Expert Report: Technology

Technological Solutions for a Low-car City

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Technological Solutions for a Low-car City

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Abstract – This report explores the role and potential contribution of available technologies to the transition of the eastern part of Amsterdam's city center to a low-car zone. The municipality of Amsterdam aims to transform the area according to the objectives of the *Agenda Amsterdam Autoluw* – which is linked to the themes of *mobility, spatial and social*. This research explored strengths and weaknesses of technologies according to these objectives of *Autoluw*. By performing a multi-criteria analysis on seven technologies, their suitability is explored for potential contribution to a low-car city. Whilst all technologies are suitable, some score higher for certain themes. For *mobility*, mobility-as-a-service can contribute most to the objectives since it supports the use of alternative modes of transportation. Automated barriers can help to create a dynamic environment, which fits with the *spatial* theme. Geofencing and ISA as a technology can contribute most to the *social* theme since it can drastically improve traffic safety for pedestrians and cars.

Keywords: low-car city, technology, mobility, public space, car traffic, transportation system

1. Introduction

In recent years cities have been facing the effects of rapid urbanization, resulting in complex and multidimensional urban challenges. This leads to new requirements for development and a need to efficiently plan and adjust urban areas (Wang et al., 2022). As one of the key cities in the global economic network of the 21st century – Amsterdam suffers from a growing number of permanent residents and visiting tourists (Gemeente Amsterdam, 2020). Next to this, the city's transportation system has been put under pressure due to an increasing number of vehicles (Gemeente Amsterdam, 2013). As a result, the city faces challenges regarding traffic safety, congestion, noise nuisance and air pollution related to transport (Gemeente Amsterdam, 2020; Foltýnova et al., 2020). Consequently, car dependency, which also limits the functionality of public spaces, is one of the issues addressed in the municipality's policies.

Amsterdam aims to address these issues through policies such as the *Mobiliteitsaanpak Amsterdam 2030.* Next to car traffic reduction, municipal policies strive for sustainable and alternatives modes of transportation (Gemeente Amsterdam, 2013). To create an efficient and sustainable transport system, many innovative policies have been attempted in the past. Those policies often require smart technologies to assist in the implementation process and to enhance effectiveness. Experts have come to agree that technologies can play a large role in solving, or at least alleviating, urban problems and challenges (Wang et al., 2022). So far, several technological initiatives aimed at managing traffic flow and sharing real-time information have been tested and assessed in multiple cities globally (Debnath et al., 2011).

Through the *Agenda Amsterdam Autoluw,* the city focuses on creating low-car zones in different parts of the city (Gemeente Amsterdam, 2020). It touches upon changes that are required for the city to remain livable and accessible, with the eastern part of the city center as its current focus. To enhance this low-car approach and address future mobility challenges, five objectives were formulated. These objectives can be divided into three different themes: *mobility*, *spatial* and *social*. Regarding the *mobility* theme, the agenda focuses on facilitating alternative transport modes – such as walking, cycling, public transport and shared mobility - while also acknowledging the role of cars. Next to this, the municipality strives to improve air quality and traffic safety according to guidelines from the EU and World Health Organization (WHO) (Gemeente Amsterdam, 2020).

The city aims to create more room for comfortable public spaces and different facilities and these objectives can be assigned to the *spatial* theme. Public spaces in the city should provide room for citizens and visitors to both meet and spend their free time (Gemeente Amsterdam, 2020). The functionality of a city largely depends on the number of facilities that are present in the public space, such as underground waste containers and bicycle parking spots. Therefore, the city wants to provide room for these facilities where possible. For the *social* theme, Amsterdam focuses on making the city accessible to all regardless of any differences in abilities or socio-economic status (Gemeente Amsterdam, 2020).

To realize the objectives of the *Agenda Autoluw,* the municipality has set up multiple (pilot) projects to do research on how urban mobility issues could be dealt with. Within these pilot projects several technologies have been tested out on differing scales to determine to what extent they can help alleviate these issues. This ranges from physical barriers to speed limit control for cars and other vehicles. Furthermore, there have been conferences and platforms set up to increase and stimulate knowledge development and knowledge sharing (MRA Platform Smart Mobility, 2023). A question remains to what extent technologies can contribute to the objectives of the *Agenda Autoluw,* especially for the eastern part of the city center.

1.1 Research Objective and Questions

The city of Amsterdam is aiming for car reduction and a change in the role and impact of cars in the eastern part of the city center. We arrived at the following research objective:

"Support the Agenda Autoluw by exploring the strengths and weaknesses of technological solutions with a multicriteria analysis (MCA) in the context of the low-car city within the eastern part of Amsterdam's city center."

Following this objective, this general research question (GRQ) was formulated:

"How can technological solutions contribute to the objectives of the Agenda Autoluw in the eastern part of Amsterdam's city center?

To supplement the GRQ, the following secondary research questions (SRQs) were defined:

1. What technological solutions are available to contribute to a low-car city?
2. Which criteria describe the suitability of the technological solutions for the objectives of the low-car city?
3. What are the strengths and weaknesses of the technological solutions?

1.2 Study Area Description

Before the methodology of the study can be described, it is crucial to delineate the boundaries of the study area and explore its challenges. It encompasses Weesperstraat, Valkenburgerstraat and the entrance to the IJ-tunnel. This area is characterized by multiple cultural and educational facilities, next to high-density residential areas, such as Waterloopleinbuurt and Weesperbuurt (Gemeente Amsterdam, 2021). The study area's boundaries are shown in Figure 1.

At this moment, the different functions are not as well connected due to major roads crossing through the area. Interventions in this eastern part of the city center can create opportunities for improving quality of public space and slow traffic routes. Especially a couple of locations in the area will be influenced most by a low-car approach, such as Weesperplein, Weesperstraat, Mr. Visserplein and Valkenburgerstraat (Gemeente Amsterdam, 2021).

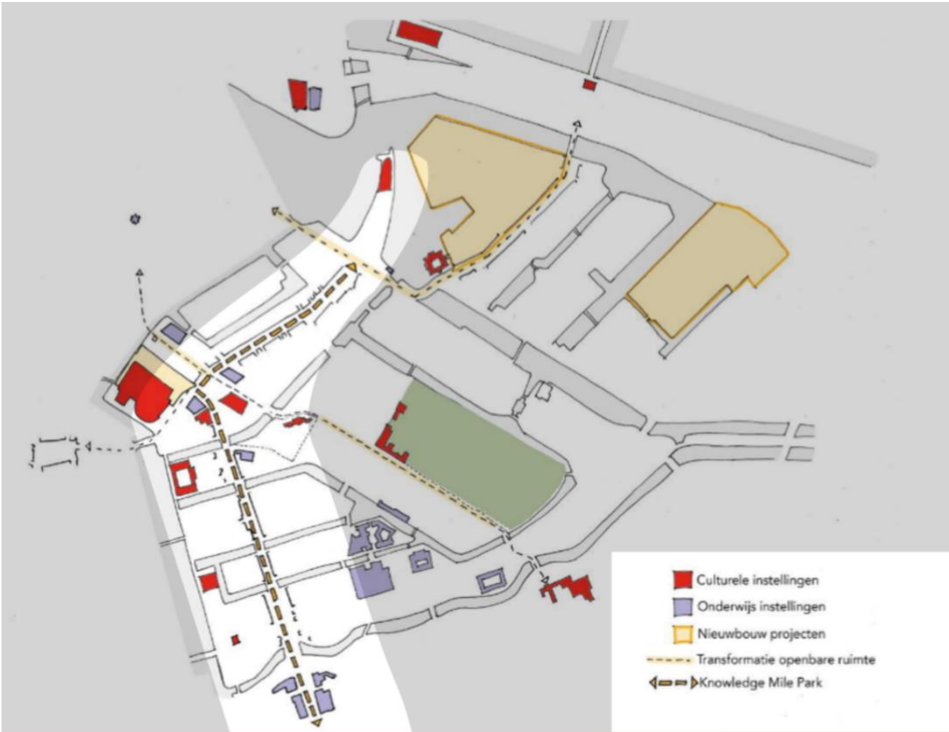

Figure 1. Study case area Oostelijke Binnenstad. Adapted from Gemeente Amsterdam (2021).

2. Methodology

This study performed an MCA on technologies which could support a low-car city approach for the study area. It starts with the collection of a wide range of technologies that are relevant to SRQ 1 into a catalogue. To answer SRQ 2, the MCA's criteria are defined holistically with respect to the objectives of *Agenda Autoluw* and thus they encompass the three themes of mobility, spatial and social. The data collection methods for these questions are presented in subchapter 2.1. Finally, the MCA was performed for SRQ 3 after a preliminary criteria assessment. Importantly, the intended purpose of this MCA was not to identify the best scoring technology. Rather, it highlighted the strengths and weaknesses of each technology. An overview of the complete methodology is provided in Figure 2.

The study uses MCA over other methods of analysis because it is a process that can support decision-making, whilst keeping in mind the specific needs of a study area. Most importantly, it also allows for the systematic comparison of various alternatives based on a set of criteria instead of unscientific methods such as intuition (Bouyssou et al., 2006). It is a step-by-step process that aids decision-makers and policy makers in organizing a decision problem, understanding the preferences and needs, and formulating a decision recommendation that aligns with these preferences and needs. As an analysis approach, it has been used in a wide range of complex decision-making domains, such as energy systems, water supply systems and others (Cinelli et al., 2020).

The MCA process for this study resembles most closely the assessment indicator models as described by Awasthi et al. (2018) with its original purpose to assess the sustainability of transportation systems. Notably, it is a well-tested model with a variety of use cases within the field of transport planning such its application towards the identification of suitable alternative measures to sustainably improve urban mobility (Lima et al., 2014). This is done with the purpose of showcasing the strengths and weaknesses of the technologies studied to support the *Agenda Autoluw*.

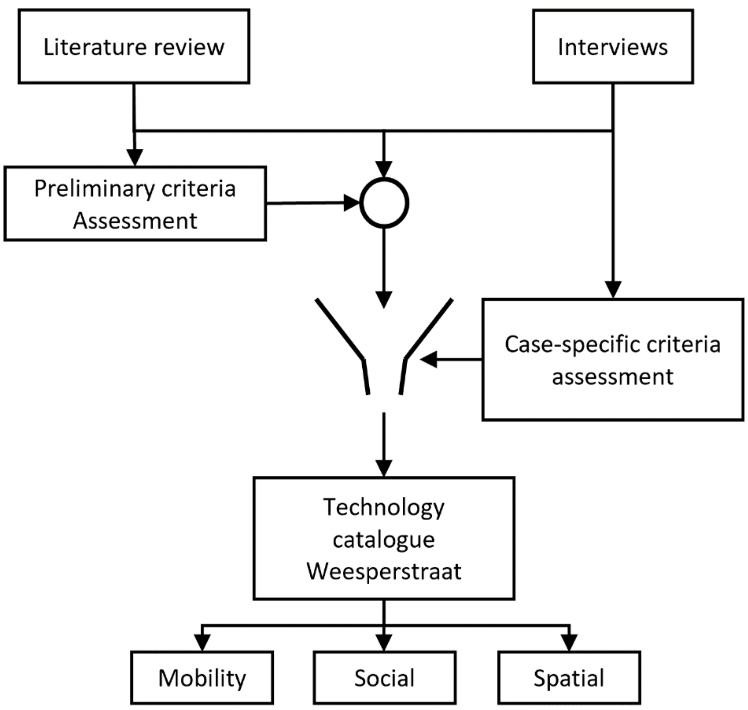

Figure 2. Research framework data collection to technology catalogue.

2.1 Data Collection

To find an answer to our research question, literature review and semi-structured interviews are used as qualitative methods for the data collection. This paper uses scientific and grey literature for the selection of criteria for the MCA and takes case specific criteria of the municipality of Amsterdam into account. Interviews are used only afterwards for the validation of weights used for the criteria in the MCA. The technology catalogue is similarly built using literature to create a comprehensive list of solutions. In this case, interviews supplement the literature and offer greater insight into specific technologies.

In the literature review, both scientific and grey literature is consulted in addition to articles produced by private business or news agencies. The Boolean combinations which were used as search terms are presented in Table 1.

Table 1. Overview of keywords used as Boolean combinations for data collection. Not all searches used all three keywords. Combinations of only the first and second columns were also used. The fourth keyword was only included after the criteria for the MCA were defined.

First keyword	Second keyword	Third keyword	Fourth keyword
Low-car* OR	Case study* OR Criteria* OR MCA*	Maas* OR Mobility-as-a-Service* OR Mobility as a Service* OR Automated barrier* OR Dynamic Traffic Management* OR Geofencing* OR ISA* OR Intelligent speed assistance* OR Scancar* OR Gamification* OR Mobility data*	Regulation* OR Infrastructure * OR Culture* OR Data* OR Ethics* OR Traffic reduction* OR Traffic flow* OR Parking* OR Safety* OR Connectivity* OR Noise* OR Air* OR Landscape*

The secondary method, semi-structured interviews, were conducted with academic and governmental experts. During each interview, the audio was recorded with the interviewee's consent and processed into a summary of insights. No consent was given for the distribution of either the recordings or interview notes. In total, we interviewed 4 experts, whose names and purpose of the interviews can be found in Table 2.

Table 2. List of interviewees and the purpose of each interview.

Name Interviewee & Date(s)	Purpose of interview(s)
T. Kuipers (12 July 2023 & 15 July 2023)	Validation of weights and criteria used for the MCA.
F. Duarte (6 June 2023)	Expansion of technology catalogue and in-depth information about technologies.
B. van Arem (26 July 2023)	Validation of weights and criteria used for the MCA.
T. van Heukelingen (5 June 2023)	Expansion of technology catalogue and in-depth information about technologies.

2.2 Preliminary Criteria Assessment

The preliminary criteria assessment followed the process shown in Figure 3, starting with the creation of the initial technology catalogue which consisted of approximately forty technologies. After the removal and merging of extremely similar technologies, a catalogue of twenty-one solutions was created (Annex 1).

The preliminary criteria assessment was performed based on the three most-important criteria of the MCA. The criteria and their indicators were derived solely from literature and an overview can be found in the first column of the MCA rubric in Annex 2. Due to time constraints, it was determined that a total of five criteria was an adequate number for the purposes of the MCA. The criteria were selected based on the authors' academic and professional experience and they are supported with literary sources. The details of this process are given in subchapter 4. The scoring of the indicators ranges from 1 to 5 which is adapted from the 'very poor to very good' rating scale as described by Kumar (2011). The indicators are also weighed and when summed for their corresponding criterium, they equal 1. The criteria themselves are also weighed and amount to 1 when summed. Ultimately, seven technologies were selected using the three most important criteria. Again, due to time constraints only a limited number of technologies could be selected without compromising the quality of the analysis.

