More space and improved living conditions in cities with autonomous vehicles

Vleugel, Jaap; Bal, Frans

Publication date
2017

Document Version
Peer reviewed version

Published in
WIT Transactions on Ecology and the Environment

Citation (APA)

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.
MORE SPACE AND IMPROVED LIVING CONDITIONS IN CITIES WITH AUTONOMOUS VEHICLES

J. M. VLEUGEL¹ & F. BAL²
¹TU Delft, Civil Engineering & Geosciences, The Netherlands.
²RISSK, The Netherlands.

ABSTRACT

Many people live in cities today. Many more will do so in future. This increases the demand for space and (space for) transport. Space to expand roads is usually scarce. Building tunnels or elevated bridges is very expensive. Solving one bottleneck creates a next bottleneck downstream. More road infrastructure leads to more cars and more cars to more congestion and externalities. Megacities invest in large-scale (preferably underground) public transport. Smaller cities lack the required number of travellers and the money to warrant the high investment costs. In a sustainable city the supply of goods, services, water, energy and transportation should differ from the current practice. New car technologies are interesting, in particular the nearly roadworthy self-driving (autonomous) cars. It is still very demanding to let these share roads with conventional cars, cyclists and pedestrians. Cities lack the space for a separate network for these cars, yet. A socially challenging alternative would be to replace all private cars by shared electric self-driving cars and small shuttle buses and integrate these with mass transport, cycling and walking. Passenger transport would need much less space for driving and parking. Congestion will vanish. Local air pollution, noise and use of resources to produce cars and road materials are reduced. Reclaimed space can be used to create a more sustainable and social environment and to optimize city logistics. The building blocks of such a (public-private) system exist already or will become available in the future.

Keywords: Space, mobility, car technology, externalities, sustainable planning.

1. INTRODUCTION

1.1 The many challenges of sustainability

Sustainability [1] is a very complex topic that attracts a high level of interest. It is relevant in discussions about global ecological issues like climate change and deforestation, and local issues like air pollution. (Environmental) economists explain environmental degradation caused by humans as a systems failure: a combination of market- and government failure [2].

Sustainability has also a socio-economic dimension. This is in particular visible at international conferences, where rich and poor countries struggle to find common ground. Individuals should be educated to no longer separate their small contribution from the global environmental problems. They should also have the financial means to behave more sustainable. These are essential for an effective treatment of non-sustainable behaviour: a tragedy of the commons [3].

The core challenge is: how to find a synergy between ecological, social and economic concerns and interests? [4] What is the role of technical development in reaching this synergy? Is technology ‘good’ or ‘bad’? Technology may indeed increase energy efficiency; reduce (air) pollution and other impacts. Yet, who or what determines which technologies are developed, introduced and used in practice? Are they technical “fixes” with a short lifespan or structural solutions? Are they still effective at a higher level of
demand (for the product or the activity) or will degradation of the environment and depletion of natural resources continue at a slower pace?

Here, the focus is on developed countries where many have access to transparent sources of information and financial means. This makes it more an individual choice whether one accepts or rejects sustainability. Two extremes are seen in practice. There are those who downplay or even deny the human contribution to climate change or environmental degradation. They may argue that there still is time to develop new and cheaper technologies, or hope that others take a higher share and/or pay for the transition. Their interests lie with the short term. They do not care publicly. On the other extreme there are those who have changed the way they live, work, buy or use means of transport in order to save on energy, reduce emissions, pollution etc. The majority is somewhere in between.

The debate about the necessity of sustainability, its direction and goals, form and planning is on going. There are signs that those who say no to sustainability are becoming a minority. Technical breakthroughs have lowered the costs of ‘greener’ technologies. Entrepreneurs make a positive business case of these enabling technologies. Consumers are interested if these substitute technologies add to their quality of life in a cost-effective way.

1.2 Urbanization, sustainability and use of space

In 2014 54% of the world population lived in urban areas, compared to 34% in 1960. The WHO expects a global urban population growth of resp. 1.84% (2015-2020), 1.63% (2020-2025) and 1.44% (2025-2030) [5]. Urban areas are attractive because they offer better jobs, houses, education, services and more extensive transport networks than rural areas. The demand for space in cities will grow as a consequence: a process also known as urban sprawl.

