolated financial figure, such as the creation of multimodal hubs, the development of MaaS platforms, or traffic calming interventions, an "average unit cost" was formulated. The definition of a unique and representative benchmark for these interventions proves complex, as they are characterized by costs and impacts that are highly diversified, depending

strictly on the specific application context and territorial morphology. The effectiveness and implementation expenditure of such "soft" or regulatory measures are intrinsically linked to the pre-existing infrastructure and local demand density. Consequently, these values were derived by cross-referencing public price lists for road works, market analyses for digital services, and European benchmarks on public space redevelopment, ensuring that the physical output generated by the model remains consistent with current implementation standards. Specifically, the parameters were estimated or hypothesized by evaluating the costs and benchmarks reported in sources [40], [41], and [42] of the bibliography.

Unit Cost

Policy	Metropolitan	Urban	Extra-Urban	Unit of measure
Parking pricing	7,000 €	7,000 €	7,000 €	€/parking meter
Road pricing	6.67 €	6.67 €	6.67 €	€/m^2
LTZ	0.80 €	0.80 €	0.80 €	€/m^2
LEZ	2 €	2 €	2 €	€/m^2
30 km/h	0.08 €	0.08 €	0.08 €	€/m^2
Pedestrianisation	200 €	200 €	200 €	€/m^2
Construction of cycle paths	200,000 €	200,000 €	200,000 €	€/km
Fare reduction	84 €	84 €	84 €	€/ticket
Fare free	449 €	449 €	449 €	€/ticket
Subway construction	150,000,000 €	150,000,000 €	150,000,000 €	€/km
Bus fleet renewal	400,000 €	400,000 €	400,000 €	€/bus
Train fleet renewal	8,000,000 €	8,000,000 €	8,000,000 €	€/train
Increase in bus frequency	150 €	150 €	150 €	€/ride
Increase in train frequency	1,500 €	1,500 €	1,500 €	€/ride
Tram Costruction	22,000,000 €	22,000,000 €	22,000,000 €	€/km
DRT	125,000 €	125,000 €	125,000 €	€/bus
BRT	8,000,000 €	8,000,000 €	8,000,000 €	€/km
Park & ride	7,000 €	7,000 €	7,000 €	€/parking meter
Bike sharing	25,000 €	25,000 €	25,000 €	€/station
Car sharing	25,000 €	25,000 €	25,000 €	€/vehicle
Hub multimodale	5,000,000 €	2,500,000 €	1,000,000 €	€/hub
MaaS	120 €	120 €	120 €	€/user

Table 3-2: Unit Costs Table (White=Empirical Derivation; Grey=Hypothetical-Analytical Assumptions)

Elasticities: The Capacity to Generate Modal Shift

The second and most critical pillar concerns the elasticity coefficients (*Table 3-3*), defined as the percentage of modal shift generated for each unit of physical output delivered. This parameter is not static; rather, it reflects the complexity of psychological, economic, and convenience-related barriers that influence users' choices.

- **Empirical Derivation (% Shift / Output):** The elasticities classified as empirical (white cells) represent the result of a reverse calculation performed on the analysed case studies, in which the ex-post observed modal shift percentage was divided by the physical magnitude of the implemented intervention. This procedure made it possible to isolate, for example, the actual impact of each additional kilometre of cycling network in Copenhagen or the user-attraction effect generated by the introduction of one square meter of Road Pricing infrastructure in Stockholm.

- **Hypothetical-Analytical Assumptions and Logical Hierarchy**: For policies whose modal shift data were fragmented or not directly attributable to a single investment, elasticities (grey cells) were estimated according to a hierarchy grounded in logical and functional reasoning. For example, it was assumed that the elasticity of a 30 km/h zone should be proportionally lower than that of a metro line, given its significantly lower capacity in terms of seat-km supply, and also lower than that of a Limited Traffic Zone (LTZ), due to the reduced level of perceived inconvenience imposed on users.
  Similarly, a Demand Responsive Transport (DRT) system was assumed to be less attractive than metro, tram, or BRT systems, particularly in metropolitan contexts, while being relatively more attractive in extra-urban areas where conventional public transport services are more limited.

