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Sustainable mobility strategies deconstructed: a taxonomy of urban vehicle access regulations

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Abstract

Background In recent decades, cities worldwide are increasingly adopting vehicle access policies and technologies to alleviate the negative externalities related to high car use in the urban built environments. As such, car-oriented infrastructures and mobility policies implemented post-World War II are giving way to sustainable mobility strategies that aim to make cities healthier, more livable and more inclusive for all.

Purpose Most of these strategies are considered as stand-alone cases related to a specific environmental, political and social urban context. However, similarities and patterns between different strategies can provide information on the replicability of mobility strategies in other urban contexts.

Methods Through a literature review, this paper illustrates the wide range of urban vehicle access regulations (UVAR) applied within sustainable mobility strategies. In addition, we critically examine the process from ideation over design and implementation to operation phase for 12 West-European cities and define what measures are combined to end up with a sustainable mobility strategy.

Results This results in a taxonomy of UVAR interventions, subdivided in three categories: spatial interventions, pricing aspects and regulatory measures. We also highlight a number of complementary supportive measures implemented to counter the often restrictive nature of UVAR.

Results The paper shows that the strategies highlighted in the case studies are an amalgam of different UVAR and supportive measures. As such, deconstructing various sustainable mobility strategies enables us to shed light on the available UVAR options cities can combine to define consistent and robust sustainable mobility strategies.

Keywords Mobility policies, Sustainable development, Urban vehicle access regulations

1 Introduction

From the 1950s, motorized traffic started to dominate European cities. Cars increasingly claimed scarce public space and motorized traffic was responsible for negative externalities such as congestion, pollution and road fatalities [31]. City centers, once vibrant and thriving places, suffered from reduced livability, sharper inequalities, deteriorating accessibility and inefficient mobility. In recent decades, cities have begun to recognize the need to reduce the negative externalities of motorized traffic and thus improve urban livability, safety and health [41]. Not only city-level policymakers, but also the European Union addressed the need to evolve towards a more competitive and sustainable urban mobility transition in Europe [16]. As a result, European cities have increasingly been introducing vehicle access regulating

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strategies. Prioritizing access to and use of public space for certain types of road users can be a powerful tool to optimize urban mobility and to minimize negative externalities of urban traffic, thus in this way contributing to the sustainable urban mobility transition of cities [40].

There is a wide range of urban vehicle access regulations (UVAR) that cities can implement to restrict access to the built environment, with most access restricting strategies applying a combination of several of these measures. Over time, a diversity of access restricting policies has been adopted in European cities, most of them using different rules and requirements. However, diversity in policies causes complexity, fragmentation and makes compliance to the local schemes harder [6]. The EU asserted specific action on UVAR through the Commission Staff Working Document 'A call for smarter action on Urban Access Regulations', which was part of the 2013 Mobility Package. The main goal was to create a more harmonized and coherent approach of implementing urban access regulations across the European Union to ease compliance and understanding of the local schemes [17].

The characteristics of vehicle access strategies are determined by the specific environmental, political and social urban context, as well as both local and (inter) national rules and circumstances, resulting in a different approach in each country or even each city. As a result, these strategies are often considered as stand-alone cases, having distinct characteristics and rules. However, studying similarities and patterns between different strategies can provide valuable information on the replicability of mobility strategies in other urban contexts. In this paper, we therefore analyze the diverse range of UVAR options through literature review and a case study analysis of the implementation process in 12 Western European cities. This allows us to better understand how to imagine, design and implement robust mobility strategies.

The paper starts by explaining the methodology of the research, which combines a literature review on urban vehicle access regulations resulting in a UVAR taxonomy with an extensive analysis focused on applying this taxonomy to different sustainable mobility strategies throughout Western Europe. Subsequently, the results section illustrates the taxonomy of UVAR (based on the literature review) and the sustainable mobility strategy process assessment (based on the case study analysis). We conclude with a discussion on the merits of the research, its limitations and possible outlines for future research.

2 Methodology

This paper defines a taxonomy of UVAR options that can be applied within sustainable mobility strategies through a literature review. This literature review focuses on (1) overview papers that already classify access regulations into categories and (2) specific papers that highlight implementations of certain UVAR options. The former are used to define the framework for the taxonomy, whereas the latter are applied to revise this framework with up-to-date information on the different UVAR options currently available.