Citizens are in need of food and other (essential) goods and services, such as clean water, energy, a comfortable house, jobs, and efficient transportation systems. In a sustainable city, it makes sense to produce food, other goods and energy locally or regionally if producing conditions allow, instead of importing these from all over the world. Mass produced goods have a moderate price, because of low wages, poor working conditions and lack of effective environmental policies in most of these producing countries [6, 7].

1.3 Sustainable cities and transport

With so many people living in cities and many more to follow, it becomes even more important to effectively manage transport and its impacts.

Cities have local environmental policy targets and instruments. Car free and environmental zones have become common. Local emissions standards may also prevent the use of (certain) vehicles on a temporary or permanent basis. A sustainable, liveable, city goes beyond that. It should have a clean, energy- and space-efficient traffic system.

A sustainable lifestyle leads to more cycling and walking and less car use. Mobile communications and the Internet can avoid some trips. Mixed traffic creates conflicts between road users and traffic accidents [8], which may seriously deter people from cycling or walking. Countries with dedicated infrastructure have more people who cycle and walk and less traffic accidents. With more citizens more of such infrastructure is necessary.
1.4 Environmental policies and vehicle technology

The car industry exists well over a century. The environmental impact of mass motorization was largely neglected until the 1970’s. Then it gradually changed in response to warnings from scientists, demands by car owners (fuel efficiency) and citizens (air quality, noise). Policy-makers in developed countries have issued increasingly tighter energy efficiency and emission standards and other regulation (treatment of waste, recycling).

Road transport took around 81% of all energy used in transport (374 Mtoe) in EU-27. A decoupling of transport growth (+30%) and CO2-emissions (+10%) took place between 1999 and 2008 [9].

Environmental policies stimulate introduction of more energy-, resource efficient and cleaner technologies. Is it possible to reach national or local targets regarding energy reduction and emissions to the air by technical progress alone? A major study into future energy scenarios for The Netherlands for 2050 sheds some light on this. Technical progress in car and fuel technologies and the future demand for transport are quite uncertain. It also takes decades to phase out current car technologies. In the reference scenario transport would generate 43 Megaton of CO2 (on a well-to-wheel (WTW) basis) in 2050. The national policy target for 2050 is -60% of this amount. It could come from electric cars and LNG powered trucks in cities and a partially green electricity production. This is quite an optimistic scenario, which strongly deviates from the current situation. Substantial use of hydrogen cars is needed to go beyond this minus 60%. If technical progress does not speed up, then fewer kilometres per person are necessary (volume reduction). About 10-20% of the WTW emissions of CO2 are from the well-to-tank (WTT) process. A greening of that process is uncertain, but relevant, because it could compensate for slow progress in automotive technology or volume reduction. Alternatively, faster technical progress may put less stress on the improvement of the WTT process. Emission reduction of CO2, NOx and PM10 is necessary because of climate and health concerns. If local emission standards (which are not met along many city roads today) would be increased substantially, then an even bigger effort would be necessary [10].

1.5 New automotive technologies

In this paper two technologies are in focus. The first is engine and fuel technology (section 2.3). The second is self-driving vehicles (section 2.4).

1.6 Goal and main questions

1.6.1 Goal
The paper sketches a future where a city could have a more sustainable and space-efficient integrated transport system. The research started with [11].

1.6.2 Main questions
The following questions will be addressed:
1. Which types of land-use in cities need more space in future? This question has already been addressed qualitatively in sections 1.2 and 1.3.
2. Which uses of space are enhancing each other and which do not or may even exclude each other?
3. What are the design criteria and constraints for an alternative transport system for a city?
4. What amount of space could potentially be released to non-transport activities if a new integrated transport system would be in use?
5. What would be the potential reduction in emissions of CO₂, NOₓ, and C₅Hₓ?
6. How realistic is the proposed transport system? Is public policy needed to introduce and support this new transport system?

