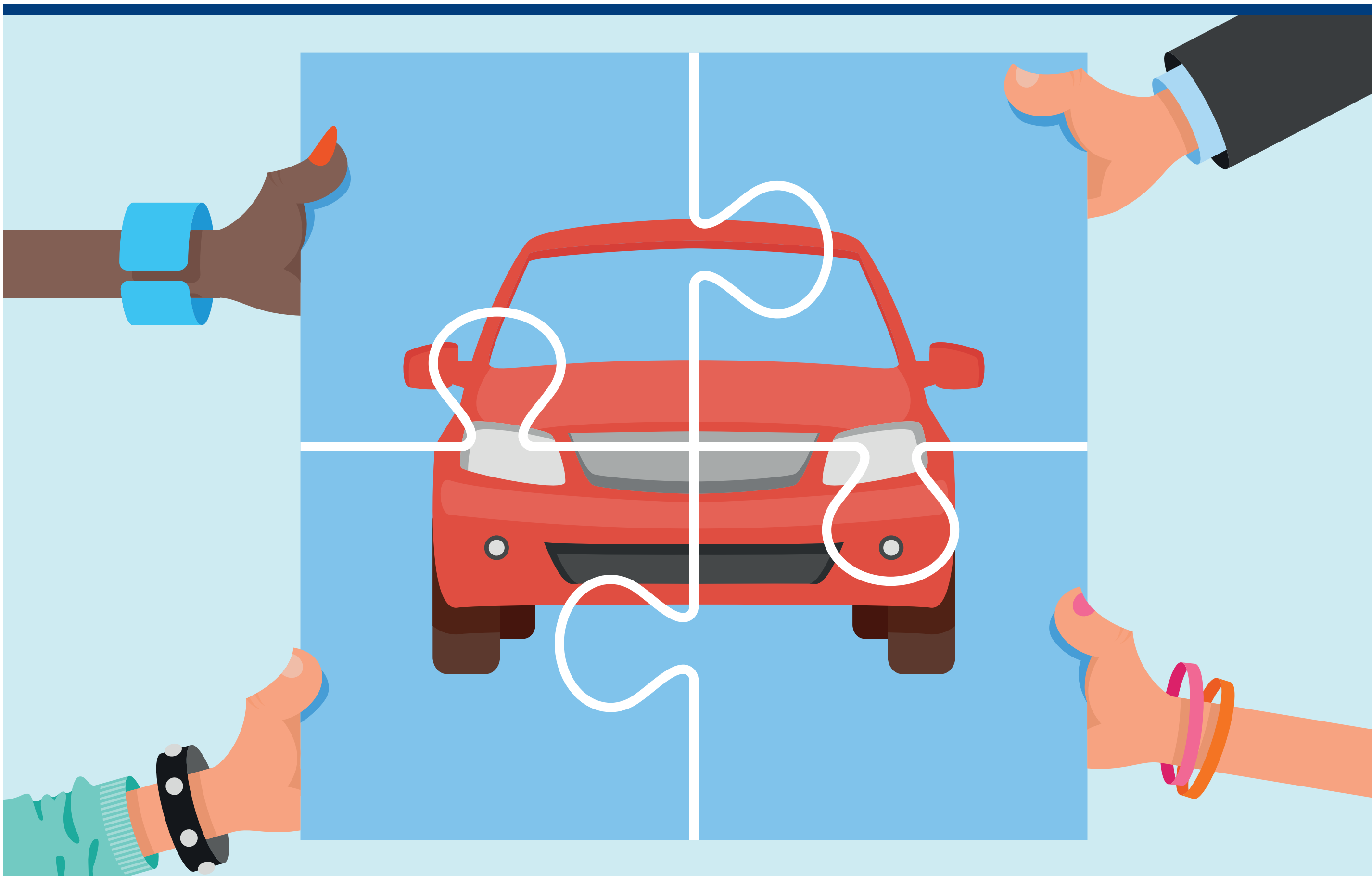
International Transport Forum

CPB Corporate Partnership Board



Shared Mobility

Innovation for Liveable Cities

Corporate Partnership Board Report

OECD

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Foreword

The work for this report was carried out in the context of a project initiated and funded by the International Transport Forum's Corporate Partnership Board (CPB). CPB projects are designed to enrich policy discussion with a business perspective. They are launched in areas where CPB member companies identify an emerging issue in transport policy or an innovation challenge to the transport system. Led by the ITF, work is carried out in a collaborative fashion in working groups consisting of CPB member companies, external experts and ITF staff.

The CPB companies involved in this project were: Ford, Google, HERE, INRIX, Michelin, PTV Group, Volvo, Uber. The principal authors of this report were José Viegas and Luis Martinez of the International Transport Forum, with substantial inputs from Philippe Crist. The project was coordinated by Philippe Crist and Sharon Masterson of the International Transport Forum.

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Executive summary

Background

The way in which people move has undergone several revolutions in the past: from walking on foot, to animal-powered mobility, to vehicles propelled by combustion engines using fossil fuels. Today the next mobility revolution is underway, based on the use of real-time streams of data that make it easier and more efficient to provide citizens with optimised access to their cities. This report investigates one particular scenario that evidence suggests could occur: the large-scale deployment of shared vehicle fleets that provide on-demand transport.

Building on our 2015 report *Urban Mobility System Upgrade: How Shared Self-driving Cars Could Change City Traffic*, this study models the impact of replacing all car and bus trips in a city with mobility provided through fleets of shared vehicles. The simulation is, again, based on real mobility and network data from a mid-size European city, namely Lisbon, Portugal. In this follow-up study, we examine a different configuration where shared mobility is delivered by a fleet of six-seat vehicles ("Shared Taxis") that offer on-demand, door-to-door shared rides in conjunction with a fleet of eight-person and 16-person mini-buses ("Taxi-Buses") that serve pop-up stops on demand and provide transfer-free rides. Rail and subway services keep operating in the current pattern.

The simulation looks at impacts on the number of vehicles required and the total kilometres driven, and the effects on congestions, CO_2 emissions and use of public space. Additionally – and crucially – it also examines how citizens experience the new shared services and how they affect social inclusion measured in the level of accessibility of jobs, schools and health services.

Findings

Congestion disappeared, traffic emissions were reduced by one third, and 95% less space was required for public parking in our model city served by Shared Taxis and Taxi-Buses. The car fleet needed would be only 3% in size of the today's fleet. Although each car would be running almost ten times more kilometres than currently, total vehicle-kilometres would be 37% less even during peak hours. The much longer distances travelled imply shorter life cycles for the shared vehicles. This enables faster uptake of newer, cleaner technologies and contributes to more rapid reduction of CO_2 emissions from urban mobility.

Citizens gain in many different ways. They no longer need to factor in congestion. Almost all of their trips are direct, without need for transfers. Mobility is much cheaper thanks to the highly efficient use of capacity; prices for journeys in the city could be 50% or less of today even without subsidy. Huge amounts of space previously dedicated to parking can be converted to uses that increase livability, from public parks to broader sidewalks, and more and better bicycle lanes. Particularly striking is how a shared mobility system improves access and social inclusion. In the simulation, inequalities in access to jobs, schools or health services across the city virtually disappeared.

The transition phase from individual use of cars to shared mobility is critical to success. It is also a challenge. Managing individual car access to the city by limiting the number of days cars can be used may provide one potential path, although it would certainly be difficult to implement. We tested a scenario in which private cars were allowed to drive in the city two working days per week. This already provides significant reductions of congestion and emissions. It also allows car owners to experience the shared mobility solutions on the other days of the week and to nudge them towards recognising that driving one's own car in the city may often not be the most convenient option.

Policy Insights

Shared mobility benefits depend on creating the right market conditions and operational frameworks

Today's technologies make possible shared transport solutions that provide quality mobility to all citizens with significantly reduced traffic volumes, fewer emissions, less need for public parking space, at prices well below the current ones. Importantly, significantly improved equity in accessibility levels and hence social inclusion can be achieved. While there are many ways to manage dispatching in a shared mobility system, one of the most promising approaches would be to charge a single entity with matching demand and supply. However, authorities must carefully reflect on its statute and the supervision of its performance in order to protect consumers from market power abuse and to ensure efficient outcomes.

Shared mobility has significant environmental benefits, even with current engine technology

Shared fleets enable very significant reductions of CO_2 emissions even with current internal combustion engines. Intensive per-vehicle use implies accelerated fleet replacement and thus, potentially, quicker penetration of newer, cleaner technologies. But electric vehicles with current technology and autonomy can also be deployed very efficiently in a shared mobility system. This could provide an even quicker and stronger reduction of carbon emissions, if the sources for electric power are sufficiently clean.

Shared mobility will radically change public transport and most traditional bus services will disappear

Demand-responsive Taxi-Buses that do not follow fixed routes and time tables but provide direct service from origin to destination at the push of a smartphone button would redefine the concept of urban public transport. The phase-out of most traditional bus services would be a likely consequence. These changes are so fundamental that existing operators may act to block a deployment and this will have to be anticipated by policy makers. Labour issues could be mitigated by the fact that more Taxi-Buses than conventional busses will be needed. Traditional, scheduled public transport still makes sense but only when providing both high capacity and high frequency of service.

Shared mobility changes the business model of the car industry

The drastic reduction in the number of cars needed would significantly affect car manufacturers' business models. The different and more intensive use of the shared vehicles will require different models with, for instance, much more robust interior fittings. New service-based business models will develop, but who will manage them and how they will be monetised remains an open question. The role of authorities, both on the regulatory and fiscal side, will be important in guiding developments or potentially maintaining impediments.

Public authorities must guide the deployment of shared mobility systems and anticipate their impacts

Well-informed and sometimes bold public policies will be necessary to guide the process of change. This is related to the introduction of shared mobility services as such, but also on the management and allocation of public space released from car parking. Possible alternative uses for that space include enlarging sidewalks, bicycle tracks, and recreational areas or adding commercial uses such as delivery bays. As some off-street parking would also be made redundant, it could be used for logistics distribution centres.

1. Introduction

Mobility is an important component of all human activity, ensuring the access of citizens to exercise their social rights and the capacity to partake in productive activities. In an urban environment, with higher population densities and levels of economic activity, mobility drives economic development and contributes to social equity.

Yet, for all the benefits it confers on citizens, transport activity is also seen as a major urban challenge due to the environmental and social impacts it often engenders, especially in highly motorised and car dependent regions. Increasing purchasing power, which in many countries has surpassed the increase of transportation costs, and technology development has lowered the relative costs of cars just as disposable income has increased. Even in developing countries, where household income is lower, motorisation levels are rapidly increasing, though their use is still largely below walking and public transport.

Single-occupancy car use generates individual and collective benefits but these are eroded and, in some cases, obviated by environmental impacts, loss of transport system efficiency due to congestion, social inequity and exclusion, as well as road crashes and strong dependence on fossil fuels. Against that backdrop, any effort to provide high quality transport options for citizens must incorporate an understanding of the underlying factors that drive transport decisions and underpin the dominance of the private car. The private car presents a clear advantage over other transport options in three key areas: flexibility, comfort and availability. These characteristics of the private car may significantly blur the perception of other modes and explain the attraction of the car as an attractive choice to many individuals and households.

Typically, the response to the negative impacts of car-dominated transport systems – when there has been one – has been to promote public transport and, to a lesser extent, walking and cycling. Contrary to the latter two, deploying ever more extensive and good quality public transport comes at a heavy cost, especially for those services that are poorly used outside of peak periods or core parts of urban areas. Despite the active promotion of public transport (PT) networks, public transport continues to lose market share to private vehicles in most developed economies.

Three main approaches to mitigating urban mobility problems have been proposed: influence demand to reduce travel needs (avoid), promote more sustainable transport options (shift) and deploy better technology and reorganise supply (improve).

From a technological perspective (improve), the efforts in the last decades have concentrated on the development of cleaner energies and more efficient vehicle engines. Other significant developments were obtained through the reduction of the environmental impact of transportation infrastructure. These measures tend to be effective in the short term; however, the overall impact on the system in the long run might be negligible if transport demand continues to increase at the same pace.

From the avoid perspective, some policies have been recently designed to act on the supply side, not only promoting tele-activities but also providing more efficient infrastructure and land-use distribution. This concept emerged in the US during the last few decades under the designation of Transit Oriented Development (TOD), where the objective is to develop "Smart Growth" areas with mix land-uses and that are compact and walkable, usually around rail stations. This new urban development paradigm aims to promote accessibility to a wider variety of activities, encouraging walking and the use of more sustainable transport options instead of single car use. This is a promising approach but one for which the long-term wider impacts are uncertain.

Shifting demand towards more sustainable transport options has shown to be promising as well, perhaps more so than some of the other approaches outlined beforehand. Several cities have sought to promote more efficient and rational use of existent transport systems. These Travel Demand Management (TDM) approaches introduce or promote more efficient transport options or create behavioral and financial incentives towards more efficient mobility.

There are many different measures that can be used in TDM and some of them have already been successfully implemented: moral campaigns (e.g. eco-driving); the promotion of non-motorised transport modes; or parking policies aiming at reducing cars in city centres and, congestion charges in London and Stockholm. The promotion of Intelligent Transport Systems (ITS) may also enhance the efficiency of the transport system.

Recently, the promotion and integration of shared transport options, within a so-called shared economy paradigm has emerged. This new mobility paradigm may represent an interesting option to better manage transport in cities. This concept has been in discussion for several decades but only in more recent years, technology has evolved sufficiently and its key instrument - the smartphone - spread enough across the population to allow for the shared mobility market to gain some scale and become more viable.

This new approach to demand management aims at exploring mobility resources more efficiently, while preserving good levels of comfort and flexibility normally associated with the private car. The proposed shared modes explore how to increase low levels of private vehicle use in both space and time since cars are typically used during peak hours and rarely for more than 10% of the day. They also display very low levels of occupancy. Despite this, they are highly valued assets – so highly valued that households put up with the expense and low usage in order to derive specific benefits relating to comfortable, door-to-door and schedule-less travel. This low efficiency at the personal level is replicated at the social level with congestion and emissions exacerbated by the quite low occupancy levels of private cars. Could this inefficiency be reduced while retaining these benefits?

The traditional shared mobility market tries to explore these two dimensions (sequential or parallel share of vehicles) by segmenting supply to improve demand satisfaction. Two main transport options have been widely explored: carpooling (space sharing among a group of friends) and carsharing (time sharing). Additionally, two other shared transport alternatives that further explore this spectrum of shared mobility efficiency: ridesharing or Shared Taxis, which represent an expansion to the existing taxi system where different passengers or parties share the same vehicle for parts of their rides, and on-demand minibus services, that expand or replace the regular bus concept beyond fixed routes and fixed schedules to improve public transport provision efficiency and efficacy. Both alternatives explore time and space sharing solutions.

With the arrival of ubiquitous internet access and dedicated app-based services, carsharing has quickly grown in popularity and sophistication and numerous successful services have been deployed around the world. At the same time, there has been an analogous development in terms of technological sophistication with ridesharing services, especially for app-based on-demand services. These can take the form of taxi-like services or peer-to-peer real-time ridesharing. As with app-based carsharing, these forms of ridesharing have proven to be tremendously popular and pioneering companies in this field have been very successful.

Several studies have explored through simulations the role of shared mobility services either as additional service in the mobility market (Martinez et al., 2015), or by fully deployed systems that would replace all motorised mobility in a city (Fagnant and Kockelman, 2014; Zachariah et al., 2013).

Our work is based on a simulation platform that allows the exploration of different shared transport scenarios that preserve the behavioral preferences and citizens’ mobility profiles of today. We develop a comprehensive simulation model that is able to reproduce as accurately as possible the interaction between users and shared mobility options in a realistic transport network and urban context. This system allows insights for understanding what type of performance should be expected from the implementation of different mobility systems. We chose to develop this model on the basis of agent-based techniques given the difficulty in representing the complex spatial-temporal relation between vehicle supply and passenger demand by other types of aggregated and disaggregated simulation methods. The usefulness of agent based models has been well demonstrated in several areas of transportation analysis (Arentze et al., 2010; Davidsson et al., 2005; Roorda et al., 2010; Tang et al., 2012; Vliet et al., 2010). These models allow a detailed representation of the interactions of multiple agents in a realistic synthetic environment where the intent is to re-create and predict the appearance of a complex phenomenon, which is the case of the mobility market. The objective is to obtain high level indicators from describing accurately the lower level reality of shared mobility supply interacting with current mobility demand.

This report constitutes an update of the Corporate Partnership Board report published in May 2015, incorporating not only joint consideration of two modes of demand-responsive services (Shared Taxis and Taxi-Buses) but also significant improvements in the algorithms used for matching demand and supply and a much wider exploration of the results of that process in terms of the indicators produced for analysis of its quality of service, productive efficiency, cost competitiveness and equity of accessibility.

The main source of the very large gains of efficiency and accessibility obtained in the model runs for this work, as reported below, is the combination of the demand-responsive service with the shared used of the vehicles. Therefore, this report investigates those elements principally and leaves aside, for the time being, any further investigation of automated driving and carsharing services that were included in the 2015 report.

2. Design of potential shared mobility services

This section presents the conceptual design of the shared services that are tested on the simulation platform. Two market segments were addressed: a ridesharing system (Shared Taxi), which emulates a taxi-like system where customers accept small detours from their original direct path and share part of their ride with others, and a dynamic bus-like service with minibuses (Taxi-Bus), where customers pre-book their service at least 30 minutes in advance (permanent bookings for regular trips could represent most requests) and walk short distances to a designated pop-up stop. In all cases travelers get a transfer-free trip from origin to destination. The following table presents a brief characterisation of these two modes.

Table 1. **Shared mobility services specification adopted**

Mode	Booking	Access time	Max. waiting time	Max. total time loss*	Vehicle type
Shared Taxi	Real time	Door-to-door	5 minutes (<= 3 km), up to 10 minutes (>= 12 km)	(detour time + waiting time) from 7 minutes (<= 3 km), up to 15 minutes (>=12 km)	Minivan currently seating 8 rearranged to seat only 6, providing easy entry and exit
Taxi-Bus	30 minutes in advance	Boarding and alighting up to 300 m away from door, at points designated in real time	Tolerance of 10 minutes from preferred boarding time	Set by the minimum linear speed from origin to destination (15 km/h)	Minibuses with 8 and 16 seats. No standing places

*Tolerance of each customer to waiting times and detour times is defined in relation to the total length of the trip of that customer.

The specifications for these services were designed to entice a high level of acceptance of modal transfer by current car drivers, by providing them with the three quality attributes of flexibility, comfort and availability.

The mobility alternatives were designed to fully replace current motorised road transport alternatives (car, motorcycle, taxi and bus), implying a modal shift of users to the new transport alternatives or to the previous options that remain available (walking/biking, metro and rail).

