THE IMPACT OF SHARED AND AUTONOMOUS ROBO-TAXIS ON FUTURE URBAN MOBILITY

A SIMULATION APPROACH FOR MILAN 2030

AGENZIA MOBILITÀ AMBIENTE TERRITORIO

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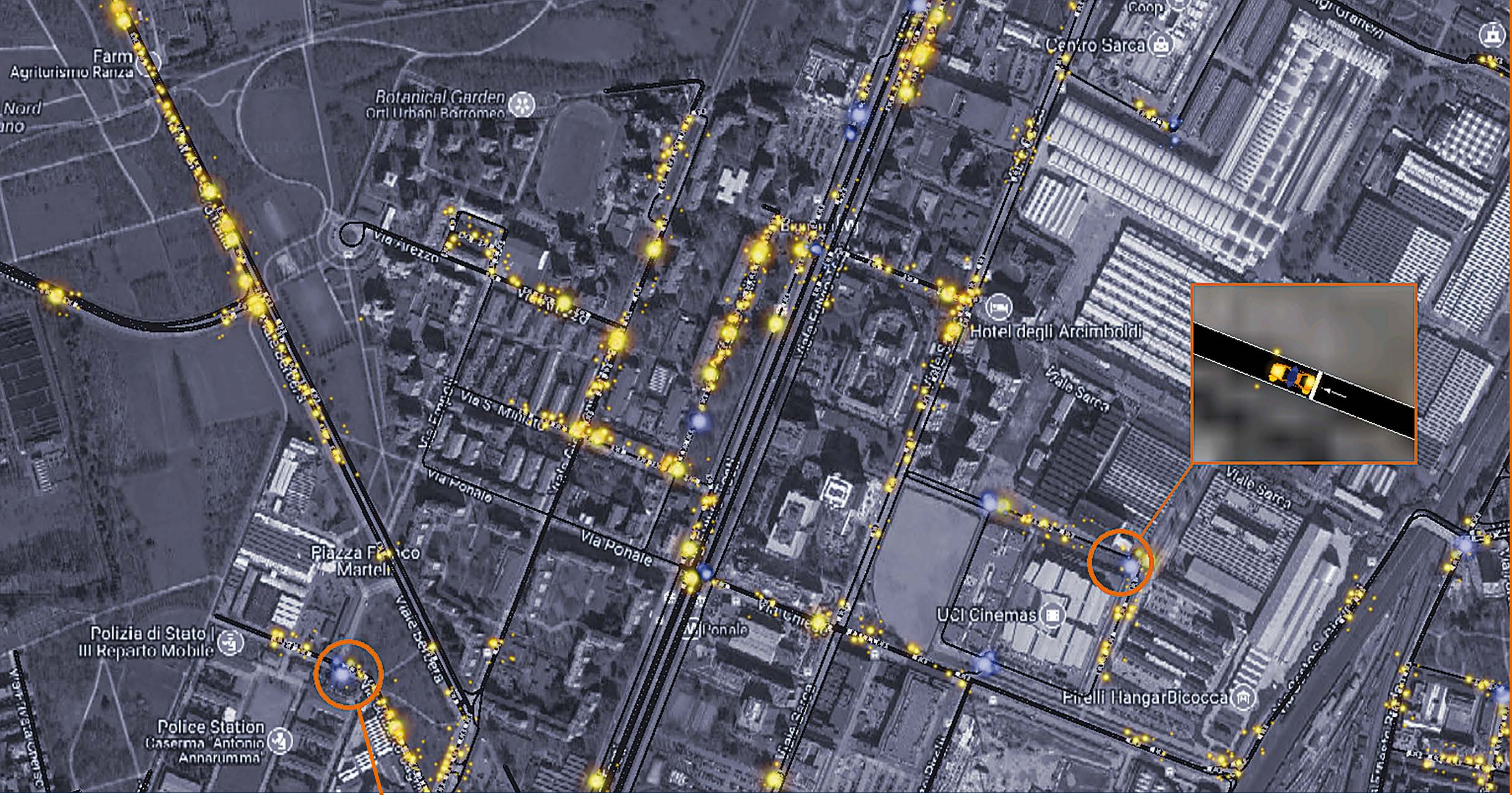

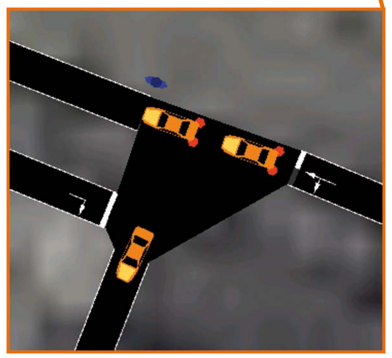

Screenshot of the robo-taxi simulation based on the SUMO simulation platform:
Robo-taxis (vehicles) and passengers (blue dots).

MILAN 2030

No Congestions. Low Emissions. Liveable!

Senza traffico. A bassa emissione. Vivibile!

9.500 robo-taxis as algorithm controlled micro busses
9.500 robo-taxi come algoritmo di micro autobus controllati

10% peak shaving to reduce peak demand
10% di riduzione del picco in modo da ridurre l'elevata domanda

Smart incentives to balance mobility modes
Incentivi intelligenti per bilanciare i tipi di mobilità

- 40% Emissions
- 40% Emissione

- 100% Congestions
- 100% Congestione del traffico

- 30% Individual Traffic
- 30% Traffico individuale

Shared and autonomous robo-taxis more efficiently make use of the existing mobility infrastructure, by effectively increasing the average vehicle utilization by reducing the individual traffic. All congestions in Milan can be freed and emissions reduced by 40% by introducing 9.500 robo-taxis, along with smart incentives to reduce and control the peak travel demand.

I Robo-taxi condivisi o usati autonoma-mente, fanno un uso piú efficace dell'infrastruttura di mobilità giá esistente, aumentando efficacemente l'utilizzo medio del veicolo, riducendo il traffico individuale. Il congestionamento del traffico di Milano puó essere eliminato e le emissioni ri-dotte del 40%, introducendo 9,500 Robo-taxi insieme ad incentivi intelligenti per ridurre e controllare l'elevata domanda di mobilitá.

ROBO-TAXI CONCEPT
EFFICIENTLY SHAPING MOBILITY AND PROMOTING PUBLIC LIFE

CONCETTO DEI TAXI-ROBOT
MODELLARE EFFICACEMENTE LA MOBILITÀ E PROMUOVERE LA VITA PUBBLICA

Our study on the impact of robo-taxis in Milan reveals that congestion-free cities with low emissions are within reach. Robo-taxis will combine the advantages of shared on-demand mobility services and autonomous driving.

Our results can be summarised by four main conclusions:

- Free traffic flow with 30% robo-taxi usage and 10% peak-shaving
  A 30% rate of users switching from cars to robo-taxis in combination with a peak demand decrease of 10% will resolve city wide congestion. Shared taxis with drivers can be used during the transition.
- Peak demand reduction achievable through smart incentives
  Smart strategies for incentives that reach consumers are the key in order to shift mobility demand from peak-times to off-peak times. This will balance the mobility demand during the day and shave the peaks.
- 6 seater vehicle as core component of robo-taxi fleet
  To serve the dynamic, urban travel routes, medium size 6 seaters should be used as the core component. Smaller capsules (individual) and larger robo-busses (long distance) will complement the fleet.
- 9,500 robo-taxis can cover demand in Milan
  In order to serve Milan in the above setting by shared on-demand services only 9,500 robo-taxis would be needed in the city.