Elasticity

Policy	Metropolitan	Urban	Extra-Urban	Unit of measure
Subway construction	0.0118	0.005	0	km
LTZ	1.25E-08	9.38E-09	4.00E-09	m^2
LEZ	1.66E-08	1.00E-08	5.00E-09	m^2
30 km/h Area	4.50E-09	3.00E-09	1.20E-09	m^2
Parking pricing	1.00E-04	7.50E-05	4.00E-05	parking meter
Road pricing	3.33E-09	2.00E-09	1.00E-09	m^2
Pedestrianisation	1.33E-06	7.00E-07	2.00E-07	m^2
Fare reduction	1.10E-08	7.00E-09	3.00E-09	tickets
Fare free	1.30E-08	9.00E-09	4.00E-09	tickets
Bus fleet renewal	0.0005	0.00075	0.0003	bus number
Train fleet renewal	0.0008	0.0006	0.0004	train number
Increase in bus frequency	0.000007	0.000015	0.00001	ride
Increase in train frequency	0.00002	0.000012	0.000007	ride
Tram Costruction	0.006	0.002	0.0005	km
DRT	0.0001	0.00015	0.0002	bus
BRT	0.004	0.002	0.0005	km
Park & ride	0.00015	0.00012	0.00005	parking meter
Construction of cycle paths	0.0000297	0.00002	0.00001	km of bike lanes
Bike sharing	0.00015	0.0001	0.00005	station
Car sharing	0.00005	0.00006	0.00002	vehicle
Hub multimodale	0.03	0.01	0.005	hub
MaaS	0.00003	0.000015	0.000005	users

Table 3-3: Elasticities Table (White=Empirical Derivation; Grey=Hypothetical-Analytical Assumptions)

Logical Validation and Model Limitations

Although the metamodel relies on analytical estimates to ensure the completeness of the policy catalogue, the validity of the tool lies in its internal consistency and the transparency of its assumptions. The parameterization does not aim to provide an absolute mathematical truth, but rather to define a reference framework for the analysis of relative cost-effectiveness. Acknowledging the intrinsic uncertainty of the hypothesized data (grey cells) and balancing it with the robustness of empirical data (white cells) allows the metamodel to function as a strategic compass, highlighting the most promising investment trajectories based on the best historical evidence available in transport engineering.

3.5. Meta model Architecture in Excel

The technical architecture of the metamodel, implemented through Microsoft Excel, represents the operational translation of all the theoretical, empirical, and geographical premises analysed in the previous sections. The tool is designed to function as an analytical interface, capable of processing heterogeneous variables to provide a comprehensive overview of the feasibility and effectiveness of sustainable mobility strategies. The structural organization of the file is designed to ensure maximum data transparency and reproducibility of results, being arranged in interconnected worksheets that reflect the territorial segmentation of the Functional Urban Areas (FUA).

Structure of Worksheets and Data Flow

The metamodel is organized into worksheets dedicated to Metropolitan, Urban, and Extra-Urban areas. Each sheet is structured as a matrix where the rows correspond to the 22 selected intervention policies, categorized as Push and Pull measures, and the columns represent the sequential steps of the calculation chain (*Figure 3-1*):

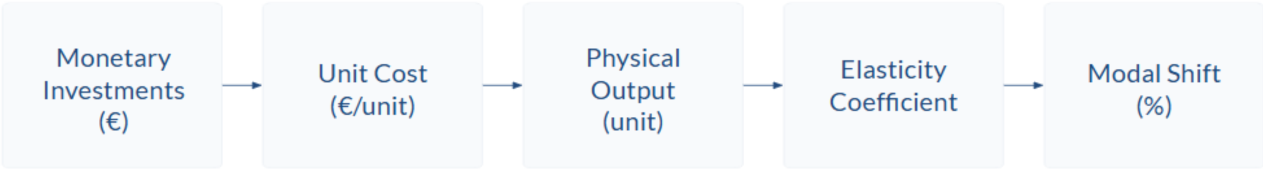


Figure 3-3: Meta-Model Scheme

- Financial Input (€): An editable cell where the monetary allocation for the specific policy is entered.
- Unit Cost Matrix: A protected section containing reference values (€/unit) derived from case study analysis (white cells) or market averages (grey cells). The software automatically divides the investment by the unit cost to determine the Physical Output generated.
- Vector of Specific Elasticities: In this section, the model applies the elasticity coefficient corresponding to the FUA area in question. The worksheet's logic ensures that, for example, in the "Extra-Urban" sheet, the elasticity for metro construction is set to zero, inhibiting any modal shift calculation for that measure, regardless of the investment entered.
- Modal Shift Calculation (%): The final cell of each row multiplies the physical output by the elasticity, returning the expected percentage of modal shift for that specific measure.

Implementation of Simulation Scenarios

The analytical power of the Excel architecture lies in its ability to operate through two distinct simulation type, designed to support different stages of the decision-making process:

1) **Plausible Investment Scenario (Impact Analysis):** In this configuration, the user enters realistic budgets based on hypothetical public spending plans. The metamodel allows immediate visualization of the distribution of modal shift across the various policies, highlighting which interventions produce the most significant results for a "standard" level of expenditure. This mode is essential for assessing the effectiveness of coordinated policy packages within the context of available resources.