1.7 Scope and time horizon

Developed countries challenged by urbanization can also provide the conditions for new ways of transporting people and goods. New car technology is tested on their roads. A virtual city with 1 million people is used to assess the potential to reduce space and emissions of cars if shared self-driving electric shuttles replace conventional cars. The time horizon of the paper is 2040. This year aligns with the current road tests of AV and the growing use of electric cars and a reasonable pace of technical progress. It allows for a gradual adaptation of the road infrastructure and services like fuel stations. The virtual city is sustainable by 2040.

The country of reference is The Netherlands, because of the growing use of electric cars and electric public transport. The city of reference is Amsterdam with 834,713 citizens (2016), which may grow past 900,000 in 2040 [12]. This paper is also relevant for readers in developing countries. They may learn from experiments and (costly) mistakes in developed countries. There are more ways to develop socio-technical systems. An example is the telephone system. African nations skipped the rollout of cable networks and went straight for wireless networks, because of technical, practical and financial reasons.

1.8 Set-up

The paper continues with section 2 – Sustainable cities and their challenges. Section 3 deals with methodology and scenario assumptions. Section 4 presents the estimated reduction in the use of space and emissions after introduction of the new transport system. Section 5 follows with an evaluation and final conclusions.

2. SUSTAINABLE CITIES AND THEIR CHALLENGES

2.1 Introduction

Land-use in and around cities is continuously changing due to public and private policies and initiatives [13]. In cities with effective spatial planning, developers have many options to (re-)use space. Some of these are compatible and may be in the same plan. For instance, new houses can be combined with (clean, low noise) jobs in mixed developments. Empty offices may be turned into apartments for students and starters. Empty factories can be re-used or renovated or demolished to provide space for different activities. In a sustainable city also more green spaces and water are needed. The number of citizens will drastically rise in future. Combining both, a city either expands or some activities reduce their spatial footprint. Roads are omnipresent. Traffic using them has positive (socio-economic) and negative effects (externalities); air pollution, noise, accidents, di-section of areas, consumption of energy and other resources, use of space for driving and parking and serious health concerns. The challenge is how to move more people and significantly reduce these externalities and impacts.
This answers research question 2 in a qualitative way.

2.2 Towards a smart and sustainable transport system

2.2.1 Introduction
A new transport system may be designed with systems engineering [14]. Its capabilities should match the following key requirements: sustainable, space-efficient, available and affordable, no technical or other implementation barriers.

The requirements, criteria and constraints below are those of the authors.

2.2.2 Design criteria
The new transport system should then fulfil the following criteria:
1. Reduces energy consumption and zero air pollution;
2. Reduces noise emission;
3. Reduces amount of space used directly and indirectly;
4. Reduces quantity of raw materials used in production, construction and maintenance of vehicles and infrastructure;
5. Reduces need for mobility and number of kilometres driven per unit of time (‘smart’ mobility’ [15]);
6. Optimizes accessibility and transfer between subsystems (‘seamless’);
7. Fulfils demand by scalable, flexible supply (‘on demand’);
8. Uses proven technology and accepted concepts like shared cars [e.g. 16];

2.2.3 Design constraints
The following constraints are used to optimize the system:
1. All vehicles are owned by a public-private entity, they are in shared use;
2. Vehicles and services are complementary, not competitive;
3. User fees differ per target group, vehicle occupancy rate and time of the day;
4. The new system does not violate (local) laws and regulation.

This answers research question 3.

2.2.4 Final design goal
The new transport system should ultimately allow more people to live in a city in a sustainable way and help to slow down urban sprawl.