Subsequently, the resulting UVAR taxonomy is applied to analyze the sustainable mobility strategy implementation for 12 Western-European cities (Fig. 1). Through a combination of desk top research on policy documents and additional stakeholder interviews, we have established the process from ideation over design and implementation to operation. All of the case study cities are still in the operation phase of the sustainable mobility strategy and, therefore, are still relevant for supporting decision making in other cities. The case studies are chosen to encompass a wide range of strategy types (spatial interventions, pricing aspects and other regulations), city sizes (small- or medium-sized as well as larger cities), implementation scales (city center, entire city or neighborhood level) and city maturity levels (early adopters and newcomers). A general overview of the mobility strategy implemented in the 12 case studies is found in Table 1.

The case study analysis consists of the case study lifecycles and UVAR implementations for each of the 12 cities. Information on the mobility strategy was gathered through policy documents, city websites and stakeholder interviews, enabling us to define the key events (decisions, reports, implementation of UVAR measures, etc.) of the policy. This allowed us to gain insights in decisions on and evolutions in the policy strategy, from the identification of the problem in the early stages until the implementation and operation of the measures in the later stages.

This mobility strategy process consists of four stages, defined by three gates. The transition from the ideation to the design phase, the design to the implementation phase and the implementation to the operation phase are marked by the decision-making, adoption and commissioning gate, respectively [50]. The ideation phase focuses on identifying the problem, setting the agenda and defining a first set of solutions (albeit in a conceptual stage). The ideation phase ends with the decision making gate, which highlights the particular course of action, and is followed by the design phase. In this phase, the initial concept is developed and the mobility strategy is technically and strategically designed. The design phase results in the adoption gate, where the final design is approved and the mobility strategy is legitimized. The adoption gate is followed by the implementation phase, where the policy is executed. Finally,

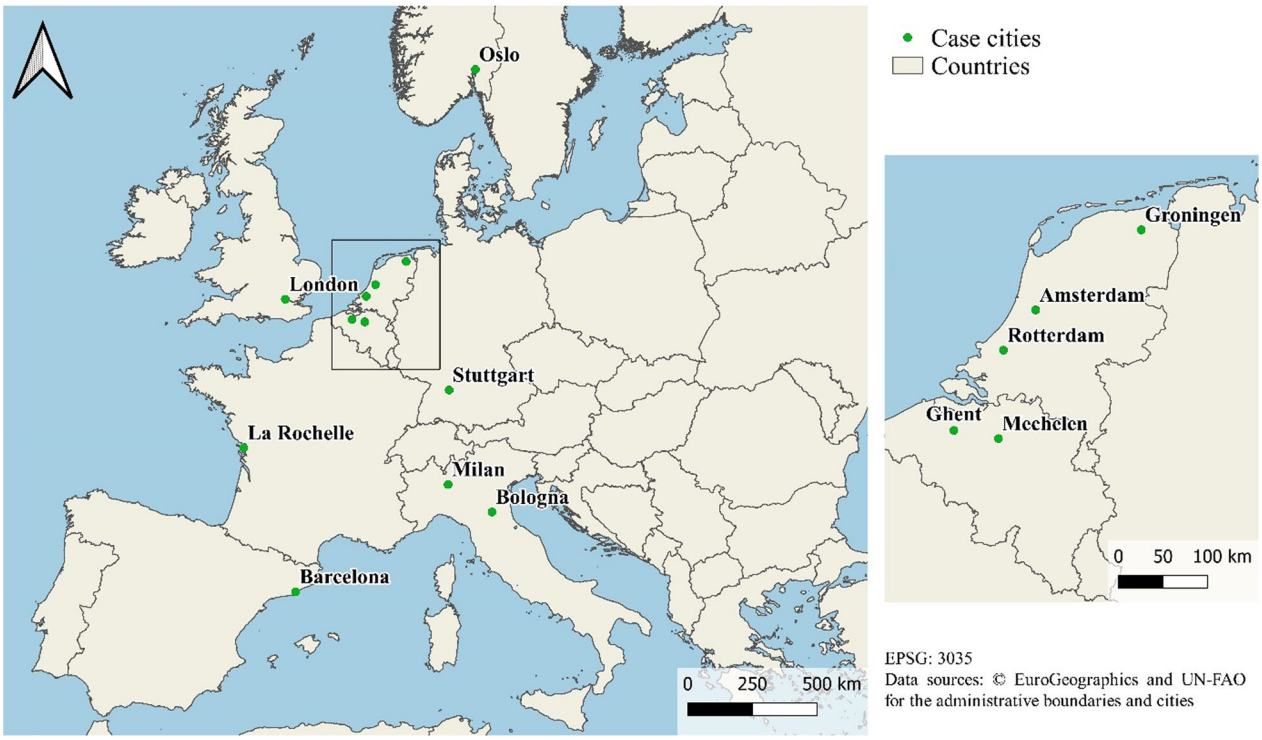

Fig. 1 Location of the twelve case study cities examined

the commissioning gate results in a final decision for the full-scale implementation, and is followed by the operation phase. This final phase continues as long as the (full-scale) strategy stays in place.