2) **1% Target Shift Scenario (Relative Efficiency Analysis)**: This function represents the most advanced application of the DSS. Using inverse calculations or the "Goal Seek" function, the model automatically computes the financial investment required to achieve exactly a 1% increase in modal shift for each policy. This setup transforms the metamodel into a Cost-Effectiveness Analysis tool, enabling immediate horizontal comparison: the planner can clearly see how, to achieve the same 1% shift, the investment required for a 30 km/h zone may be orders of magnitude lower than that needed for a tram line, while still accounting for the different capacities of each measure to absorb total demand.

User Interface and Methodological Transparency

The architecture allows for easy scalability: adding new policies or updating unit costs and elasticities, following new technological evidence such as advancements in AI or V2X systems, only requires inserting new parameters into the source matrix, without altering the underlying calculation logic.

In conclusion, the Excel architecture is not merely a calculation support tool, but functions as a dynamic model synthesizing the economic costs of supply with the behavioural responsiveness of demand, calibrated to the specific functional geographies of the Italian territory.

Below (*Table 3-4, Table 3-5, Table 3-6, Table 3-7, Table 3-8, Table 3-9*) are illustrated the different metamodel schemes, differentiated by Metropolitan, Urban, and Extra-Urban areas and divided into the two scenarios: Hypothetical-Realistic Investments and the 1% Scenario.

		Metropolitan Area					
		Policy	Monetary Investment	Unit Cost	Physical Output	Elasticity	Modal Shift
PUSH	ECONOMIC MEASURES	Parking pricing	5,000,000 €	7,000 €	714.2857143	1.00E-04	7%
		Road Pricing	300,000,000 €	7 €	44977511.24	3.33E-09	15%
	REGULATORY AND ACCESS MEASURES	LTZ	10,000,000 €	1 €	12500000	1.25E-08	16%
		LEZ	10,000,000 €	2 €	5000000	1.66E-08	8%
		30 km/h zone	1,000,000 €	0 €	12500000	4.50E-09	6%
	INFRASTRUCTURAL MEASURES	Pedestrianisation	10,000,000 €	200 €	50000	1.33E-06	7%
PULL	PT FARE	Fare Reduction	500,000,000 €	84 €	5952380.952	1.10E-08	7%
		Fare Free	500,000,000 €	449 €	1113585.746	1.30E-08	1%
	IMPROVING SERVICE QUALITY	Subway construction	3,000,000,000 €	150,000,000 €	20	0.0118	24%
		Bus fleet renewal	100,000,000 €	400,000 €	250	0.0005	13%
		Train fleet renewal	100,000,000 €	8,000,000 €	12.5	0.0008	1%
		Increase in bus frequency	1,000,000 €	150 €	6666.666667	0.000007	5%
		Increase in train frequency	10,000,000 €	1,500 €	6666.666667	0.00002	13%
		Tram Costruction	250,000,000 €	22,000,000 €	11.36363636	0.006	7%
		DRT	10,000,000 €	125,000 €	80	0.0001	1%
		Construction of cycle paths	200,000,000 €	200,000 €	1000	0.0000297	3%
		BRT	250,000,000 €	8,000,000 €	31.25	0.004	13%
	DEVELOPING INTERMODALITY	Park & Ride	5,000,000 €	7,000 €	714.2857143	0.00015	11%
		Bike Sharing	10,000,000 €	25,000 €	400	0.00015	6%
		Car Sharing	10,000,000 €	25,000 €	400	0.00005	2%
		Hub Multimodale	10,000,000 €	5,000,000 €	2	0.03	6%
		Maas	1,000,000 €	120 €	8333.333333	0.00003	25%

Table 3-4: Meta-Model (Metropolitan Area)

Ultimo salvataggio della cartella di lavoro: Adesso

		Urban Area					
		Poli		t Cost	Physical Output	Elasticity	Modal Shift
PUSH	ECONOMIC MEASURES	Parking pricing	5,000,000 €	7,000 €	714.2857143	7.50E-05	5%
		Road Pricing	300,000,000 €	7 €	44977511.24	2.00E-09	9%
	REGULATORY AND ACCESS MEASURES	LTZ	10,000,000 €	1 €	12500000	9.38E-09	12%
		LEZ	10,000,000 €	2 €	5000000	1.00E-08	5%
		30 km/h	1,000,000 €	0 €	12500000	3.00E-09	4%
	INFRASTRUCTURAL MEASURES	Pedestrianisation	10,000,000 €	200 €	50000	7.00E-07	4%
PULL	PT FARE	Fare Reduction	500,000,000 €	84 €	5952380.952	7.00E-09	4%
		Fare Free	500,000,000 €	449 €	1113585.746	9.00E-09	1%
	IMPROVING SERVICE QUALITY	Subway construction	3,000,000,000 €	150,000,000 €	20	0.005	10%
		Bus fleet renewal	100,000,000 €	400,000 €	250	0.00075	19%
		Train fleet renewal	1,000,000,000 €	8,000,000 €	125	0.0006	8%
		Increase in bus frequency	1,000,000 €	150 €	6666.666667	0.000015	10%
		Increase in train frequency	10,000,000 €	1,500 €	6666.666667	0.000012	8%
		Tram Costruction	250,000,000 €	22,000,000 €	11.36363636	0.002	2%
		DRT	10,000,000 €	125,000 €	80	0.00015	1%
		Construction of cycle paths	10,000,000 €	200,000 €	50	0.00002	0%
		BRT	250,000,000 €	8,000,000 €	31.25	0.002	6%
	DEVELOPING INTERMODALITY	Park & Ride	5,000,000 €	7,000 €	714.2857143	0.00012	9%
		Bike Sharing	10,000,000 €	25,000 €	400	0.0001	4%
		Car Sharing	10,000,000 €	25,000 €	400	0.00006	2%
		Hub Multimodale	10,000,000 €	2,500,000 €	4	0.01	4%
		Maas	1,000,000 €	120 €	8333.333333	0.000015	13%