Il nostro studio sull'impatto dei robo-taxi a Milano mostra che città prive di traffico e con basse emissioni sono un obiettivo raggiungibile. I robo-taxi combineranno i vantaggi dei servizi di trasporto condiviso su a richiesta con quelli della guida autonoma.

I nostri risultati possono essere riassunti in quattro conclusioni principali:

- *Circolazione senza traffico con il 30% di robo-taxi e il 10% di livellamento dei picchi*
  Una percentuale pari al 30% di utenti che passano dall'auto ad un robo-taxi, combinata con una diminuzione dei picchi di domanda del 10%, risolverebbe la congestione del traffico della città.
- *Riduzione dell punte massime di domanda ottenibile tramite tariffe intelligenti*
  Strategie di tariffazione intelligente sono la chiave per spostare la richiesta di servizi di trasporto dai periodi di punta a quelli di calma, permettendo di equilibrare la mobilità durante il giorno e attenuare i picchi.
- *Veicoli a sei posti come element base della dotazione di robo-taxi*
  Per sopperire alla richiesta della dinamica viabilità cittadina, la dotazione die base é costituita da veicoli di media grandezza a sei posti. Questa andrà poi integrata da veicoli piú capienti robo-bus (per le lunghe distanze).
- *9.500 robo-taxi possono soddisfare la domanda nella città di Milano*
  Sarebbero necessario soltanto 9.500 robo-taxi per servire Milano con servizi di trasporto condivisi o a richiesta.

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CONTENTS

HOW ON-DEMAND MOBILITY & AUTONOMOUS DRIVING WILL IMPACT URBAN LIVING

AN INTRODUCTION TO THE TOPIC

On-demand mobility services, autonomous driving, dynamic pricing algorithms and vehicle electrification will change the way people experience mobility in urban environments. Smart cities based on data-driven and algorithm-based technologies will become a global trend over the next decade. Thereby, the development of sustainable future mobility services is one of the major topics that will impact urban living.

Metropolitan areas experience a sustained growth and are estimated to be home for 60% of the world's population by 2030. Megacities with more than 10 million inhabitants arise and mobility is already breaking down in many large cities, leading to congested streets, high emissions, traffic accidents, overstrained public transport and the lack of parking space for residents. In recent years, innovations in technology and digitalization have had a great impact on designing sustainable mobility concepts to counteract this trend. Urban developers count on the integration of on-demand mobility services, autonomous driving vehicle electrification, and dynamic pricing systems into urban mobility.

The advantages of on-demand mobility and autonomous driving are obvious.
Autonomous vehicles are expected to reduce traffic accidents and facilitate everyday life for persons with reduced mobility such as elderly or handicapped people. In combination with car-to-car and car-to-infrastructure communication, higher traffic efficiency, lower pollution and lower costs can be achieved. The list of benefits is clearly not exhausted by these examples. But why is it taking so long to finally make use of the benefits self-driving cars offer? The answer is simple: A cultural change is necessary in order to accept the changes of new mobility concepts in a digitalized city by both, the people living in urban areas as well as the responsible public authorities. From an implementation perspective, the necessary infrastructure requires charging stations, car-to-infrastructure communication and, as long as there is a mixture of self-driving and conventional vehicles on the roads, appropriate arrangements to ensure seamless integration.

In the future we won't necessarily own a car, but might summon a driverless car whenever needed.
On-demand mobility services have grown in recent years, particularly important here is one-way car- and bike-sharing that gives users more flexibility in cities. Among younger generations the importance of owning a car decreases and there is openness towards car-sharing concepts. Today, the average occupation of a private car is 1.3 persons, leading to many more vehicles on the road than actually necessary[1]. In addition, an average private car today is used only a few hours a day and parked the rest of the day. Economically, this results in a disproportionate amount of space required for parking in cities. One of the most promising ideas to counteract this problem is the combination of on-demand services with autonomous vehicles, which we call "robo-taxis". If the robo-taxis themselves and the service behind are well designed, shared and autonomous robo-taxis can become more convenient than private cars, paving the way for a significant reduction of vehicles on the road.

Our study on the impact of robo-taxis in Milan reveals that congestion-free cities with low emissions are within reach.
We performed a study that included the analysis of traffic count data, mobile phone data to analyse mobility demand, and also congestion data. This data was combined with extensive simulations of conventional (classical) cars and self-driving robo-taxis taking Milan as an exemplary city.

Our results can be summarised in four main conclusions:

- Free traffic flow achievable with 30% shared robo-taxis and 10% peak-shaving
  A 30% rate of users switching from cars to robo-taxis in combination with a decrease in peak demand by 10% can resolve city-wide congestion.

- Peak demand reduction achievable through smart incentives
  Smart incentive strategies that reach consumers are the key in order to shift mobility demand from peak-times to off-peak times. This will balance the mobility demand throughout the day.

- 6 seater vehicle as core component of robo-taxi fleet
  To serve the dynamic, urban travel routes, medium size 6 seaters should be used as the core component. Smaller capsules (individual) and larger robo-busses (long distance) will complement the fleet.

- 9,500 robo-taxis can cover demand in Milan
  In order to serve Milan by shared on-demand services only 9,500 robo-taxis would be needed in the city.

In summary, on-demand mobility services, autonomous driving and vehicle electrification are expected to have a huge impact on urban mobility. Complementing these game-changing concepts with suitable incentives and the necessary infrastructure, we believe it is possible to achieve significant changes which manifest themselves achieving quality goals of free traffic flow, reduced parking space, reallocation of public space and the reduction of emissions.

THE CASE OF MILAN SMART AND INNOVATIVE MOBILITY SERVICES FOR MILAN'S CITIZENS AND TOURISTS

Valentino Sevino & Roberto Porta from Milan's mobility agency "Agenzia Mobilità Ambiente Territoro" (AMAT) explain the City of Milan's congested traffic situation, the resulting social and environmental implications, and their innovative mobility concepts.

Traffic volumes in cities around the world keep growing as a consequence of economic growth, population increase and urbanisation. Transportation is Europe's biggest climate problem accounting for 26% of the EU's total greenhouse gas emissions according to the European Environment Agency (EEA). Global warming, local emissions, traffic jams and the saturation of urban spaces are major challenges to face for any city's administration.

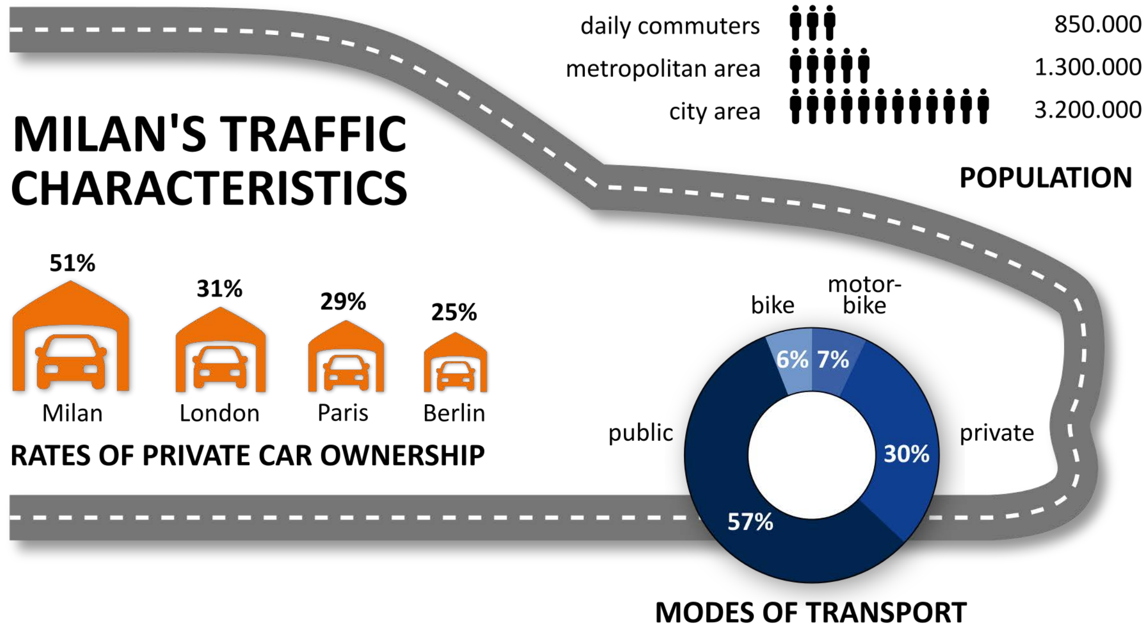
Milan's city characteristics: population and traffic demand