2.3 Car technology 1: Engines and fuels

In the past decade (hybrid)-electric car technology has reached maturity. In 2016 1% of all cars on the road were electric worldwide. These numbers differ per country and city. National governments may subsidize purchase of electric cars, like The Netherlands, Norway and the USA [17]. Regional or local governments may also have specific policies (e.g. for local charging). More electric cars are sold, but the large majority of new cars still have a conventional engine. The industry is also testing hydrogen fuel with a similar driving range as petrol and Diesel, which is still a decisive buying argument over electric cars, which are more expensive and have to be recharged regularly. Car manufacturers share development of technology and production of parts, which speeds up technical development and reduces the cost per vehicle [18].
2.4 Car technology 2: Self-driving

A self-driving car has additional technical systems [19], which allow it to drive itself through traffic. There are five stages of self-driving (0 = no automation and 5 = driver-less car). Current cars use stage 2 (speed control, lane assistance based on data from camera’s and radar/lidar). The driver supervises the car and must be ready to take control of the driving wheel at all times.

2.5 The new transport system

In 2040 all cars will be replaced by so-called e-shuttles of 2 sizes: cars (4-5 passengers) and minibuses (8-18 passengers). These are level 5 cars with centralized supervision as fallback. A mix of on-demand and scheduled supply is foreseen. In order to have a balanced use of e-shuttles and mass transit and to optimize the amount of vehicles simultaneously underway, trip payment is based on the vehicle occupancy rate and the value of time of the passengers. Road infrastructure will be redesigned to meet the demands of the new system.

3. METHODOLOGY AND SCENARIO ASSUMPTIONS

3.1 A model

In an ideal world the interests of all stakeholders would be perfectly in tune. Large open databases would allow researchers to build and use very complex multi-dimensional and multi-layered models of a city, supported by real-time data about behaviour of all individuals in the city. In the real world technical, financial, privacy and practical constraints ask for a more aggregated approach. A MS Excel model was developed to estimate current and future use of space savings and emissions after the introduction of the integrated transport system.

3.2 Spatial footprint (current)

Cars use road- and parking space. For parking a car requires around 10m² (4 x 2 plus turn in/out). At least 212 hectares (1 ha = 10⁴ m²) is needed for parking.

Table 1: Car data in the base scenario.

<table>
<thead>
<tr>
<th>Numbers</th>
<th>Car occupancy (average persons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car travellers</td>
<td>350,000</td>
</tr>
<tr>
<td>Cars</td>
<td>212,120</td>
</tr>
<tr>
<td>Parking space</td>
<td>212,1210 m²</td>
</tr>
</tbody>
</table>

Amsterdam has an historic city centre, an extensive canal network and road network. It has much more water than the average city. In 2011 its space was used as follows [20]: Traffic (7.3 %, roads 5.5% (or 1202,57 hectares)), houses (20.6%), business (10.5%), water (24.8%), agriculture (12%), forest or nature (2.1%), recreation (11%), development (6%) and services (4.8%) all in 2011.

It is assumed that roads take at least 10% of the space in the virtual city, due to road geometry, space for noise barriers and separation, and parking.

Car driving is by far the most inefficient way of using space (Fig. 1).
3.3 Mobility scenarios

To estimate daily mobility, daily averages for The Netherlands [21] were used, except for public transport, where much higher values were used, because the national average includes many areas without regular public transport (Table 2).

Table 2: Mobility scenario’s for 2017 and 2040

<table>
<thead>
<tr>
<th>Mode of transport</th>
<th>Travellers per day</th>
<th>Kilometres per day</th>
<th>Travellers per day</th>
<th>Kilometres per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>100.000</td>
<td>1</td>
<td>130.000</td>
<td>1</td>
</tr>
<tr>
<td>Biking</td>
<td>295.000</td>
<td>3</td>
<td>383.500</td>
<td>3</td>
</tr>
<tr>
<td>Moped/scooter</td>
<td>5.000</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e-Moped/scooter</td>
<td></td>
<td></td>
<td>5.500</td>
<td>15</td>
</tr>
<tr>
<td>Bus electric</td>
<td>0</td>
<td>0</td>
<td>130.000</td>
<td>15</td>
</tr>
<tr>
<td>Bus Diesel</td>
<td>80.000</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus CNG</td>
<td>20.000</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Metro</td>
<td>50.000</td>
<td>15</td>
<td>65.000</td>
<td>15</td>
</tr>
<tr>
<td>Tram</td>
<td>100.000</td>
<td>15</td>
<td>130.000</td>
<td>15</td>
</tr>
<tr>
<td>Car petrol</td>
<td>280.000</td>
<td>15,3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Car Diesel</td>
<td>66.500</td>
<td>15,3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Car PHEV petrol</td>
<td>28.000</td>
<td>15,3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Car FEV</td>
<td>7.000</td>
<td>15,3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Taxi</td>
<td>1.000</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>e-Van (trips)</td>
<td>0</td>
<td>0</td>
<td>1.200</td>
<td>30</td>
</tr>
<tr>
<td>Van (trips)</td>
<td>1.000</td>
<td>30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>e-Truck (trips)</td>
<td></td>
<td></td>
<td>1.200</td>
<td>30</td>
</tr>
<tr>
<td>Truck (trips)</td>
<td>1.000</td>
<td>30</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>e-Shuttle</td>
<td>0</td>
<td>0</td>
<td>455.000</td>
<td>50</td>
</tr>
</tbody>
</table>