Table 3-5: Meta-Model (Urban Area)

		Extra-Urban Area					
		Policy	Monetary Investment	Unit Cost	Physical Output	Elasticity	Modal Shift
PUSH	ECONOMIC MEASURES	Parking pricing	5,000,000 €	7,000 €	714.2857143	4.00E-05	3%
		Road Pricing	300,000,000 €	7 €	44977511.24	1.00E-09	4%
	REGULATORY AND ACCESS MEASURES	LTZ	10,000,000 €	1 €	12500000	4.00E-09	5%
		LEZ	10,000,000 €	2 €	5000000	5.00E-09	3%
		30 km/h	1,000,000 €	0 €	12500000	1.20E-09	2%
	INFRASTRUCTURAL MEASURES	Pedestrianisation	10,000,000 €	200 €	50000	2.00E-07	1%
PULL	PT FARE	Fare Reduction	500,000,000 €	84 €	5952380.952	3.00E-09	2%
		Fare Free	500,000,000 €	449 €	1113585.746	4.00E-09	0%
	IMPROVING SERVICE QUALITY	Subway construction	3,000,000,000 €	150,000,000 €	20	0	0%
		Bus fleet renewal	100,000,000 €	400,000 €	250	0.0003	8%
		Train fleet renewal	1,000,000,000 €	8,000,000 €	125	0.0004	5%
		Increase in bus frequency	1,000,000 €	150 €	6666.666667	0.00001	7%
		Increase in train frequency	10,000,000 €	1,500 €	6666.666667	0.000007	5%
		Tram Costruction	250,000,000 €	22,000,000 €	11.36363636	0.0005	1%
		DRT	10,000,000 €	125,000 €	80	0.0002	2%
		Construction of cycle paths	10,000,000 €	200,000 €	50	0.00001	0%
		BRT	250,000,000 €	8,000,000 €	31.25	0.0005	2%
	DEVELOPING INTERMODALITY	Park & Ride	5,000,000 €	7,000 €	714.2857143	0.00005	4%
		Bike Sharing	10,000,000 €	25,000 €	400	0.00005	2%
		Car Sharing	10,000,000 €	25,000 €	400	0.00002	1%
		Hub Multimodale	10,000,000 €	1,000,000 €	10	0.005	5%
		Maas	1,000,000 €	120 €	8333.333333	0.000005	4%

Table 3-6: Meta-Model (Extra-Urban Area)

		Metropolitan Area					
		Policy	Monetary Investment	Unit Cost	Physical Output	Elasticity	Modal Shift
PUSH	ECONOMIC MEASURES	Parking pricing	700,000 €	7,000 €	1.00E+02	1.00E-04	1%
		Road Pricing	20,012,001 €	7 €	3.00E+06	3.33E-09	1%
	REGULATORY AND ACCESS MEASURES	LTZ	640,000 €	1 €	8.00E+05	1.25E-08	1%
		LEZ	1,206,273 €	2 €	6.03E+05	1.66E-08	1%
		30 km/h zone	177,778 €	0 €	2.22E+06	4.50E-09	1%
	INFRASTRUCTURAL MEASURES	Pedestrianisation	1,500,375 €	200 €	7.50E+03	1.33E-06	1%
PULL	PT FARE	Fare Reduction	76,363,636 €	84 €	9.09E+05	1.10E-08	1%
		Fare Free	345,384,615 €	449 €	7.69E+05	1.30E-08	1%
	IMPROVING SERVICE QUALITY	Subway construction	127,118,644 €	150,000,000 €	8.47E-01	0.0118	1%
		Bus fleet renewal	8,000,000 €	400,000 €	2.00E+01	0.0005	1%
		Train fleet renewal	100,000,000 €	8,000,000 €	1.25E+01	0.0008	1%
		Increase in bus frequency	214,286 €	150 €	1.43E+03	0.000007	1%
		Increase in train frequency	750,000 €	1,500 €	5.00E+02	0.00002	1%
		Tram Costruction	36,666,667 €	22,000,000 €	1.67E+00	0.006	1%
		DRT	12,500,000 €	125,000 €	1.00E+02	0.0001	1%
		Construction of cycle paths	67,340,067 €	200,000 €	3.37E+02	0.0000297	1%
		BRT	20,000,000 €	8,000,000 €	2.50E+00	0.004	1%
	DEVELOPING INTERMODALITY	Park & Ride	466,667 €	7,000 €	6.67E+01	0.00015	1%
		Bike Sharing	1,666,667 €	25,000 €	6.67E+01	0.00015	1%
		Car Sharing	5,000,000 €	25,000 €	2.00E+02	0.00005	1%
		Hub Multimodale	1,666,667 €	5,000,000 €	3.33E-01	0.03	1%
		Maas	40,000 €	120 €	3.33E+02	0.00003	1%