Milan is the second-most populated Italian city, with 1.35 million inhabitants (about 7,400 habitants per km²) and about 3.2 million in its metropolitan area (about 2,000 inhabitants per km²)[2]. Every day 850,000 people enter Milan and 270,000 exit the city – resulting in a total of 5.3 million trips per day. Although most people use public transport to get around Milan (57% of all trips in Milan are taken by public transport, 30% by cars, 7% by motorbike and 6% by bicycle), the city still has one of the highest European rates of car ownership (50.5 cars every 100 inhabitants) compared to London (31), Berlin (29) or Paris (25), and also one of the highest concentrations of particulate matter among large European cities.

The Sustainable Urban Mobility Plan (SUMP): First steps towards a more efficient mobility infrastructure

It is for these critical reasons that Milan has just adopted the Sustainable Urban Mobility Plan (SUMP) for a more efficient mobility based on sustainability, inclusion and innovation. By combining urban development, innovation and sustainability, and putting the policy focus on environment and life quality, the city of Milan is committed to make the city more liveable, safe and accessible, ensuring social equity and sustainable mobility. The initiative aims at reshaping Milan's overall mobility infrastructure over the next 10 years, redefining the boundaries of the metropolitan city and serving large suburban areas. The plan is based on the goal of true balance between mobility demand, quality of life, environmental and health protection. It also ensures high accessibility to the city through optimization of availability and integration of different public and/or private transport systems. Furthermore, it aims at gradually reducing the dependence on private cars, encouraging a move towards more environmentally friendly modes of transport (with particular attention to the trips between Milan and its surrounding area and to freight transport), thus ensuring appropriate mobility networks and services.

> "Milan has one of the highest rates of private car ownership in Europe"
>
> Valentino Sevino, Director AMAT



Dynamic road pricing will help to reduce traffic during peak-hours.

Measures like road pricing, enhancing public transport, and boosting shared mobility are the key actions of the city's strategy to improve livableness and wellbeing of citizens and city users. The congestion charge (Area C) implemented in Milan has already proven to effectively reduce the traffic in the city centre by 30%.

Additionally, as stated in the plan, pushing shared mobility was recognised as a crucial driver that contributes to reduce private car traffic in the city. For that reason, citizens and city users have seen an increasing number of alternatives to private cars in a very short time: nearly 3,000 shared cars (27% fully electric) with more than 600,000 subscribers, 4,650 bikes (among which 1,000 e-bikes), including both a traditional station-based bike sharing system with almost 60,000 yearly subscribers and also 12,000 free-floating shared bikes since October 2017, and 100 fully electric shared scooters are currently circulating in Milan.

Digital solutions for Mobility as a Service (MaaS) will combine all mobility systems in one mobile app

Increasing digitalization has led the city of Milan to record amounts of data coming from different operators. The data is now publically available on a web portal where people can get informed on the real-time situation of all transport systems. This platform represents the first step towards the ambitious goal set by the city of Milan, which is a better integration of all available mobility systems.

The SUMP dedicates a whole paragraph on fares integration through innovative solutions that are next to be implemented by the city of Milan. This will also be done in form of the so called "Mobility As A Service" (MaaS) solution, where every mode of transport (public transport, bike, taxi, demand-responsive transport including autonomous vehicles and shared mobility services) is available in only one mobile app. The MAAS is the new frontier through which the city of Milan is laying the foundation to offer new, smart and affordable mobility services to its citizens and city users.

> "We seek a true balance between mobility demand, quality of life, environmental and health protection"
>
> Roberto Porta,
> Mobility Expert AMAT of Urban Mobility

OUR VISION ON THE KEY GAME CHANGERS

ROBO-TAXIS COMBINE THE ADVANTAGES OF CAR SHARING AND AUTONOMOUS DRIVING

Within the wide range of evolving new technologies, four key factors have been identified that play the role of fundamental game changers for urban mobility: On-demand mobility services, autonomous driving, electric mobility and dynamic pricing.

On-demand mobility services such as car-sharing, bike-sharing, taxi-sharing or mobile apps for public transport have become increasingly more popular over the last years. Their main advantage is the reliable availability of a service without the need for a long-term investment and their spread has already led to lower car ownership within younger generations. On-demand mobility services are attacking the necessity of a privately owned car, effectively reducing the number of cars in a city.

A second important factor is the development and substantial progress towards autonomous driving. This innovative technology based on artificial intelligence and fleet learning will not only assist the driver but also enable new driverless mobility systems, resulting in a new mobility experience, improved traffic efficiency, and reduced traffic-related accidents.

Thirdly, the significant progress in the development of battery capacity as well as the expected availability of charging infrastructure will enable electric mobility to be a future choice of power. Electric mobility will have a significant improvement on CO2 and particle matter emissions as well as noise emissions.

And fourthly, the possibility of dynamic pricing becomes more practicable, i.e., adjustments of prices for the use of mobility services based on the current traffic density. These dynamic pricing concepts are already used in public transport with off-peak prices, but will become even more relevant for new on-demand mobility services in order to flatten out peak demands – also known as "peak-shaving".

> "Cities should clearly define quality objectives for both quality of life and quality of mobility"
>
> Dr. Eckhardt, BMW Competence Center of Urban Mobility

Our shared robo-taxis concept combines on-demand mobility and autonomous driving

We foresee that the full potential of car sharing will be tapped once the vehicles are used in combination with autonomous driving: A pool of self-driving mini-buses – referred to as "robo-taxis" – allows users to request a vehicle for a certain route via a mobile app. Using an intelligent matching algorithm, the robo-taxis can be sent to users sharing common directions. The challenge lies in designing a convenient service by reducing waiting times, avoiding unnecessary detours, providing working spaces with a high-speed internet connection and by providing a user-friendly app. If all this is implemented successfully, shared robo-taxis can compete with private cars, because of their advantages – no more parking space searches and free use of the time while driving.

INTERVIEW ON THE NECESSITY OF WIN-WIN SOLUTIONS IN URBAN MOBILITY

DR ECKHARDT, HEAD OF CENTER OF COMPETENCE URBAN MOBILITY AT BMW GROUP

Dr Carl Friedrich Eckhardt
BMW Competence Center of Urban Mobility

An interview with Dr Carl Friedrich Eckhardt, Head of BMW Group's Center of Competence Urban Mobility on the role of game changers and their impact on urban living.

e.lab team: BMW Group has established its Center of Competence Urban Mobility three years ago. What was the motivation to do so?