3. Methodology

General framework

In this work we developed an agent-based model that simulates the daily mobility of Lisbon, Portugal. The model is formed by three main agents that interact in a common environment: users, vehicles, and dispatcher. The model is based on real trip-taking activity replicating the patterns and schedules observed in the survey. Transport infrastructure and supply set the context with the real street and road network and where public transport supply is represented by available routes (bus, metro, and rail). The model addresses the interaction between people (clients) and vehicles, simulating their connection and how, in terms of timing and location, the trip services are performed. The approach is based on a static representation of the traffic environment where origin-destination flows are allocated to a complete, topologically correct road network representation that accounts for per-link occupancy (and thus for speeds), by time of day. Travel time is attributed to each link in the road network, varying with the time of the day and the traffic flow using it, based on which the optimal path between any pair of nodes of the network is identified.

When shared alternatives are enabled in the model, the central dispatcher system manages the centralised task of assigning trip requests to vehicles using the location of shared vehicles, their current occupancy level and the location of clients as its main inputs. The model estimates trip routing on the basis of an algorithm that generates the lowest time path between any pair of nodes of the network.

The city is divided in a homogeneous grid of 200m x 200m cells which is used for the selection of allowed passenger groups and allocation of taxis to clients as well as the assignment to current public transport routes. All trip origins and destinations are linked to the closest node of the road network.

The next sections describe how demand is generated in the model, the behavior of the clients, the definition of operation of shared vehicles and how the centralised dispatcher manages the interaction between demand and supply.

Demand and mode choice

Based on an extensive mobility survey conducted in Lisbon Metropolitan Area (LMA) (Câmara Municipal de Lisboa, 2005), we created a synthetic population of trips within the city, aggregated by the aforementioned 200m x 200m grids. The synthetic travel simulation model used was developed and calibrated for the LMA in previous studies (Viegas and Martínez, 2010).The model output contains all the trip extremes not only disaggregated in space (at the census block level) but also in time (presenting different trip departure and arrival times) for a synthetic week day in the reference year of 2010 (Viegas and Martínez, 2010)[1].

Each trip is characterised not only by its time of occurrence, origin and destination, but also by trip purpose, traveler's age and by whether or not the traveler has a transit pass. Additionally, based on Census data and other mobility surveys (Martinez and Viegas, 2009; Moura et al., 2007; Santos et al., 2011), each trip is further characterised by the traveler's gender, income and by whether the traveler has a driving license or not, car, motorcycle, parking spaces at home and at work. The purpose of the trip determines the activity duration, which can be used to calculate parking costs.

The destination grids are characterised by parking cost and parking pressure (ratio of demand to supply), both depending on time of day, linking the available demand data with the statistics and pricing of Lisbon's parking.

For all modes currently available – car, motorcycle, taxi, walking, bus or tram, metro or suburban train, combination between light and heavy transport modes – the trip is characterised by access time, waiting time, travel time, cost and number of transfers (if applicable) (Santos et al., 2011).

To determine the modal choice of the users in the reference configuration (current mobility), the agent-based model (ABM) incorporates the discrete choice model (DCM) described in (Eiró and Martínez, 2014). The original model aimed at assessing the impact of new shared mobility options in the LMA using stated preferences data. The original model was adapted in the reference configuration here since only the modes covered in that survey were considered. Annex 1 of this report provides an overview of the model specification and calibration results for the model.

Having the full characterisation of the trip as input, the DCM calculates the probability of choosing each mode. A mode is assigned to the client by simulation where modes with higher probability will be chosen more often.

Currently, one user is equivalent to one trip, i.e. clients do not cluster in parties neither have memory. Therefore previous experience does not have an impact on future choices. It also means that each decision is made individually and is not activity-based, nor the daily routines of the client's family are considered in the choice. This is a limitation that could be explored in the future by seeking to replicate plausible trip-chaining activity.

In the Shared Taxi and Taxi-Bus scenarios, a rule-based lexicographic choice process was adopted based on socio-demographic and mobility attributes of the user. The mode choice process in the Shared Taxi and Taxi-Bus scenarios has the following sequential rules (see Box 1).

Box 1. **Rules for mode choice process in Shared Taxi and Taxi-Buses**

- Walking:
    1. trips with distance <= 300 metres
    2. 300 meters < trips with distance <= 1500 metres
        - Stochastic choice following a walking acceptance distribution calibrated for Lisbon in (38)

    otherwise
- Metro or rail:
    1. Number of transfers <=1 and stochastic choice following the total access time (origin + destination) to stations acceptance distribution calibrated for Lisbon in (38)

    otherwise
- Shared Taxi:
    1. Owning car as main driver and not owning a public transport pass
        - Stochastic random number generator (<=0.7)
    2. Not owning car as main driver and not owning a public transport pass
        - Stochastic random number generator (<=0.5)

    otherwise
- Taxi-Bus:
    1. Remaining users that do not select the previous options

This procedure is implemented for each generated client and allows the estimation of modal diversion in each shared mobility configuration. The Taxi-Bus selection is constrained to the availability of services that aggregate at least 50% occupancy at some point during the route. The users that select Taxi-Bus and for whom the dispatcher cannot reach the 50% threshold are then diverted (upgraded) to the Shared Taxi option at no extra cost for the user.

Table 2 presents the aggregate statistics of modal choice of users in the system for a synthetic trip population of 1 138 696 daily trips inside the core of the city of Lisbon (some 96 km^2). The results show that individual motorised transport users (car, motorcycle and taxi) switch mainly to the Shared Taxi and Taxi-Bus alternative, while walking and metro users mainly remain in the reference mode, except in cases of long walking distances or bad metro connectivity where users divert to motorised shared alternatives. Users that previously combined rail and bus modes mainly switch to shared alternatives, either due to poor rail connectivity or due to long access time to metro and rail.

Table 2. **Analysis of mode diversion**

Reference configuration mode	Reference modal choice	Mode in new configurations			
		Walk	Metro or rail	Shared Taxi	Taxi-Bus
Private car	45.50%	11.04%	21.75%	40.67%	26.54%
Motorcycle	1.25%	10.79%	23.54%	39.40%	26.27%
Taxi	2.25%	4.70%	11.57%	39.83%	43.91%
Bus	14.01%	2.27%	19.15%	33.20%	45.38%
Walk	21.21%	79.71%	1.81%	16.47%	2.01%
Metro or rail	13.89%	1.19%	51.45%	19.72%	27.63%
Metro or rail + bus	1.89%	0.14%	8.35%	36.39%	55.12%
Overall modal share in new configuration		22.66%	20.82%	31.46%	25.05%

When the model chooses a shared option, a new user (agent) is generated in the simulation environment, with a departure node, an arrival node and a starting time. Currently, one user is equivalent to one trip, i.e. users do not cluster in parties at the outset of their trip (though they do share vehicles whilst underway in the Shared Taxi and Taxi-Bus simulations).

Users

In the simulation environment, a trip is generated when a user requests a departure from a point towards another point. The model accounts for the simulation parameters (resulting from the specification of each shared mode) and accounts for waiting time, detour time and arrival time tolerances that are defined for the model run. The dispatcher then finds, in real time or with the pre-booking for Taxi-Buses, the best possible routing and assigns one of several available vehicle types to carry out the trip in either a Shared Taxi or Taxi-Bus mode.

The user then waits for the vehicle or walks to a specified pick-up location and boards the vehicle. When the vehicle arrives at its destination, the user exits the system and a set of indicators are generated in a trip log so that they can be used for ex-post system evaluation.

Cars and minibuses

The cars agent is formulated as a reactive agent that follows the instructions of the dispatcher. Idle cars are located in stations spread across the city (60 stations for the city of Lisbon), and whenever the car is empty and not dispatched to a new trip, it is driven to the nearest station. Active cars follow the shortest path and minimise travel time for its route assignment taking into account hourly link-based road speeds.

Taxi-Buses position themselves at the departure stop of each generated route after relocating themselves from the last performed service. The system generated 320 potential stops in the city of Lisbon that can be activated during the day. The location of these stops was constrained by minimum distance between stops (300 metres) and the selection of the road node with greater connectivity in the neighbouring area in order to ensure flexible routing for the vehicles (avoid streets with traffic only in one direction or left turning blocking).

The dispatcher

The dispatcher is an entity that defines a set of rules for matching cars to users, centralising all real-time information required to produce and monitor these trips. The choice of which car or minibus to match with a user’s request takes into account a time-minimisation principle that applies not just to the requesting user but also to those already underway in the same vehicle.

A number of parametric constraints has been defined that must be satisfied for each trip route solution proposed by the dispatching system as described in the service specification section.

The model defines in parallel the dispatching of Taxi-Bus and Shared Taxis when both systems are operating. Users launch their requests and preferences that are recorded in the system. In case of a Taxi-Bus request, they are processed 30 minutes in advance. The dispatcher runs a local search algorithm that tries to maximise the number of passengers assigned complying with the users constraints at each step (best match in minibus service that warrant at least 50% occupancy at least in some part of the trip and an average (per kilometre) occupancy rate greater than 25% of the vehicle capacity). Some users that are not assigned to Taxi-Buses because of these constraints are then re-assigned (upgraded) to the Shared Taxi system as real time requests, following the Shared Taxi real time booking system automatically performing door-to-door services.

The Shared Taxi dispatching services operate a real time optimisation model that tries to minimise the additional vehicle kilometres generated by each additional user in the system, estimating the minimum insertion Hamiltonian path for each operation vehicle that is located less than one kilometre away from the boarding location of the user. Every request is analysed in order to comply with the client preferences. Yet, the request may be pending for a few minutes by the dispatcher in the expectation that the user gets a better assignment to a vehicle approaching her location that produces less additional vehicle-kilometres (and possibly additional vehicles) in the system. When 50% of the maximum waiting time of that user is reached and no convenient Shared Taxi with clients has been found, the dispatcher searches for available empty taxis nearby (on their way to the stations), and if none is found, it generates an additional vehicle departing from the closest station to serve the user.

The dispatcher also controls the vehicle movements when idle, ensuring efficient vehicle movements to stations that may require additional fleet in the near future.

4. Analysis of results

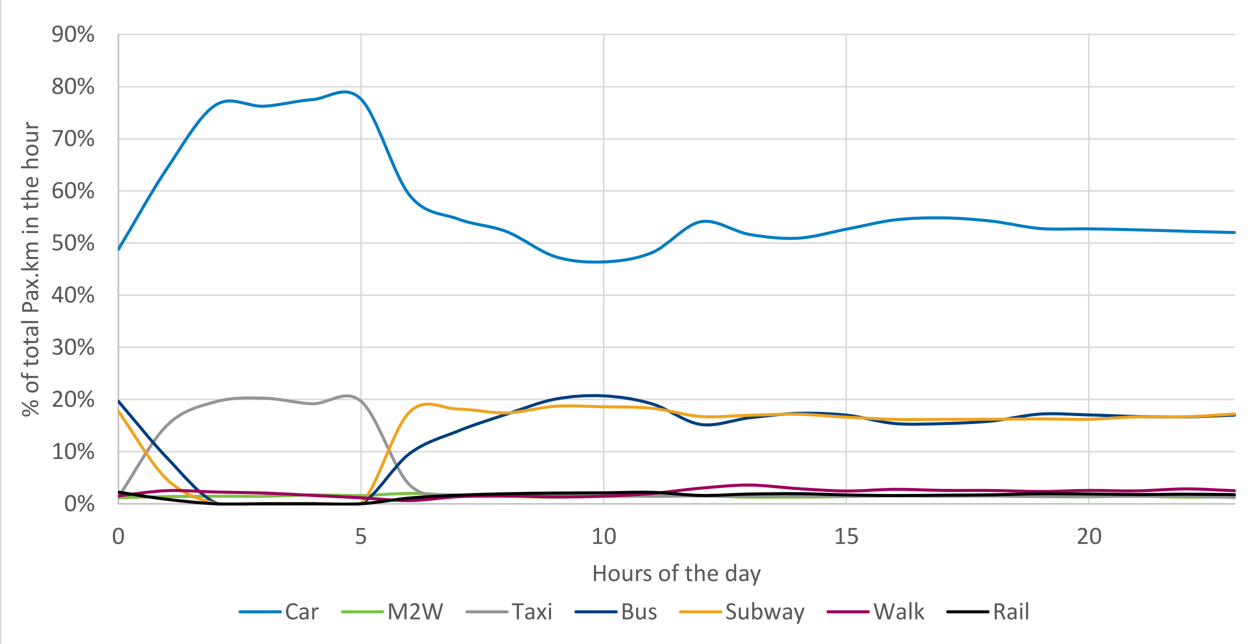
Aggregate results

Transport and emissions

The model was computed over the same synthetic population of trips for all service configurations. We will start by analysing the indicators obtained for the reference case and compare directly the estimates for each alternative configuration.

The analysis of the Baseline modes shares across the day presented in Figure 1 shows the current dominance of the private car, especially in off-peak hours. The bus and the metro present a consistent mode share around 20% that is replaced by the taxi during their non-operating hours (1 am to 5 am). The current mobility leads to a significant number of vehicle kilometres, and CO_2 emissions registered within the city of Lisbon, where the car presents an average occupancy rate of 1.2. Moreover, occupancy levels of the public transport system are low, which leads to low frequencies and consequently long travel times, especially when compared with private transportation options (i.e. car, motorised two-wheelers (M2W) and taxi).

Figure 1. **Modal shares (pax.km/h) across the day in the baseline configuration**



The introduction of the shared alternatives as discussed above in two different alternative configurations generates significant impacts on the city mobility and its externalities. This analysis was produced in equivalent motorised vehicles (private car units or pcu), as regular buses that currently operate and replaced in some of the configurations by smaller and less CO_2 intensive vehicles (minivans or minibuses). The equivalence factor to regular cars was set as 3 for regular buses, 1.3 for the eight-person Taxi-Buses and 1.7 for the 16-person Taxi-Buses (16 passenger vehicles).

The summary of the main mobility outputs across the day are presented in Table 3.

Table 3. **Vehicle-kilometres and CO2 emissions across the day for the tested configurations (baseline configuration used as base 100)**

Hour	Total VKM in pcu units			Total CO2 Emissions (ton/h), all road modes		
	Baseline	2M	3M	Baseline	2M	3M
0	52 118	81.15%	85.13%	12.43	72.62%	72.76%
1	52 310	70.96%	74.24%	12.39	63.90%	63.77%
2	46 093	75.23%	80.65%	10.86	68.11%	69.75%
3	42 489	76.03%	81.91%	10.02	68.82%	70.76%
4	36 734	72.78%	77.77%	8.66	65.89%	67.23%
5	37 262	73.85%	77.07%	8.78	66.85%	66.64%
6	58 456	80.07%	86.76%	13.81	72.30%	74.62%
7	205 674	76.67%	68.57%	48.6	69.25%	58.59%
8	286 009	79.47%	64.09%	67.6	71.80%	54.86%
9	185 688	94.50%	81.29%	43.91	85.30%	69.87%
10	112 312	102.68%	91.41%	26.57	92.60%	78.71%
11	67 890	96.72%	91.42%	16.09	87.06%	78.70%
12	93 499	85.19%	85.21%	22.12	76.84%	73.36%
13	117 981	85.83%	83.29%	27.99	77.22%	71.44%
14	120 606	81.68%	77.81%	28.71	73.22%	66.54%
15	112 159	86.07%	82.48%	26.6	77.44%	70.77%
16	139 848	81.87%	79.08%	33.13	73.73%	67.89%
17	181 446	80.69%	73.66%	42.92	72.78%	63.25%
18	187 272	85.90%	75.46%	44.22	77.64%	64.90%
19	134 466	94.21%	81.94%	31.78	85.07%	70.52%
20	94 170	95.72%	87.17%	22.27	86.38%	75.08%
21	85 997	81.90%	79.29%	20.45	73.48%	67.93%
22	82 990	68.71%	70.64%	19.88	61.18%	60.10%
23	84 350	66.52%	69.36%	20.23	59.21%	58.88%
All day	2 617 817	2 249 788	2 081 255	620.0	504.1	422.9
2010%	100%	83.4%	77.2%	100%	79.0%	66.2%

The results demonstrate the significant reductions of vehicle-kilometres (vkm) and emissions in the alternative configurations compared to the baseline, especially during off-peak periods, where modal share is currently more favourable to private motorised modes.

The different system configurations depend on the presence or not of Taxi-Buses in addition to walking and use of the metro system. The two-mode (2M) configuration considers that the metro system stays in operation and all remaining trips are allocated to Shared Taxis (and walking). The three-mode configuration considers that the metro system stays in operation and that all remaining trips are allocated to both Shared Taxis and Taxi-Buses (in addition to walking). The results of these different scenarios on vehicle kilometres produced and CO2 emissions, hour-by-hour, are displayed in Table 3.

The main operational indicators of the shared alternatives show high occupancy levels. Compared to the current daily averages for motorised road modes in Lisbon – 1.2 people per private car and 13 passengers per 80 passenger buses. This improvement in vehicle use is the key to the reduction in vkm and CO_2 emissions. Furthermore, only 3% of Lisbon's current private car fleet is required to produce the same mobility as in the 2010 synthetic trip population. Savings are even greater in terms of parking space requirements (as the Shared Taxis are in motion a much larger share of the time), allowing a total release of the on-street parking space (about 20% of the kerb-to-kerb space in the city) and a significant reduction of the off-street parking facilities that could be converted to other uses (e.g. logistic centres).

The large-scale release of public space no longer needed for parking generates very significant benefits: first-order effects include provision of much wider and more pleasant spaces for pedestrians and cyclists, and the second-order effects may include further enticing people to walk and cycle because it will have been made much safer and convenient. These are important effects to bear in mind since preserving and even developing levels of active travel will be important in light of the potential for the reduction in walking implied by much greater numbers of door-to-door trips with minimal walking access.

The reduction in car fleet being significantly larger than the reduction of vkm is a consequence of the much more intensive use of cars than at present. In average, each Shared Taxi vehicle in the three-mode configuration is in active service 10.0 hours per day and travels about 265 km, equivalent to some 80 000 km/year to 90 000 km/year. This very intensive use naturally shortens the life cycle of vehicles and thus introduces a much quicker turnaround of the fleet. That in turn allows a much faster penetration of the new and cleaner technologies, and with it a powerful second order effect in the reduction of emissions.

Table 4. **Operational indicators of the tested alternative shared mobility configurations**

Aggregate Indicators	Two-modes	Three-modes
Avg. Pax on board (Sh.taxis)	2.3 (peak 3.0)	2.0 (peak 2.6)
Avg. Pax on board (Taxi-Bus)	---	4.2 (c8) / 11.4 (c16) Peak: 5.0 (c8) / 14.6 (c16)
Fleet size (Sh. taxis + buses)	4.8%	2.8% (cars) Bus*: 568% veh. / 79 % (pl.)
VKM (weighted) all-day	83%	77%
VKM (weighted) peak-hour	79%	64%
CO_2 emissions	79%	66%

* - but these will be minivans and minibuses with capacities of 8 and 16, people not standard 80-person urban buses.