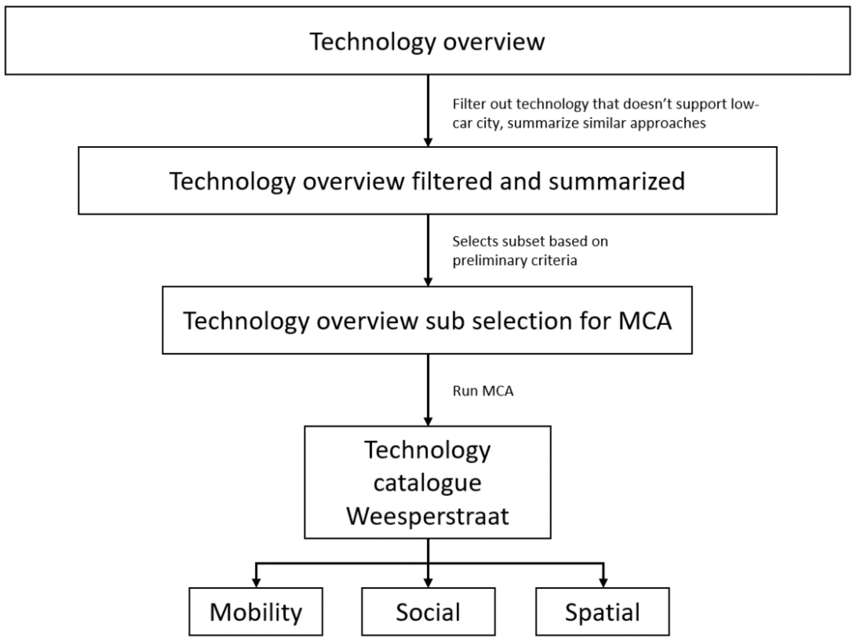

Figure 3. Process of preliminary criteria assessment.

2.3 Multicriteria Analysis

The results of the preliminary selection were used for the MCA where a rubric of five criteria and sixteen indicators was used to score each of the seven technologies. The scoring of individual technologies is provided in chapter 5. The case-specific criteria assessment, which is the MCA, was performed in several steps adapted from Figure 4: Initially, every technology was assessed for all indicators, which all correspond to one of the criteria. The assessment was performed by filling out the rubric provided in Annex 2 and selecting an indicator score on the scale of 1 to 5 using both case studies and predictive research. Next, all scores were standardized using relevant standardization methods. This ensured that all scores are between zero and one, and to avoid the results are affected by differences in units. Then, the weights were determined for both the indicators and criteria to obtain an end score for each technology. The scores were first determined for each criterium based on its indicators and their weights. Thus, the final score consists of a weighed range of five scores which showcases the strengths and weaknesses of the technology. Weights were implemented to provide priority to the criteria that were deemed as more important for the purposes of the *Agenda Autoluw* of the municipality of Amsterdam based literature and interviews.

To ensure that the MCA results are robust, several final steps were taken. A difference analysis was conducted to assess the dependence of the overall scores on the assigned weights and standardization methods. The difference analyses are performed by changing various weights. The validation of this weighing was done based on the feedback received from the commissioner of the study in addition to an interview with an external expert upon his recommendation.

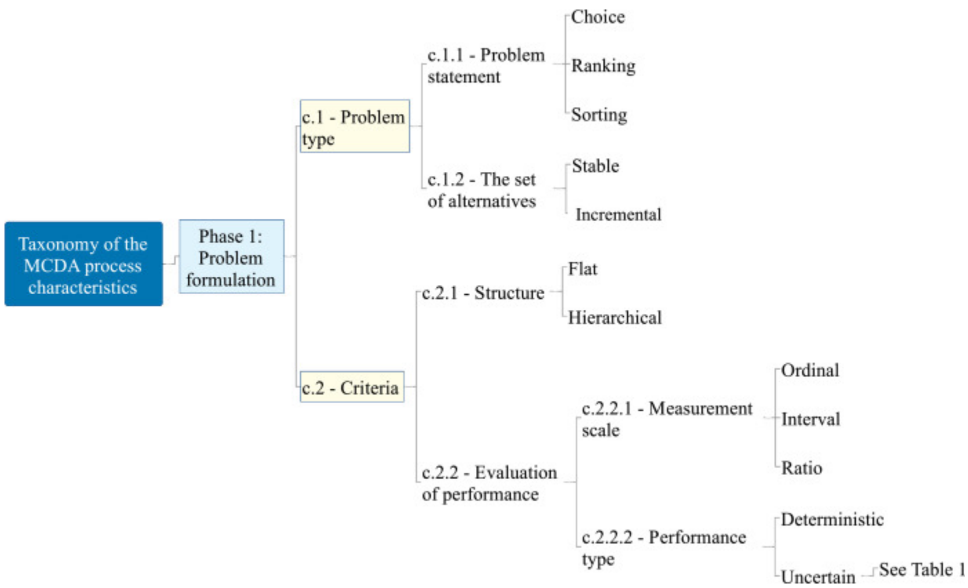

Figure 4. An overview of the first phase of an MCA (Cinelli et al. 2020)

3. Technology Selection

Based on a literature review, a comprehensive list of technologies was created. In a broad sense, each technology related to a low-car city and its subthemes mobility (e.g., maas-apps, drones or mobility hubs), spatial planning (e.g., digital twin, predictive road maintenance with remote sensing or the quantum gravimeter), social behavior (e.g., gamification or geofenced live events), and the built environment (e.g., low noise road cover or bio-receptive concrete). The complete list of explored technologies can be found in Annex 1.

While the literature indicated a strong influence by some of these technologies on the number of cars in urban environments, others only had a very limited or indirect effect on the low-car city. For example, a technology like the MESA radar that could theoretically contribute to a safe drone traffic would not affect the number of cars in the foreseeable future and thus it was deleted from the list. Also, some technologies had a big overlap and were either combined into a package of technologies or an overarching technology. This can be seen in Figure 5 with the example of dynamic traffic management system which is a combination of convolutional-neural-network-based congestion prediction, real time modelling, a digital twin and more.

To delineate the technologies even further, three preliminary indicators were developed and applied to the technology catalogue. First, a rough assessment was made regarding the degree of facilitating the low car city, as this is the main objective of the analysis. Second, the estimate was performed regarding the technological maturity and feasibility of implementing the technology in the study area to minimize uncertainty. Third, a rough estimate was made about the compatibility of the technology with current infrastructure to avoid very costly and complex adaptations that need to be done in the study area.

As illustrated in Figure 5, technologies like bio-receptive concrete or low noise road cover did not have a foreseeable impact on the low-car city. Neither did they increase traffic whilst still mitigating some of its negative effects (e.g., noise pollution). On the other hand, the impact of drone deliveries on the traffic was possible to estimate, but as seen in pilots of the retailer Amazon (Link & Dave, 2023), neither the technological maturity nor the needed infrastructure (e.g., regulatory framework) was sufficient. The compatibility to the current infrastructure was rated with low scores for technologies that either need a high effort for the physical implementation such as the low noise road cover or automated barriers.

Furthermore, compatibility was rated as low when there is a lack of standardization and level of implementation as seen in the example of Vehicle2X communication (Butcher, 2021). Based on these preliminary criteria a selection of seven technologies can be deployed. The selection ranges from specific technologies to brought technology packages and is described in Table 3 with more details.

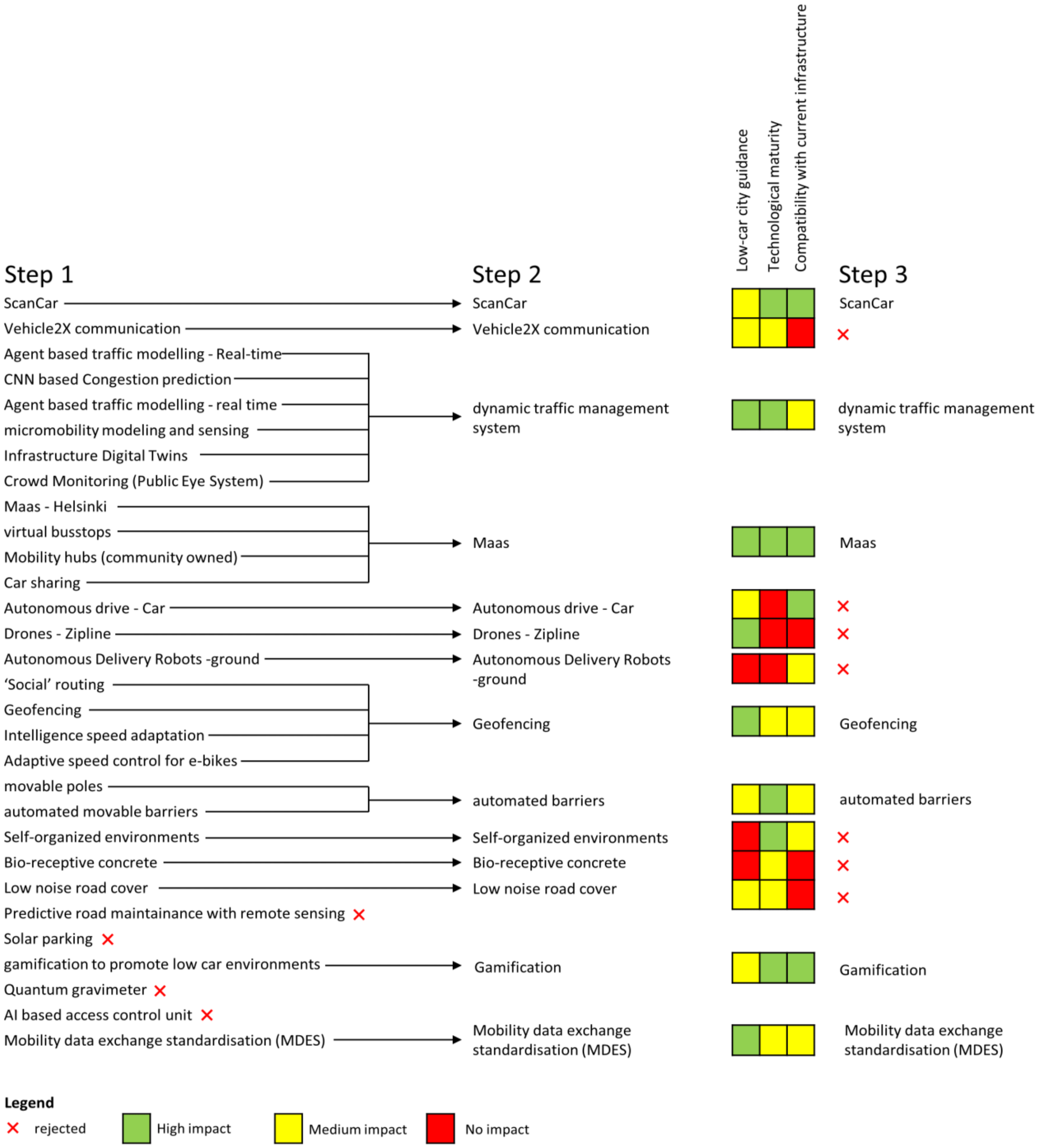

Figure 5. The selection of technologies from the initial twenty-one to the final seven.

Table 3. Description of the seven selected technologies

Technology	Description
1. Mobility-as-a-Service (MaaS)	MaaS aims to transform mobility in smart cities by providing an alternative to private transportation. Arias-Molinares and Palomares (2020) conclude after an extensive literature review with the definition of Kamargianni and Goulding (2018) "multiple modes of transport (public and private), one single application, user-oriented approach, mobility packages, real-time information, multimodal journey planner and payment integration". This paper follows this definition and thus bundles technologies like mobility hubs, carsharing and a maas-app in one technology-package.
2. Dynamic Traffic Management Systems (DTMSs)	DTMSs play a crucial role in preventing congestion and improving efficiency by collecting data from various sources and utilizing predictive analysis to address potential issues. TMS solutions include speed adjustment at traffic lights, congestion detection and prevention, and alternative route recommendations (Paiva et al., 2021). This paper combines besides others (see Figure 5) micro-mobility flow modelling, congestion prediction and digital twins in this package of technologies.
3. Geofencing	Referring to the use of GPS or Radio-frequency Identification technology to create virtual boundaries or zones in specific geographic areas. These boundaries can be defined by physical coordinates, such as latitude and longitude, and can trigger certain actions or restrictions when a device or vehicle enters or exits the designated area (Caggiani et al., 2023). Specific technologies that are considered in this paper are social routing and adaptive speed limits for e-bikes.
4. Automated barriers	Referring to the physical objects that prevent pedestrians or vehicles from passing through a specific point. These barriers can incorporate camera verification, push buttons, remote control, time specific control, among others (Power Right Fire Energy & Security, n.d.).
5. Scancars	Scancars are cars equipped with a set of sensors and are operated by a human driver. Currently, a set of twelve cameras is used to detect the number plates of parked cars and their validity for parking enforcement in cities like Amsterdam and Rotterdam. Scancars can also be used to collect other data such as images, 3D-point clouds and other data (AMS Institute, n.d.).
6. Gamification	Referring to the use of game design, such as badges, leaderboards and challenges to incentive desired behavior in a non-game context. The most used gamification elements are points, badges, leaderboards, levels, and challenges. One approach to increase activities and engagement in the city can be the controlled placements of points of interest leveraging augmented reality and ICT (Kazhamiakin et al., 2015). In an interview, Fabio Duarte (2023) names the placement of Pokémon's in the game Pokémon-go as one example to change travel behavior of people in public space. Furthermore, this paper also incorporates geofenced live events like virtual concerts.
7. Mobility Data Exchange Standardization (MDES)	MDES between the municipality and navigation providers is envisioned as streamlining and improving the sharing of data between municipalities, road traffic users and third parties such as navigation providers. In an interview, Tijmen van Heukelingen (2023), who is closely related to the Datapedia project highlighted the positive effect of streamlined communication on navigation and traffic flow.

4. Criteria Selection

To gain deeper insights into how several technologies can help the Amsterdam municipality bring their low car vision to fruition, several criteria are needed because the transition from one sociotechnical paradigm to another is a multidisciplinary problem (Geels, 2002). To achieve this, a wide variety of theoretical frameworks has been found in literature. First, a look has been taken into criteria that describe a sustainable and smart urban mobility system, and how these relate to the policy goals of Amsterdam. Second, an innovation system view is adopted to assess the maturity of a technology from a sociotechnical lens. Third, a look has been taken into theories that can help explain the adoption and diffusion of innovations. At last, a look has been taken into the economic aspects that are deemed important by scientific literature.