3 Results

3.1 UVAR taxonomy

To our knowledge, only three studies have classified vehicle access regulations. Comi et al. [10] and Lopez [30] define three main categories of access regulations for freight traffic, namely prohibitions, charging and prioritization measures. In addition, different measures to restrain car traffic have been classified by Jones and Hervik [24]: restrictions on speed and capacity (physical restrictions), regulatory controls and charging. Contrary to the literature on the categorization of UVARs, research about specific access regulation strategies and case-study analyses is extensively available.

Based on the literature and in line with Jones and Hervik [24], we have grouped access regulations into three broad categories: spatial interventions, pricing aspects and regulatory measures. These UVAR categories are subdivided in UVAR groups, which consist of different UVAR measures (Fig. 2). In the category of spatial interventions, pricing aspects and regulatory measures, we have distinguished 13 UVAR in 6 overarching groups (Sect. 3.1.1), 11 UVAR in 2 overarching groups (Sect. 3.1.2) and 10 UVAR in 5 overarching groups (Sect. 3.1.3), respectively.

3.1.1 Spatial interventions

A first category of measures that cities can implement to restrain urban car traffic is the implementation of spatial interventions. Spatial strategies are generally a collection of often small-scale interventions aimed at reducing or restricting motorized traffic, parking spaces and speed or prioritizing sustainable transport modes over motorized vehicles. The UVAR measures in the category of spatial interventions often have a high flexibility, as the smaller scale allows for easy adaptation and differentiation according to the local context.

Multiple cities are adopting actions to calm traffic both in speed and volume. Chicanes, speed cushions, lane narrowing, raised crosswalks or other features and designs to reduce traffic speed are introduced in many neighborhoods [5, 21, 27]. Furthermore, various cities have adopted measures to filter traffic flows in a certain street or area. Traffic volumes can be reduced by introducing for example one-way regimes or turning bans on intersections, narrowing of streets or by closing streets for certain traffic modes (e.g., by using bollards) [2, 15, 47]. Another common intervention is the reallocation

Table 1 Short summary of the 12 case study cities and their respective sustainable mobility strategies

City, country	Sustainable mobility strategy	Description
Barcelona, Spain	Superblock scheme	Various building blocks in the city are combined into one superblock of around 400m × 400m. Within these superblocks, public space was freed up to manage traffic and promote active travel modes by limiting motorized vehicle access
Ghent, Belgium	Traffic circulation plan	Through traffic is limited and accessibility by sustainable transport modes is increased by reducing the number of motorized vehicles in the area inside the inner ring road. The circulation plan divides the city in sectors and car-free areas to increase the livability
Mechelen, Belgium	Cycling zone	The entire city center is converted to a cycle zone, consisting of 179 cycling streets where cyclists have priority, and motorized vehicle are considered as guest in the public space and have to drive at a reduced speed
Groningen, The Netherlands	Traffic circulation plan	A traffic circulation plan that divides the city into four parts. Cars wanting to travel from one part to another are required to take the ring road, whereas pedestrians and cyclists are allowed to move freely
Oslo, Norway	Car-free livability program	On-street parking spaces in the city center are removed, with exemptions to parking spaces for freight and differently-abled people. The intention was to reduce traffic volume by discouraging car use in the city center and to redesign public areas to improve livability, specifically targeting pedestrians and cyclists
Milan, Italy	Congestion charge	A congestion charge is applied to the city center (*Cerchia dei Bastioni* area), replacing the former pollution charge. It is active from 7h30-19h30, Monday to Friday, excluding public and bank holidays. If a vehicle enters the charging zone during these times, it needs to pay the congestion charge
Greater London, UK	Pollution charge	Pollution charging mechanisms are combined on two different scales: in the area up to, but not including, the North and South Circular Roads, vehicles need to meet the ULEZ emissions standards or their drivers must pay a daily charge to drive within the zone. In the area of Greater London, lorries and other vehicles over 3.5 T that do not meet LEZ standards need to pay an entry fee
Rotterdam, The Netherlands	Parking management	Vehicle access in the city is regulated through pricing measures, primarily in order to shift from on- to off-street parking. The strategy specifically focuses on fixed pricing according to parking zones, permits for inhabitants and price differentiation between on- and off-street parking
La Rochelle, France	Delivery regulation	Deliveries in the city center are regulated with a time window to ensure that inhabitants and businesses in pedestrian areas can still receive deliveries. The aim is to have 100% of deliveries in the city center by 2025 made with low-emitting vehicles
Bologna, Italy	Limited-traffic zone	A limited-traffic zone is implemented in the city center, where access is enabled through the purchase of permits. Speed was reduced and pedestrians were prioritized in some streets. Emissions standards are applied, strengthening over time to a zero-emission zone
Amsterdam, The Netherlands	Zero-emission zone	The city-wide strategy started in 2008 as a camera-enforced low-emission zone for lorries, only under a covenant. It is tightened by vehicle type, fuel and in future phases. It was extended to all vehicles in 2017, and aims to become a zero-emission zone in 2025–2030
Stuttgart, Germany	Low-emission zone	Various measures have been implemented city wide, including a low-emission zone (since 2008), a diesel ban (since 2019) and a *feinstaubalarm* (2018–2020). The last one is an emergency scheme where citizens were requested to not use private motorized vehicles during the activated alarm period