The results obtained with the three-mode configuration are so much better - for the indicators visible in Table 4, but also for many others that are reported below, that this configuration was retained as clearly the most interesting and all subsequent analysis is relative to this configuration.

On accessibility

Transport serves as a means to an end – access of people to jobs, essential public services, culture, education, health services and social interaction. And yet this action function is often forgotten. For this reason, we sought to investigate the impacts the three-mode configuration has on overall accessibility. This analysis looks at accessibility across the geographical area of the city (using each grid cell as point of origin), both in general (average) and in terms of the distribution of cells accessible. Because of the impact on social inclusion, we specifically compare accessibility levels using public transport modes in the current and in the simulated configuration (plus walking in both cases). In this context, the current configuration includes walking and services by metro and rail, and by bus, whereas the simulated configuration includes walking, the same services by metro and rail and by Taxi-Bus.

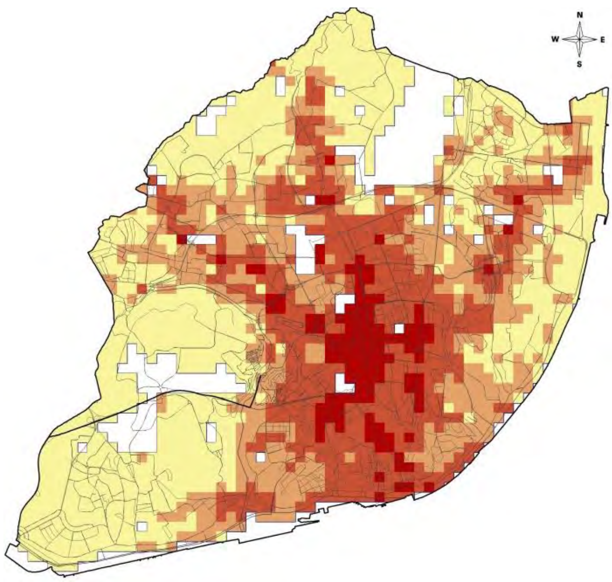
The first accessibility metric considered was the percentage of all the jobs in the city that can be reached starting from each grid cell. Using the number of jobs in each city block, available in the geographic information system of the city of Lisbon, and computing the shortest travel time from each grid cell to all the others in the public transport modes for each configuration, we looked at the number of jobs that can be reached within 30 minutes.

The two maps that form part of Figure 2 show the levels of accessibility across the city, using four classes corresponding to the quartiles of percentage of jobs. The poorest class of accessibility is formed by the grid cells which can reach no more than 25% of the jobs in the city in 30 minutes, whereas the best endowed class includes the grid cells that within that time can reach more than 75% of the jobs in the city.

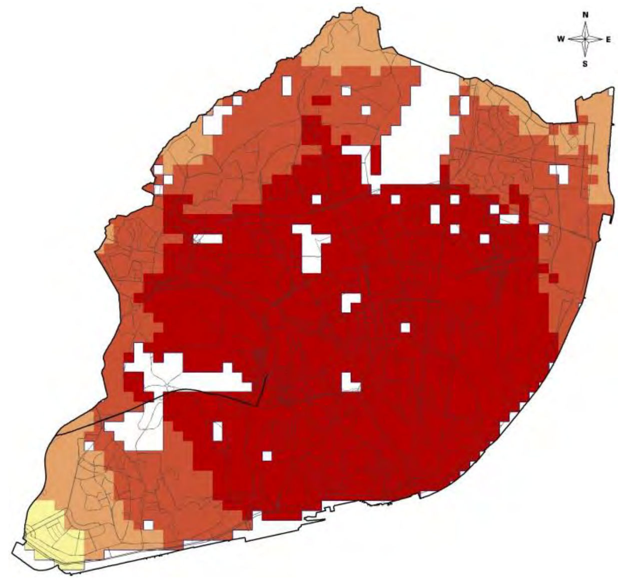
Figure 2. **Access to jobs summary**

Access to Jobs

Current Configuration



Simulated three-mode configuration



Equity Indicators

Indicator	Current Configurat.	Three-mode simul. config.
P90/P10	17.3	1.8
Gini coeff.	0.27	0.11

The graphical perception of the difference between the two configurations is strong enough to not need much further explanation, but it is worthwhile highlighting that in the current configuration the two lowest classes of accessibility dominate the landscape whereas in the simulated configuration the highest class is totally dominant, meaning that the majority of the grid cells have at least 75% of the jobs in the city reachable within 30 minutes. Two quantitative indicators are given to express the scale of change on equity:

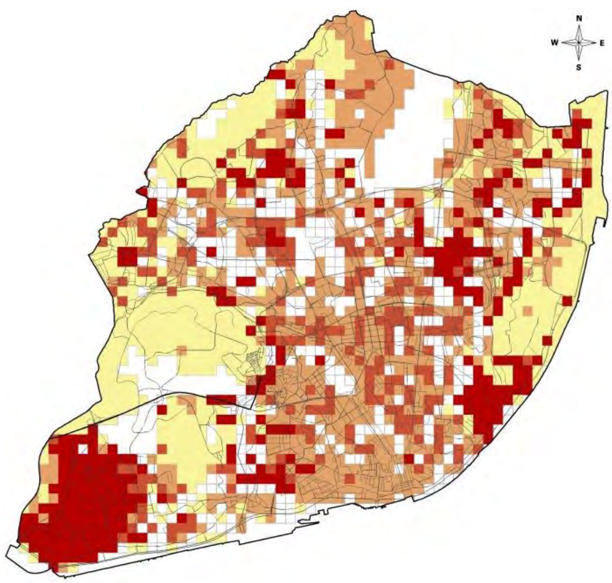
- The P90/P10 ratio represents the ratio between the number of jobs accessible in 30 minutes to the 10% best served person and the number of jobs accessible in 30 minutes to the 10% worst served person. The value of this quotient goes down from a very inequitable 17.3 to a quite equitable 1.8;
- The Gini coefficient is the most used indicator of inequality. For this analysis, it is applied to the percentage of jobs accessible to each person within 30 minutes. In the current configuration it takes the value of 0.27 (a value often found in the distribution of income in societies) but in the simulated configuration it goes down to a very low 0.11.

The next target of access considered is health facilities (hospital and health centres), using the area of those facilities as an indicator of the significance of the target being accessed. The same 30 minute threshold is adopted, with the results presented in Figure 3.

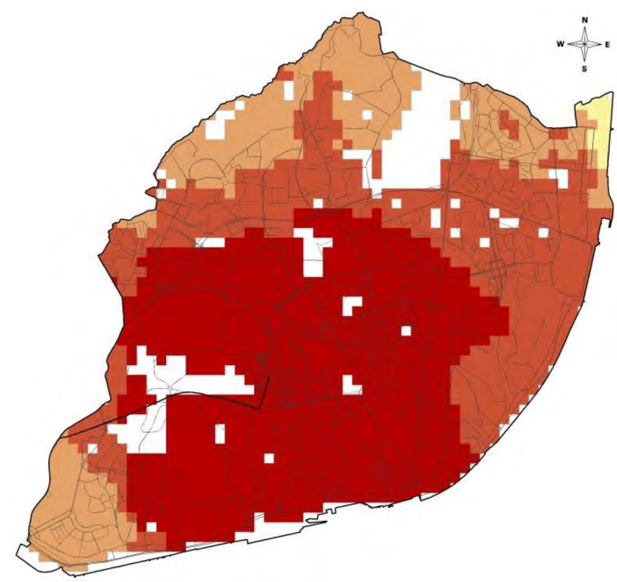
Figure 3. **Access to health facilities**

Access to Health Facilities (Hospitals and Health Centres)

Current Configuration



Simulated three-mode configuration



Equity Indicators

Indicator	Current Configurat.	Three-mode simul. config.
P90/P10	39.0	2.5
Gini coeff.	0.26	0.08

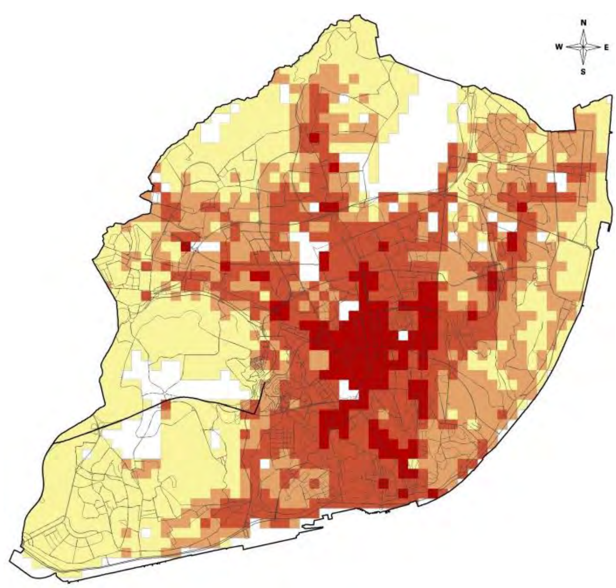
The level and direction of change is similar: the majority of the grid cells goes from the two lowest classes to the highest class, and the improvement in equity is very strong: The quotient P90/P10 is reduced from 39 to 2.5 and the Gini coefficient from 0.26 to 0.08.

One more very relevant target of access is education facilities (secondary and higher levels), with mass measured by the capacity in students in each facility. The same 30 minute threshold is adopted; the results are presented in Figure 4.

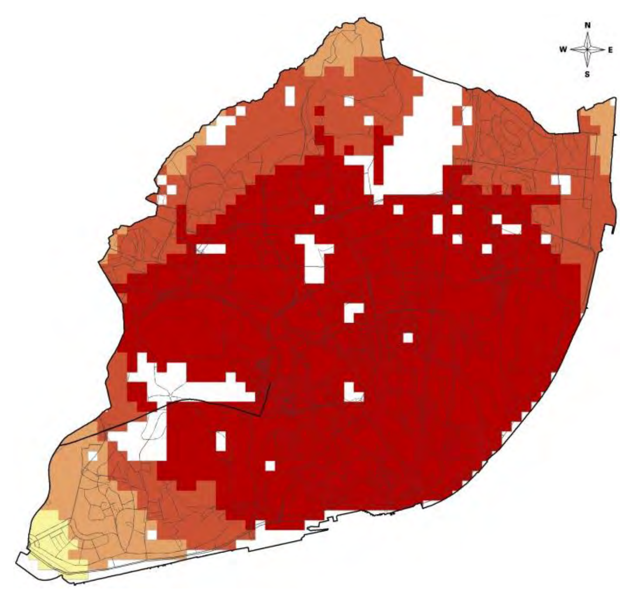
Figure 4. **Access to education facilities**

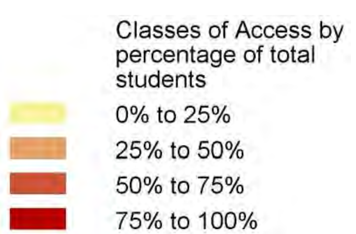
Access to Education Facilities (Secondary and Higher levels)

Current Configuration



Simulated three-mode configuration





Equity Indicators

Indicator	Current Configurat.	Three-mode simul. config.
P90/P10	29.2	2.0
Gini coeff.	0.26	0.01

A similar result as for the other two accessibility indicators is also achieved for education facilities: the majority of the grid cells goes from the two lowest classes to the highest class, and the improvement in equity is even stronger: The quotient P90/P10 is reduced from 29.2 to 2.0 and the Gini coefficient from 0.26 to an almost perfectly equitable 0.01.

In conclusion, if the aggregate results related to congestion and emissions were very good, the results on accessibility (based on public transport) are even more so – by far. This is due to the radical paradigm change, through which everybody gets a direct service in whatever direction desired, instead of having to use a finite number of services organised to cover the territory but always aligned with the dominant movement vectors.

It is important to note that these results were obtained assuming a unique computerised dispatch centre for all mobility requests. This concept assigns a very critical role (and power) to the entity providing such service. The loss of efficiency associated with a possible fragmentation of the highly sophisticated matchings being done across the day in two or three units, and the potential risk of abuse of the personal data being collected suggest careful reflection about the public or private nature of such entity, as well as about the design of the supervision of its performance.

Other potential dispatching arrangements are possible. One might imagine that the dispatcher manages an instant auction amongst all of the trips it wishes to match to clients such that several operating fleets bid on each trip with the price reflecting the most optimal (from a vkm and efficiency perspective) one. Other models could include an independent third-party dispatcher that allocates trips and several fleet operators that are only trip-takers, that is, they have no say in the dispatching process. We have not investigated alternative dispatching arrangements nor looked into the potential gains or dis-benefits that may arise from different market and service configurations associated with these and thus there is an open research question to be addressed.

5. Detailed results

In this section, we look at the results obtained for the three-mode configuration in more detail to better understand the factors that give rise to the results described earlier. We investigate aspects of quality of service, productive efficiency, and performance by shared mode in the following sections.

Quality of service

As the quality of service specifications are quite demanding, it is important to track what was achieved in the simulation. The following figures show identical percentile curves (P25, P50, P75 and P90) for a series of indicators across the hours of the day, starting with Taxi-Bus services and then for the Shared Taxis.

a) Access distance to boarding/alighting stops and access + waiting time in the Taxi-Bus service

Here we look at walking distances to/from the boarding/alighting point followed by access+waiting time for boarding Figures 5 and 6. Since the user specifies his/her preferred time of boarding, this waiting time represents the deviation (forward) from that preferred time to the real time of boarding. In all cases, the levels of service are very high, much better than currently, and very importantly, virtually constant across the whole day. For instance the 75th percentile of access distances is always slightly above 300 m, whereas the same percentile total time for access+waiting is 10 minutes at all times, day and night.

Figure 5. **Access distance to boarding/alighting stops in the Taxi-Bus service - Percentiles**

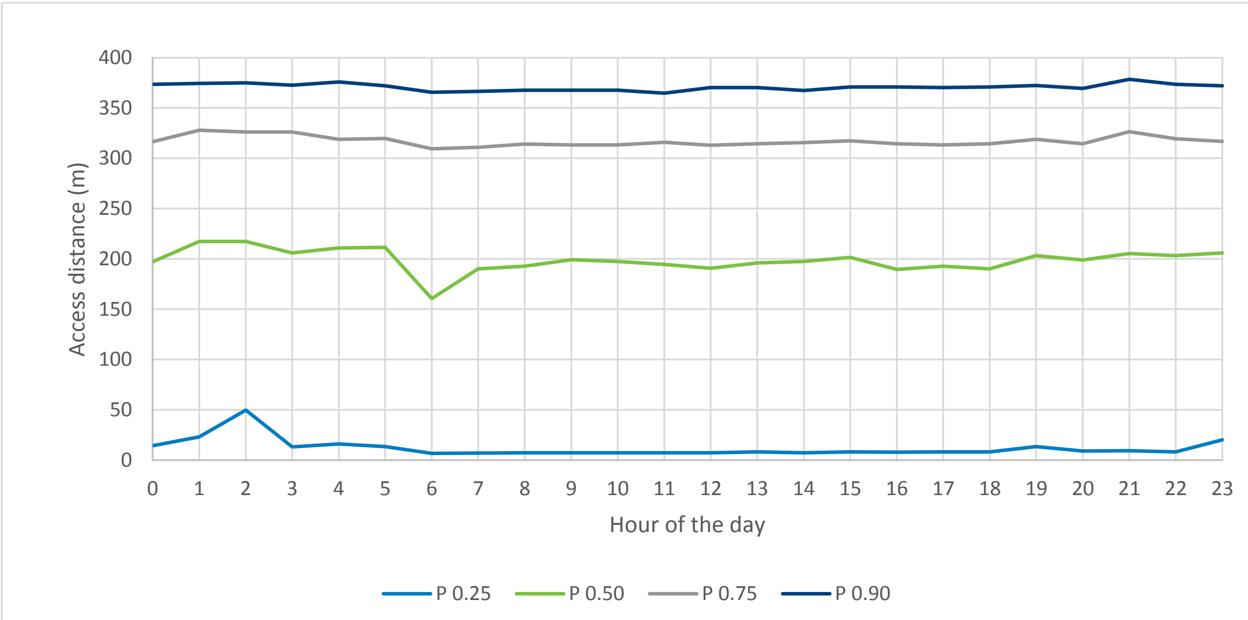
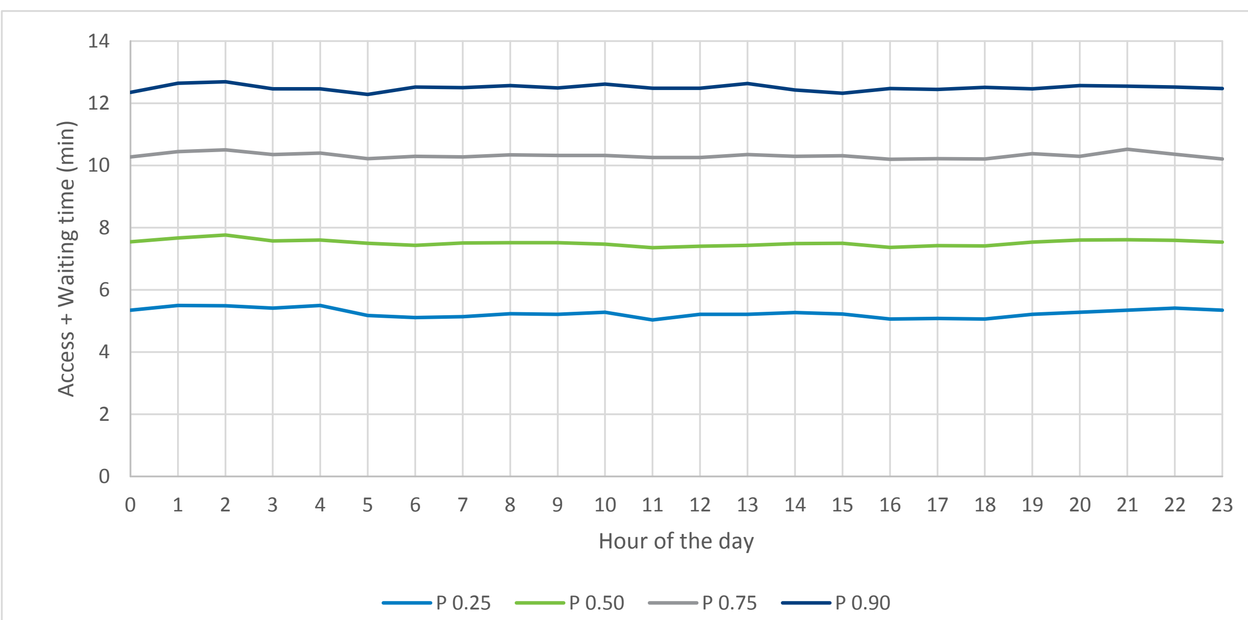


Figure 6. **Access + waiting time in Taxi-Bus service - Percentiles**



b) Waiting time and total lost time (wait + detour) in Shared Taxi service

Figures 7-9 show the same four percentiles for the waiting time for a Shared Taxi service (from the moment the request is made). As for the service with Taxi-Bus, the quality remains virtually at the same level during the 24 hours of the day. As specified in the requirements, the maximum tolerance for waiting depends on the trip length, and the resulting pattern of service is visible, but hardly: Using again the 75th percentile for illustration, for trips below 3 km length the wait is typically just below 3 minutes, for trips between 3 km and 6 km, the same indicator has values around 3.5 minutes, and for trips above 6 km, it increases to about 4 minutes.