4.1 Sustainable Urban Mobility Criteria

As stated in their *Agenda Autoluw* and their Mobility Plan for 2030 the municipality of Amsterdam aims to prioritize attractive public spaces and provide more room for cyclists and pedestrians. Cars will have priority on certain major roads but not everywhere in the city. Street parking is being reduced, with a focus on underground parking and park and ride facilities (Gemeente Amsterdam, 2013). These aims suggest that car traffic reduction, reduction in street parking, and quality of public space are important criteria as established in the policies of the *Agenda Autoluw* (Table 4).

The municipality is also taking action to ensure safety and accessibility. Measures include reducing traffic in the city center, improving air quality, and considering options to accommodate different modes of transportation. The Mobility Plan for Amsterdam in 2030 outlines goals such as creating more space, enhancing cycling infrastructure, and prioritizing pedestrian areas. To ensure safety, the city aims to prevent accidents by, promoting better traffic habits, and enhance overall road safety. The Long-term Traffic Safety Plan focuses on reducing serious injuries and deaths by 25%, with annual evaluations to adjust policies as needed. Key areas of focus include improving road users' behavior, creating safer traffic conditions, implementing specific safety practices for each mode of transport, and enhancing safety in public spaces (Gemeente Amsterdam, 2013). Consequently, the following criteria can be identified: *traffic flow improvement, improved accessibility, connectivity, and safety improvements* (Table 4).

Chatziioannou et al. (2023) define thirteen sustainable urban mobility indicators (SUMIs) that help to assess the sustainability of an urban mobility system. Some of these can be found in Table 4 with their relation to the policy goals of Amsterdam. Some policy goals do not match to any SUMIs but are kept due to their importance to the low car city concept.

Gemeente Amsterdam (2019) also aims to further digitalize the Amsterdam mobility system in its Smart Mobility program. They strive for more data collection to further improve safety, accessibility and connectivity, but also gain more insight for more targeted measures. This is in line with the statements of Paiva et al. (2020), who also mention the privacy and ethical concerns around smart and sustainable mobility systems.

Table 4. Criteria for the themes of mobility and spatial as found in municipal Agenda Autoluw policy documents.

Policy Goal Amsterdam	Description	Scientific Support
Car Traffic Reduction	Cars are not priority mode of transport in area, there will be a focus on other transportation modes	Only supported by municipal policy.
Traffic Flow Improvement	Reduction in congestion and traffic jams	Congestion and delays (Chatziioannou et al., 2023)
Reduction in Street Parking	Parking underground and further away from city center	Only supported by municipal policy.
Safety Improvement	Reduction in accidents, but also social safety	Road deaths, traffic safety (Chatziioannou et al, 2023)
Accessibility	Accessibility of transport modes in multiple ways – located nearby, price etc.	Affordability public transport, accessibility public transport for mobility impaired groups, access to mobility services (Chatziioannou et al., 2023)
Connectivity	The extent to which different parts of public spaces are well connected to each other and reachable by different transport modes	Multimodal integration, access to mobility services as mentioned by (Chatziioannou et al., 2023)
Quality of Public Space	Quality of public space is determined by multiple factors – such as safety, level of comfort, meeting places	Air pollutant emissions, greenhouses gas, noise hindrance (Chatziioannou et al., 2023)
Digitalization Mobility System	Collecting data to improve safety, accessibility and connectivity. Also use data to improve efficiency in policymaking by more targeted measures	Smart mobility and privacy (Paiva et al., 2020)

4.2 Technological Maturity Criteria

To assess how well developed a certain technology is, the Technological Innovation Systems (TIS) approach as described by Hekkert (2007) is of use. TIS describes seven functions of an innovation system, which can be scored to give an overview of the development of the technology (Table 5). First, *entrepreneurial activity* concerns the commercialization of new technology. *Knowledge development* concerns the generation of new knowledge through R&D and testing. The *knowledge diffusion* function involves the sharing of knowledge by different stakeholder groups. *Guidance* refers to the development and implementation of policies and measures that set the direction of technological development. The *market formation* function refers to the creation of supply and demand for a technology. *Resource mobilization* involves the allocation of financial, human and infrastructure resources towards the technological solution. Finally, *legitimization* concerns the promotion of a technological solution to improve awareness and combat misinformation.

Table 5. Overview of indicators for the development of a technology as established by Hekkert (2007).

Criterium	Description	Indicators
Entrepreneurial activity	Creation of supply	Presence of active entrepreneurs
Knowledge development	Generation of (technical, social, etc.) knowledge around technology	R&D projects, patents, investment in R&D
Knowledge diffusion	Sharing of knowledge between different stakeholder groups	Conferences, workshops, network size & intensity
Guidance	Policy and measures setting direction of technological development	Government targets, industry targets, articles in professional journals
Market formation	Creation of demand	Subsidies, environmental standards, niche markets
Resource mobilization	Allocation of financial and human capital towards development of technology	Investments, number of jobs, lack of access reported by core actors
Legitimization	Creating awareness and battling misinformation around technology	Interest groups, lobby activities

4.3 Innovation Adoption Criteria

A critical aspect of implementing technology that facilitates a low car city is making sure that the technology is actually adopted by stakeholders such as residents and the Municipality of Amsterdam. As such, several criteria must be established to assess the chances of adoption of a certain technology. One framework widely used in the diffusion of technology is developed by Rogers (2003), where it is argued that there are five attributes that influence diffusion (Table 6). *Relative advantage* concerns the performance of an innovation compared to the status quo. *Complexity* concerns how difficult an innovation is to understand, use, and purchase. C*ompatibility* concerns how an innovation fits in the life of an individual, how well it fits with existing infrastructure, and how it fits in culture. *Trialability* concerns how easily an innovation can be tested. Finally, *observability* concerns how the benefits of an innovation can be seen and how it affects social status.

Table 6. Overview of social criteria for the adoption of technological solutions as described by Roers (2003).

Criterium	Description	Indicators
Advantage	Performance compared to status quo	Travel times
Complexity	Difficulty of technology and user experience	Ease of use
Compatibility	How the innovation fits in life of adopter, infrastructure and culture, as well as other technologies	Regulatory Physical Cultural
Trialability	How easily product can be tested	Ease of obtaining test
Observability	How well the advantages and social status can be seen	

4.4 Economic Criteria

The financial aspect of technology is also of importance for whomever aims to implement it, the City of Amsterdam in this case, as resources are scarce. Additionally, it is relevant for the citizens who need to pay for the use of some technologies, whether directly or indirectly. Rodrigues da Silva et al. (2022) mention several financial criteria that have been used in MCAs for the selection of mobility projects in urban settings (Table 7). First, *investment costs*, the initial costs to implement the project. Second, *operation costs* are considered, which are costs related to operation and maintenance of the project. Third, *operation revenues*, which relates to the generation of revenue during the project. Additionally, Rodrigues da Silva et al. (2022) mention several socioeconomic costs that relate to residents, tourists and other stakeholders. These include *costs of public transportation*, *price of parking ticket*, and *project lifecycle* which relates to the durability of the project. As a result, there are various criteria available to assess the financial impact of the implementation of a technology on both the municipality and its citizens.

Table 7. Overview of socio-economic criteria for the implementation of technological solutions as found by Rodrigues da Silva et al. (2022).

Criterium	Description	Indicators
Investment Costs	Initial costs of project execution	Comparable projects
Operating Costs	Costs related to operating and maintenance of project	Labor intensiveness, comparable projects
Operating Revenue	Revenue related to operating of project	Scale
Costs of Public Transportation	Price to pay to users of public transport	Investment costs, operating costs
Parking Costs	Price to pay to park vehicle	Costs of nearby parking
Project Lifecycle	Durability of project	Durability, life cycle analysis

4.5 Criteria for Case-Specific Assessment

To perform the MCA, a subset and mix of the criteria discussed above was used (Table 8). First, the complexity of implementing a technology was chosen to gain insight into the different technologies, derived from the compatibility criteria as defined by Rogers (2003). Superior technologies are not always the best solution due to incompatibility with culture, infrastructure and/or regulatory frameworks (Geels, 2002). For example, heavy investments in physical infrastructure might be needed, drastic behavior changes and current regulatory frameworks could slow down or even inhibit the implementation of technologies (Geels, 2002). Second, the technological maturity of a technology was deemed important since the technology needs to be ready for implementation. This criterium was derived from the knowledge development and knowledge diffusion criteria as mentioned by Hekkert (2007). Third, the ability to collect data was also assessed because this can facilitate further development of Amsterdam into a smart city, and improvements in decision making with the support of data (Gemeente Amsterdam, n.d.).

Next to this, ethics of data collection were considered in order to see what measures of data protection are in place. Fourth, the compatibility with the policy goals of the Amsterdam municipality was deemed important because the technologies should enable the municipality to achieve its policy goals. This was derived from the guidance criterium as mentioned by Hekkert (2007). Being in line with government goals helps in the mobilization of resources into a technology to further develop it. This criterium was split into a mobility criterium and an environmental criterium. The mobility criterium concerns all policy goals related to car use, traffic flow, parking demand and other traffic-related policy goals. The environmental criterium concerns noise nuisance, air pollution and quality of spatial environment. The indicators related to these criteria are derived from Chatziioannou et al. (2023) and the Amsterdam Mobility Plan 2030, and the *Agenda Autoluw*. Further details concerning the scoring of alternatives can be found in the rubric in Annex 2.

Table 8. Criteria selected for the case-specific assessment of technological solutions, the MCA.

Criterium	Description	Indicators (I1-I16)
Complexity Implementation	What are the barriers of implementation in terms of social, infrastructural and regulatory aspects?	Compatibility with culture (Rogers, 2003) Compatibility with infrastructure (Geels, 2002) Compatibility with regulations (Geels, 2002)
Technological Maturity	In what stage of development is the technology, ready to be implemented or still in early development?	Amount of test projects (Hekkert, 2007) Amount of knowledge sharing between stakeholders (Hekkert, 2007)
Data Collection	How can the technology facilitate ethical data collection to improve the city?	Amount of potential data points (Sapienza et al., 2016) Privacy concerns (Sapienza et al., 2016)
Low Car City Guidance (Mobility)	How well does the technology facilitate or enable a low car city in terms of mobility?	Effect on car dependence (Gemeente Amsterdam, 2013) Effect on traffic flow (Chatziioannou et al., 2023) Effect on street parking (Gemeente Amsterdam, 2013) Traffic Safety (Chatziioannou et al., 2023) Connectivity (Gemeente Amsterdam, 2013)
Low Car City Guidance (Environmental)	How well does the technology deal with environmental and spatial policy goals?	Noise nuisance (Chatziioannou et al., 2023) Air pollution (Chatziioannou et al., 2023) Quality of spatial environment (Van Der Meer et al., 2019)

5. Multicriteria Assessment for the Low-Car City

By running a multi criteria analysis, this paper aims to show how the selected technologies can be valued with a comprehensive and case-specific bundle of criteria. This results in a tool that can be used to support decisions and highlight strengths and weaknesses of specific technologies on the different challenges and domains of a low-car city.

Chapter 4 justified the decision of criteria C1 to C6 with each having three to six indicators based on literature and policy documents of the municipality of Amsterdam. An overview can be seen in Table 9. Chapter 3 described the process of the technology selection and results the set of technologies from T1 to T7 with each having a high potential to contribute towards the low-car city. As mentioned in the methodology, the rubric was ultimately used to score each indicator for every technology in an equal and transparent way, and to minimize bias by different assessors. For each technology, the MCA was performed based on the same rubric and supported by literature (Annex 3).

Table 9. Summary of MCA objectives, technologies and criteria

Criterium	MaaS (T1)	DTMSs (T2)	Geofencing (T3)	Automated barriers (T4)	Scancars (T5)	Gamification (T6)	MDES (T7)
Complexity Implementation (C1)	R1.1	R2.1	R3.1	R4.1	R5.1	R6.1	R7.1
Technological Maturity (C2)	R1.2	R2.2	R3.2	R4.2	R5.2	R6.2	R7.2
Data Collection (C3)	R1.3	R2.3	R3.3	R4.3	R5.3	R6.3	R7.3
Low Car City Guidance (Mobility) (C4)	R1.4	R2.4	R3.4	R4.4	R5.4	R6.4	R7.4
Low Car City Guidance (Environmental) (C5)	R1.5	R2.5	R3.5	R4.5	R5.5	R6.5	R7.5

5.1 Weights used for the MCA

As a crucial part of a multi criteria analysis, weights must be assigned transparent (Table 10). As described in the methodology, the initial weights were based on the assessment of literature by the authors. The second and third set were developed in an interview with an external expert and the research commissioner respectively.

Table 10. Overview of weights as assigned by the authors, commissioner and external expert.

Criterium	Indicators	Authors		Commissioner		Expert	
C1	Regulatory compatibility (I1)	0.25	0.33	0.25	0.4	0.3	0.25
	Physical compatibility (I2)		0.33		0.3		0.25
	Cultural compatibility (I3)		0.33		0.3		0.5
C2	Level of implementation (I4)	0.2	0.6	0.2	0.6	0.15	0.5
	Level of implemented knowledge (I5)		0.4		0.4		0.5
C3	Generation and processing of data (I6)	0.1	0.4	0.1	0.5	0.15	0.8
	Ethics of data collection (I7)		0.6		0.5		0.2
C4	Promotion of low-car behavior (I8)	0.25	0.25	0.25	0.15	0.3	0.05
	Car traffic reduction (I9)		0.25		0.25		0.05
	Traffic flow improvement (I10)		0.15		0.1		0.1
	Reduction in street parking (I11)		0.15		0.1		0.05
	Safety improvements (I12)		0.1		0.25		0.5
	Connectivity (I13)		0.1		0.15		0.25
C5	Noise nuisance (I14)	0.2	0.33	0.2	0.3	0.1	0.1
	Air pollution (I15)		0.33		0.4		0.1
	Landscape effect (I16)		0.33		0.3		0.8

5.2 Scoring of Technologies

Based on the insights from the previous chapters, the MCA is performed for each technology. This chapter provides insights into the reasoning and justification for the determined scores. As described earlier, each technology was scored separately in the rubric schemes which can be found in Annex 3. Additionally, the differences in scores between different weights as listed in Table 10 are also described.

5.2.1 Mobility-as-a-Service

As far as the complexity of implementation is concerned, Mobility-as-a-Service (MaaS) is scoring moderate. The required mobility infrastructure already exists in Amsterdam, as there is a public transportation system and several private mobility providers such as Check and taxi drivers. However, some regulatory conflicts might arise when it comes to differing interests (Aghari et al., 2020). An example is the conflict between taxi drivers and Uber in the city (van Anst, 2018). Regulators can also be hesitant to approve new modes of transport (Aghari et al., 2020). Furthermore, cultural difficulties might occur when it comes to car owners and the elder group that is less tech-savvy. Moreover, there is an alignment needed between public and private competitors such as NS and taxi drivers (Butler et al., 2021).