Table 3-7: Meta-Model (Metropolitan Area): 1% Scenario

		Urban Area					
		Policy	Monetary Investment	Unit Cost	Physical Output	Elasticity	Modal Shift
PUSH	ECONOMIC MEASURES	Parking pricing	933,333 €	7,000 €	1.33E+02	7.50E-05	1%
		Road Pricing	33,350,000 €	7 €	5.00E+06	2.00E-09	1%
	REGULATORY AND ACCESS MEASURES	LTZ	853,333 €	1 €	1.07E+06	9.38E-09	1%
		LEZ	2,000,000 €	2 €	1.00E+06	1.00E-08	1%
		30 km/h	266,667 €	0 €	3.33E+06	3.00E-09	1%
	INFRASTRUCTURAL MEASURES	Pedestrianisation	2,857,143 €	200 €	1.43E+04	7.00E-07	1%
PULL	PT FARE	Fare Reduction	120,000,000 €	84 €	1.43E+06	7.00E-09	1%
		Fare Free	498,888,889 €	449 €	1.11E+06	9.00E-09	1%
	IMPROVING SERVICE QUALITY	Subway construction	300,000,000 €	150,000,000 €	2.00E+00	0.005	1%
		Bus fleet renewal	5,333,333 €	400,000 €	1.33E+01	0.00075	1%
		Train fleet renewal	133,333,333 €	8,000,000 €	1.67E+01	0.0006	1%
		Increase in bus frequency	100,000 €	150 €	6.67E+02	0.000015	1%
		Increase in train frequency	1,250,000 €	1,500 €	8.33E+02	0.000012	1%
		Tram Costruction	110,000,000 €	22,000,000 €	5.00E+00	0.002	1%
		DRT	8,333,333 €	125,000 €	6.67E+01	0.00015	1%
		Construction of cycle paths	100,000,000 €	200,000 €	5.00E+02	0.00002	1%
		BRT	40,000,000 €	8,000,000 €	5.00E+00	0.002	1%
	DEVELOPING INTERMODALITY	Park & Ride	583,333 €	7,000 €	8.33E+01	0.00012	1%
		Bike Sharing	2,500,000 €	25,000 €	1.00E+02	0.0001	1%
		Car Sharing	4,166,667 €	25,000 €	1.67E+02	0.00006	1%
		Hub Multimodale	2,500,000 €	2,500,000 €	1.00E+00	0.01	1%
		Maas	80,000 €	120 €	6.67E+02	0.000015	1%

Table 3-8: Meta-Model (Urban Area): 1% Scenario

		Extra-Urban Area					
		Policy	Monetary Investment	Unit Cost	Physical Output	Elasticity	Modal Shift
PUSH	ECONOMIC MEASURES	Parking pricing	1,750,000 €	7,000 €	2.50E+02	4.00E-05	1%
		Road Pricing	66,700,000 €	7 €	1.00E+07	1.00E-09	1%
	REGULATORY AND ACCESS MEASURES	LTZ	2,000,000 €	1 €	2.50E+06	4.00E-09	1%
		LEZ	4,000,000 €	2 €	2.00E+06	5.00E-09	1%
		30 km/h	666,667 €	0 €	8.33E+06	1.20E-09	1%
	INFRASTRUCTURAL MEASURES	Pedestrianisation	10,000,000 €	200 €	5.00E+04	2.00E-07	1%
PULL	PT FARE	Fare Reduction	280,000,000 €	84 €	3.33E+06	3.00E-09	1%
		Fare Free	1,122,500,000 €	449 €	2.50E+06	4.00E-09	1%
	IMPROVING SERVICE QUALITY	Subway construction	0 €	150,000,000 €	0.00E+00	0	1%
		Bus fleet renewal	13,333,333 €	400,000 €	3.33E+01	0.0003	1%
		Train fleet renewal	200,000,000 €	8,000,000 €	2.50E+01	0.0004	1%
		Increase in bus frequency	150,000 €	150 €	1.00E+03	0.00001	1%
		Increase in train frequency	2,142,857 €	1,500 €	1.43E+03	0.000007	1%
		Tram Costruction	440,000,000 €	22,000,000 €	2.00E+01	0.0005	1%
		DRT	6,250,000 €	125,000 €	5.00E+01	0.0002	1%
		Construction of cycle paths	200,000,000 €	200,000 €	1.00E+03	0.00001	1%
		BRT	160,000,000 €	8,000,000 €	2.00E+01	0.0005	1%
	DEVELOPING INTERMODALITY	Park & Ride	1,400,000 €	7,000 €	2.00E+02	0.00005	1%
		Bike Sharing	5,000,000 €	25,000 €	2.00E+02	0.00005	1%
		Car Sharing	12,500,000 €	25,000 €	5.00E+02	0.00002	1%
		Hub Multimodale	2,000,000 €	1,000,000 €	2.00E+00	0.005	1%
		Maas	240,000 €	120 €	2.00E+03	0.000005	1%