Figure 7. **Waiting time in Shared Taxi service (trips with <3 km) - Percentiles**

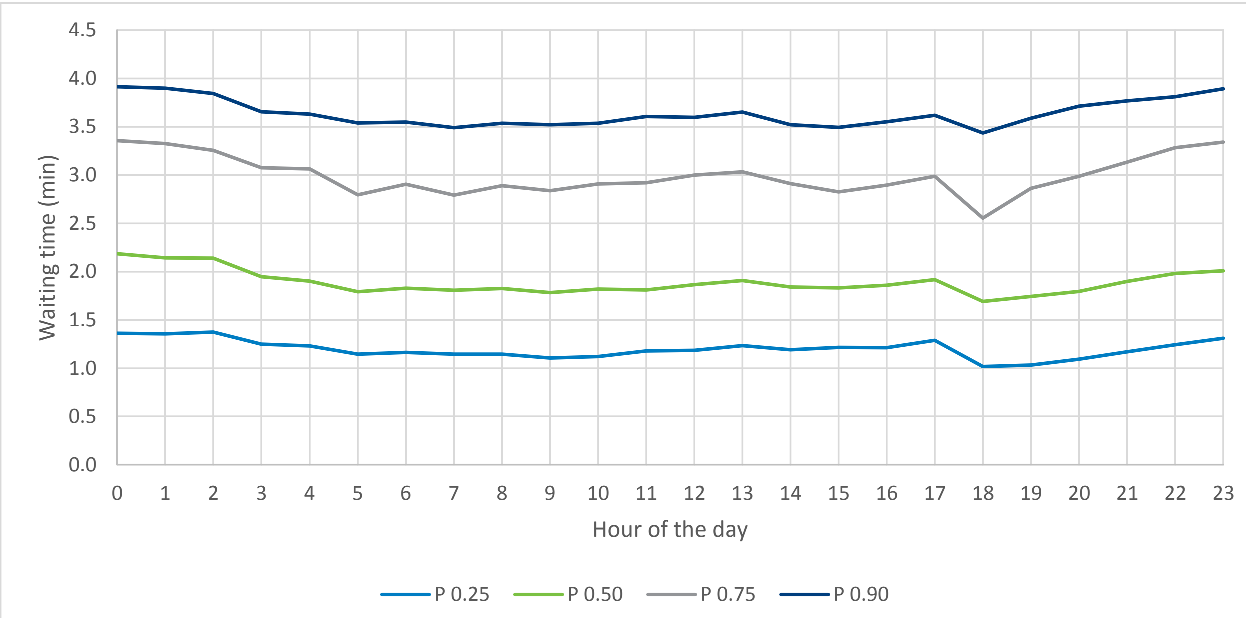


Figure 8. **Waiting time in Shared Taxi service (trips with 3 – 6 km) - Percentiles**

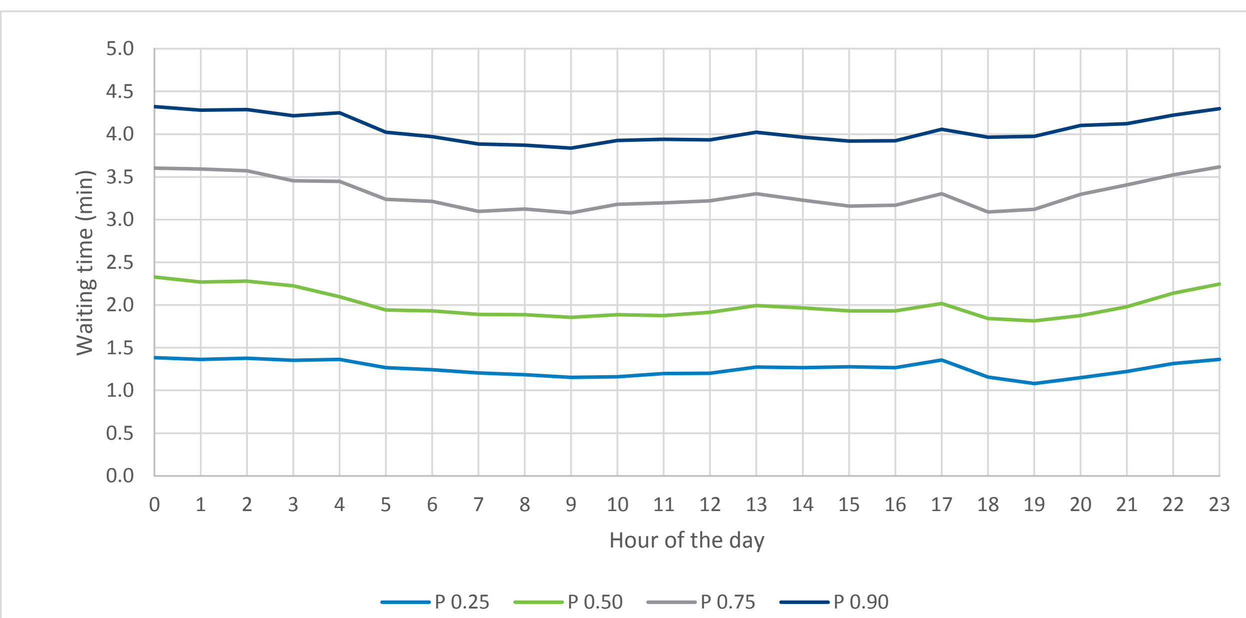
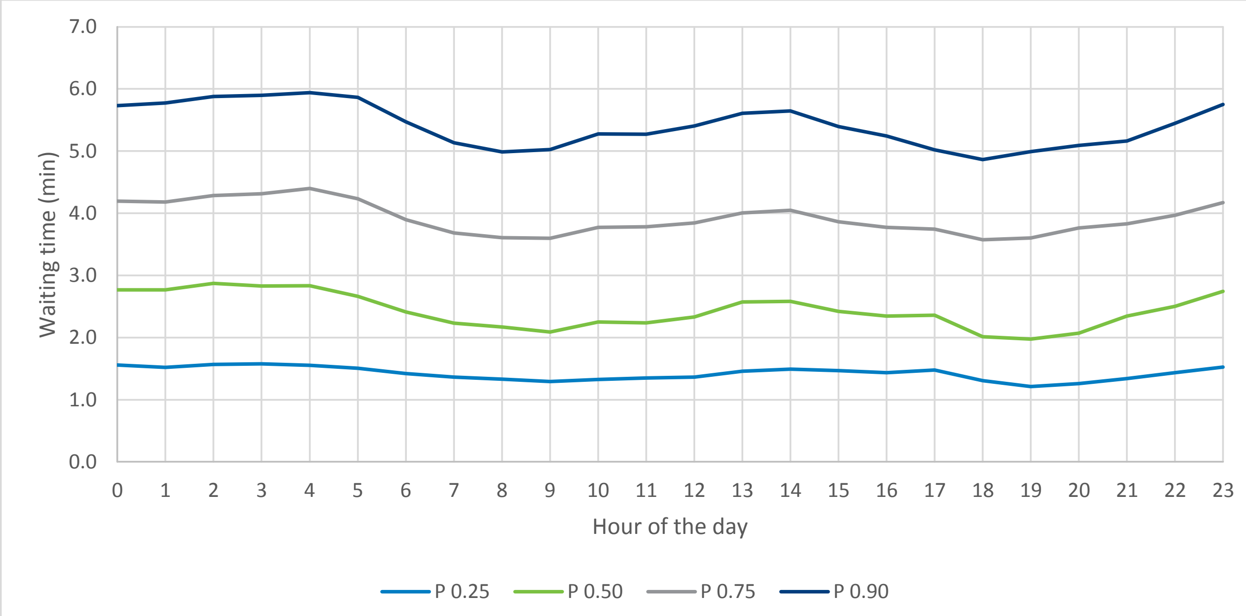


Figure 9. **Waiting time in Shared Taxi service (trips with >6 km) - Percentiles**



Figures 10-12 illustrate the total lost time (wait + detour) in Shared Taxi services, using the same four percentiles as for the previous graphs. Here again, very small variations across the hours of the day and across the trip lengths, the 75th percentile always taking values between 4 and 5 minutes.

Just as seen for Taxi-Bus services in comparison to current bus services, all of these values are significantly better than the current patterns for single user taxi. Moreover, these total lost times are certainly smaller than the typical times lost looking for a parking place and walking from the place of parking to the real destination.

Figure 10. **Total lost time in Shared Taxi service (trips with 3 km) - Percentiles**

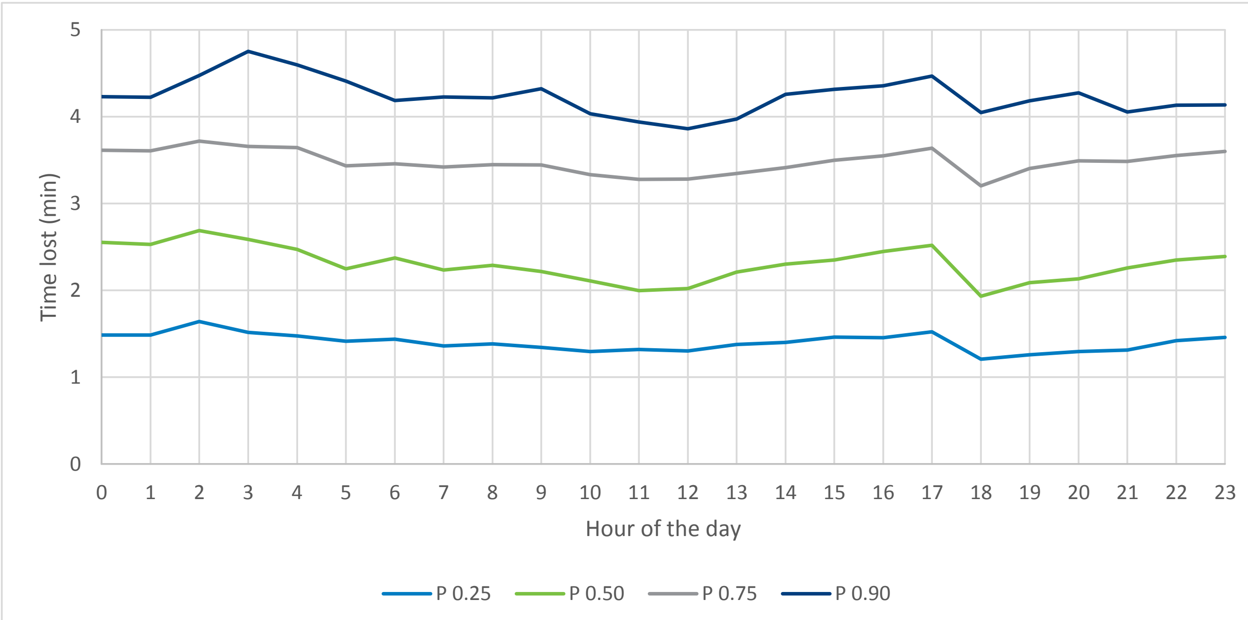


Figure 11. **Total lost time in Shared Taxi service (trips with 3 – 6 km) - Percentiles**

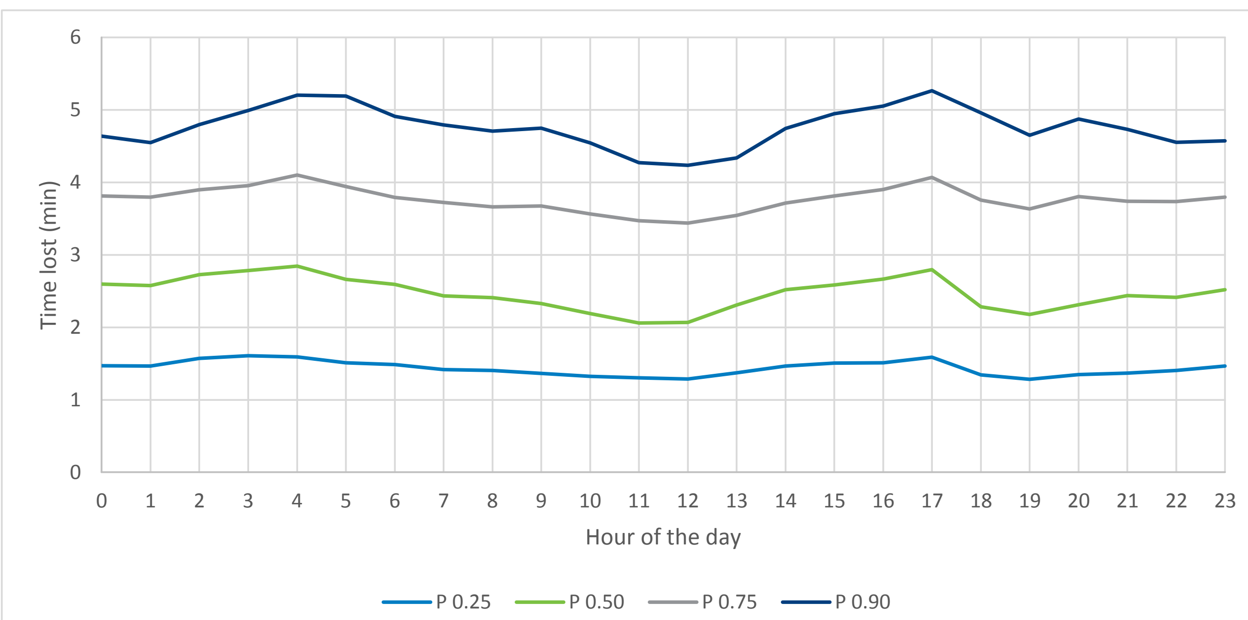
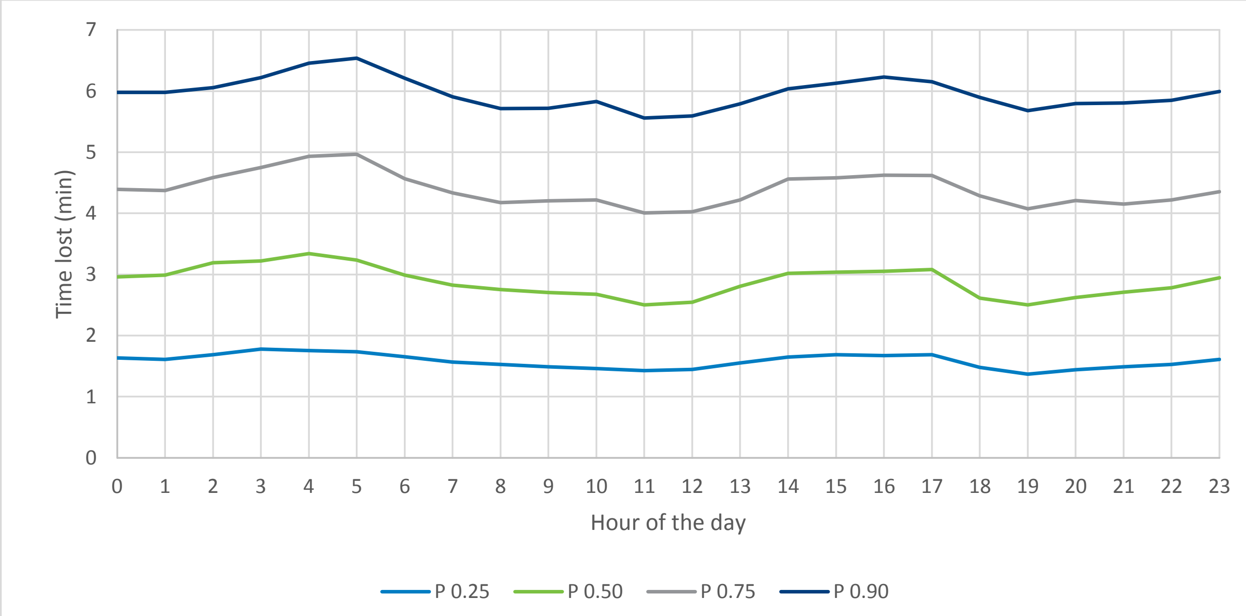


Figure 12. **Total lost time in Shared Taxi service (trips with > 6 km) - Percentiles**



c) Spatial and time detour in Taxi-Bus and in Shared Taxi services

The next dimension of quality of service that we look at is that of detours related to extra travel distances generated through picking up additional passengers and deviations in travel times from the original trips in the synthetic trip population. These are measured in relation to base case trips. What emerges is that detours and travel time deviations visibly increase during the night hours, as demand is thinner and longer connections between consecutive clients are necessary.

Starting with Taxi-Bus services, as seen in Figures 13 and 14, and looking again at the 75th percentile, the spatial detour varies between 1.7 and almost 2.0 km, whereas the time detour is virtually constant at about 2 minutes. There is less variation of the total time lost during the night than for the distance because the traffic speeds are higher during this period.