Carl Friedrich Eckhardt: An essential part of BMW Group's strategy Number ONE Next is about exciting people and shaping individual premium mobility. This is not only developing premium cars and mobility services. It is also about understanding the entire eco system of urban mobility. This is key as customer experiences are also determined by framework conditions in cities. Therefore, it is wise to understand cities' visions and strategic objectives as well as the means they take and the constraints they are dealing with. In the end, we develop win-win-solutions together with city representatives and other stakeholders and implement them at large scale together with them.

e.lab team: Can you please further explain why win-win-solutions are crucial?

Carl Friedrich Eckhardt: We are convinced that it is possible to improve quality of life in cities and the quality of mobility at the same time. In order to exploit this great opportunity, we need to cooperate with cities and their stakeholders. Typically, people perceive this relationship as a conflict. However, this is not any longer the case. The precondition for this is to exchange views and explain the concept.

First, we need to differentiate between objectives, instruments, and effects. In political practice, these three are often mixed-up. But it is crucial for us to understand what the real political concern is. Otherwise we cannot develop solutions for them. Second, many solutions unfold their benefits for customers and the public alike only if they are available at critical masses. Often this has to do with path-dependencies or chicken-and-egg-problems. These challenges can only be overcome in a cooperative environment. Finally yet importantly, sometimes innovations are needed but politically sensitive. Again, cooperation can help finding politically welcomed solutions.

e.lab team: Can you give examples why framework conditions in cities influence user experiences your customers?

Carl Friedrich Eckhardt: In practically all larger cities car drivers spend hours on congested roads and lose valuable time searching for public parking spaces. This is exactly the contrary of experiencing sheer driving pleasure. In addition, the experience of our (potential) electric vehicle customers depend very much on the existence and quality of a public charging network and additional benefits in their daily uses. Our growing group of new customers preferring (auto-)mobility without owning a car enjoy the sheer pleasure of on-demand mobility only if availability is significantly high and they can reach their destinations easily. This has a lot to do with parking regulations. Finally yet importantly, the benefit of autonomous driving, be it in a privately owned car or in an on-demand environment, very much depends on regulation. Typically, authorities do not regulate what needs to be regulated: externalities of road transport. Instead, they regulate technologies and services. This is not in the interest of our customers – who are, as voters, "customers" of politicians.

e.lab team: When it comes to road traffic. How could a win-win-solution look like?

Carl Friedrich Eckhardt: To start with, cities should clearly define quality objectives for both quality of life and quality of mobility. At the interface between the two quality of life could be defined as space making and enhancing the quality of public space and air quality. Quality of mobility could be defined in general terms as travel time and comfort of travelling across all modes. With regard to road traffic one could use average speed or the time needed to find a parking space. If we had dynamic and differentiated pricing in place, we had strong incentives for users to use low-emission or even zero emission cars as well as all sorts of on-demand mobility services and – most importantly, autonomous driving could easily unfold its benefits for the public in terms of traffic flow and safety. It's as easy as that. But in order to make it happen, we need to work on it. Together.

e.lab team: Dr. Eckhardt, we thank you very much for the interview and for sharing BMW's vision with us.

ROBO-TAXIS CAN REDUCE TRAFFIC BY 30% AND EVER FURTHER
OUR SIMULATION RESULTS FOR MILAN

Shared robo-taxis are the solution to traffic congestion in Milan. By combining smart pricing strategies to achieve peak-shaving of 10%, a 33% acceptance rate among current car users and 9,500 robo-taxis as an on-demand mobility service, the number of vehicles can be reduced by at least 30%, eliminating congestions. Powered electrically, the introduction of the robo-taxi fleet, centered on comfortable six-seaters, will also lower PM emissions to a level of 40% below the threshold, even at peak times.

Our analysis of the impact of robo-taxis on the metropolitan traffic in Milan is mainly based on real-world AMAT detector data such as vehicle counts[3], Google API data[4] for average travel times along certain roads and Telecom Italia mobile phone usage data[10] to derive the mobility demand. Using the open-source simulation software SUMO we built a generic simulation tool that can be used to run simulations on any city network given the necessary map and travel-route data.

Furthermore we integrated a self-developed robo-taxi module into our simulation tool. This component enables us to analyze classical traffic, robo-taxi traffic as well as a mixture of both – which we expect to be the most realistic scenario during an adaptation phase. Our robo-taxi approach is valid for both autonomously driving vehicles and human-controlled shared taxis. This is crucial for the relevance of this study, as the latter can be implemented immediately, even before autonomous driving is available.

For the classical simulations we assume a utilization of 1.3 passengers per vehicle and an average vehicle length of 4.5 meters. The microscopic model is a standard car-following model that also includes deviations from optimal driving to reproduce realistic human behavior. In contrast, the implemented robo-taxis can have different capacities (i.e. 2, 6, 12, …) and function as a shared taxi service. During each simulation run, microscopic and macroscopic parameters such as road densities, road flows, vehicle travel times, person waiting times and emissions, are written out for analysis and visualization purposes.

Using the traffic data for Milan, our simulations focus on the commuting traffic into downtown along Viale Fulvio Testi, coming in from Parco Nord Milano and the Sesto San Giovanni area in the north.

Data for commuter traffic along the Viale Fulvio Testi shows extreme delay peaks during the rush hour intervals between 7 and 9 a.m. as well as 5 and 7 p.m. A vehicle reduction by 30% will suffice to ensure free flowing traffic.

Currently over 2,500 vehicles commute into the city via Viale Fulvio Testi between 8 and 9 a.m. during a regular week day. These masses are too much for the road infrastructure, causing congestion and delays. The average travel time at the peak hour is more than doubled compared to free traffic flow at off-peak times (Figures 1 and 2). Considering that the existing infrastructure cannot easily be changed, the primary adjustment factor to eliminate the delay peaks is the number of driving vehicles. Using the real-world detector data to calibrate our

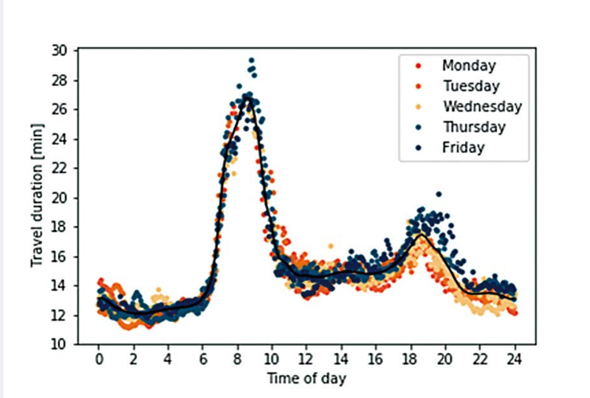


Figure 1
Travel time duration for the inbound direction of Viale Fulvio Testi along an 8.3 km route. Values have been recorded in 5 minutes intervals for several days, iteratively extracting them from the Google Maps Distance Matrix API. A substantial peak is observed for the morning rush hour between 7 am and 9 am. The slow-down from free traffic to peak hours is roughly by a factor of 2.2. Viale Fulvio Testi is a 6-lane road leading from the North of the outskirt into the city.