Table 3-9: Meta-Model (Extra-Urban Area): 1% Scenario

3.6. Summary of Results and Discussion of Evidence

The application of the metamodel to the three functional geographies (Metropolitan, Urban, and Extra-Urban) made it possible to quantify the differential effectiveness of modal shift policies, confirming that territorial morphology is the primary determinant of investment performance. Scenario analysis, particularly the one based on the 1% modal shift target, provided crucial evidence for establishing a hierarchy of strategic priorities.

To visually assess this hierarchy, two comparative charts (Linear and Logarithmic scales) (*Figure 3-4; Figure 3-5*) were developed. As shown in these figures, a clear divergence emerges between the macro-categories of intervention:

- **Efficiency of "Push" Policies**: Regulatory and deterrence measures, such as Road Pricing, LTZ, and Parking Pricing, require significantly lower financial investments to achieve the 1% target. These policies act directly on the marginal cost of car use, making the transition to sustainable modes an economically driven choice for users with limited public expenditure.
- **Onerousness of "Pull" Policies**: Conversely, incentive and infrastructure-based policies exhibit implementation costs that are several orders of magnitude higher. While essential for absorbing demand, major works like Subway Construction, Fleet Renewal, or Fare Free schemes require massive capital to attract users by improving service quality and comfort.
- **Strategic Insights from Logarithmic Analysis**: The logarithmic representation highlights that digital or "soft" measures, particularly MaaS, occupy an intermediate cost bracket. This confirms their role as efficiency catalysts, capable of optimizing the return on heavy infrastructure investments by lowering cognitive barriers and facilitating seamless intermodality.

From the detailed comparison of the model's outputs across the different Functional Urban Areas (FUA), the following main findings emerge:

- **Efficiency of Major Infrastructure :** In Metropolitan areas, although the construction of metro and tram lines requires the largest financial investment to achieve a 1% shift, these works remain the essential backbone for handling massive demand volumes that “soft” policies could not absorb on their own.

- **The Central Role of Active Mobility in Urban Areas:** In Urban Areas, the metamodel highlights an extremely favourable cost-benefit ratio for 30 km/h zones and cycling infrastructure. In this context, the elasticity of road-space reallocation policies is higher than in other areas, as they target short-distance trips where cars are less competitive in terms of travel time.
- **The Crucial Role of DRT in Low-Density Areas:** For Extra-Urban Zones, the model confirms the ineffectiveness of fixed-route lines in favour of demand-responsive transport (DRT). The specific elasticity assigned to this measure reflects its ability to respond to fragmented demand, making it the only Pull policy truly capable of offering flexibility comparable to private cars.
- **The Maas Multiplier Effect:** Across all three zones, digital integration via Maas platforms emerges as an efficiency factor that reduces the “cost” of modal shift for all other modes. The technology lowers cognitive barriers and facilitates intermodality, thereby optimizing the return on every euro invested in physical services.

In conclusion, the results of the metamodel demonstrate that a sustainable transition cannot disregard a data-driven and territorially differentiated approach. The tool highlights that the success of modal shift depends on planners’ ability to select the technologies and policies with the highest elasticity in each specific context, leveraging the cost-effectiveness of Push measures to balance the necessary but expensive investment in Pull infrastructure.