Regarding technological maturity, MaaS scores high. There are seven regional pilot projects to be implemented or have been finished in several Dutch cities (Aghari et al., 2020;

Gemeente Amsterdam, n.d.-b; Goulding & Kamargianni, 2018). In addition, a platform has been set up aiming to promote sharing knowledge and to discuss potential implementations of the MaaS Concept within the Metropole Region of Amsterdam (MRA Platform Smart Mobility, 2023).

MaaS scores moderate on *Data Collection*. There is a lot of data that can be collected through this technology regarding mobility behavior, however there are privacy concerns that lead to lowering of the score. The concerns are associated with personal and payment information collection, as well as intellectual property problems for mobility providers (Butler et al., 2021).

When it comes to adhering to Amsterdam's mobility policy, MaaS does a good job. MaaS solutions have been shown to reduce car ownership, car traffic, reduction in congestion and a reduction in parking demand (Aghari et al., 2021; Butler et al., 2020; Paiva et al., 2021). However, there could also be an increase in car traffic and congestion increasement if the MaaS is implemented incorrectly in the form of car focused MaaS solutions such as Uber (Aghari et al., 2021). Jittrapriom et al. (2017) state that MaaS solution can also improve connectivity as several modes of transportation can be integrated into application.

Due to the reduction in car dependency and traffic (Aghari et al., 2021; Butler et al., 2020; Paiva et al., 2021), both noise nuisance and air pollution are expected to be reduced. There is no evidence for an improvement of the landscape.

MaaS shows a significant difference in scores for all criteria except technological maturity when different weights are used (Figure 6). The expert set leads to the highest grade in data while resulting in the lowest for all other criteria. The authors' set of weights gives the highest score to mobility and lowest for data. Finally, the commissioner's weights lead to the highest score for the environment criterion.

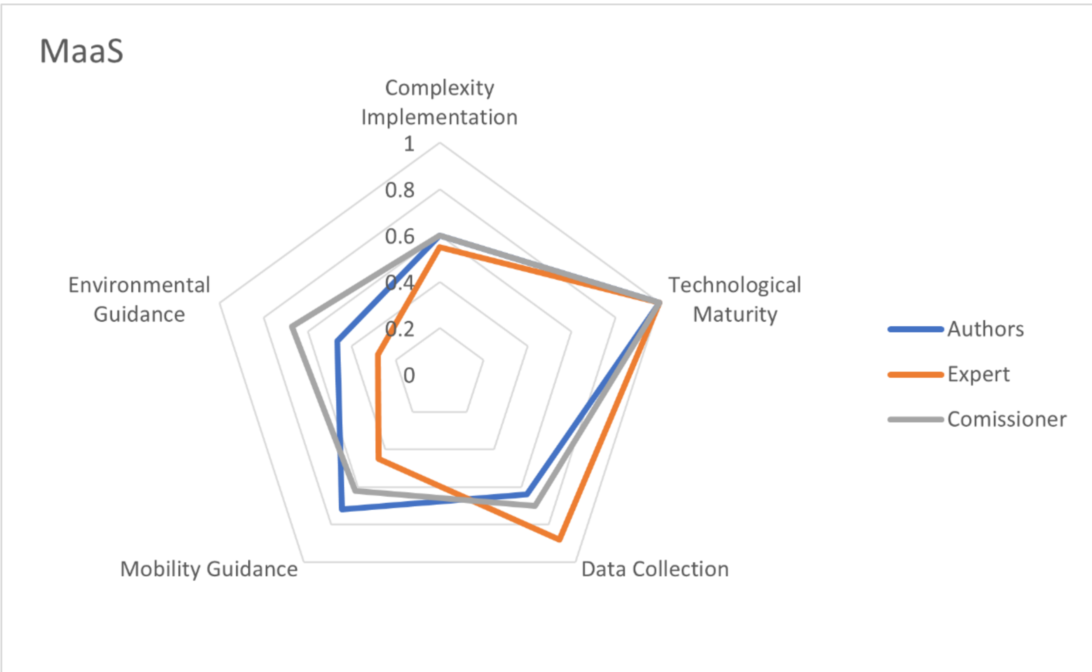

Figure 6. Radar chart of MCA scores per criterion and set of weights for MaaS.

5.2.2 Dynamic Traffic Management System

The complexity of implementation scores good for DMTS. The implementation of DTMS involves some challenges, such as the implementation of Internet of Things (IoT) infrastructure in traffic lights, sensors and cameras. However, some of this infrastructure is already present in Amsterdam (Huiskens & Vlemmings, 2021). In addition, several big data management issues need to be resolved, such as the integration of different data sources into standard data formats is still needed (de Souza et al., 2017).

DTMS score high on technological maturity. DTMS are being tested in a wide range of European cities, including Amsterdam (Huiskens & Vlemmings, 2021). For instance, Socrates2.0 project was set upon a cooperation of road authorities, service providers and car manufacturers, i.e., municipality of Amsterdam, TomTom, BMW, etc. Together they have been developing intelligent ways to collect, exchange and use traffic data throughout the complete value chain for traffic management and information services (Huiskens & Vlemmings, 2021).

With regards to data collection DTMS score high, DMTS collect many different datapoints such as congestion, accidents, routes, speed and other traffic data. Despite not being heavily personalized, the data still comes with some privacy issues such as vehicle tracking, and also some potential security concerns (de Souza, 2017).

DMTS have a moderate score concerning the mobility aims of Amsterdam. This is mainly because there is little evidence of a reduction in car ownership and car traffic, since DMTS is a background technology. On the other hand, DMTS have proved to improve traffic flows and safety (de Souza, 2017; Huiskens & Vlemmings, 2021; Dutka, 2023). Also, alternative routing could divert parking away from the center and a reduction in street parking (Dutka, 2023). DMTS score low on the environmental criterion. DTMS can help to reduce air pollution as fuel consumption of vehicles is improved (De Souza, 2017). However, there is little evidence of improvement of the landscape and a reduction in noise.

While the scores for the complexity of implementation and technological maturity criteria remain the same under different sets of weights, the remaining two show a difference (Figure 7). The most significant difference is in environmental guidance where a change with a factor of approximately 2.5 can be seen as the weights set by the commissioner place a higher value on this criterion.

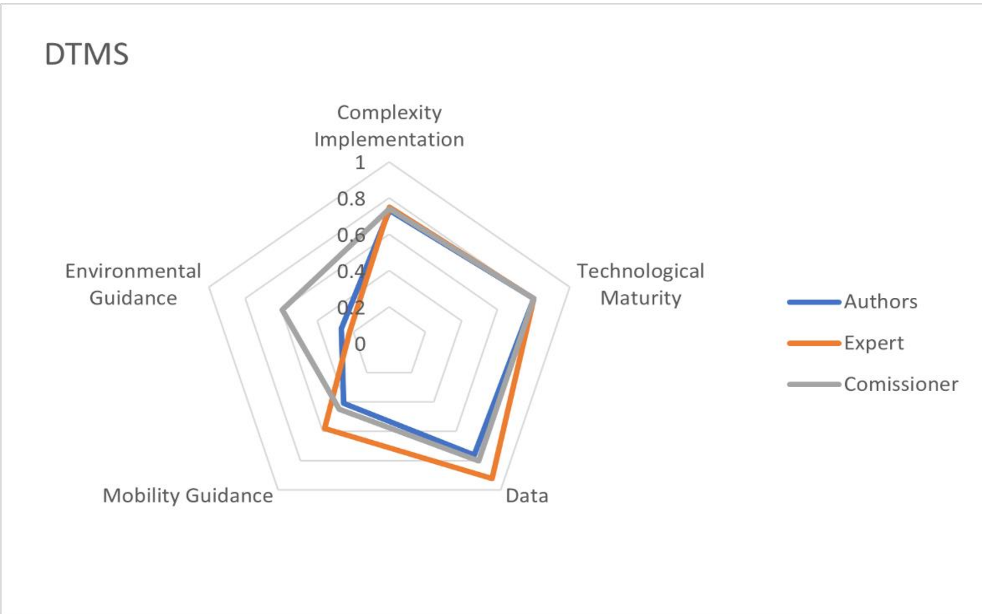

Figure 7. Radar chart of MCA scores per criterion and set of weights for DTMS.

5.2.3 Geofencing and Intelligent Speed Assistance

Geofencing scores moderate (10/15) for the complexity of its implementation. According to Statler (2016), “geofences do not require the deployments of any physical hardware”. But when it comes to implementing traffic management, other technologies from mobile objects’ sides need to be combined, such as Intellectual Speed Assistance (ISA). No obvious regulatory conflicts are found, though the existence of joint regulation or guidelines for the use of geofencing is low (Hansen et al., 2021). Furthermore, privacy concerns and limitation on citizens’ freedom form some cultural barriers for this technology (Bowyer, 2022).

Scoring high (10/10) on technological maturity means that geofencing has not only been implemented in quite a lot projects, but also involved international and different kinds of stakeholders, which can promote the knowledge exchange on multiple levels. Examples are ReVeAL (Sadler, 2020), GeoSence (Hansen et al., 2021), and NordicWay projects.

Regarding the data part, geofencing scores well (7/10), since it can directly collect data from tracking users that enter or exit a virtual perimeter (Bowyer, 2022). However, as a location-based technology, geofencing might collect more personal data about the user than originally intended (Mcintosh, 2019). Moreover, high ethical concerns were raised by geofence warrant, which had led to misidentifying guilty of a crime for an innocent citizen (Bowyer, 2022).

As far as Amsterdam’s policies are concerned, Geofencing complies with it by a moderate score (17/25). The technology can be applied for driver behavior monitoring (Hansen et al., 2021), but there are few proactive incentives within it to promote low-car behavior change. Setting limited traffic zones with geofencing can reduce the car traffic and street parking; real-time traffic updating in the form of geofences can also lead to a more efficient route and traffic flow (Sadler, 2020). As for safety improvement, Sweden can be a successful example that has been the pioneer to begin geofencing trials for vehicle-related safety and now has one of the lowest crash death rates in the world (Mohn, 2022).

Defining limited-access or electric-model geofence for a certain area can significantly reduce noise and air pollution. Combining with ISA, geofencing can contribute to less emissions at lower speed (Mohn, 2022). Such functions are not manifested in a direct way, so geofencing only gets a moderate score for the environmental indicator.

There are significant differences in aggregate scores between the three sets of weights (Figure 8). While the difference in the complexity of implementation criterion is minimal, the environmental, mobility and data criteria have very different values. Interestingly, the expert set of weights sets a much higher value for the mobility and data criteria whilst the commissioner set results in a higher score for the environment criterion.

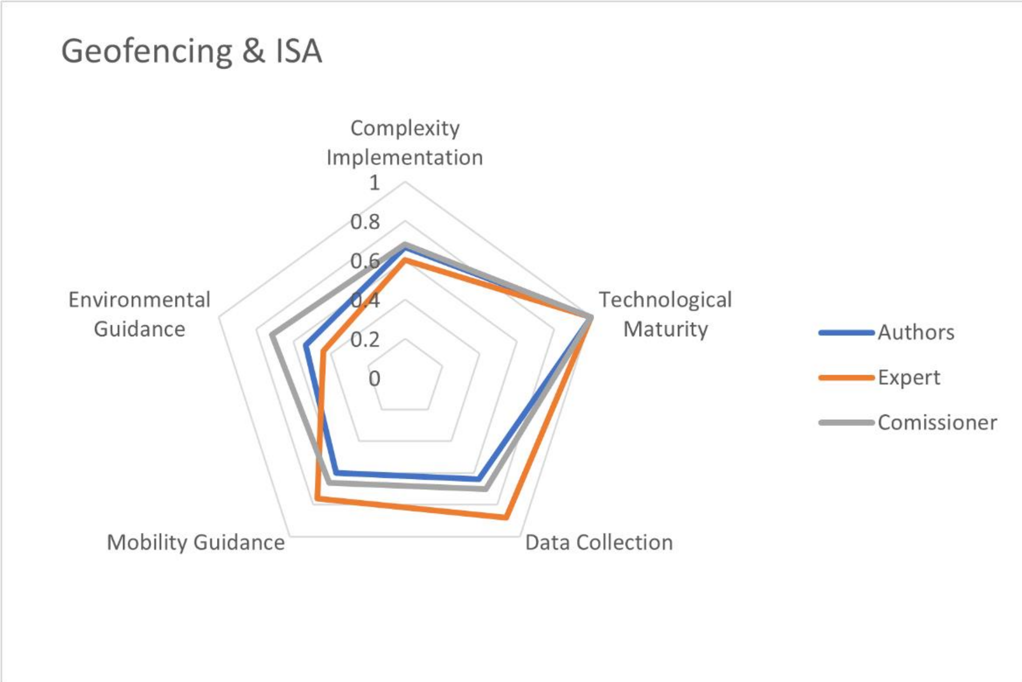

Figure 8. Radar chart of MCA scores per criterion and set of weights for Geofencing and ISA.

5.2.4 Automated Barriers

Complexity of implementation concerning automated barrier technology scores relatively high. As Amsterdam has already installed movable poles in the city center. These poles prevent cars without exemption license accessing certain areas. (Gemeente Amsterdam, 2019). Thus, the technology is considered to have high regulatory and cultural compatibility within Amsterdam. As a physical measure, implementing automated barriers does not necessarily require significant new construction. Although, some installation work like cabling is still needed to implement it in the current road infrastructure (Grant, 2016).

As for the technological maturity indicator, automated barrier scores high. This technology is commonly implemented, and there are many companies that manufacture related products. For advanced application, there is a product named Automated Rapid Movable Barrier (ARMB®) from the company Traffic Tech, so far it has only been installed throughout New South Wales (Traffic Tech, 2021). VEVA® is in similarity with ARMB® but has been implemented in multiple places in the Netherlands. However, media and scientific articles regarding this technology are difficult to find on the internet.

The technology relies on sensors and external controllers to provide positional and diagnostic information. It cannot collect and store data per se (Gemeente Amsterdam, 2019), but the information about a vehicle or driver is pre-collected when the license is needed. This data gathering process is usually guarantees privacy by requesting consent from the subject of data collection. So, it gets a high score for data indicator.

When it comes to mobility policies, automated barrier aligns with them for a moderate score. In the case of municipality, automated barrier supplies physical help to the limited car access regulation in central part of the city (Gemeente Amsterdam, 2019), so that it promotes low-car behavior, car traffic reduction and street parking reduction. ARMB® or automatic movable barrier can improve the traffic flow capacity redistribution like borrowing a lane from off-peak side of the road (Grant, 2016). And it can significantly increase safety on the road by prohibiting vehicles from entering the area where an accident happens or diverting a road for emergency use (Traffic Tech, 2021).