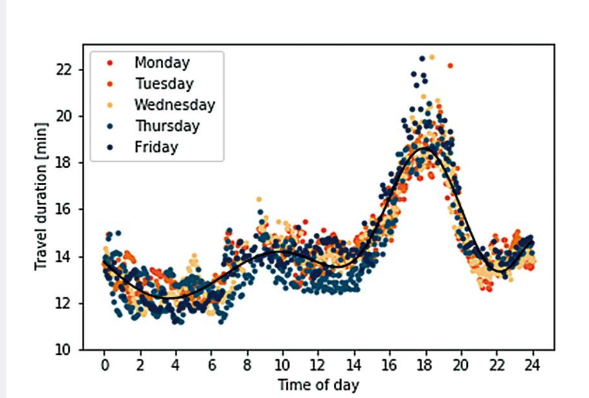


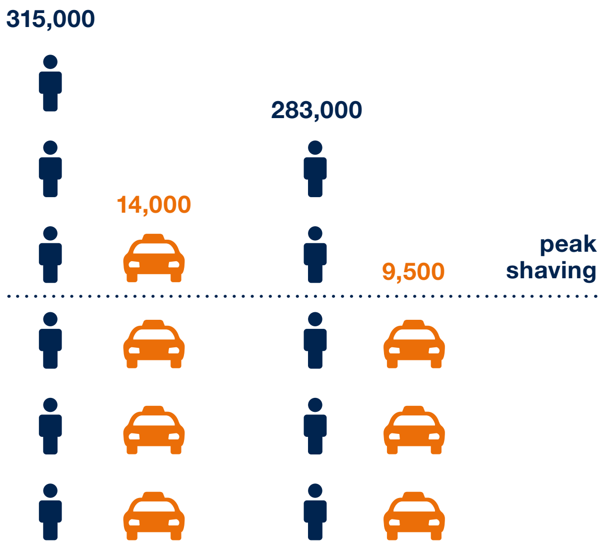
Figure 2
Travel time duration for the opposite direction as in Figure 1 along the same route on Viale Fulvio Testi. For the outbound direction the peak in the afternoon rush hour between 5 pm and 7 pm is prominent. Also visible is that this is worst on Fridays.

classical simulations we reproduced the critical densities that cause a breakdown of the traffic and a transition from the free-flowing state into a congested traffic state. An analysis of the average velocity of the commuting vehicles indicates the critical transition to be at a level of 70% of vehicles relative to the peak. In other words, free flowing traffic can be achieved with 30% less vehicles at peak time, see Figure 3 and 4.

A required 30% reduction of the vehicles at peak demand for free traffic flow effectively means that almost 50% of the commuters, respecting passenger car and utilization ratios, have to switch to the robo-taxis mobility service.[5] Considering that one third of car users are not emotionally attached to a private vehicle, but open to other forms of (shared) mobility services, this number is rather high. Assuming that it is likely to achieve a transition rate of only one third, there would be the need for complementing measures: if the overall demand at peak times is decreased by 10%, then switching rate of one third becomes sufficient.[6] Accordingly, we propose that "peak-shaving" measures are mandatory to reach free flowing traffic and should be implemented through smart pricing strategies.

Smart incentive strategies are key in order to shift mobility demand from peak-times to off-peak times and balance the mobility demand throughout the day. With 10% peak-shaving, free traffic flow will be reached with an adaption rate of 33% robo-taxis users.

Peak-shaving measures for urban transportation intend to decrease the peak mobility demand by promoting shifts to off-peak travel times. Effectively implemented such measures balance out the overall mobility demand throughout the day, becoming an important contributor to the success of future mobility services.



As previously mentioned, peak-shaving measures will reduce the required robo-taxi user rate – allowing for a quicker and more feasible transition to free-flowing traffic. Additionally, the effects of these measures have a high impact on the required robo-taxi fleet size and the associated costs (service, maintenance, electricity, …). The lower the peak demand, the fewer robo-taxis are required to ensure constant mobility service coverage. By also reducing the gap between the minimum and

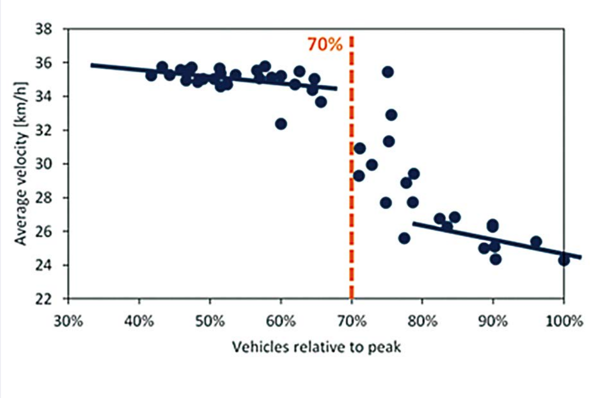


Figure 3
Combining different data sources we can visualize the formation of jammed streets, taking Viale Fulvio Testi as an example. Sources of data are real-time extractions from the Google Maps API (Figs. 1 and 2), combined with AMAT's vehicle counts (Fig. 3). As the plot reveals, the number of vehicles has to be around 30% below the peak-time level in order to achieve free traffic.

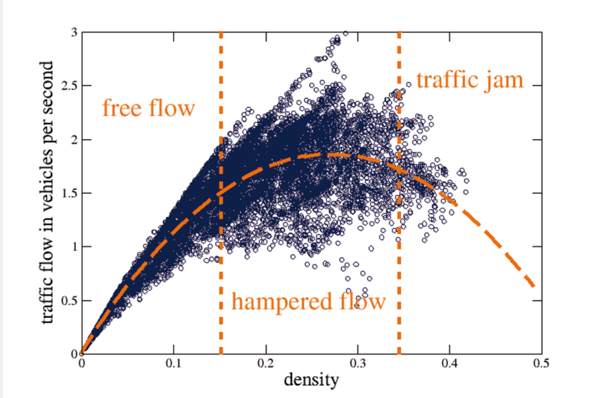


Figure 4
The fundamental diagram of our simulations, connecting the road densities to the vehicle throughput, show the transitions from free-flowing to congested and to jammed traffic states at increasing densities.

maximum mobility demand, the utilization of the robo-taxis throughout the day is balanced, increasing the effectiveness of each individual robo-taxi. In the case of Milan smart pricing strategies should be part of the Mobility as a Service (MAAS) application, adjusting prices for all modes of transport throughout the day to balance demand effectively.

Milan currently has the highest rate of car ownership per inhabitant of the largest European cities at 50.5%. As a result, parking spaces are scarce and emission levels are critical. Shared robo-taxis solve both of these problems and increase the quality of life in Milan. Particulate matter emissions are reduced to a level 40% below thresholds and parking areas are freed, such that they can be transformed into valuable public space.

AMAT monitors particulate matter emissions at various spots throughout Milan. At peak times the PM emissions are over 100 μg/m³, and in the past the regulatory threshold of 40 μg/m³ per day has been breached frequently (particulate emissions were exceeded in Milan on 125 days in 2007). Different measures have been taken by the city to address the traffic and emissions problems already. Shared robo-taxis would help to improve further: As it can be seen in Figure 6, our simulations confirm the expected general linear relationship between vehicle densities and PM-emissions. Assuming a 33% acceptance rate and 10% peak-shaving to reduce the total amount of vehicles by 30%, already human-controlled shared taxis running on a combustion engine could decrease PM-emissions by 30%. Taking into account, that the introduced robo-taxis will most likely be powered electrically, this rate extends to a range from 35% to 40%. Further considering the optimized driving behavior and efficiency achieved by future autonomously driving robo-taxis, the emissions rate should be further decreased. We expect emissions to be at least 40% below current thresholds once shared robo-taxis form a well-accepted mode of transport.