The following assumptions were also used:
- The number of people living in the city will rise by 30% compared to 2017.
- Daily mobility per mode of transport stays the same.
Sustainable mobility will lead to more cycling and walking. There will be more elderly people, which have a (much) lower daily mobility.

3.4 Ecological footprint

Emissions of CO₂, NOₓ and PM₁₀ were estimated as follows:
1) Mode of transport, average number of travellers per day, propulsion category, energy category, energy mix, estimated distance in kilometres per mode, split by engine/fuel type per day etc., occupancy rate.
2) Multiply combination 1) kilometres with the emission parameters per fuel.
3) Multiply 2) by number of days per year.
4) Sum 3).

4. IMPACT OF THE NEW TRANSPORT SYSTEM

4.1 Introduction

This section presents the use of space and emissions by the new transport system based on the data and assumptions of section 3.

4.2 Re-use of space in 2040

4.2.1 Parking space
It follows from section 3.2 that 212 ha of space were used for parking. In future, permanent parking will disappear near buildings, because shared vehicles will be parked and recharged in special garages off-street. Not all of the 212 ha can be re-used, because of two reasons. First, if parallel lanes are removed, then some bypasses are needed to prevent gridlock. Second, dedicated parking lots should be available per street to improve the rather challenging city logistics [23]. Hence, a reduction of parking space to 80% (42.4 ha) is assumed.

4.2.2 Roads
It is argued [24] that all people in this country could be transported with 20% of the cars on the road today. This assumes that cars would have an occupancy rate of 4-5, where 1.65 persons is the current average. If we assume a more modest occupancy rate of e-shuttles and some expansion of the public transport network to deal with peak demand, then the new integrated transport system might still take much less space, probably -50% or around 1100 hectares in case of a city like Amsterdam. Applied to that city, this means that the area available for development (now 6%) would be roughly twice the size.

Re-use of space on a large scale is in the blood of cities. It has happened with railways and tramlines, but for roads it was not practiced, yet.

Research question 4 is now answered.

4.3 Emissions in 2017 and 2040

The new integrated transport system based on large-scale electrification and shared use has a major impact on the emissions in the virtual city (Table 3).