Automated barrier scores rather low in environmental indicator. By prohibiting cars from entering certain areas, the technology can reduce air pollution and noise nuisance for these areas (Gemeente Amsterdam, 2019). But its potential transfer effects on other places are not clear. Whilst the technology can improve the functionality of the landscape through its influence on the number of cars, the appearance of the barriers can in turn negatively affect its aesthetic value.

There are considerable differences in the data collection criterion under the set of weights as determined by the expert (Figure 9). However, the differences remain minimal in all other indicators except in the environmental criterion where a difference of 0.08 can be seen.

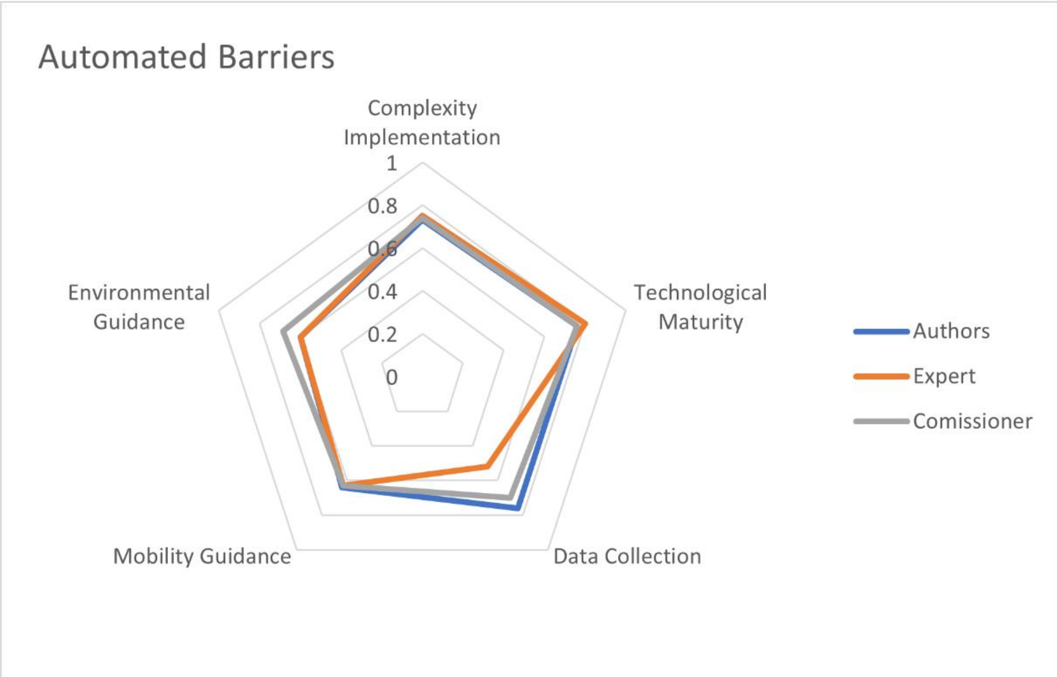

Figure 9. Radar chart of MCA scores per criterion and set of weights for automated barriers.

5.2.5 Scancar

The Scancar grades high on the criterium complexity of implementation. The possibility for regulatory conflicts or major adjustments needed regarding law are minimal as the technologies has already been implemented in pilot projects in multiple Dutch cities including Amsterdam (AMS Data Steward, 2022; AMS Institute, n.d.). As a technology, the Scancar does not require any changes in the physical enviroment, since it can already make use of the current infrastructure. This technology has already been implemented on a larger scale, in different cities such as Amsterdam and The Hague (SCANaCar, n.d.). It is also compatible with social norms and customs – since it does not add any new elements but simply helps to automate the process of parking control (Mahub, 2012).

For technological maturity, the Scancar achieves a high score. It is being used in multiple cities in the Netherlands and Europe and has already been implemented on a larger scale. Representation can be found in scientific literatures, and in several articles, the use of this technology is explored and discussed.

This technology also scores relatively well on the criteria of data. The Scancar uses object recognition software to scan and identify cars, after which the license plate number is checked against the National Parking Register in Amsterdam (Gemeente Amsterdam, n.d.-a).

In this way, data is collected on the permission of cars to park in that specific spot. This is then further processed by a human inspector (Gemeente Amsterdam, n.d.-a). There are multiple features added to this service to prevent any breaches of privacy (Roman et. al, 2018).

As far as mobility is concerned, the Scancar achieves a moderate score. It gets a low score in promotion of behavioral change, since it functions in the way of enforcement by monitoring street parking rather than the way of motivating. There is not much evidence for a reduction in car traffic through implementing this technology, but it can improve the traffic flow because it will be easier for cars to find a parking spot (AMS Data Steward, 2022). The Scancar actively helps to increase livability and accessibility by playing a big role in street parking reduction in the city (Gemeente Amsterdam, n.d.-a). Regarding the reduction in street parking, the technology is not primarily meant to reduce the number of parked cars, but to rather ensure compliance with law (AMS Data Steward, 2022). There can be small improvements in safety, but there are no major changes expected when it comes to connectivity (Roman et al., 2018). For the spatial criterium, the Scancar scores relatively low as only some literature supports the reduction of noise nuisance, air pollution and improvements in the landscape.

Little difference exists in aggregate scores between the weights as determined by the authors and the experts (Figure 10). Again, the primary difference in scores exists solely in the environmental criterion where the commissioner aggregate score is higher by a factor of 1.6.

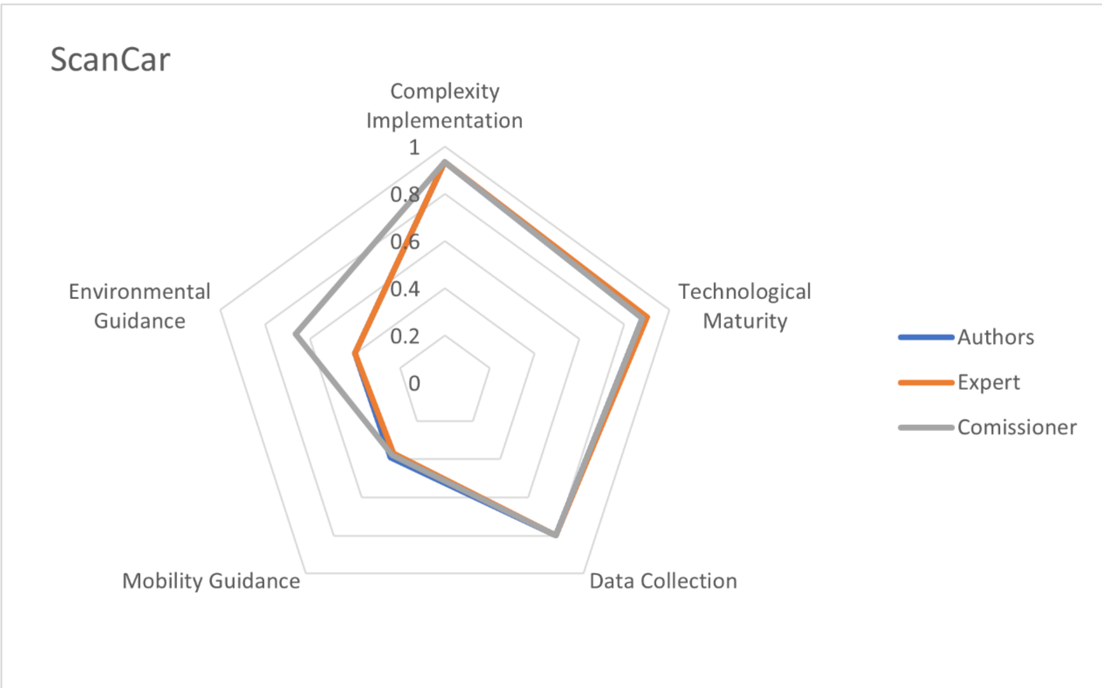

Figure 10. Radar chart of MCA scores per criterion and set of weights for the Scancar.

5.2.6 Gamification

Complexity of implementation concerning gamification technologies is scored moderate since there can be regulatory conflicts due to privacy concerns (Kumar, 2020), but also due to the use of phones in traffic. In addition, recruiting and retaining users has proven to be challenging (Wang et al., 2022, Bowden & Hellen, 2018), which indicates a lack of cultural compatibility. However, there is little change needed in physical infrastructure as it is a digital technology (Wang et al., 2022).

As far as maturity is concerned, gamification has been applied in various projects, but when it comes to implementing it for traffic decisions such as choosing modes of transport and routing the use has been limited and when implemented, this often has been on relatively small scale (Minnich, 2023). Consequently, there are few relevant cases where gamification was applied in the transportation context. Gamification is being discussed quite a lot, but there has not been that much of a focus on its use within transportation (Duarte & Álvarez, 2021). Therefore, it is scored moderately as well (8/10).

For data collection, gamification scores well since a lot of data can be collected with gamification apps such as travel choices, distances and routes (Bowden & Hellen, 2018). However, there are some situations in which privacy and ethical concerns such as the collection and sharing of personal data might arise (Wang et al., 2022).

When it comes to contributing to the aims mentioned in the municipal mobility policies, gamification scores moderate. Gamification can support a change towards a low car behavior and can reduce car traffic next to improving the traffic flow (Bowden & Hellen, 2018). When looking at the reduction in street parking and safety improvements, there is a lack of data addressing this concern.

Minor differences in aggregate scores are apparent in the complexity of implementation and mobility guidance criteria when different sets of weights are applied (Figure 11). A stronger contrast can be seen in environmental and data criteria. In the latter, the expert's weights result in the highest score with little difference between the authors and commissioner sets. On the other hand, the commissioner set leads to the highest score in environmental guidance.

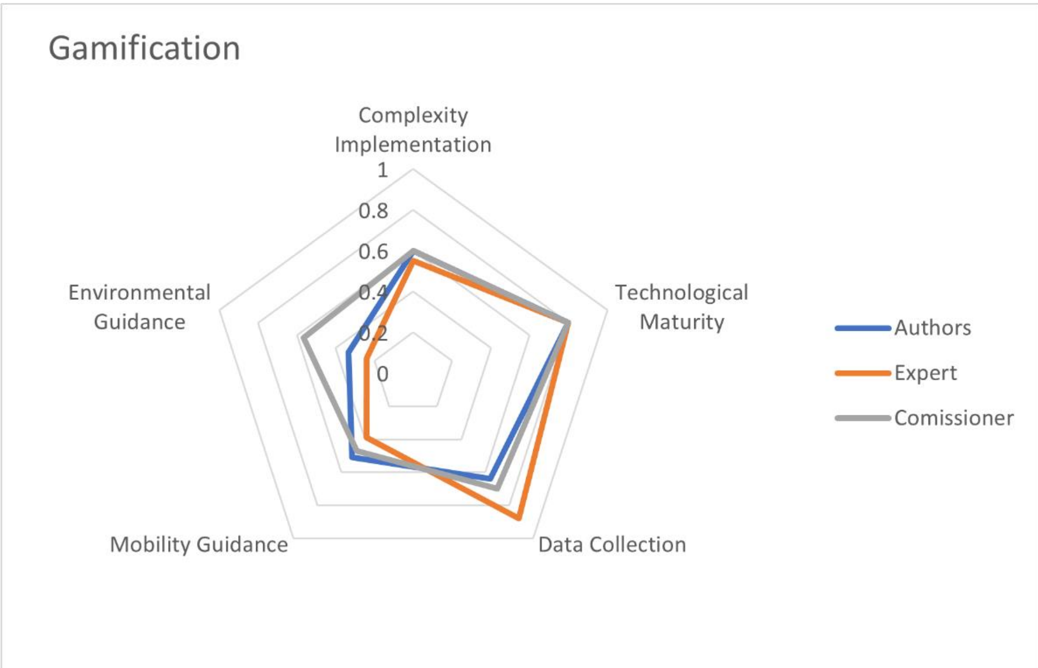

Figure 11. Radar chart of MCA scores per criterion and set of weights for gamification.

5.2.7 Mobility Data Exchange Standardization

As a technology, the optimized mobility data exchange standardization (MDES) grades high at a score of 13 out of 15 with minor possibility of conflict with existing regulations. As a purely digital technology, there is also no potential for incompatibility with physical infrastructure (Groenendijk et al., 2021; RDT Noord-Holland en Flevoland, 2022). However, there are obstacles in the organizational culture of data providers as there are limits to sharing of data between competitors (Groenendijk et al., 2021).

In terms of technological maturity, MDES achieves the maximum score as multiple pilot projects exist within the province of Noord-Holland and the city of Amsterdam (Groenendijk et al., 2021; RDT Noord-Holland en Flevoland, 2022). There is also plentiful evidence of discourse around the technology both during live events and in literature (Amsterdam Smart City, 2023; Barceló & Kuwahara, 2010; Nationaal Toegangspunt Mobiliteitsdata, 2023; VNG Realisatie, 2023.)

Due to its singular focus on the distribution of standardized traffic data, MDES scores merely 3 out 10 for the third criterion. It does not generate data, but it does facilitate the provision of standardized data which is suitable for further processing (Groenendijk et al., 2021; RDT Noord-Holland en Flevoland, 2022). Hence a score of 2 instead of 1 for the first data generation indicator. Regarding ethics, MDES scores the minimum as there is no evidence for privacy-preserving measures in existing projects. There are however concerns for unethical data collection in traffic as found by Chen et al. (2019).

For the mobility criterion, MDES scores low with the maximum score in connectivity. This is because although the existing initiatives seek to provide standardized data on a wide variety of transportation types and traffic related phenomena this is only achieved by facilitating cooperation between stakeholders (Groenendijk et al., 2021; RDT Noord-Holland en Flevoland, 2022; VNG Realisatie, 2023). Minimum scores are attained for car traffic and street parking reduction as neither are the objective of MDES. There is however some evidence for the potential of the technology to influence the behavior of road users and it may support mobility managers in improving the flow of traffic which warrants a score of 2 (Groenendijk et al., 2021). In the environmental criterion, MDES scores the minimum of 3 out of 15 as no evidence was found for its impact on air pollution, noise nuisance or the landscape.

When assessed under a different set of weights, the primary difference lies in the score on the environmental criterion which is significantly higher for the set which was received from the commissioner of the study. For all other criteria, the aggregate score changes little when different weights are used (Figure 12).