> "New customers prefer mobility without owning a car […] only if availability is significantly high and they can reach their destinations easily"
>
> Dr Eckhardt, BMW Competence Center of Urban Mobility

As a second benefit, improving the quality of life, robo-taxis negate the necessity of a privately owned vehicle within the metropolitan area. Ideally, the adaptation of the on-demand mobility service ultimately reduces the number of privately owned cars in the city. Parking spots at the side of the road, or even whole parking garages, could be transformed into greenspaces, children's playgrounds, coffee bars etc. Already today the area gains through the introduction of robo-taxis have to be taken into account by city planners for the infrastructure of tomorrow.

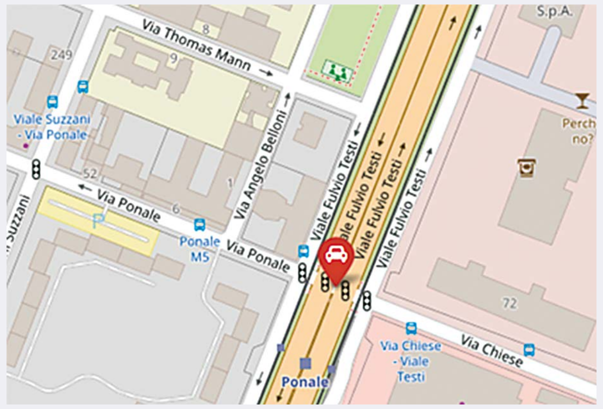


Figure 5
Traffic sensors operated by AMAT count the number of vehicles passing at different times of the day. One such sensor is installed on Viale Fulvio Testi, measuring traffic in both directions.

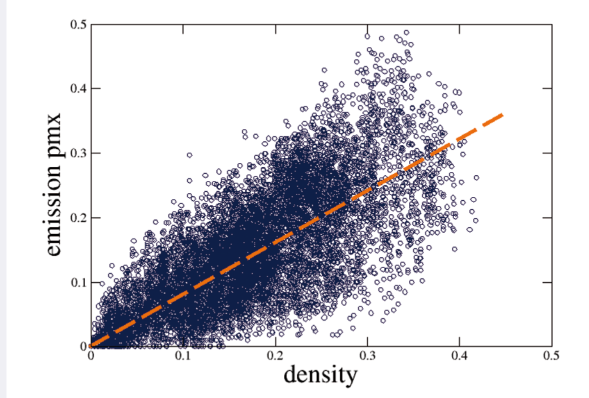


Figure 6
The emissions tracked in the simulation suggest a linear dependency between road densities and particulate emissions.

9,500 robo-taxis are needed as on-demand mobility service to serve all of Milan and to free up traffic congestion. The robo-taxi fleet should be centered on a six-seater vehicle as the core component.

Currently Milan has approximately 850,000 rush-hour commuters every day, of which around 315,000 are travelling in a private vehicle. With 1.3 persons per car, 240,000 individual vehicles are entering the city every day. In order to determine the required number of robo-taxis to meet this demand, the average utilization of a robo-taxi needs to be known.

Different robo-taxi sizes can be applied to different use-cases. The larger the robo-taxi the more likely are increased waiting times and increased travel times due to deviations from optimal routes. A robo-taxi with 20 or more seats can be useful for long-distance trips, but might not be the optimal choice for short to medium trips within a metropolitan city, where flexibility and speed is crucial. One- or two-seater robo-taxis are ideal to allow full flexibility for the individual user. While we expect these robo-taxis to play a relevant role in the future of autonomous mobility, they do not achieve the required vehicle reduction for free traffic flow at this time and do not provide efficiency gains when implemented as human-controlled taxis immediately – these are simply the taxis of today. Such smaller robo-taxis require a decongested traffic situation in which autonomous one/two-seater vehicles do not negatively impact the overall traffic flow. In order to reach such a state we propose to center the robo-taxi fleet around six-seater vehicles as the core component. Six-seater vehicles combine the features of smaller and larger robo-taxis, allowing for enough flexibility to keep delay times during travel at acceptable levels, but also combining the routes of multiple users to effectively reduce the overall vehicle numbers. Our estimation is that this size will keep extra times for detours below a level of 10 minutes at an average speed of 25 km/h, see Figure 7. Considering the dynamics of the pick-ups and drop-offs, it is unlikely that the robo-taxi will be completely full at all times. Rather, we expect the six-seater robo-taxis to offer an average utilization of five passengers.

Assuming an average utilization of five passengers per robo-taxi during rush hour we expect 9,500 robo-taxis to cover the peak mobility demand.

Waiting times for robo-taxis will be lower than the current delay due to parking-related traffic. In combination with user-friendly design and on-board services, this will simplify the transition to on-demand mobility services.

To ensure the acceptance of robo-taxis by the public, the user experience of the mobility service has to be favorable to the private car. On the one hand this needs to be considered in the design of the robo-taxis which should offer comfortable room for every passenger and services such as WiFi. On the other hand, the waiting times associated to the mobility service are crucial. To have a comparison, we used our robo-taxi simulation to analyze waiting times and compared these to the current average delay due to parking-related traffic. Since robo-taxis do not park, unless maybe in strategically located depots, they do not create any parking-related

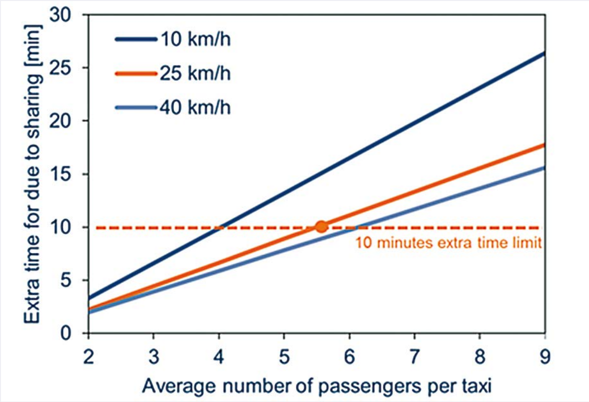


Figure 7
Detours for picking up and dropping off passengers lead to extra time. If we set 10 minutes as the limit that users are willing to accept and assume an average velocity of 25 km/h, then the average occupancy per taxi must be slightly above 5 persons.