Figure 13. **Spatial detour in Taxi-Bus service - Percentiles**

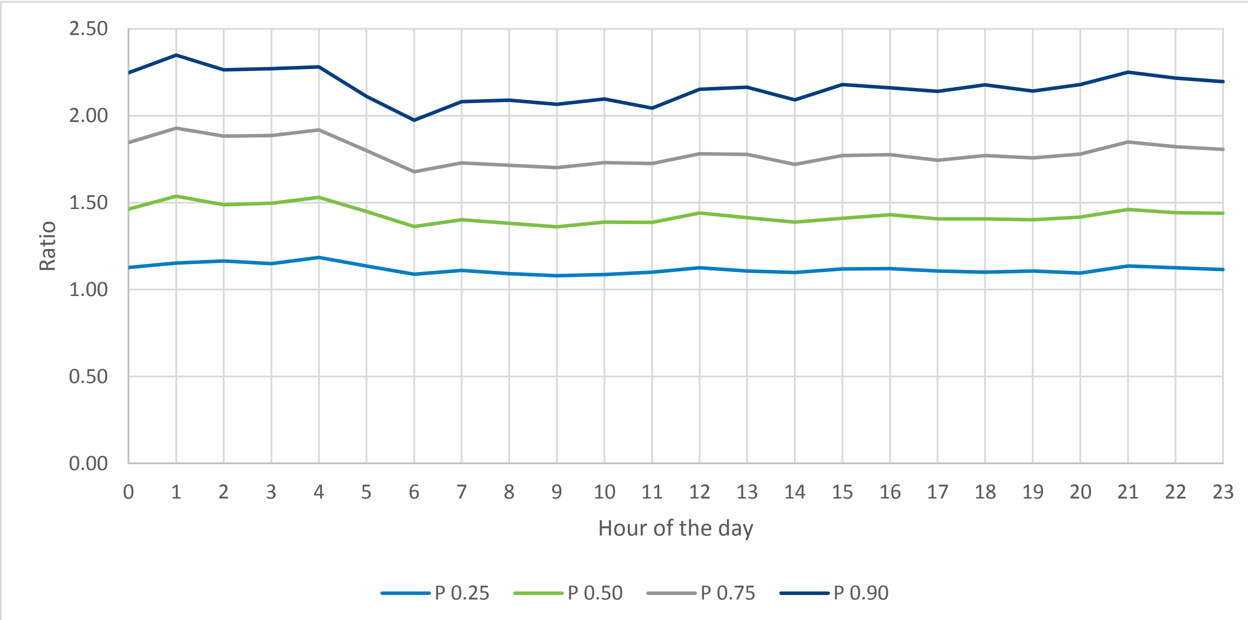
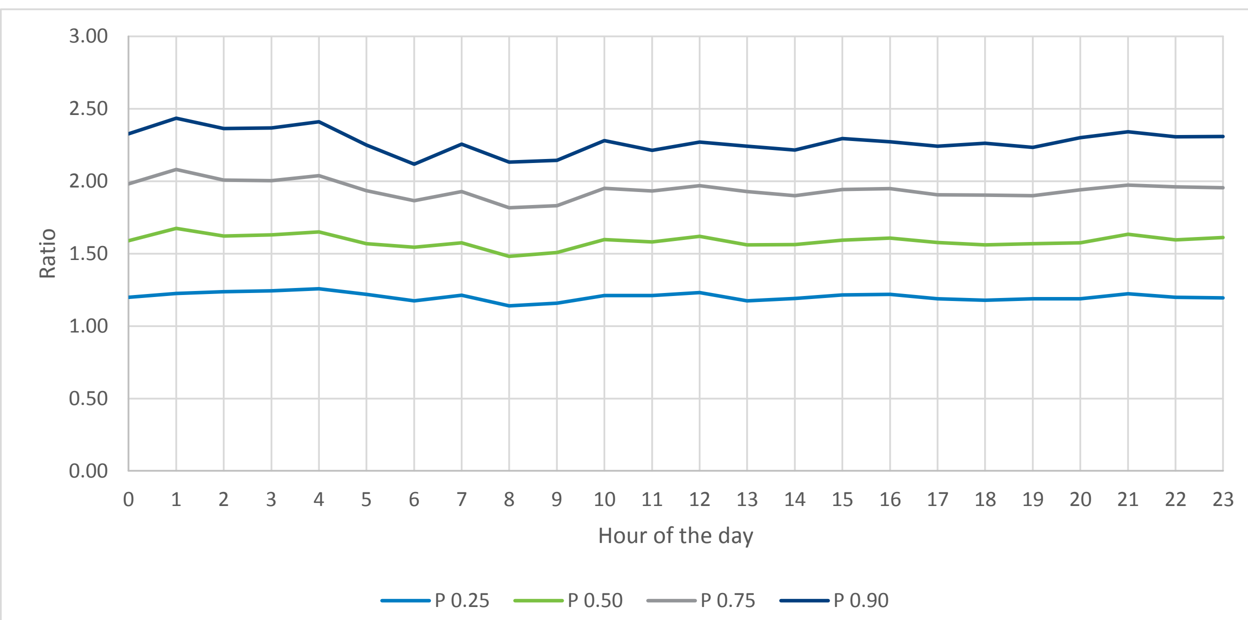


Figure 14. **Time detour in Taxi-Bus service - Percentiles**



For the Shared Taxi services illustrated in Figures 15 and 16, the 75th percentile of the spatial detour is relatively stable and oscillates between roughly 1.4 and 1.6 km, whereas the time detour presents significant variations (although staying always at acceptable quality levels) at the periods of increasing demand. As it will be seen in some other figures below, in these periods vehicle occupancy (ridership) increases, and the difference is essentially due to those connections and boarding / alighting times of the additional passengers. Still, the 75th percentile stays mostly between 1.5 and 2 minutes, with only a brief lapse between 6:00 am and 7:30 am where it climbs to 2.2 minutes.

Figure 15. **Spatial detour in Shared Taxi service - Percentiles**

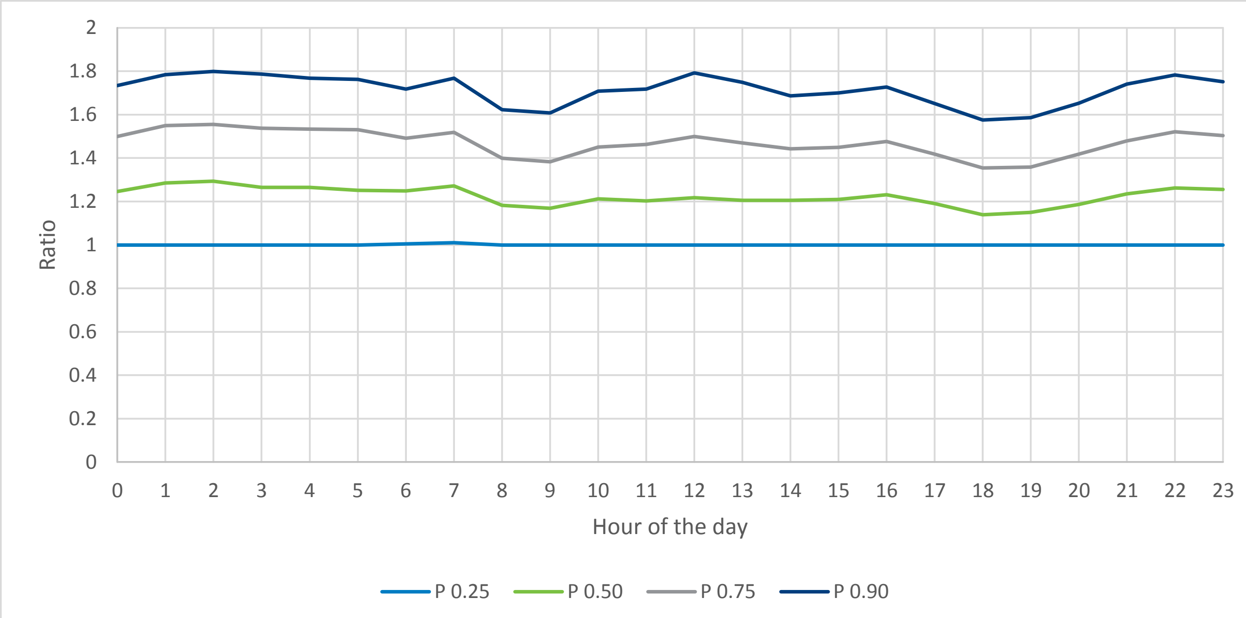
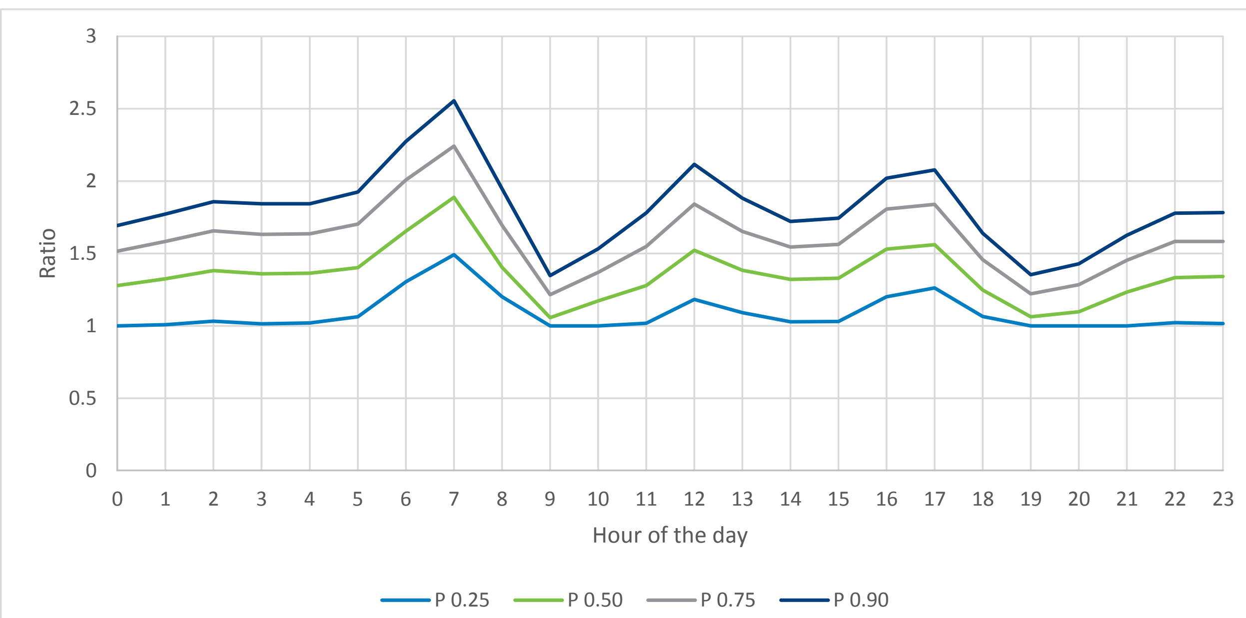


Figure 16. **Time detour in Shared Taxi service - Percentiles**



In synthesis, the analysis of service quality shows very high levels in all dimensions, virtually constant across all 24 hours of the day. This is notable especially for Taxi-Bus services for which all trips are carried out directly from origin to destination, without transfers.

These levels are certainly far better than those enjoyed today by clients of public transport (versus the Taxi-Bus) and of the single-user taxi (versus the Shared Taxi). The Shared Taxi also compares very well with the use of the private car, as the short additional travel time and distance are good compensation for not having to worry about finding a parking place and walking from it to the real destination.

Productive efficiency

In investigating issues relating to productive efficiency, we look, in sequence, at indicators of vehicle occupancy (ridership), length of individual services, speeds, fleet requirements, vehicle kilometres produced, kilometres transported, and the impact of operating the service in both 4- and 8-hour shifts for drivers. For each type of indicator, the values for 8- and 16-person Taxi-Buses, and for the Shared Taxis are considered in sequence. In all cases, the curves in the graphs represent values across the 24 hours of the day.

Starting with ridership for the eight-person and 16-person Taxi-Buses (Figures 17 and 18), the 50^{th} percentile (median) shows values that are very stable at half the capacity for the eight-seater and a bit more variable but consistently above that half capacity for the 16-seater.

Figure 17. **Taxi-Bus ridership 8 characterisation - Percentiles**

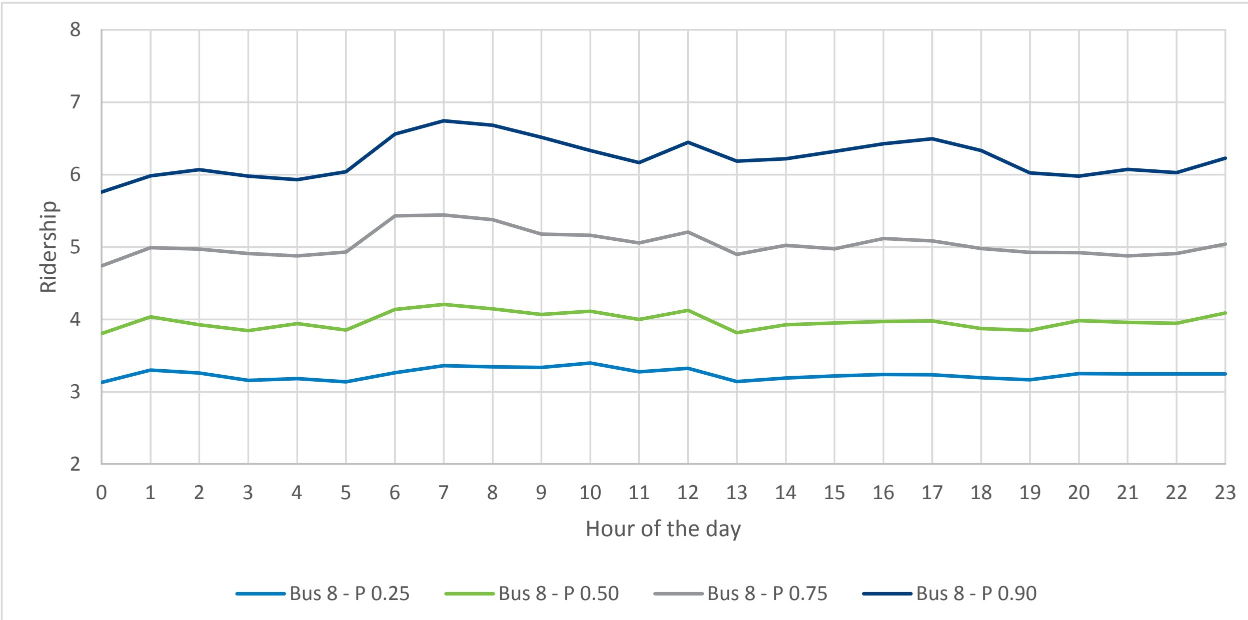
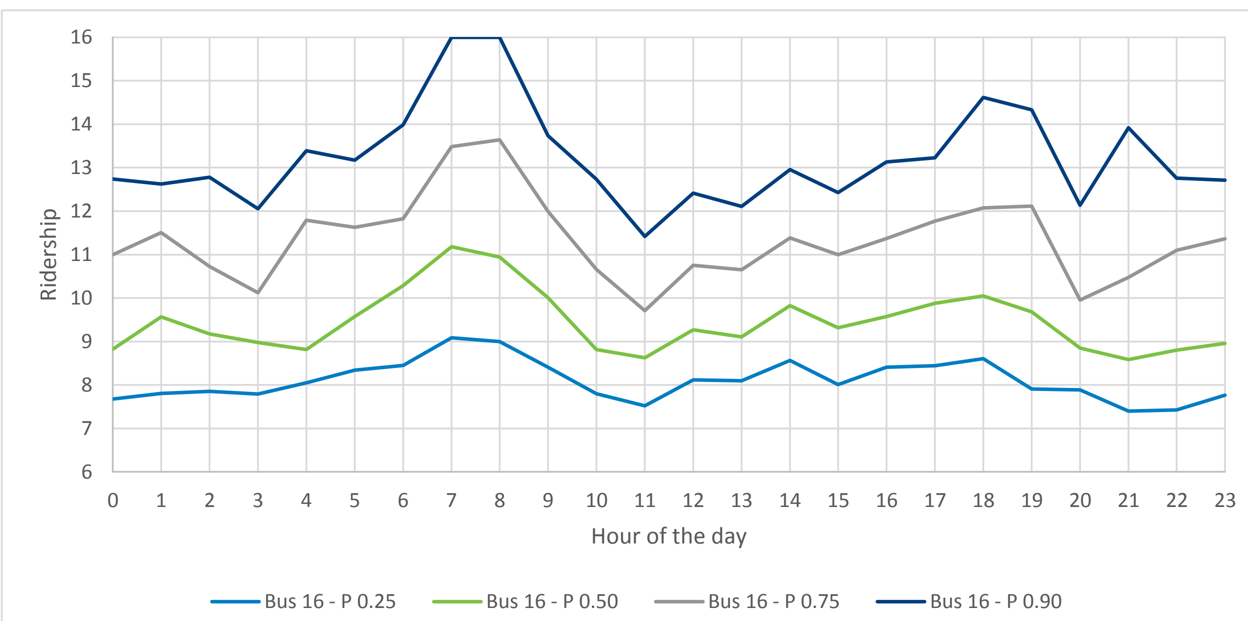


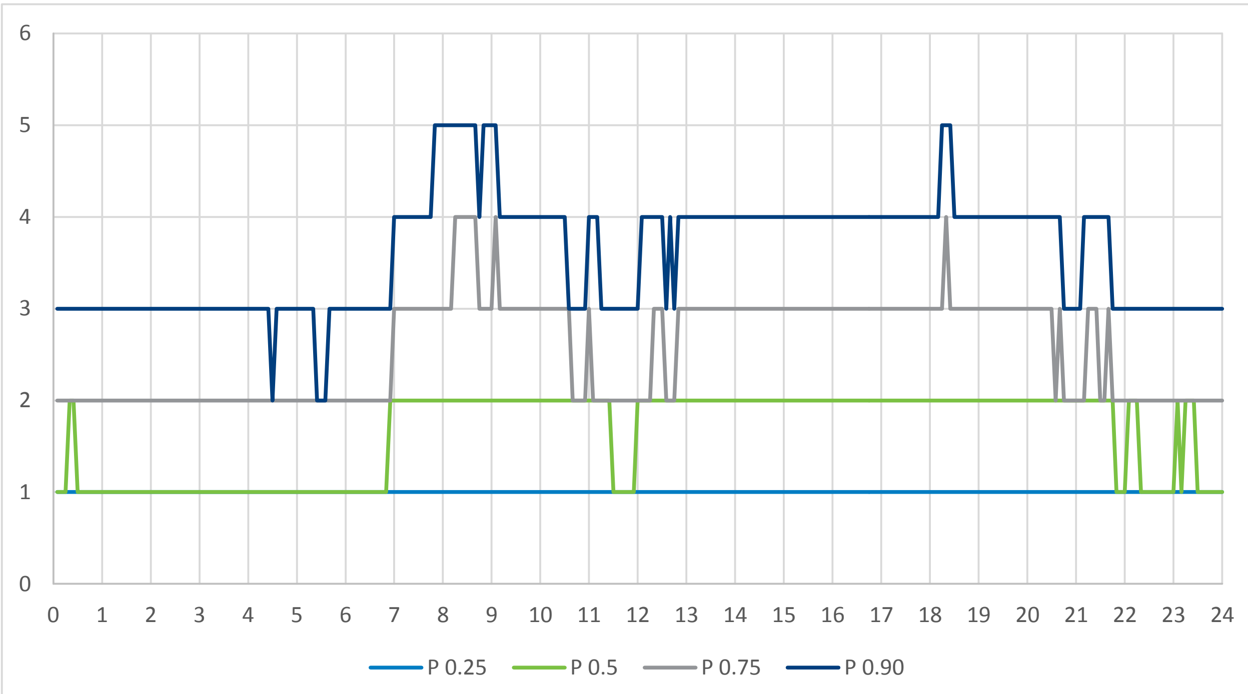
Figure 18. **Taxi-Bus ridership 16 characterisation - Percentiles**



Ridership in Shared Taxis (ie. the party-size – see Figure 19) naturally presents more variations than in Taxi-Bus services, as demand is satisfied in real-time in contrast to an assembly period of 30 minutes for Taxi-Buses (and the possibility of upgrade to Shared Taxis when demand is below the required minimum for a potential Taxi-Bus service).