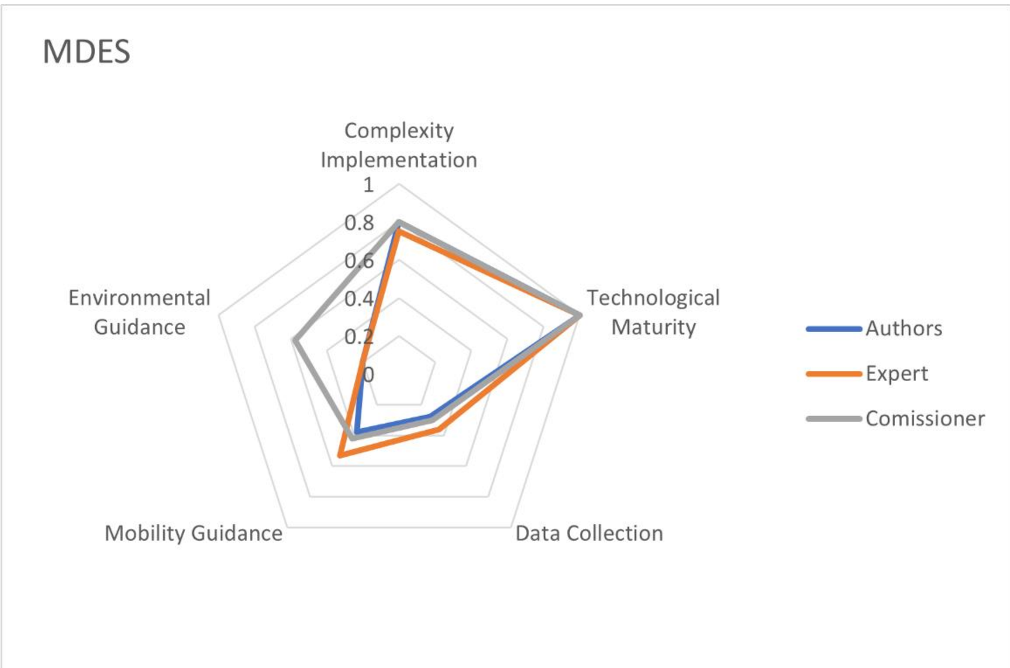

Figure 12. Radar chart of MCA scores per criterion and set of weights for MDES.

6. Discussion

This study carries significant implications for the development of a low-car city in Amsterdam as several suitable technologies and their strengths and weaknesses were identified. These results can be used to inform more specific policy recommendations where an integrated approach towards implementing the *Agenda Autoluw* is presented. Although, future research should be dedicated towards an in-depth analysis of the proposed technologies to clearly delineate their use cases, implementation costs, and limitations for the study area in Amsterdam.

However, the research is limited by several factors ranging from data collection to the choice of analysis method. First, the scoring of technologies is based solely on data obtained from literature despite the data collection not being exhaustive. Only a limited number of sources were consulted for each technology due to time constraints and thus the results may not be entirely valid. If the collection of sources was exhaustive, different scores may have been assigned. Although, it must be mentioned that the scores correspond to the expectations of the authors. Additionally, some possibly outdated sources were used when more recent publications could not be found. Since significant technological leaps may occur within short timespans, using more recent sources could result in different scores. The type of consulted literature was also inconsistent as both case studies and predictive research were collected.

Second, despite the use of literary sources and a well-delineated rubric to grade technologies, the scoring and weighing may still be influenced by authors' bias. Most importantly, the scoring was also not done by a single person. Consequently, the bias is not constant as each researcher has a different background. The minimize the bias in the weighing of criteria, external experts were consulted to validate the chosen weights although only a very limited number was reached.

The third limitation lies in the comparability of the analyzed technologies. The seven technologies range from physical barriers to digital platforms with a variety of different purposes, such as improving logistics or influencing travel behavior. A fair comparison of very different technologies is difficult even if an MCA is crafted specifically for comparing alternatives. Additionally, the criteria used for the comparison may not fully capture the differences between the technologies. For example, a criterion for the financial costs of implementation was omitted from the rubric due to difficulty of finding reliable sources for that data.

7. Conclusion

This research explored how different technologies can help to attain the objectives of *Agenda Autoluw*. The technologies were evaluated with an MCA according to their potential contribution towards the low-car city in the eastern part of Amsterdam's city center. To identify all technologies relevant for the study, a large catalogue was created with over thirty entries. To establish criteria for the MCA, different theoretical frameworks were explored and a rubric of five criteria was created. Finally, seven technologies selected from the catalogue underwent the MCA and a sensitivity analysis to establish their potential contribution towards the mobility, spatial and social goals of *Agenda Autoluw* (Figures 13, 14, 15).

Three technologies were consistent outliers under the three sets of weights, and thus they could significantly contribute towards the *Agenda Autolu*w. For the mobility theme, MaaS could support the *Agenda* by providing more room for alternative transport modes if it was implemented, although without direct improvement to the spatial environment. Despite this, it could still improve the quality of public space indirectly by promoting and making alternative modes of transport convenient to users. Its implementation in Helsinki has already led towards the reduction in car traffic and street parking in favor of greater demand for alternative transportation modes.

Automatic barriers hold great promise for the spatial theme due to their ability to make an environment dynamic. Through the smart use of this technology, it would be possible to remotely expand or reduce the number of lanes available on roads and thus influence the traffic flow according to the needs of the controller. This could also improve the safety of traffic as the environment can be dynamically altered to ensure the safest possible form of the road. Additionally, the barriers could be used to change the number of available parking spots and thus increase or decrease the amount of available space according to demand.

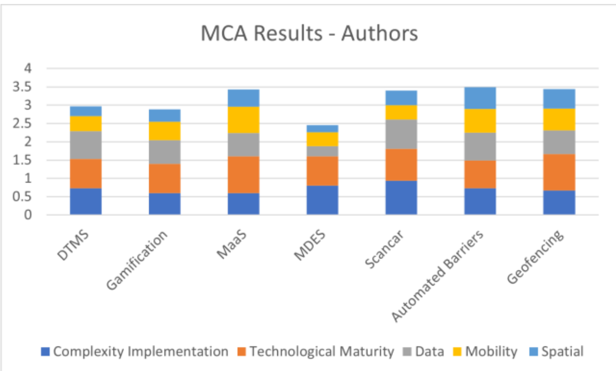

Figure 13. Summarized MCA results with authors' weights.

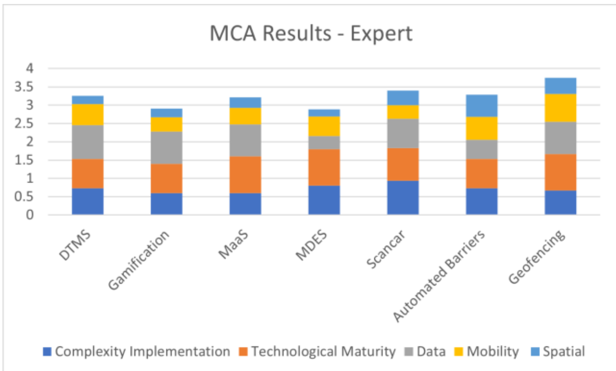

Figure 14. Summarized MCA Results with expert's weights.

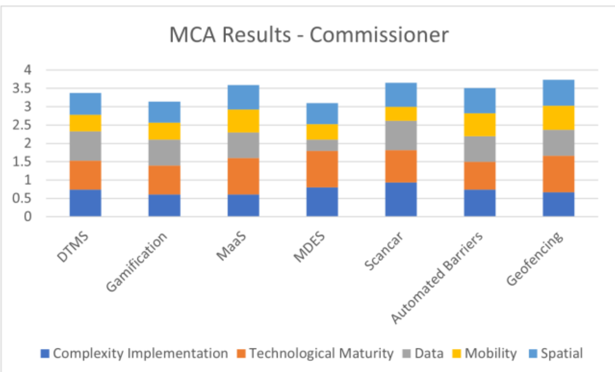

Figure 15. Summarized MCA results with commissioner's weights.

Finally, the social theme can benefit most from geofencing and ISA due to its potential to drastically improve safety of traffic for both pedestrians and drivers. By placing digital speed limits which correspond to the needs of the space in question, it is possible to enforce safe behavior of drivers through technology. Both car and e-bike riders are a safety concern in Amsterdam, and the implementation of geofencing and ISA may serve as the next step towards improving safety for both pedestrians and drivers.

Most importantly, the remaining four technologies still have their clear use cases and their potential contribution towards a low-car city cannot be understated. The ScanCar for example does not clearly solve the objectives of the three themes, but it still scores consistently well under all sets of weights. Its implementation may not positively promote alternative modes of transport, but it can be used to enforce parking restrictions or yield insight into various phenomena around micro-mobility. On the other hand, gamification will not enforce adherence to new rules, but it may promote a low-car way of thinking in a fun and inclusive manner. With games, residents can be motivated to explore the previously car-dominated public spaces and be informed about the benefits of low-car design. DTMS and MDES did not grade highly in aggregate scores, but they can still lead towards significant improvements in connectivity between various modes of transport and the general efficiency of the traffic flow.

Novel technologies can contribute towards the objectives of the low-car city in a variety of ways. Some of these solutions are able to solve only a small number of issues, such as promoting a low-car way of thinking in the case of gamification, whilst others such as MaaS address a greater number of objectives. Ultimately, all technologies have their strengths and weaknesses which makes each one a suitable solution for a different type of problem. In the case of the low-car city, it is crucial to consider all technologies which were examined in this study because a silver-bullet does not exist for reducing urban car dependency. Instead, an integrated approach is necessary where technologies are combined synergistically to achieve the best possible outcome for all metropolitan stakeholders.

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Annex 1: Technology Catalogue

Technology	Description	Purpose
Scancar	Car equipped with sensors (cameras, 3D-Sensors) (AMS institute, n.d)	Currently used for numberplate detection for parking enforcement and 3D-Scans.
Vehicle2X Communication	Communication between cars and other road users like ambulance or traffic lights (Weiß, 2011)	Avoid congestions and increase safety
Agent-Based Traffic Modelling	Traffic modelling that considers behavior of autonomous agents (such as a driver) (Karima et al., 2012)	Better traffic prediction to improve infrastructure and avoid congestions
CNN-Based Congestion Prediction	Increase the prediction capabilities of traffic models by using neural networks trained on historic data (Benhamza et al., 2012)	Traffic prediction to avoid congestions and optimize traffic management
Micro-mobility Modelling & Sensing	A range of technologies from multiple light-detection-and-ranging (LI-DAR) sensors (Sun, 2020) to Computing System (Yu, 2020) for tracking and modeling Micro-mobility.	To monitor results of measures for low car city and improve users' experience regarding micro-mobility.
Infrastructure Digital Twins	Virtual replicas of transport systems that incorporate real-time data and simulation models (Intertraffic, 2021).	It has the potential to enable more sophisticated traffic modelling, efficient transport systems and lower emissions across entire road networks.
Crowd Monitoring (Public Eye System)	A monitoring system with counting cameras and Wi-Fi sensors that give insight into numbers and densities of pedestrians (Gemeente Amsterdam).	To provide data for evidence of mobility changes within certain pilot areas like Weesperstraat, and to improve the safety and comfort of busy pedestrian spaces.
Mobility-as-a-Service (MaaS)	An integrated system (such as an app) which includes information from mobility providers on several modes of transport (Butler et. al, 2020)	Combining information from multiple providers within one platform increases accessibility of and connectivity between different modes of transport
Virtual Busstops	Specific pick-up or drop-off locations for people using mobility services, but which are not physical access points (Harmann et. al, 2022)	Mobility services can be optimized by using virtual bus stops as access points for people making use of this service.
Mobility Hubs	Physical (community-owned) locations which have a variety of different transport modes for citizens to share. This can also be connected to a digital platform (Intertraffic, 2021)	Mobility hubs can increase sustainability and use of active modes of transportation.
Car Sharing	Offering a car ride to multiple people so the car can be shared when having the same destination, this can for example be done through a platform (Ferrero, 2018)	Car sharing increases sustainability in the sense that there are less vehicles needed to get citizens to their destination.
Autonomous Cars	Automated cars that do not require steering by drivers, at all or in predetermined situations (Liljamo, 2018)	Improvements in the transport system, namely regarding traffic safety and efficiency.
Drones - Zipline	Drones are often referred to as unmanned aerial vehicles (UAVs), that are able to perform a range of different tasks, such as delivery of products (Daley, 2023)	Improvements in logistics can help increase efficiency in deliveries while decreasing the number of vehicles needed to perform this.
Autonomous Delivery Robots	Automated – ground-based - robots focused on delivery of producs and goods (Intertraffic, 2021)	It can increase efficiency within the last mile delivery industry but can also perform additional tasks such as security monitoring and cleaning sidewalks.
Social Routing	Social Routing requires integration of information from cities and mobility providers to inform citizens with traveling options that fulfill social benefits (Sander, 2021).	To stimulate drivers to choose an alternative route with wider collective benefits and less societal and environmental impact

Geofencing	Geofencing concerns the use of GPS or RFID technology to create virtual boundaries or zones in specific geographic areas (Caggiani et. al, 2023), this can trigger certain actions when a vehicle enters a specific zone.	Functions as an alarm to users about adjustments to the street and can trigger certain actions for vehicles.
Intelligent Speeds Assistance	ISA means a system to support the driver in maintaining the appropriate speed for the road environment by providing dedicated and appropriate feedback (EU 2019/2144, art 3, section 3)	To create a safer traffic environment and reduce emissions by installing feedback systems on vehicles for speed limits.
Adaptive Speed Control – E-bikes	A method of E-bikes' speed control which adapts to the traffic situation (Hermann, 2015).	Increasing comfort and fuel use efficiency for driving, while making E-bikes a better alternative for cars, ensuring road safety at same time.
Movable Poles	Pole that sinks into the ground, usually camera or code or keycard operated	Limiting car access to certain areas.
Automated Movable Barriers	Barrier that can move for e.g., dynamic placemaking (Schneider Electric, 2021)	Redistributing traffic capacity for flow efficiency and prohibiting access within accidents area to increase safety.
Self-Organized Environments	Areas with minimal traffic signs and lights. Self-organized environments rely on citizen's knowledge of traffic rules (Gersherson, 2011)	Decreasing the number of traffic signs might lead to citizens being more conscious and careful in traffic.
Bio-Receptive Concrete	Type of concrete which supports the development of mosses and other flora (AMS Institute, n.d.)	Bio-receptive concrete can help increase biodiversity in urban areas.
Low Noise Road Cover	Type of road cover which minimizes noise made by car tires (Highways Department, 2016)	Reduce the noise nuisance raised by vehicles on the road.
Predictive Road Maintenance Remote Sensing	Road quality monitoring and prediction platform which advises public road authorities and commercial construction firms. (RoadEO, n.d.)	To give more information on when and where the next road segment needs to be maintained.
Solar Parking	Parking spots under solar panels with EV charging station (Blok, 2023)	This increases the number of spots electric vehicles can use for parking and charging in the city (and is also sustainable).
Quantum Gravimeter	Data collection tool for sensing underground objects such as pipes/wiring in the urban/construction context (Sitepoint, n.d.)	This makes the process of sensing for objects easier whenever there are any underground works needed for a specific location.
AI Access Control Unit	safety screening tool and access control unit for public spaces, institutions and events (Evolv Technology, n.d.)	This tool can help detect potential dangers within public spaces and increase safety by communicating this to connected systems.
Mobility Data Exchange Standardization (MDES)	MDES is a framework for standardizing and sharing mobility data that agencies and operators can use (Kernan, 2020).	Helping operators and cities exchange information in a standard format so they can ingest data and build systems to understand program success.
Gamification	Applying game elements to promote desired behavior in a non-game context. The most used gamification elements are points, badges, leaderboards, levels, and challenges (Kazhamiakin et al., 2015).	Gamification can be used to increase livability at specific locations and can also be focused on changing travel behavior.