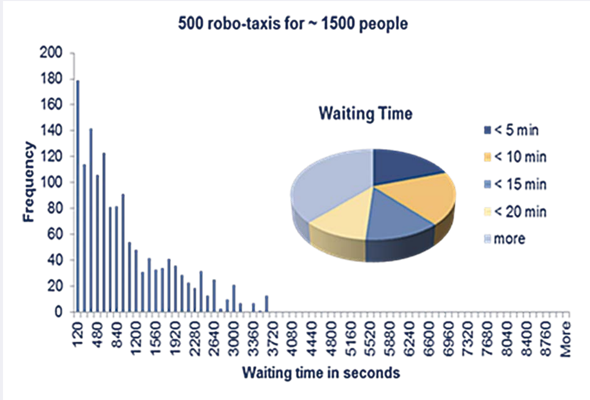
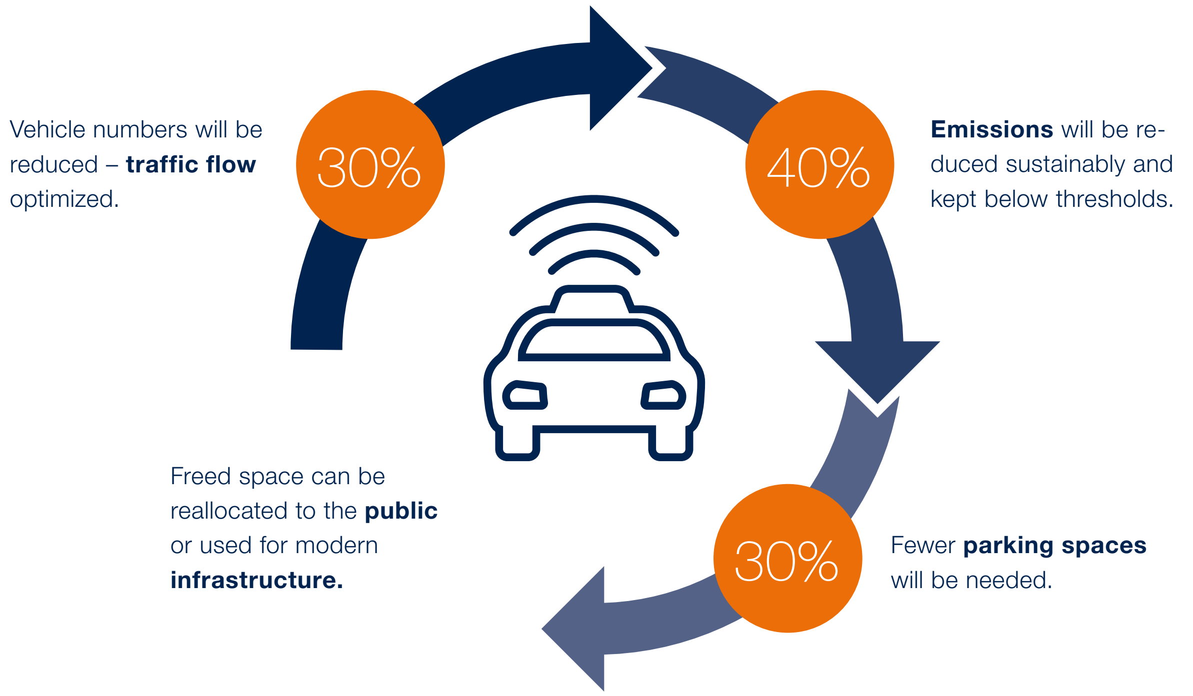


Figure 8
Waiting Times in our robo-taxi simulation are comparable, and even favorable, to average delay times due to parking searches and parking search related traffic congestions.

traffic. In our simulation results, where the robo-taxis achieved an average utilization of four passengers, we see that the majority of the occurred waiting times is favorable in comparison to parking-related traffic.

Introducing 9,500 six-seater human-controlled robo-taxis as an on-demand mobility service in Milan can immediately solve the traffic problems of today. If 10% peak-shaving is achieved through smart pricing strategies a 33% user rate of robo-taxis – supported by low waiting times and user friendly on-board design and services – will ensure free flowing traffic and emissions well below thresholds. Further operational efficiency will be achieved in the future due to the introduction of autonomous vehicles.



ACCOMPANYING MEASURES RECOMMENDED FOR IMPLEMENTATION OUR IDEAS TO BRING ROBO-TAXIS ALIVE

Robo-taxis will have a great impact on our daily lives of tomorrow but already impact the city planners and policy makers of today. To ensure optimal utilization of the vast infrastructural possibilities and to allow for a smooth transition, we highlight "quick wins" and their short-term implementation.

We have shown that traffic and emissions problems of today's urban environments can be significantly improved if 30% to 45% of the commuters switch to robo-taxis. This implies that the feasibility of the robo-taxi approach will greatly depend on three main aspects.

- The most important requirement is a wide-spread acceptance and adaption of "shared" robo-taxis as a beneficial alternative to both public transport and private cars.
- Additionally, the cost-benefit ratio reflecting the implementation costs for the city on the one hand but also the opportunities of free flowing traffic and freed public space have to ensure an economic value.
- As a third aspect, the technical feasibility implies that both autonomous vehicles and the regulatory framework will be in place to allow for the robo-taxi implementation.

Since an overnight transition to city-wide, fully autonomous robo-taxi mobility services is not feasible, we propose a step-wise implementation of short-term goals. The success of robo-taxis greatly depends on the public acceptance, the economic cost-benefit ratio for the city as well as the technical feasibility. "Robo-taxis" driven by a classical driver already present most of the benefits and allow for an immediate implementation.

Use human-controlled "robo"-taxis and benefit from the new mobility concept right now
Do not wait until autonomous driving technology is ready. Instead, we see human-controlled shared taxis with algorithmic route optimization as a concept that can bridge the time until the autonomous technology is ready. An app-controlled service, where a shared taxi can be called on-demand, would already offer the same service and a high percentage of the benefits as robo-taxis and most importantly can be implemented immediately.

Create a mobile app to understand the mobility demand
For cities it is crucial that they understand the origin-destination-matrix (ODM) of the commuters, and that the mobility services are custom designed to meet the given demand. Create an mobile app as single entry point to various mobility sharing services such as bikes, e-bikes, public busses and robo-taxis. And use that app to track and understand the mobility demand (i.e., like the MaaS application planned for Milan).

CREATING ECONOMIC AND SOCIAL VALUE

Test the social aspects already on human-controlled shared taxis: best interior layout, size and willingness to wait
Human-controlled shared taxis allow for testing the public acceptance as well as for finding the fitting measures for incentives to motivate a transition to this mobility service. Assuming acceptance, such an offer will already create traffic and parking relief to the greatest extent. The enormous time spent in a traffic-jam or looking for a parking spot will dissolve and this time saving will outweigh the time waiting until the robo-taxi arrives. Autonomous robo-taxis will then only further increase the efficiency from an operational view.

Transform waiting time into productive time by showing when the robo-taxi arrives
Use the mobil on-demand app to keep the users updated, where available robo-taxis are right now and how long it will take to reach you. Also after booking the app should show the expected time of arrival. In that sense, the “waiting time” is transformed into additional productive time or leisure time.

Implement clever pricing strategies to motivate your citizens to use shared on-demand mobility
To facilitate the service, cities should think about incentives to motivate the public to use shared (robo)-taxis over a private car today. From a pricing perspective this is achieved by minimizing the cost of the (robo)-taxi service due to ride sharing, while at the same time introducing further road and parking charges for private vehicles. Also, waiting times should be attractive, so that within the city they do not have to wait longer for a robo-taxi than for other, existing means of public transport.

Think about the economic value and alternative usage of newly free urban space
Additionally, we suggest that city planners consider the future effects of on-demand shared mobility services in their infrastructural planning today. Starting from the implementation of human-controlled robo-taxis, both road space and parking spaces will be freed up and can be transformed into public space.

Reshape the city’s infrastructure by installing decentralized e-charging stations and robo-taxi depots
Electric charging stations have to be installed throughout the city to run the human-controlled robo-taxis as well as the autonomous robo-taxis.

Looking further ahead service depots will need to be built up for the autonomous robo-taxis. Since there are peaks in the demand, there will be times (e.g. at night) at which only few robo-taxis are needed to match the mobility demand. The extra robo-taxis will drive to the depots for parking, service and maintenance, such as charging and cleaning. These depots should be placed strategically, where they are close enough to high demand areas, but do not take away quality public space.

Start a survey and test the acceptance of the robo-taxi approach
Surveys will help to understand the acceptance and incentives will allow to increase the acceptance. To successfully introduce the concept of robo-taxis surveys should be conducted, asking for the opinion, constraints in usage and acceptance of the robo-taxi approach. Especially concerns of the public about safety, liability and ethics concerning autonomous vehicles need to be assessed.

Create “pilot areas” where robo-taxis complement existing mobility services
Based on the survey results robo-taxis could first be introduced in an area with a high acceptance, complementing existing mobility services. From there on the availability of the service can be spread and promoted further.