With computations made for each 15 minute period, and looking at the 50th percentile, Figure 19 shows that single party trips are essentially seen at night rising to parties of 2 or more between 7:00 and 22:00 with a brief decrease between 11:30 and 12:00. Looking at the 75th percentile, there are significant periods where party size is above 3. Still, at all hours of the day, the 25th percentile is at 1, corresponding to single client services.

Figure 19. **Party size on board Shared Taxi**



Looking next at the length of individual services for 8- and 16-person Taxi-Buses (Figures 20 and 21), we note that eight-seaters have a 50th percentile trip length that is a bit longer (around 8km) than that of the 16-seaters (around 6km). Similar ranking occurs in the other percentiles.

In both cases, these lengths avoid excessively short and inefficient services. Even the 25th percentile has a length of about 6 km for the eight-seaters and of about 4 km for the 16 seaters.

Figure 20. **Length of Taxi-Bus 8 services (along the day) - Percentiles**

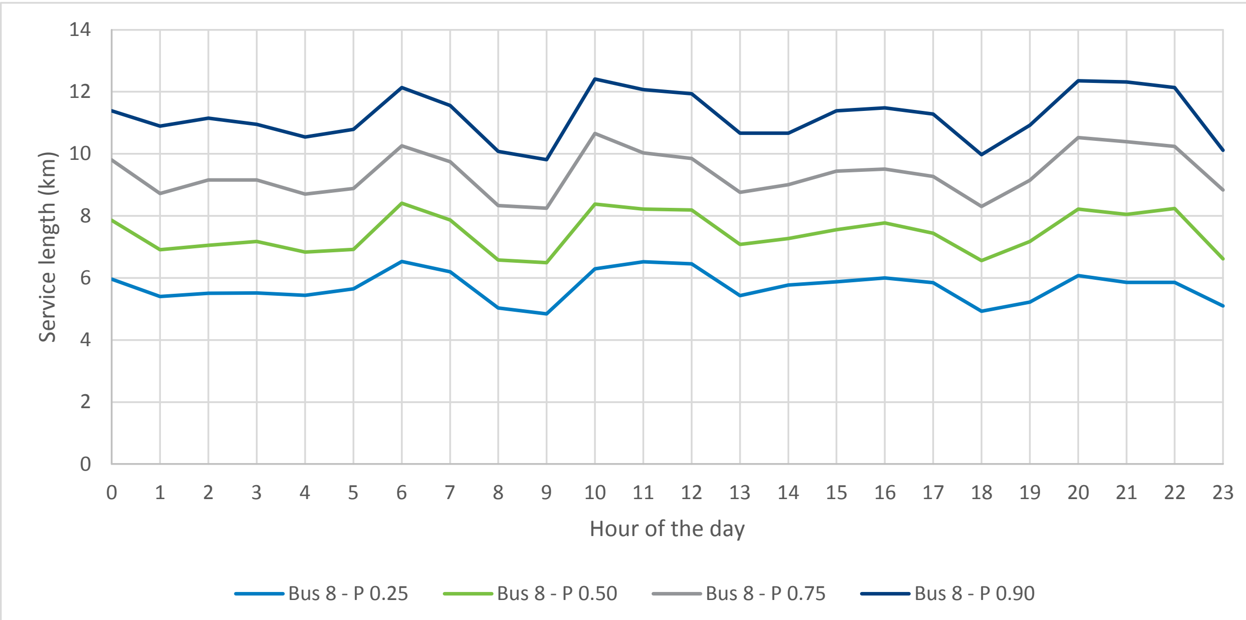
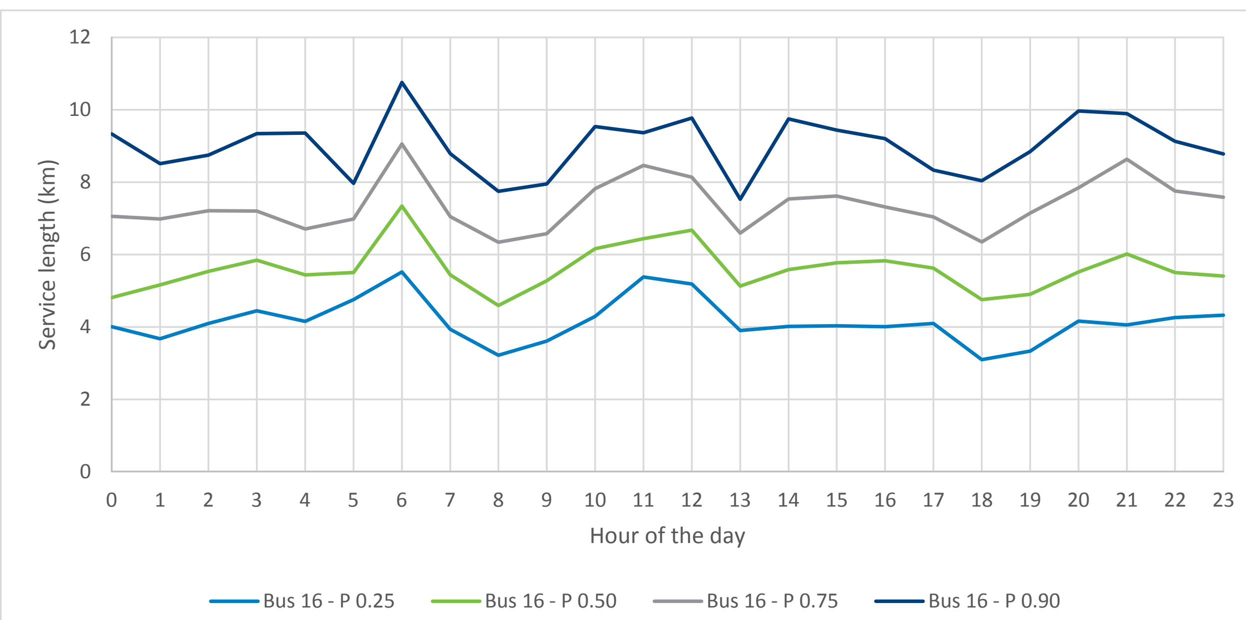


Figure 21. **Length of Taxi-Bus 16 services (along the day) - Percentiles**



For the case of Shared Taxis, both the number of clients served in each service cycle (i.e. between two moments with an empty taxi which also represents a series of consecutive clients keeping at least one client on board at all times) and the distance covered in each such cycle have been analysed.

Figure 22 illustrates the number of clients per service cycle for Shared Taxis. Here, the median is at 2.0 or above essentially between 7:00 am and 10:00 pm, with a break of about one hour from 11:30 to 12:30, when it falls to 1.0. It reaches 3.0 for significant periods between 8:00 and 10:00 am, and occasionally around 10:30 and then in brief periods in the late afternoon, between 17:30 and 20:00. The 75th percentile grows to values of 4 or 5 from 7:30 to 11:00 and for most of the time between 13:30 and 20:30. The 90th percentile is at 5 most of the day, but reaches 6 or even 7 at the morning and evening peaks.

Figure 22. **Number of clients per service cycle in Shared Taxi - Percentiles**

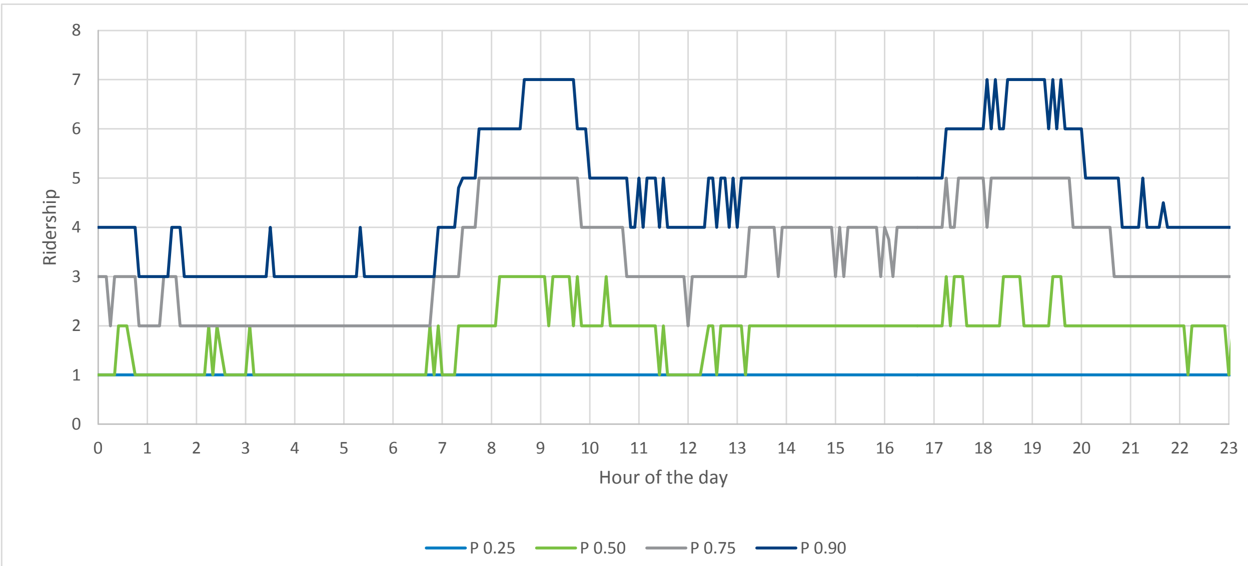
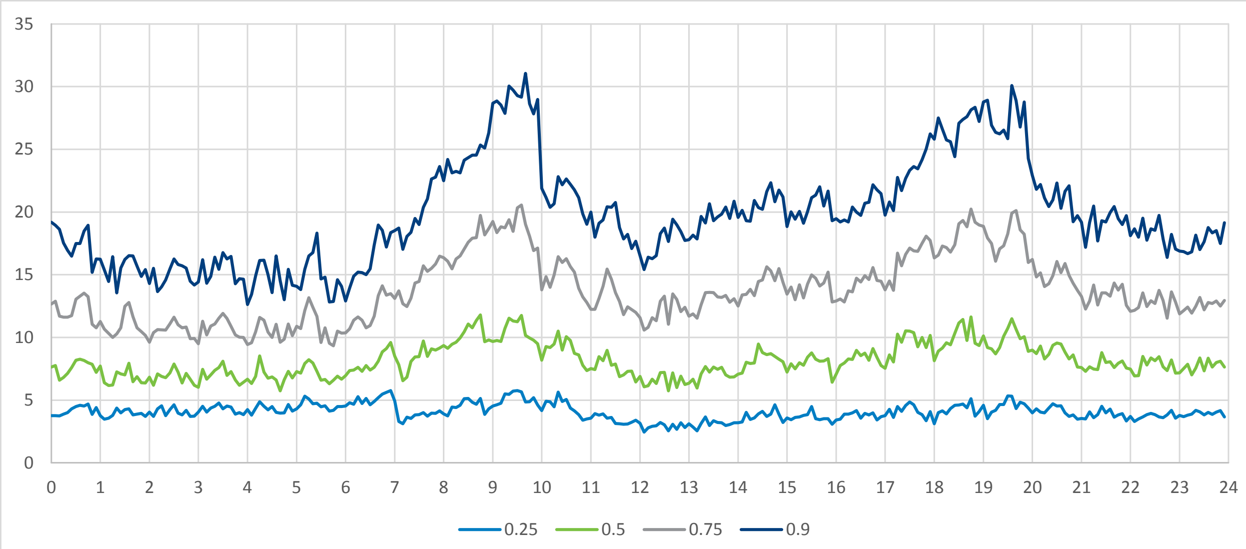


Figure 23, illustrating the distance covered in each service cycle, shows a similar oscillation pattern, with the median mostly around 10km, the 75th percentile at between 12 and 18 km during the daylight hours, with brief moments close to 20kms, and the 90th percentile staying most of the daylight hours at 20 km or above, reaching values close to 30 km at the peak periods. The 25th percentile represents the cycles with only client, with distances covered rarely exceeding 5 km.

Figure 23. **Distance covered by service cycle in Shared Taxi - Percentiles**



Figures 24 and 25, illustrating Taxi-Bus speeds in service reveal that the gap between the various percentiles is quite narrow, and that the values are very similar for the eight-seaters and the 16-seaters. There are visible variations across the hours of the day, with lower speeds in period of higher traffic volumes. Since these speeds include consideration of the times for boarding and alighting, perhaps the most important outcome of this analysis is that the speed levels are quite similar to those achieved by the buses in the current supply. As is well known, these speeds are mostly affected by the general speed of traffic in the network and by the distance between stops.

Figure 24. **Speed of Taxi-Bus 8 services (along the day) - Percentiles**

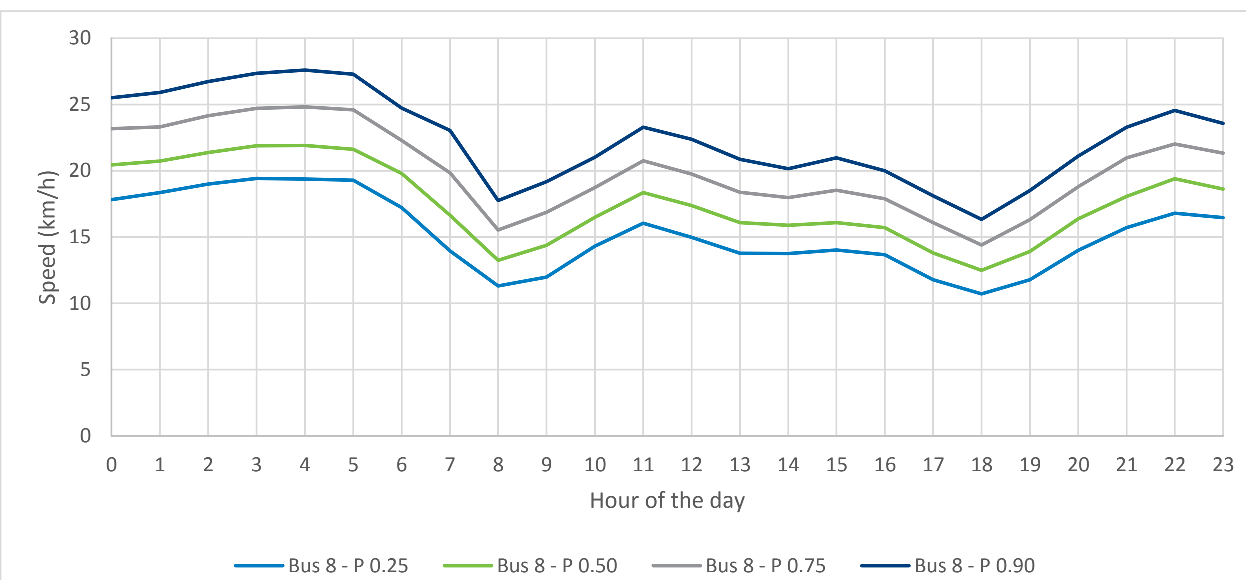
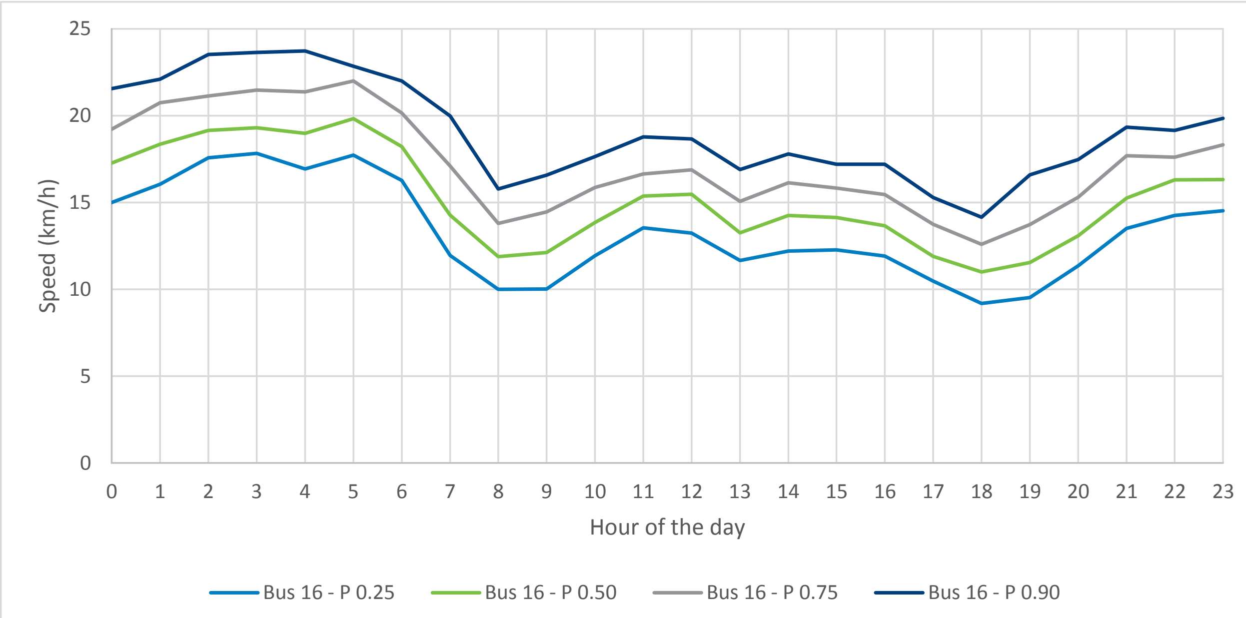


Figure 25. **Speed of Taxi-Bus 16 services (along the day) - Percentiles**



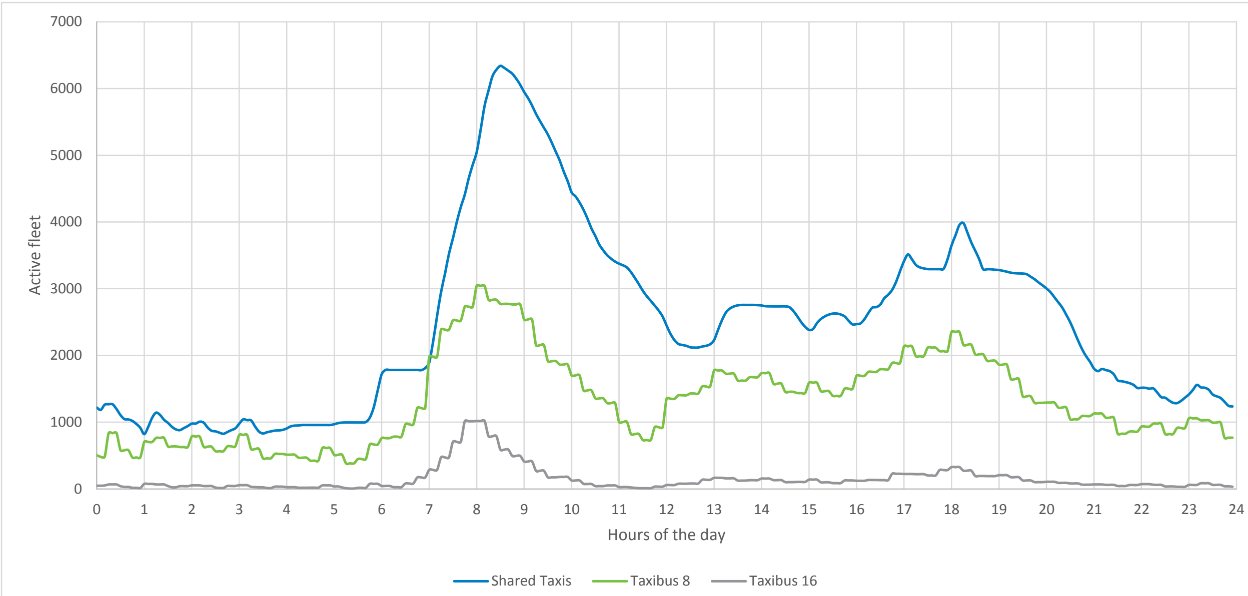
Another very important aspect of productive efficiency is fleet size. The required fleet across the hours of the day was computed, for each type of Taxi-Bus and for Shared Taxis and results are illustrated in Figures 26 and 27.