Table 3: Estimated local emissions by mode of transport.
<table>
<thead>
<tr>
<th>2017 - Mode of transport</th>
<th>CO₂</th>
<th>NOₓ</th>
<th>PM₁₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Biking</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Moped/scooter</td>
<td>6,885,281</td>
<td>3793</td>
<td>4,612</td>
</tr>
<tr>
<td>Bus Diesel</td>
<td>93,943,511</td>
<td>389,954</td>
<td>91,462</td>
</tr>
<tr>
<td>Bus CNG</td>
<td>44,739,618</td>
<td>61,100</td>
<td>842</td>
</tr>
<tr>
<td>Metro</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tram</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Car petrol</td>
<td>392,586,175</td>
<td>216,277</td>
<td>262,993</td>
</tr>
<tr>
<td>Car petrol parking</td>
<td>25,659,227</td>
<td>14,136</td>
<td>17,189</td>
</tr>
<tr>
<td>Car Diesel</td>
<td>91,394,450</td>
<td>379,373</td>
<td>88,980</td>
</tr>
<tr>
<td>Car Diesel parking</td>
<td>5,973,493</td>
<td>24,796</td>
<td>5,816</td>
</tr>
<tr>
<td>Car PHEV petrol</td>
<td>8,836,724</td>
<td>4868</td>
<td>5,920</td>
</tr>
<tr>
<td>Car PHEV petrol parking</td>
<td>577,564</td>
<td>318</td>
<td>387</td>
</tr>
<tr>
<td>Car FEV</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Taxi</td>
<td>23,178,225</td>
<td>96,212</td>
<td>22,566</td>
</tr>
<tr>
<td>Taxi parking</td>
<td>1,545,215</td>
<td>6414</td>
<td>1504</td>
</tr>
<tr>
<td>e-Van</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Van</td>
<td>5,770,905</td>
<td>23,955</td>
<td>5,618</td>
</tr>
<tr>
<td>Van parking</td>
<td>192,365</td>
<td>798</td>
<td>187</td>
</tr>
<tr>
<td>Truck</td>
<td>25,543,350</td>
<td>106,029</td>
<td>24,869</td>
</tr>
<tr>
<td>Truck parking</td>
<td>851,445</td>
<td>3534</td>
<td>829</td>
</tr>
<tr>
<td>Total (gram)</td>
<td>727,677,547</td>
<td>1,331,558</td>
<td>533,774</td>
</tr>
<tr>
<td>Total (Kton)</td>
<td>727</td>
<td>1.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Note: It is assumed that the average search for a parking place takes 5 minutes and 1 kilometre. This (under-)estimation already adds considerably to emissions.

4.4 Validation of the results

The estimated use of space can be put in perspective. In 2015 [25], Amsterdam had 228,691 cars and 156,473 parking locations, partially offered in parking garages. There are more cars than parking locations at street level, because of the policy to restrict car use. The 212,120 cars in the model city are rather realistic.

CO₂ emissions for the same year were estimated as 843 kton: 690 (cars), 127 (mid-heavy trucks), 26 (very low emission buses). Our 727 Kton was based on the mobility scenarios. Use of the actual data for Amsterdam would have closed the gap between the two datasets. The model is therefor regarded as valid.

4.5 Conclusions

The integrated transport systems leads to a major reduction in the use of space (50%) and emissions by transport: 727 Kton of CO₂, 1,3 Kton of NOₓ and 0,5 Kton of PM₁₀. This answers research question 5.
5. EVALUATION AND FINAL CONCLUSIONS

To propose a new system for the currently largely unsustainable passenger transport seems daring, but less if one takes into account technical progress. Self-driving cars will enter the mass market. The technology is partially already inside conventional cars. A new system is needed because mass motorization has reached its limits. Within a few years from now many (major) cities will face gridlock. Building more roads inside a city is usually impossible. Building roads around a city enhances urban sprawl and destroys the environment. Roads are full again after a few years. Accessibility is essential for the socio-economic prosperity of cities. Cars use far too much energy and as a consequence emit large amounts of CO$_2$, NO$_x$ and PM$_{10}$, to name just of few of the many externalities. Many people and businesses have reduced energy consumption and ecological footprint by shifting to different products or lifestyles. Transport is still an exception; it continues to grow, as do its total energy consumption and emissions. Electrification of individual cars is not enough; it is the volume that matters most. Another reason is that it uses far too much space compared to an alternative system. This alternative helps to reduce the use of space and emissions, which is necessary to make cities sustainable and liveable again. Change will also come because mobility needs and preferences regarding ownership and use of cars are changing. Electronic communication may replace mobility partially as well. Policy instruments like environmental zones and car-free streets, parking policy, charging infrastructure etc. should be accompanied by road redesign to support the introduction of shared self-driving cars.

REFERENCES


This paper is part of our joint research initiative STEER (Strategic Transport Environment and Energy Research). We thank the anonymous reviewer.