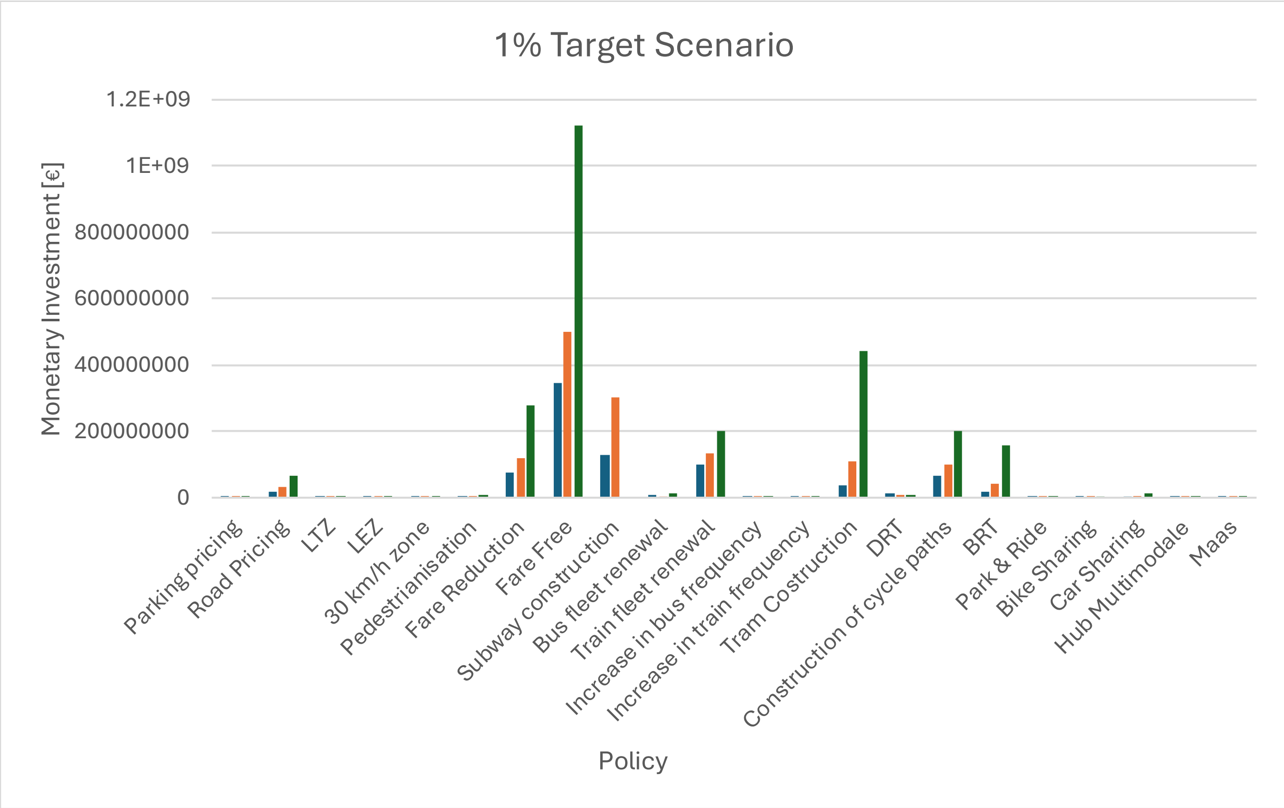


Figure 3-4: 1% Target Scenario Graph (Blue=Metropolitan Area, Orange=Urban Area, Green=Extra-Urban Area)