This computation was made initially assuming totally free entry and exit of service (as if dealing with fully automated vehicles). As it can be seen in the Figure 26, there are marked peaks for all three types of vehicles. For Shared Taxis the highest value is 5 886, but values above 4 000 only occur for less than two consecutive hours, roughly between 7:30 and 9:30. Needs above 3 000 exist only for less than 3 hours in the morning (7:30 - 10:15), and another 2.5 hours in the evening (17:00 - 19:30). The average across the 24-hour cycle is 2 088 vehicles (35% of the maximum).

For eight-person Taxi-Buses the maximum is 3 042 vehicles, but here the peak is a bit less pronounced. A need above (or almost at) 2 000 exists during roughly 2 hours in the morning (7:15 - 9:30) and then for less than 2 hours in the evening (17:00 - 18:45). The average across the 24-hour cycle is 1 328 vehicles (44% of the maximum).

For 16-person Taxi-Buses the maximum is 1 018, with a more strongly marked peak than for the other types of vehicles. Only for one hour (7:30 - 8:30) are the needs above 600. Needs above 200 only occur between 7:00 and 9:30, and then between 16:45 and 19:15. The average across the 24-hour cycle is 147 vehicles (14% of the maximum).

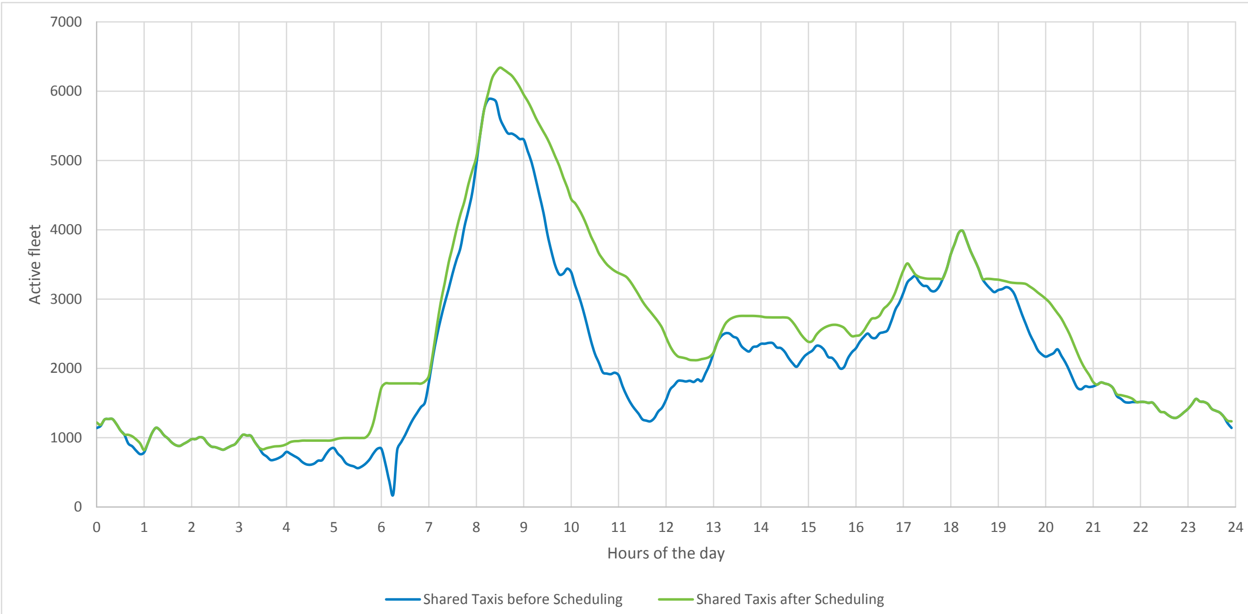
Figure 26. **Active fleet of Shared Taxi and Taxi-Bus (before scheduling)**



A more realistic analysis (for the present state of technology and regulation) was undertaken next, by searching for the optimum provision of service using professional drivers, some working with shifts of 4 hours and some with shifts of 8 hours (with a break of between 1 and 2 hours after the first 4 hours of duty). Only the analysis for the Shared Taxis is presented here, as it is the larger fleet and with the more pronounced peak (Figure 26).

The optimisation algorithm includes an "incentive" towards the 8-hour shifts, but the strong peak in the demand clearly shows that there will be very significant diseconomies if all drivers are employed with 8-hour shifts (Figure 27).

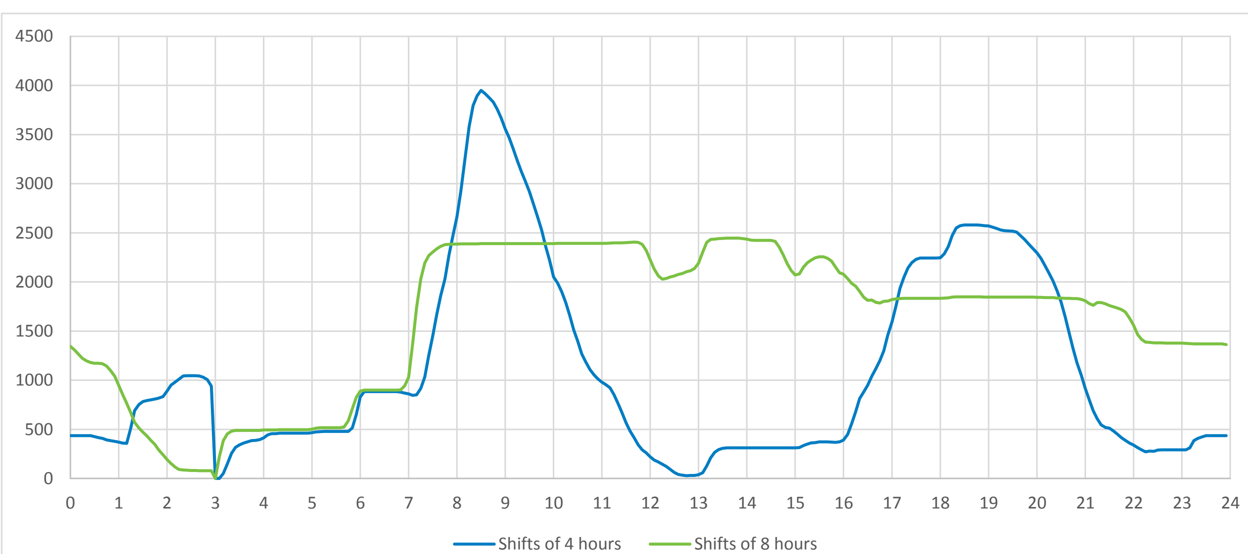
Figure 27. **Active fleet of Shared Taxis (before and after scheduling)**



The introduction of this constraint naturally forces an increase in the resources needed, although the general shape of the curves remains the same. The new maxima are 6 339 for Shared Taxis (8% increase).

Naturally in the optimum solution shifts do not all start at the same time. The pattern of drivers on duty across the hours of the day is shown in Figure 28. There the crucial role played by 4-hour shifts in servicing the peaks can be seen.

Figure 28. **Time distribution of Shared Taxis drivers' shift**



Performance by Shared Mode

In this aspect of evaluation the first indicators considered were the traffic volumes produced by each of the types of vehicles used. As mentioned above, equivalence coefficients were used to translate the traffic impact of each of these vehicle types into "private car units" (PCUs).

These values are presented next (with only one point for each hour), first in absolute terms, and then as a fraction of the total. The strong peak of the morning and the less marked but longer peak of the evening are well visible in Figure 29, whereas the Figure 30 shows that the fraction of each of these modes is practically constant across the day, with the Shared Taxi around 79%-80%, the eight-person Taxi-Bus oscillating between 16% and 18% (with a short peak of 21% at 6 am) and the 16-person Taxi-Bus varying between 3% and 5% with values up to 9% between 7 am and 8 am.

Figure 29. **Vkms produced by Shared Taxis and Taxi-Buses along the day**
(equivalent vehicles units. 1 equals to current private car)

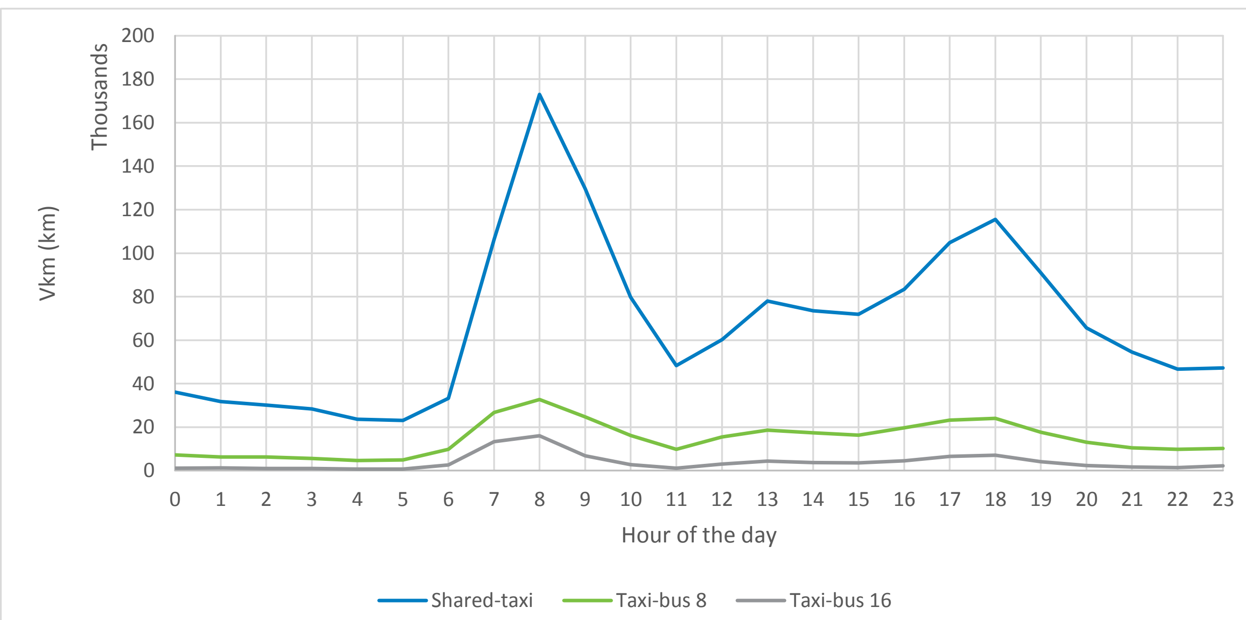
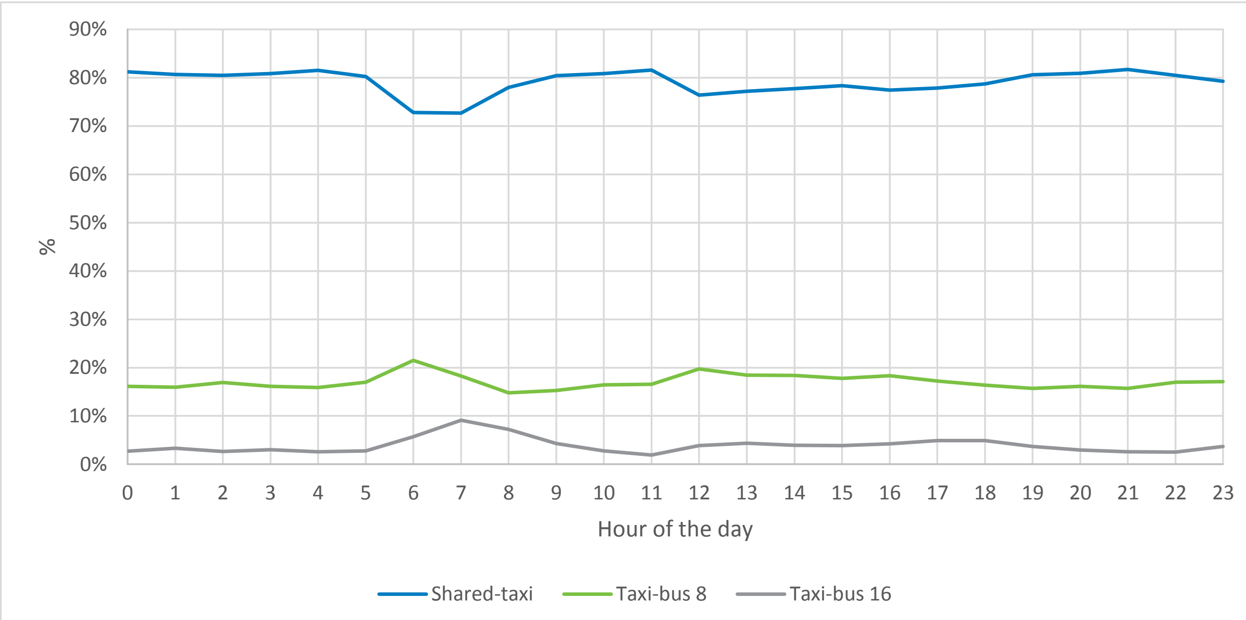


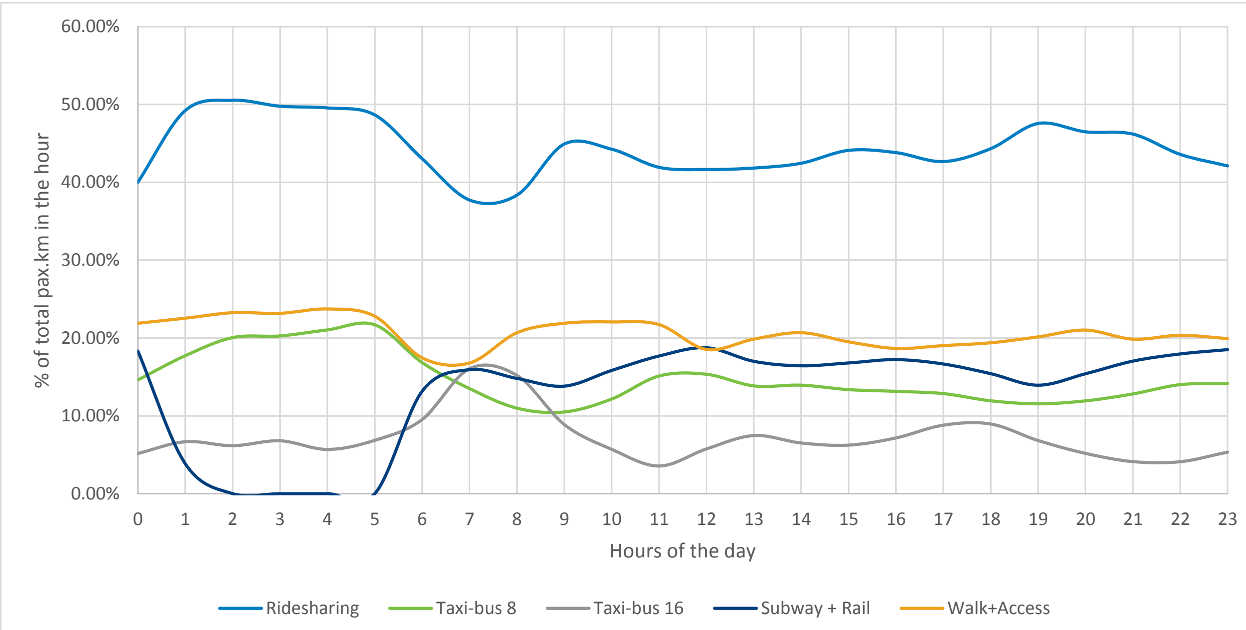
Figure 30. **Share of Vkms by Shared Taxis and Taxi-Buses along the day**
(equivalent vehicles units. 1 equals to current private car)



A richer perspective is possible if the analysis is made on the passenger.kms transported by each mode in each hour (modal shares), as shown in the Figure 31, in which not only the new three modes are presented but also railway+metro and walking (taken as walking from origin to destination plus walking for access to/from public transport boarding/alighting points). In this figure, the dominating mode is the Shared Taxi, with values essentially between 40% and 50%, not very different from those seen in Figure 1 for the private car today, except during the night period, where the current system barely provides any public transport service and the simulated configuration keeps that service through the whole day.

Walking also keeps a largely stable market of around 20% (hourly values between 17% and 23%), just slightly higher than the shares of railway+metro in the hours of operation (values between 14% and 19% between 7 am and midnight). Taxi-Bus services as whole provide between 17% and 30% of the passenger.kms with an average of 22%. The eight-seaters represent at least two-thirds of this joint service, but the 16-seaters become slightly dominant (58% of the joint service) during the morning peak as could be expected.