Annex 2: Rubric

Criteria & indicators	Scoring Indicators				
	5/5	4/5	3/5	2/5	1/5
1. Complexity Implementation:					
1a. Regulatory **compatibility**	No conflicts with existing regulations and no additional adjustments to regulations needed		Some conflicts with regulations, or some adjustments needed		Irreconcilable conflict with existing regulations
1b. Physical **compatibility**	No conflicts with existing infrastructure and minimal changes required to make technology compatible		Some conflicts with existing infrastructure, or some adjustments needed		Irreconcilable conflict with existing infrastructure or immense effort for implementation needed
1c. Cultural **compatibility**	No conflicts with cultural environment and minimal challenges towards social norms and customs		Some conflicts with cultural environment, or some challenges towards social norms and customs		Irreconcilable conflicts with cultural environment, or great challenges towards social norms and customs
2. Technological maturity					
2a. Level of **implementation**	The technology is already implemented in the public space either within or outside the project area		The technology is developed and ready for implementation, but no or few project can be found having implemented it		Technology is defined solely as a concept without a prototype.
2b. Level of **implemented knowledge**	The technology is openly and consistently discussed during cultural and scientific events such as seminars with plentiful representation in grey and scientific literature. The available knowledge facilitates the implementation of the technology.		The technology is somewhat discussed in cultural and scientific events with representation in at least grey literature. The available knowledge somewhat facilitates the implementation of the technology.		The technology is not discussed during cultural and scientific events at all with minimal literature available outside of its point of origin
3. Data					
3a. Generation and processing of data	Data generation is an inherent element of the technology and it is gathered continuously in a format suitable for further processing.		Data generation can be included in the technology although it is not an inherent part of it.		Data cannot be generated with the technology.

3b. Ethics of data **collection**	The generation of data includes by default measures to protect against breaches of privacy and generation from subjects of data collection who did not give informed consent.	Data generation occurs ethically with minimal concerns for the breaches of privacy or generation from the subjects of data collection who did not give informed consent.	Data generation occurs with significant concerns for the breaches of privacy or generation from the subjects of data collection who did not give informed consent.
4. Mobility			
4a. Promotion of **low-car behavior**	The technology directly supports the social transition towards low-car behaviour.	The technology partly or indirectly supports the social transition towards low-car behaviour.	The technology does not support a change towards a low-car behaviour.
4b. Car traffic **reduction**	High reduction of car traffic as a result of the implementation of the technology	Medium reduction of car traffic as a result of the implementation of the technology	No reduction of car traffic as a result of the implementation of the technology
4c Traffic flow **improvement**	High improvement of traffic flow as a result of the implementation of the technology	Medium improvement of traffic flow as a result of the implementation of the technology	No improvement of traffic flow as a result of the implementation of the technology
4d. Reduction in **street parking**	High reduction of street parking triggered by implementation of the technology	Medium reduction of street parking triggered by implementation of the technology	No reduction of street parking triggered by implementation of the technology
4e. Safety **improvements**	High safety improvements for all traffic participants triggered by implementation of the technology	Medium safety improvements for all traffic participants triggered by implementation of the technology	No improvements in safety for all traffic participants triggered by implementation of the technology
4f. Connectivity	The technology provides a seamless connection between different modes of transportation, stakeholders and functions synergistically with other types of technologies	The technology has trouble with providing connections between different modes of transportation, stakeholders and functions relatively independently	The technology contributes nothing to connections between different modes of transportation, stakeholders and functions totally independently
5. Environmental			

5a. Noise **nuisance**	Noise nuisance by road vehicles is reduced significantly or completely directly through the implementation of the technology.	Noise nuisance by road vehicles is reduced somewhat either directly or indirectly through the implementation of the technology	Noise nuisance by road vehicles remains unchanged by the implementation of the technology.
5b. Air **pollution**	Air pollution by road vehicles is reduced significantly or completely directly through the implementation of the technology.	Air pollution by road vehicles is reduced somewhat either directly or indirectly through the implementation of the technology	Air pollution by road vehicles remains unchanged by the implementation of the technology.
5c. Landscape **effect**	The technology has a direct positive impact on the landscape by significantly improving its aesthetic value and diversifying its functions	The technology has an indirectly positive impact on the landscape by moderately improving its aesthetic value and diversifying its functions	The technology has no impact on the landscape. It does not improve its aesthetic value, nor does it diversify its functions

Annex 3: MCA Results for Each Technology

Criteria & indicators	T1. Mobility-as-a-Service	
	Score (/5)	**Justification**
1. Complexity Implementation:		
1a. Regulatory **compatibility**	3	The required mobility infrastructure already exists in Amsterdam, as there is a public transportation system and several private mobility providers such as Check and taxi drivers. However, some regulatory conflicts might arise when it comes to differing interests (Aghari et al., 2020). An example is the conflict between taxi drivers and Uber in the city (van Anst, 2018).
1b. Physical **compatibility**	4	The required mobility infrastructure already exists in Amsterdam, as there is a public transportation system and several private mobility providers such as Check and taxi drivers.
1c. Cultural **compatibility**	2	Furthermore, there might be cultural difficulties due to a lower appeal to older consumers who are less tech savvy, car owners, and there is an alignment needed between public and private competitors such as NS and taxi drivers (Butler et al., 2021).
2. Technological maturity		
2a. Level of **implementation**	5	In several Dutch cities there have been quite some pilot projects that have been finished or these are still ongoing (Araghi et al., 2020; Gemeente Amsterdam, n.d.).
2b. Level of **implemented knowledge**	5	In addition, a platform has been set up aiming to promote sharing knowledge and to discuss potential implementations of the MaaS Concept within the Metropole Region of Amsterdam (MRA Platform Smart Mobility, n.d.).
3. Data		
3a. Generation and processing of data	5	There is a lot of data that can be collected through this technology regarding mobility behavior (Butler et al., 2021).
3b. Ethics of data **collection**	2	However, there are privacy concerns associated with this data collection, as well as intellectual property problems (Butler et al., 2021).
4. Mobility		
4a. Promotion of **low-car behavior**	4	MaaS solutions have been shown to reduce car ownership, car traffic, reduction in congestion and a reduction in parking demand (Aghari et al., 2021, Butler et al., 2020, Paiva et al., 2021).
4b. Car traffic **reduction**	4	MaaS solutions have been shown to reduce car ownership, car traffic, reduction in congestion and a reduction in parking demand (Aghari et al., 2021, Butler et al., 2020, Paiva et al., 2021). However, there could also be an increase in car traffic and congestion increasement if the MaaS is implemented incorrectly in the form of auto focused MaaS solutions such as Uber (Aghari et al., 2021).
4c Traffic flow **improvement**	4	MaaS solutions have been shown to reduce car ownership, car traffic, reduction in congestion and a reduction in parking demand (Aghari et al., 2021, Butler et al., 2020, Paiva et al., 2021).
4d. Reduction in **street parking**	4	MaaS solutions have been shown to reduce car ownership, car traffic, reduction in congestion and a reduction in parking demand (Aghari et al., 2021, Butler et al., 2020, Paiva et al., 2021).
4e. Safety **improvements**	1	No evidence was found for MaaS' effect on safety.
4f. Connectivity	3	MaaS apps can connect the different modes of transport into one app, allowing for improved connectivity (Jittrapirom et al., 2017).
5. Environmental		
5a. Noise **nuisance**	3	Due to a reduction of car use (Aghari et al., 2021, Butler et al., 2020, Paiva et al., 2021), noise nuisance is expected to be reduced.
5b. Air **pollution**	3	Due to a reduction of car use (Aghari et al., 2021, Butler et al., 2020, Paiva et al., 2021), air pollution is expected to be reduced.
5c. Landscape **effect**	1	No evidence was found for MaaS' effect on landscape.

Criteria & indicators	T2. Dynamic Traffic Management System	
	Score (/5)	**Justification**
1. Complexity Implementation:		
1a. Regulatory **compatibility**	4	The implementation of DTMS involves some challenges, such as the implementation of Internet of Things (IoT) infrastructure in traffic lights, sensors and cameras (Huiskens & Vlemmings, 2021). However, some of this infrastructure is already present in Amsterdam (Huiskens & Vlemmings, 2021).
1b. Physical **compatibility**	3	The implementation of DTMS involves some challenges, such as the implementation of Internet of Things (IoT) infrastructure in traffic lights, sensors and cameras (Huiskens & Vlemmings, 2021). However, some of this infrastructure is already present in Amsterdam (Huiskens & Vlemmings, 2021).
1c. Cultural **compatibility**	4	In addition, several big data management issues between stakeholders need to be resolved, such as the integration of different data sources into standard data formats is still needed (de Souza et al., 2017).
2. Technological maturity		
2a. Level of **implementation**	4	DTMSs are being tested in a wide range of European cities, including Amsterdam (Huiskens & Vlemmings, 2021).
2b. Level of **implemented knowledge**	4	For instance, Socrates2.0 project was set upon a cooperation of road authorities, service providers and car manufacturers, i.e., Municipality Amsterdam, TomTom, BMW, etc. Together they have been developing intelligent ways to collect, exchange and use traffic data throughout the complete value chain for traffic management and information services (Huiskens & Vlemmings, 2021).
3. Data		
3a. Generation and processing of data	5	DMTSs collect many different datapoints such as congestion, accidents, routes, speed and other traffic data (de Souza, 2017).
3b. Ethics of data **collection**	3	Despite not being heavily personalized, the data still comes with some privacy issues such as vehicle tracking, and some potential security concerns (de Souza, 2017).
4. Mobility		
4a. Promotion of **low-car behavior**	1	There is little evidence of a reduction in car ownership and car traffic, since DMTS is a background technology (de Souza, 2017, Huiskens & Vlemmings, 2021, Dutka, 2023).
4b. Car traffic **reduction**	1	There is little evidence of a reduction in car ownership and car traffic, since DMTS is a background technology (de Souza, 2017, Huiskens & Vlemmings, 2021, Dutka, 2023).
4c Traffic flow **improvement**	4	On the other hand, DMTSs have proved to improve traffic flows and safety (de Souza, 2017, Huiskens & Vlemmings, 2021, Dutka, 2023).
4d. Reduction in **street parking**	3	Also, alternative routing could divert parking away from the center and a reduction in street parking (Dutka, 2023).
4e. Safety **improvements**	4	On the other hand, DMTSs have proved to improve traffic flows and safety (de Souza, 2017, Huiskens & Vlemmings, 2021, Dutka, 2023).
4f. Connectivity	1	No evidence was found for DTMS to improve connectivity.
5. Environmental		
5a. Noise **nuisance**	1	No evidence was found for DTMS to reduce noise nuisance for vehicles.
5b. Air **pollution**	2	DTMS can help to reduce air pollution as fuel consumption of vehicles is improved (De Souza, 2017).
5c. Landscape **effect**	1	No evidence was found for DTMS to improve the aesthetic value or functionality of the landscape.

Criteria & indicators	T3. Geofencing and Intelligent Speed Assistance	
	Score (/5)	**Justification**
1. Complexity Implementation:		
1a. Regulatory **compatibility**	4	No obvious regulatory conflicts are found, though the existence of joint regulation or guidelines for the use of geofencing is low (Hansen et al., 2021).
1b. Physical **compatibility**	4	Geofences do not require any deployments of physical hardware (Statler, 2016). But when it comes to implementing traffic management, other technologies from mobile objects' sides need to be combined, such as Intellectual Speed Assistance (ISA).
1c. Cultural **compatibility**	2	Furthermore, privacy concerns and limitation on citizens' freedom form some cultural barriers for this technology (Bowyer, 2022).
2. Technological maturity		
2a. Level of **implementation**	5	Geofencing has not only been implemented in quite a lot projects, but examples are also ReVeAL (Sadler, 2020), GeoSence (Hansen et al., 2021), and NordicWay projects.
2b. Level of **implemented knowledge**	5	Different projects that included geofencing involved international and different kinds of stakeholders, which can promote the knowledge exchange on multiple levels (Hansen et. al, 2021)
3. Data		
3a. Generation and processing of data	5	The technology can directly collect data from tracking users that enter or exit a virtual perimeter (Bowyer, 2022).
3b. Ethics of data **collection**	2	However, as a location-based technology, geofencing might collect more personal data about the user than originally intended (Mcintosh, 2019). Moreover, high ethical concerns were raised by geofence warrant, which had led to misidentifying guilty of a crime for an innocent citizen (Bowyer, 2022).
4. Mobility		
4a. Promotion of **low-car behavior**	2	The technology can be applied for driver behavior monitoring (Hansen et al., 2021), but there are few proactive incentives within it to promote low-car behavior change.
4b. Car traffic **reduction**	3	Setting limited traffic zones with geofencing can reduce the car traffic (Sadler, 2020)
4c Traffic flow **improvement**	4	Real-time traffic updating in the form of geofences can also lead to a more efficient route and traffic flow (Sadler, 2020).
4d. Reduction in **street parking**	3	Geofencing also can have a positive effect on reducing street parking by setting limited traffic zones (Sadler, 2020)
4e. Safety **improvements**	5	As for safety improvement, Sweden can be a successful example that has been the pioneer to begin geofencing trials for vehicle-related safety and now has one of the lowest crash death rates in the world (Mohn, 2022).
4f. Connectivity	1	No evidence was found for geofencing when it comes to increasing connectivity in the urban area.
5. Environmental		
5a. Noise **nuisance**	3	Defining limited-access or electric-model geofence for a certain area can significantly reduce noise nuisance and air pollution in addition to its indirect although positive effect on the landscape (Mohn, 2022). Such functions are not manifested in a direct way, so geofencing only gets a moderate score for the environmental indicator (Mohn, 2022).
5b. Air **pollution**	3	Defining limited-access or electric-model geofence for a certain area can significantly reduce noise nuisance and air pollution in addition to its indirect although positive effect on the landscape (Mohn, 2022). Such functions are not manifested in a direct way, so geofencing only gets a moderate score for the environmental indicator (Mohn, 2022).
5c. Landscape **effect**	3	Defining limited-access or electric-model geofence for a certain area can significantly reduce noise nuisance and air pollution in addition to its indirect although positive effect on the landscape (Mohn, 2022). Such functions are not manifested in a direct way, so geofencing only gets a moderate score for the environmental indicator (Mohn, 2022).