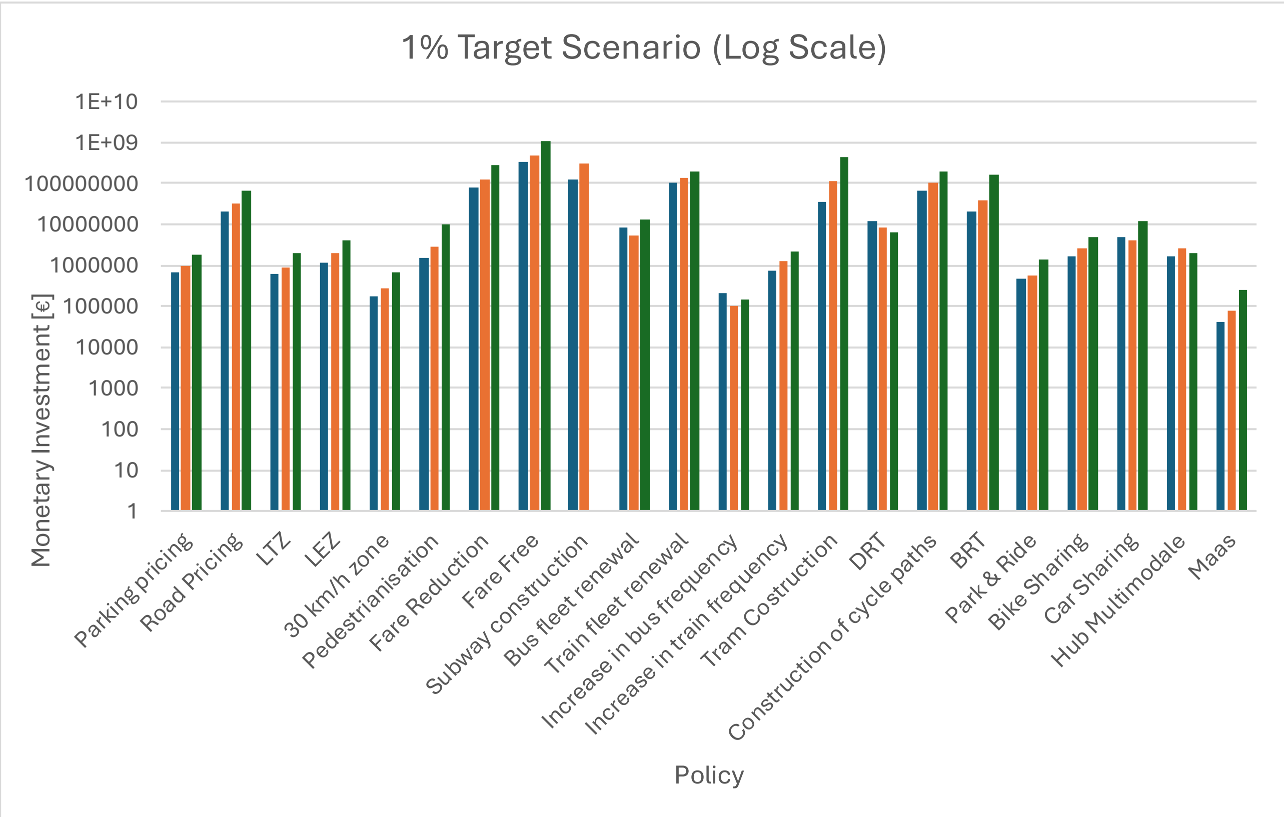


Figure 3-5: 1% Target Scenario Graph (Log Scale) (Blue=Metropolitan Area, Orange=Urban Area, Green=Extra-Urban Area

4. Final considerations

This thesis aimed to address one of the most complex challenges of modern mobility engineering: the transition toward sustainable transport systems through the implementation and evaluation of modal shift policies. The research originated from the awareness that the current mobility model, still heavily reliant on private car use, is incompatible with the decarbonization targets set by the European Green Deal and with the need to improve the liveability of urban environments. Through a systematic review of the state of the art, it clearly emerged that the success of modal shift does not depend on isolated measures, but rather on the coherent integration of deterrence (Push) and incentive (Pull) policies.

The methodological core and most original contribution of this thesis lies in the development of a parameterized decision-making metamodel. Implemented as a Decision Support System (DSS), this tool made it possible to move beyond a purely qualitative planning approach by providing a quantitative basis for evaluating the cost-effectiveness of investments. The application of the model to Functional Urban Areas (FUAs), according to the ISTAT 2021 classification, represented a crucial step in demonstrating that the effectiveness of a policy is not an absolute value, but a variable strictly dependent on territorial morphology and functional density.

The analyses conducted through the metamodel lead to key conclusions for the future management of mobility:

- Territorial Specialization of Policies: In high-density metropolitan areas, investments in heavy infrastructure (rail and metro) remain irreplaceable for managing massive demand volumes, although they involve high unit costs per unit of modal shift. Conversely, in medium-sized urban areas, active mobility and space reallocation policies (such as 30 km/h zones) show an extremely favourable cost–benefit ratio.
- The Extra-Urban Revolution and the Role of DRT: One of the most significant findings concerns low-density areas, where traditional fixed-route services systematically fail. In these contexts, Demand Responsive Transport (DRT) emerges not only as an efficient solution but as the only true pillar capable of

competing with private car use, provided it is integrated into a multimodal vision.

- Digital as a System Catalyst: New technologies, Big Data, and Artificial Intelligence should not be considered ancillary interventions, but rather “intangible infrastructures” capable of acting as efficiency multipliers. The metamodel highlighted how the adoption of Mobility as a Service (MaaS) platforms reduces the cost required to achieve one percentage point of modal shift, lowering users’ cognitive barriers and facilitating seamless intermodality.

In conclusion, the thesis demonstrates that achieving a genuine modal rebalance requires data-driven planning capable of abandoning measure-by-measure logic in favour of systemic strategies. The recommendations for policymakers emerging from this work suggest prioritizing policy packages that combine supply enhancement with a strong digital and regulatory component.

Although the metamodel presents intrinsic limitations related to the availability of empirical data for certain emerging technologies, it represents a fundamental strategic compass. Future research developments may benefit from greater data granularity derived from ITS systems and real-time monitoring, allowing for further refinement of elasticity coefficients and testing of the model at regional or national scale. The challenge of modal shift is therefore technological, but above all methodological: only through rigorous analytical tools will it be possible to transform mobility from a source of negative externalities into a driver of sustainable and inclusive development.

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