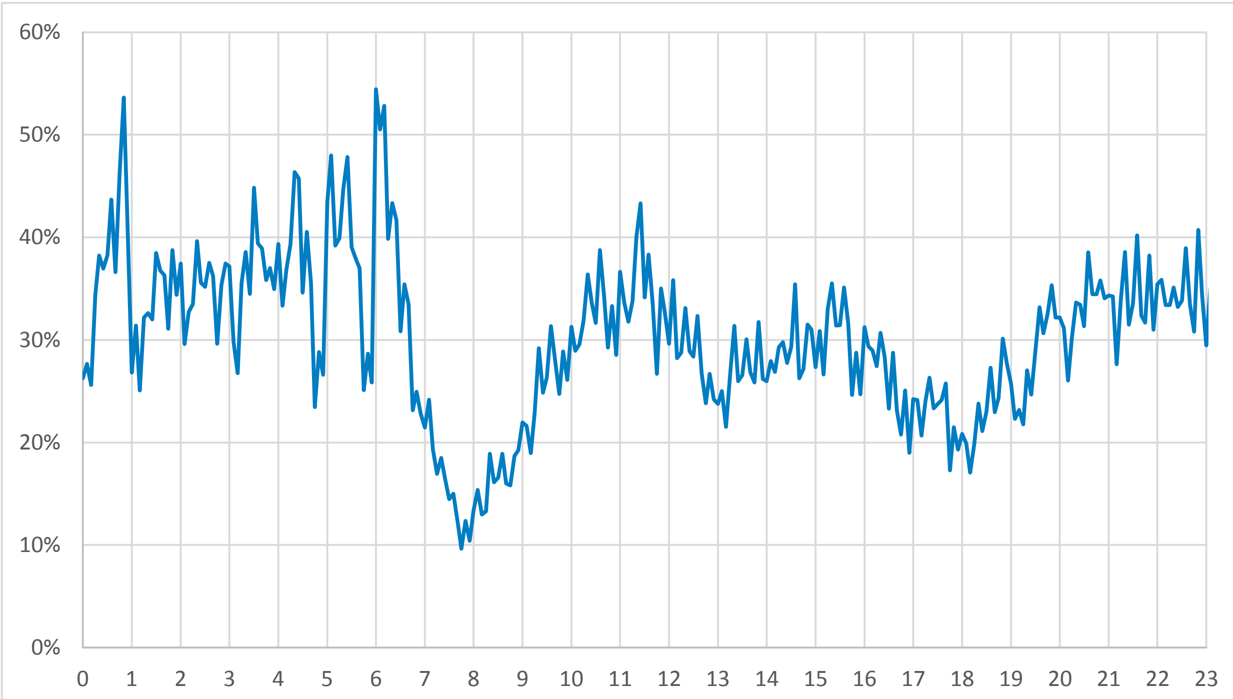
Figure 31. **Modal shared (pax.km/h) across the day**



An interesting feature of our analysis was that we found that providing Taxi-Bus service to all interested clients would lead to considerable loss of efficiency, and it would instead be preferable to serve some of those clients - those with more difficult clustering with other because of large differences in desired geographical line or time of movement - with a Shared Taxi. Because this upgrade is made by convenience of the supply side, prices charged to the client are those applicable for Taxi-Bus.

Figure 32 shows the percentages of clients upgraded to Shared Taxi by interval of 5 minutes. During the night period typical values are around 40% (with extremes just below 30% and above 50%), then they fall to levels between 10% and 20% during the morning peak and then oscillate between 20% and 30% during the rest of the day. The overall average across passengers is 25%.

Figure 32. **Share of Taxi-Bus demand upgraded**



Price Benchmark against other modes

In this section, we cursorily investigate costs and prices for shared mobility scenarios compared to the base case services.

For this, all capital and operating costs related to the shared vehicles have been estimated using the 2015 Lisbon reference. A margin of 25% was given on top of operational costs to cover non-operational costs and profits. Knowing the total fleet sizes, average distances run and passenger.km transported per day, total break-even costs per vehicle.km and prices per pax.km are estimated for each type of vehicle (service): Shared Taxi, eight-person Taxi-Bus and 16-person Taxi-Bus.

In Lisbon the dominant transport title for public transport is the monthly card covering metro and bus with unlimited travel rights within the geographic zone of its coverage (the same as simulated in this project). For some years now these cards support contactless electronic check-in and check-out, thus providing a strong dataset of actual use by each card holder. This has allowed obtaining an estimate of the daily average number of km travelled in public transport by card holders and through it the average price paid by km travelled using the monthly card. There are other relevant titles, namely a pre-loaded debit card on a "pay-as-you-go" system, but the average price per km is higher and so the price obtained from the monthly card was retained as the benchmark.

For the taxis, the tariff structure is known, with an entry fee and a distance tariff. The mobility data used for the simulation allowed a good representation of the trips made by taxi and estimation of the price paid for each trip. To facilitate comparisons, all prices were converted to a uniform tariff per km.

On these bases, the break-even prices for the new modes as percentages of the current benchmarks are as follows in Table 5.

Table 5. **Comparison of shared solutions price to current equivalent transport supply**

Modes	Shared Taxi vs. current Taxi	Taxi-Bus vs. current public transport price	Taxi-Bus vs. current public transport cost (including subsidy paid by State)
Price ratio per Pax.km	26%	43%	28%

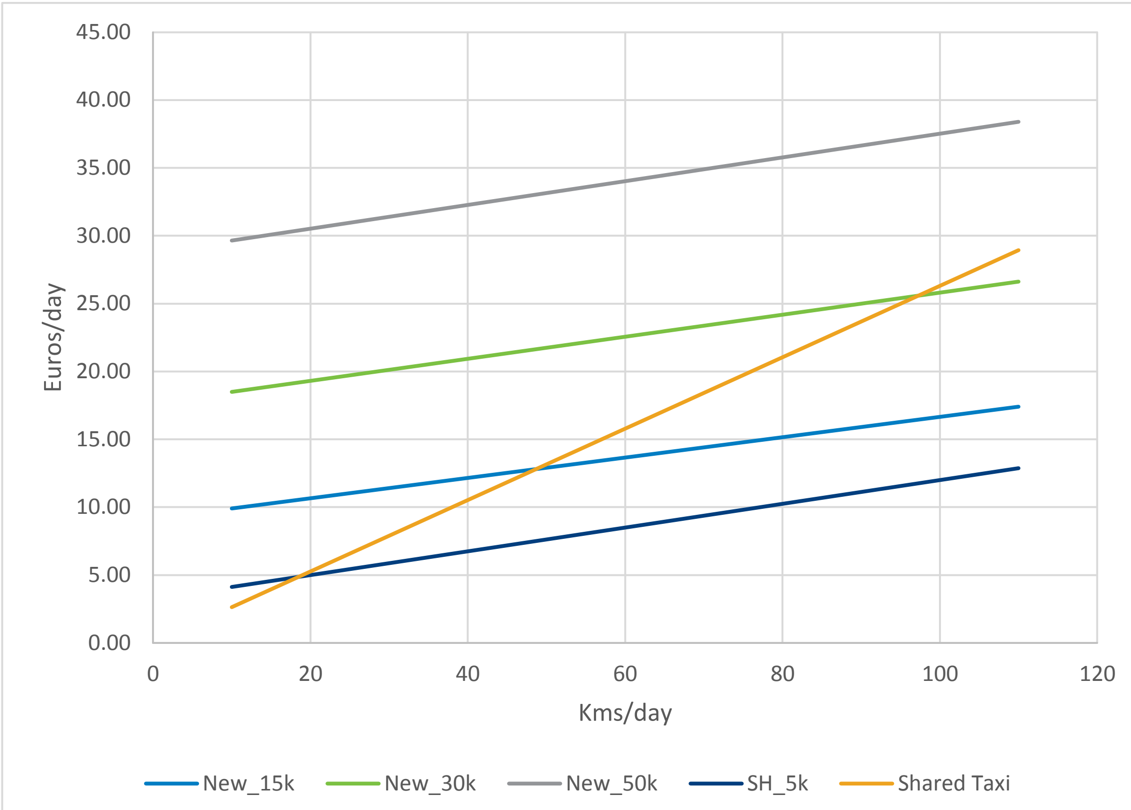
It is interesting to note that, with the quality requirements used in this study, the break-even price for the Taxi-Bus services is 68% of the break-even price for the Shared Taxis, which seems to be a good level of price differentiation.

A comparison was also made against the cost of owning and operating a private car, using the 2015 Lisbon price references as well. Three types of private car were considered, associated with their purchase prices: EUR 15 k (a small urban car), EUR 30 k (a mid-class compact car), EUR 50 k (a decent family car), as well as a second hand car for EUR 5 k (small car, six to eight years old).

An assumption was made that in the case of a private car 80% of the benefit was derived from its use in working days, so that only this percentage of the total estimated cost was put up against the use of the Shared Taxi. No consideration was made for costs for parking of the private cars as well as for the "non-monetary cost" associated with taking care of its administration and maintenance.

The calculations were made to calculate the break-even daily distance for each type of private car, and the results are presented in Figure 33.

Figure 33. **Total commuting cost/day for own car vs. Shared Taxis**



For the majority of car types in Lisbon (the EUR 15 k and the EUR 30 k), the break-even distances are well above the daily runs of their drivers, respectively at 49 km and 97 km.

These values give a clear indication that it should be possible to implement a system of the kind described here while reducing prices significantly for public transport users and for private car owners. These are consequences of the efficiency gains made possible by digital connectivity and strong penetration of smartphones, supporting a well-designed business concept.

Compatibility with electric vehicles

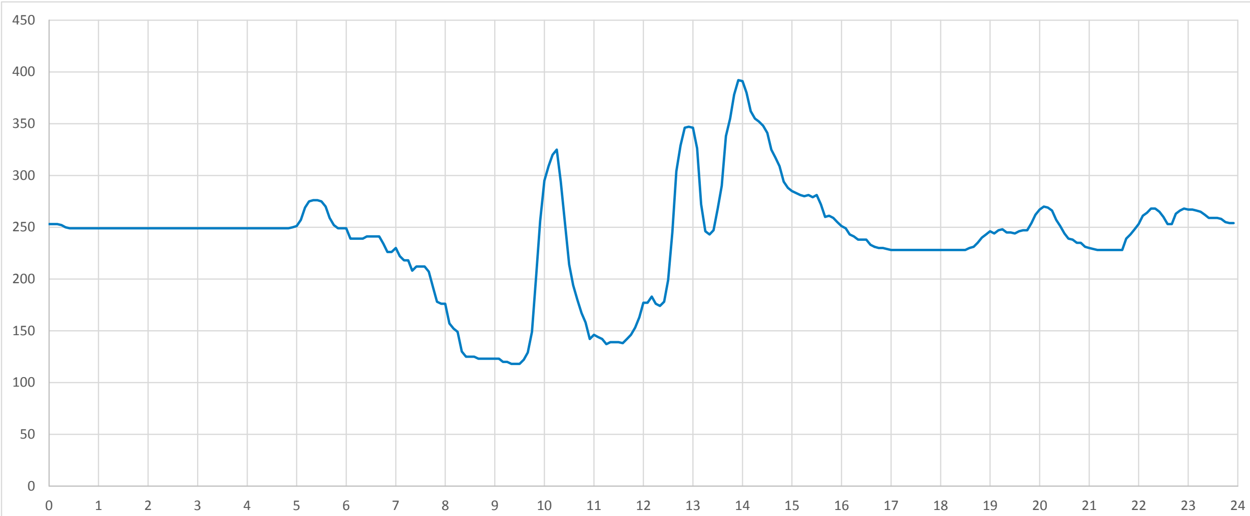
Given the preceding results (quality, efficiency, large average distances and costs) and the need to reduce carbon emissions, an additional test was made to investigate whether currently available electric vehicles would be suitable for the services described in our simulation. The test was done only for the Shared Taxi segment.

We took as the basis for the electric vehicle characterisation a recently announced commercial minivan (roughly the size corresponding to the Shared Taxi concept) with an autonomy of 170 km. It was also assumed that quick charges of 30 minutes would replenish the batteries to 80% of the full autonomy.

The shape of the demand curve (and the associated active fleet requirements) provide a very compatible basis for this recharging model, since only for less than 2 hours a day are more than 80% of the vehicles needed. An optimisation program was run with the aim of not increasing the fleet size and minimise the number of required charging stations.

The results in terms of number of vehicles in charge at any moment are shown in Figure 34.

Figure 34. **Daily vehicle charging profile**



The results indicate no increase in fleet size and a total of 392 charging points were found to be necessary - sufficient to charge 6.2% of the Shared Taxis at any given time. Charging points were allocated to each of the 60 parking stations of the Shared Taxis, in number varying from 6 to 24, with an average of 10 charging positions per parking station. The time-wise occupation of the charging positions in each parking station varies from 29% to 66%, with an average of 49%.

These values indicate that not only the use of electric vehicles is compatible with the job they have to perform as Shared Taxis, but also that charging point requirements are relatively low and thus the corresponding investment would be possible at low risk.

Moreover, given the great average distances run by the Shared Taxis each day, their total costs per km (capital, operation and labour, but not counting with the charging post) are lower than those for internal combustion engine by a margin of around 10%. Curiously; the cost advantage is virtually equal to the cost of the electric power for these vehicles at the normal rates in Portugal (for industry), which suggests that this cost difference could be used as a contribution for the investment in the charging units, keeping the total cost for the users at the same very advantageous levels seen for the traditional power train vehicles.

Analysis of the transition impacts

Even as all the aspects of performance evaluation of the urban mobility system based on shared solutions presented in this report are very positive, this performance is based on a total change from the current system largely based on the private car to a new system without use of private cars in the urban core area. Very obviously, such a radical and instant change would not be acceptable by the public, which means that a transition process must be designed, implemented and managed in cooperation with decision-makers and the public.

One system of demand management that has been put in place in many cities across the world - quite often with low acceptance, it must be recognised - is that of restricting access of private cars to the central areas of the city to only certain days of the week or month, based on license-plate numbers.

Most likely, a key factor in the low acceptance of those schemes is the poor quality of the alternative transport supply, namely the current public transport systems in those cities. If shared mobility solutions were to be of equal or superior quality to the current status quo, such a system of access management could be more popular than it has proven to be in the past.

To test the viability of such a scheme as a transition mechanism for the introduction of a shared mobility service, the same simulation program was run on the same demand data, but allowing a certain percentage of the trips currently made on private car to continue being made so with all the other trips assigned to the shared modes as described in the earlier sections of this report.

We tested scenarios where car owners could use their car one, two or three days each working week, which corresponds to having 20%, 40% and 60% of trips currently made by private car continuing to be made by that same mode. The main indicators corresponding to those situations (side by side with those of the pure shared modes as described above) are shown in Table 6:

Table 6. **Summary of main indicators with the variation of the presence of private cars**

Aggregate Indicators	0% private cars	20% private cars	40% private cars	60% private cars
Active fleet size (Sh. Taxis + priv. cars)	2.80%	2.6% + (20%)	2.4% + (40%)	2.2% + (60%)
Prices rel. to current (Sh Taxi / Taxi-Bus)	26% / 39%	28% / 41%	30% / 42%	33% / 45%
VKM (weighted) peak-hour	63%	75%	87%	98%
CO2 emissions	66%	75%	86%	97%
% parking space released	97%	77%	58%	38%

Allowing 60% of the private cars brings virtually no reduction in congestion or CO_2 emissions, thus producing no visible result of improvement, and no support for the political argument in favour of introduction of the shared mobility solutions.

On the contrary, allowing 40% of the private cars (each private car allowed two days per week) already reduces vkm at the peak hour by 13%, which essentially makes congestion disappear. The reduction of parking space needs is also very visible and would allow a quick recovery for pedestrians (and cyclists) in many parts of the city. These "quick wins" can be essential to gain political support for the change. It could even be envisaged that the announcement of the two day/week scheme could be a prelude to a further reduction of private car access introduced one or two years later possibly on the basis of a referendum thus validating the results of the initial test phase. Opening up the possibility for people to test these new mobility configurations while still retaining some level of private car access may provide just the right environment for people to experiment and change their travel behaviour on the merits of the shared mobility services.

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Annex

The model specification and calibration results are presented in Table A-1 below and nested-logit aggregates transport alternatives into:

- "Motorised Private transport" nest: private car (PC), motorcycle (MT) and taxi (TX);
- "Public transport plus walking" nest: bus (BS), walk (WK), heavy public transport – metro and rail (HV) and bus + heavy public transport (CB).

Table A-1. **Coefficients of the obtained discrete choice model**

Attributes	Transport Alternatives							
	Motorised Private transport (MP)			Public transport plus walking (PT)				
	PC	MT	TX	BS	WK	HV	CB	
ASC	NA	NA	-4.230***	-0.218*	-1.140***	-0.270*	-0.706***	
Socio-demographic attributes								
Age [25-35]	NA	NA	NA	NA	NA	0.559***	NA	
Age [35-65]	NA	NA	NA	NA	-0.308*	NA	-	
Age [+65]	NA	NA	NA	0.195*	NA	NA	-	
Income (thousand €)	NA	NA	NA	0.007***	NA	NA	NA	
Land use, car and public transport monthly pass availability								
No parking at home	NA	NA	0.237***	NA	NA	NA	NA	
No parking at destination	NA	NA	0.237***	NA	NA	NA	NA	
Own car	NA	NA	NA	NA	NA	NA	NA	
Public transport pass	NA	NA	NA	0.562***	-0.766***	0.562***	NA	
Parking Pressure [0-1]	-0.131***	NA	NA	NA	NA	NA	NA	
Transport operation attributes								
Fuel cost (€)	-0.326***	-0.326***	NA	NA	NA	NA	NA	NA
Toll (€)	-0.221***	-0.221***	-	NA	NA	NA	NA	NA
Parking cost (€)	-0.221***	NA	NA	NA	NA	NA	NA	NA
Travel time (min)	-0.026***	-0.026***	-0.026***	-0.024***	-0.005***	-0.015***	-0.015***	
Access time (min)	NA	NA	NA	-0.051***	NA	-0.053***	-0.051***	
Tariff (€)	NA	NA	-0.115***	-0.498***	NA	-0.498***	-0.498***	
Transfers	NA	NA	NA	-0.199***	NA	-0.150**	-0.150**	
Waiting time (min)	NA	NA	-0.028***	-0.028***	NA	-0.045***	-0.028***	
Nested scale (η)			1.000				1.951	
0- test significance			NA				***	
1-test significance			NA				***	

***significant at the 99% level; **significant at the 95% level; *significant at the 90% level.

†Parking pressure defined as the ratio between estimated demand and supply of parking in a specific area and time period of the day.

The model proved to have an adequate specification: ρ2=0.37 and the utility function of each transport alternative included socio-demographic variables of the user, land use, car and transit availability and instrumental attributes such as travel time and cost, all being statistically significant at a 90% confidence level.

Notes

[1] The model is stochastic because the number of trips that actually occur between two grid-cells at each hour was generated using a Poisson distribution with λ equal to the average number of hourly trips.

Shared Mobility

Innovation for Liveable Cities

Urban authorities face numerous challenges as they try to manage the access and mobility needs of their citizens. Some of these are related to uncertainty about how new services, technologies and emerging social trends affect citizens' mobility choices. This report looks at the combined impact of two major new developments: ubiquitous computing and shared mobility services. Specifically, it examines the effect of replacing all car and bus trips in a mid-sized European city with automatically dispatched door-to-door services. The report finds that such systems can massively reduce the number of cars on city streets while maintaining similar service levels as today. They also result in significant reductions of distances travelled, congestion and negative environmental impacts. Not least, automatically dispatched, door-to-door services also improve access and reduce costs to consumers.

The work for this report was carried out in the context of a project initiated and funded by the International Transport Forum's Corporate Partnership Board (CPB). CPB projects are designed to enrich policy discussion with a business perspective. Led by the ITF, work is carried out in a collaborative fashion in working groups consisting of CPB member companies, external experts and ITF researchers.

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