Criteria & indicators	T4. Automated Barriers	
	Score (/5)	**Justification**
1. Complexity Implementation:		
1a. Regulatory **compatibility**	4	Amsterdam has already installed movable poles in the city center. These poles prevent cars without exemption license accessing certain areas. (Gemeente Amsterdam, 2019). Thus, the technology is considered to have high regulatory and cultural compatibility within Amsterdam.
1b. Physical **compatibility**	3	As a physical measure, implementing automated barriers does not necessarily require significant new construction. Although, some installation work like cabling is still needed to implement it in the current road infrastructure (Grant, 2016).
1c. Cultural **compatibility**	4	Amsterdam has already installed movable poles in the city center. These poles prevent cars without exemption license accessing certain areas. (Gemeente Amsterdam, 2019). Thus, the technology is considered to have high regulatory and cultural compatibility within Amsterdam.
2. Technological maturity		
2a. Level of **implementation**	5	This technology is commonly implemented, and there are many companies that manufacture related products. For advanced application, there is a product named Automated Rapid Movable Barrier (ARMB®) from the company Traffic Tech, so far it has only been installed throughout New South Wales (Traffic Tech, 2021).
2b. Level of **implemented knowledge**	3	While the technology is widely implemented and manufactured, media and scientific articles regarding this technology are difficult to find on the internet.
3. Data		
3a. Generation and processing of data	2	The technology relies on sensors and external controllers to provide positional and diagnostic information. It cannot collect and store data per se (Gemeente Amsterdam, 2019), but the information about a vehicle or driver is pre-collected when the license is needed.
3b. Ethics of data **collection**	5	This data gathering process is usually guarantees privacy by requesting consent from the subject of data collection (Gemeente Amsterdam, 2019).
4. Mobility		
4a. Promotion of **low-car behavior**	3	In the case of municipality, automated barrier supplies physical help to the limited car access regulation in central part of the city (Gemeente Amsterdam, 2019), so that it promotes low-car behavior, car traffic reduction and street parking reduction.
4b. Car traffic **reduction**	3	In the case of municipality, automated barrier supplies physical help to the limited car access regulation in central part of the city (Gemeente Amsterdam, 2019), so that it promotes low-car behavior, car traffic reduction and street parking reduction.
4c Traffic flow **improvement**	4	ARMB® or automatic movable barrier can improve the traffic flow capacity redistribution like borrowing a lane from off-peak side of the road (Grant, 2016).
4d. Reduction in **street parking**	4	Automated barrier supplies physical help to the limited car access regulation in central part of the city (Gemeente Amsterdam, 2019), so that it promotes low-car behavior, car traffic reduction and street parking reduction.
4e. Safety **improvements**	4	And it can significantly increase safety on the road by prohibiting vehicles from entering the area where an accident happens or diverting a road for emergency use (Traffic Tech, 2021).
4f. Connectivity	1	No evidence was found for automated barriers to improve connectivity.
5. Environmental		
5a. Noise **nuisance**	3	By prohibiting cars from entering certain areas, the technology can reduce air pollution and noise nuisance for these areas (Gemeente Amsterdam, 2019).
5b. Air **pollution**	3	By prohibiting cars from entering certain areas, the technology can reduce air pollution and noise nuisance for these areas (Gemeente Amsterdam, 2019).
5c. Landscape **effect**	3	Whilst the technology can improve the functionality of the landscape through its influence on the number of cars, the appearance of the barriers can in turn negatively affect its aesthetic value.

Criteria & indicators	T5. Scancar	
	Score (/5)	Justification
1. Complexity Implementation:		
1a. Regulatory **compatibility**	4	The possibility for regulatory conflicts or major adjustments needed regarding law are minimal as the technologies has already been implemented in pilot projects in multiple Dutch cities including Amsterdam (AMS Data Steward, 2022).
1b. Physical **compatibility**	5	As technology, the Scancar does not require any changes in the physical enviroment, since it can already make use of the current infrastructure. This technology has already been implemented on a larger scale, in different cities such as Amsterdam and The Hague (SCANaCar, n.d.).
1c. Cultural **compatibility**	5	It is also compatible with social norms and customs – since it does not add any new elements but simply helps to automate the process of parking control (Mahub, 2012).
2. Technological maturity		
2a. Level of **implementation**	5	It is being used in multiple cities in the Netherlands and Europe and has already been implemented on a larger scale (SCANaCar, n.d.)
2b. Level of **implemented knowledge**	4	Representation can be found in scientific literatures, and in several articles, the use of this technology is explored and discussed.
3. Data		
3a. Generation and processing of data	4	The Scancar uses object recognition software to scan and identify cars, after which the license plate number is checked against the National Parking Register in Amsterdam (Gemeente Amsterdam, n.d.-a). In this way, data is collected on the permission of cars to park in that specific spot.
3b. Ethics of data **collection**	4	There are multiple features added to this service to prevent any breaches of privacy (Roman et. al, 2018).
4. Mobility		
4a. Promotion of **low-car behavior**	1	ScanCar functions in the way of enforcement by monitoring street parking rather than the way of motivating.
4b. Car traffic **reduction**	2	There is not much evidence for a reduction in car traffic through implementing this technology, but it can improve the traffic flow because it will be easier for cars to find a parking spot
4c Traffic flow **improvement**	3	There is not much evidence for a reduction in car traffic through implementing this technology, but it can improve the traffic flow because it will be easier for cars to find a parking spot
4d. Reduction in **street parking**	3	Regarding the reduction in street parking, the technology is not primarily meant to reduce the number of parked cars, but to rather ensure compliance with law (AMS Data Steward, 2022).
4e. Safety **improvements**	2	There can be small improvements in safety, but there are no major changes expected when it comes to connectivity (Roman et. al, 2018).
4f. Connectivity	1	There can be small improvements in safety, but there are no major changes expected when it comes to connectivity (Roman et. al, 2018).
5. Environmental		
5a. Noise **nuisance**		Only some literature supports the reduction of noise nuisance, air pollution and improvements in the landscape.
5b. Air **pollution**		Only some literature supports the reduction of noise nuisance, air pollution and improvements in the landscape.
5c. Landscape **effect**		Only some literature supports the reduction of noise nuisance, air pollution and improvements in the landscape.

Criteria & indicators	T6. Gamification	
	Score (/5)	**Justification**
1. Complexity Implementation:		
1a. Regulatory **compatibility**	3	There can be regulatory conflicts due to privacy concerns (Kumar, 2020), but also due to the use of phones in traffic
1b. Physical **compatibility**	4	However, there is little change needed in physical infrastructure as it is a digital technology (Wang et al, 2022).
1c. Cultural **compatibility**	2	In addition, recruiting and retaining users has proven to be challenging (Wang et al, 2022, Bowden & Hellen, 2018), which indicates a lack of cultural compatibility.
2. Technological maturity		
2a. Level of **implementation**	4	As far as maturity is concerned, gamification has been applied in various projects, but when it comes to implementing it for traffic decisions such as choosing modes of transport and routing the use has been limited and when implemented, this often has been on relatively small scale (Minnich, 2023). Consequently, there are few relevant cases where gamification was applied in the transportation context.
2b. Level of **implemented knowledge**	4	Gamification is being discussed quite a lot, but there has not been that much of a focus on its use within transportation.
3. Data		
3a. Generation and processing of data	5	A lot of data can be collected with gamification apps such as travel choices, distances and routes (Bowden & Hellen, 2018).
3b. Ethics of data **collection**	2	However, there are some situations in which privacy and ethical concerns such as the collection and sharing of personal data might arise (Wang et al., 2022).
4. Mobility		
4a. Promotion of **low-car behavior**	3	Gamification can support a change towards a low car behavior and thus it can indirectly reduce car traffic next to improving the traffic flow (Bowden & Hellen, 2018).
4b. Car traffic **reduction**	3	Gamification can support a change towards a low car behavior and thus it can indirectly reduce car traffic next to improving the traffic flow (Bowden & Hellen, 2018).
4c Traffic flow **improvement**	3	Gamification can support a change towards a low car behavior and thus it can indirectly reduce car traffic next to improving the traffic flow (Bowden & Hellen, 2018).
4d. Reduction in **street parking**	1	No evidence was found for this technology's effect on street parking.
4e. Safety **improvements**	1	No evidence was found for this technology's effect on safety.
4f. Connectivity	1	No evidence was found for this technology's effect on connectivity.
5. Environmental		
5a. Noise **nuisance**	3	Gamification can support a change towards low car behavior and thus it can indirectly reduce noise nuisance and air pollution stemming from cars (Bowden & Hellen, 2018).
5b. Air **pollution**	3	Gamification can support a change towards low car behavior and thus it can indirectly reduce noise nuisance and air pollution stemming from cars (Bowden & Hellen, 2018).
5c. Landscape **effect**	1	No evidence was found for this technology's effect on the landscape.

Criteria & indicators	T7. Mobility Data Exchange Standardization	
	Score (/5)	**Justification**
1. Complexity Implementation:		
1a. Regulatory **compatibility**	4	As indicated by Groenendijk et al. (2021), the traffic data exchange project SOCRATES 2.0 encountered little issues in the implementation of its pilot in Amsterdam and the standardization of traffic data exchange was welcomed by public and private data providers with the goal to jointly improve the availability and dynamism of traffic information provision.
1b. Physical **compatibility**	5	Following the description by Groenendijk et al. (2021) and RDT Noord-Holland en Flevoland (2022), the standardization of mobility data exchange is a purely digital and organizational process. Consequently, no evidence can be indentified for the potential conflicts with physical traffic infrastructure.
1c. Cultural **compatibility**	3	Groenendijk et al. (2021, p. 14) found that despite the readiness to share data between public and private information providers, there are "some boundaries if it comes to sharing data with competitors" and a more advanced cooperation model is needed to breach the obstacle of organizational culture. As trust is key to the functionality of SOCRATES 2.0, this forms a signifact obstacle towards its further application and requires the case-by-case development of a cooperation framework to ensure the technology's success.
2. Technological maturity		
2a. Level of **implementation**	5	The implementation of the multiple pilot projects of the SOCRATES 2.0 program in cities such as Amsterdam and Copenhagen indicate that the standardization of mobility data exchange is not just a concept, but rather a well-tested process ready for further implementation (Groenendijk et al., 2021). The existence of Datapedia additionally proves that such a system is already extant on a regional scale within the Netherlands although it is not yet fully implemented in all areas of the country due to a variety of organizational obstacles (RDT Noord-Holland en Flevoland, 2022). There is additional evidence for the existence of such projects globablly with the notable examples of the California PATH Program and the information provided by Australia's Transport Data Center (Barceló & Kuwahara, 2010).
2b. Level of **implemented knowledge**	5	The need for standardization of mobility data exchange is a widely discussed topic in both scientific literature and government policy documents (Barceló & Kuwahara, 2010; VNG Realisatie, 2023). Significant evidence has been found for the topic also being discussed in live events and conferences throughout the Netherlands (Amsterdam Smart City, 2023; Nationaal Toegangspunt Mobiliteitsdata, 2023).
3. Data		
3a. Generation and processing of data	2	As described by Groenendijk et al. (2021), standardization programs such as SOCRATES 2.0 do not generate data by themselves. Rather, they pool it from various information providers in a standardized format which is suitable for further processing. Similarly, the Datapedia platform obtains its data from municipalities and delivers it in a standardized format (RDT Noord-Holland en Flevoland, 2022). Consequently, while this technology does not generate data, its contribution towards the distribution of data which is standardized and suitable for further processing must be recognized.
3b. Ethics of data **collection**	1	Following the description of SOCRATES 2.0 by Groenendijk et al. (2021), there is little evidence for the inclusion of measures to ensure ethical data collection within standardized mobility data exchange programs. Rather, these programs acquire data from various providers under the assumption that this data is collected ethically. However, Chen et al. (2019) identified significant concerns around data collection in transportation within the Horizon 2020 NEOSIS project of the European Union. Without measures being proposed to address these problems, there is significant concern for the breaches of privacy or other ethical issues.
4. Mobility		
4a. Promotion of **low-car behavior**	2	As found by Groenendijk et al. (2021), there is some evidence for the potential of standardized mobility data provision to have actual impact on the behavior of road users. No further evidence was identified in literature for the direct potential of

		technology to support the social transition to low-car behavior.
4b. Car traffic **reduction**	1	Groenendijk et al. (2021) found that there is some evidence for the potential of standardized mobility data provision to impact the behavior of road users although not in reference to reducing car traffic. Ultimately, no evidence was found for the potential of the technology to reduce car traffic.
4c Traffic flow **improvement**	2	Groenendijk et al. (2021) found that there is some evidence for the potential of standarized mobility data provision to impact the behavior of road users indirectly by supporting interactive traffic management. Additionally, the SOCRATES 2.0 pilot site in Amsterdam was tested for the potential of data exchange standardization to optimize traffic flow by advising and rerouting specific road users based on live data. Although, it must be noted that this is an indirect result of the technology as many additional steps are required to achieve these results.
4d. Reduction in **street parking**	1	No evidence was found for the potential of traffic data exchange standardization to reduce street parking.
4e. Safety **improvements**	2	As found by Groenendijk et al. (2021), there is some evidence for the potential of standarized mobility data provision to have actual impact on the behavior of road users, including safer driving patterns. Additionally, VNG Realisatie (2023) noted that one of the potential, indirect benefits of standardized traffic data exchange may be its support of policy makers and traffic managers to improve traffic safety.
4f. Connectivity	5	The SOCRATES 2.0 program combines various types of mobility data including that of various vehicles by faciliating the cooperation of both public and private data providers in the sites of its pilot projects (Groenendijk et al., 2021). Similarily, Datapedia offers 15 types of standardized datasets ranging from bikes to road vehicles and parking data (RDT Noord-Holland en Flevoland, 2022). VNG Realisatie (2023) also reaffirms that the provision of standardized data for all types of mobility is crucial and only through cooperation between stakeholders can it be achieved. Additionally, it predicts that the provision of standardized data may support other improvements to traffic.
5. Environmental		
5a. Noise **nuisance**	1	No evidence was found for the potential of traffic data exchange standardization to reduce noise nuisance by road vehicles.
5b. Air **pollution**	1	No evidence was found for the potential of traffic data exchange standardization to reduce air pollution by road vehicles.
5c. Landscape **effect**	1	No evidence was found for the potential of traffic data exchange standardization to improve the aesthetic value of the landscape nor diversify its functions.