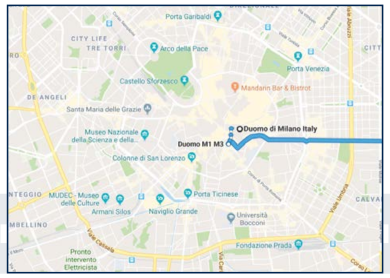
Establish a competition on the best robo-taxi layout covering 2, 6 or 8 passengers
The acceptance of the robo-taxi usage will also depend on the layout. We propose to establish a competition and include interior designers to find a layout that guarantees privacy for users and optimizes space usage at the same time. As an example, to guarantee privacy each seat might have a separate door, a smart position with relation to other seats and noise cancelling technology.

Use dynamic pricing strategies to shave peaks in mobility demand
If necessary, peak shaving and dynamic pricing can be applied to reduce the peak mobility demands and incentives can be introduced to award punctuality and social behavior. Not only pricing but also a real-time travel time prediction in the app can help to shift demand from peak times to near-peak times.

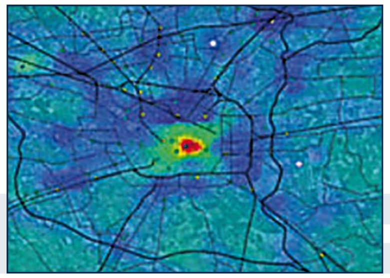
While robo-taxis are the mobility concept of the near future, human-controlled shared taxis and accompanying measures can already be implemented today. Cities will benefit from this immediately and can appropriately shape their future.

APPENDIX

OUR DATA SOURCES AND SIMULATION METHODOLOGY

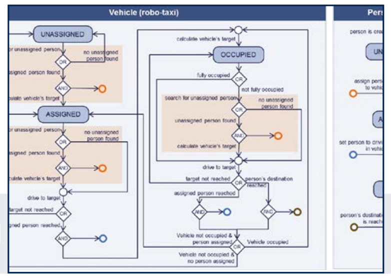


Map and Routes

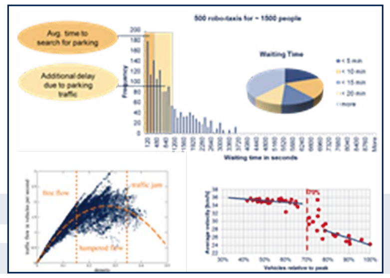


Data

SuMo tool



Robo-taxi TraCI module



Analysis

In order to assess the impact of robo-taxis on Milan's mobility challenges, we developed an optimized simulation toolbox for modelling and analysis of urban traffic systems.

The open-source software package for the Simulation of Urban Mobility (SUMO)[7] served as a framework to provide a basic vehicle interaction model and real-time simulation interface. For the purpose of this study, custom functionalities such as ride sharing, autonomous driving and advanced data processing had to be developed and implemented via Python and SUMO's Traffic Control Interface (TraCI)[8]. TraCI allows for full access while running traffic simulations, e.g., for retrieving values of simulated objects and for manipulating their behavior.

The generation of traffic flows and the model for Milan's mobility infrastructure were based on three independent input data sources.
As a first step, road networks and existing infrastructure were imported into SUMO from the OpenStreetMap project[9]. As this study focuses on macroscopic, system-wide measures, small byroads and corresponding traffic lights were removed to reduce computation times and limit the degrees of freedom in the simulation.

Individual travel patterns, especially during peak hours, were derived from mobile phone usage data published by the Telecom Italia Big Data Challenge 2014[10]. Temporal variations in the observed densities allowed an estimate of the system's origin-destination-matrix (ODM) in our region of interest.

The calibration of absolute traffic densities was based on induction loop traffic counts provided by AMAT for selected road sections.

Our simulation model was designed to analyze improvements in travel times, vehicle utilization and emission levels as a result of increased mobility automation and sharing.
Based on the previously mentioned quality goals of the city of Milan, a joint model for robo-taxis and private traffic was developed. Differences between the two travel modes were implemented by assuming an average of 1.3 passengers in a private car whereas robo-taxis could carry up to 6 passengers. In addition, robo-taxis were allowed to continue driving without any passengers on board and adapt to the current traffic situation more frequently. A matching algorithm derived from the stable marriage algorithm for unequal sets[11] was implemented to pair passengers to a robo-taxi nearby and with an already similar route. Based on our algorithms and implementations, the robo-taxi adapts its route to pick-up or drop-off additional passengers. Unoccupied robo-taxis are designed to reroute to areas of high mobility demand, whereas occupied robo-taxis drive the passengers to their destination and pick up new passengers.

The effectiveness of the passengers-to-taxi matching algorithm proved to be a key factor for our simulation results.
Our simulations in SUMO allowed to track the following output parameters: travel time and speed, waiting time of the passengers until the robo-taxi arrives and PM emissions. We performed simulations for different robo-taxi capacities and with different mobility demands, thus analyzing the sensitivity to changes in input setting for both robo-taxis and classic vehicle settings. In our simulations, the fundamental mechanism to reduce the number of vehicles, and thereby traffic, was an efficient utilization of the available transport capacity.

Simulation results were cross-checked against real-world data.
To cross-check our findings against real-real world data we also made use of the Google Maps Distance Matrix API[4]: retrieving the travel time along Viale Fulvio Testi in 5 minute intervals during several weeks allowed for accurate estimates of average speed, travel times and peak time behavior.

ABOUT THE AUTHORS
ACKNOWLEDGMENT AND YOUR CONTACT

d-fine is one of the leading European IT, risk management and financial consultancy firms with over 700 consultants. We deliver quantitative, technical and technological excellence to all our clients across Europe. Our consultants stem from analytical backgrounds which, complemented by intensive training and in-depth experience, enables us to deliver successful projects. Our core competences are based on data-driven analysis and algorithm-based implementations in order to manage uncertainty and risk in a wide range of areas. Within the think tank “e.lab” on Urban Mobility we carried out one of our first projects on a mobility topic.

The BMW’s Urban Mobility Competence Centre consist of a team of experts who are working with cities and the associated stakeholders to develop and implement new concepts for future urban mobility. In the BMW Group’s view, it is possible to further improve mobility for people living in urban areas. It is not a contradiction in terms to improve mobility and at the same time ensure cities offer a high quality of life for the people who live there.

AMAT (Milan’s Agency for Mobility, Environment and Territory) is a consulting company, totally owned by the City of Milan, committed to providing strategic planning and technical studies on urban mobility concepts and environment quality. The mission of AMAT is to support the municipal functions as for planning, designing, management, and control over territorial developments and green areas, urban planning, mobility and transports, public transports and road safety, environment, energy and climate. During the last years, AMAT has develop various smart city, active, shared, and inclusive mobility solutions and traffic restriction policies (Area C, LEZ, parking, etc.).

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5. These numbers are computed as follows: 13% of vehicles are freight vehicles, which we assume will remain unchanged. Out of 87% passenger vehicles a certain percentage x of users switches. If there are on average 1.3 persons in a private car and 5 in a robo-taxi, then the fraction of vehicles on the road is given as:
   vehicle fraction = 0.13 + 0.87*1.3/5*x + 0.87*(1-x).
   For a vehicle fraction of 0.7 (30% reduction),
   x is roughly 46%.

6. Peak shaving of 10% means that the equation above changes to vehicle fraction = 0.9*[0.13 + 0.87*1.3/5*x + 0.87*(1-x)]. Solving here for a vehicle fraction of 0.7 gives x = 34%, i.e., roughly one third of the users has to switch.

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