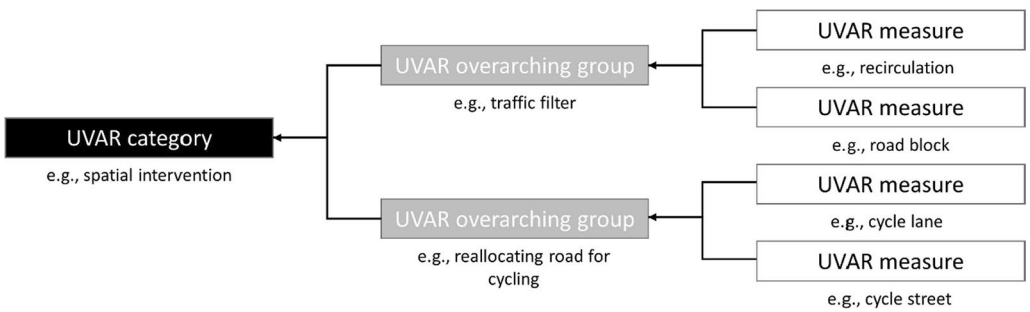

Fig. 2 Schematic for the UVAR taxonomy structure

of urban parking or road space to promote sustainable and active travel. On-street parking spaces have been replaced by parklets in Oslo, Norway and Amsterdam, The Netherlands [23, 49] and converted into shared mobility hubs in Bremen, Germany [20]. Road space was redesigned in many cities to prioritize sustainable travel modes. Pavements have been widened in the Norwegian capital Oslo [23] and cycle lanes were created in cities such as Trondheim, Norway [51] and Cáceres, Spain [39]. Also, towns such as the Greek city of Kalamaria and the German cities Offenbach am Main and Frankfurt have prioritized active road users by introducing pedestrian areas or cycling streets [7, 26, 37]. Moreover, public transport flow and speed has been improved in several urban areas by creating priority lanes for trams or busses [11, 38].

In literature, a broad group of design variations and spatial interventions aimed at reducing speed and volume of (motorized) traffic are outlined as traffic calming measures. We divide these measures into two groups: speed reductions and traffic filters. For the latter, we distinguish three different subtypes: traffic recirculation (e.g., one-way streets), road blocks (e.g., bollards, visual markings, blocks) and capacity restraints (e.g., bus traps, retractable bollards). In addition, cities can redesign parts of their public space to promote active and sustainable travel. The first type of measures relates to the repurposing of on-street parking. The literature and case study analysis provided examples of parking spaces that were converted to parklets, shared mobility zones and logistics bays. Another example is the reallocation of parking space to kiss-and-ride space, which has been implemented in several European cities (e.g., for school environments or railway stations). The analysis also shows that several cities reallocated (part of the) road space to prioritize pedestrians (by introducing (wider) pavements or pedestrian priority streets), cyclists (by introducing cycle lanes or streets) or public transport (by introducing priority lanes). The different overarching groups and a definition and city example of each of the UVAR measures for the category of spatial interventions are found in Table 2 and the UVAR taxonomy is represented in Fig. 3.

3.1.2 Pricing aspects

A second category of measures that cities can adopt is the introduction of pricing schemes. Charging schemes are mainly used to restrict vehicles or road users to access or park in a certain regulated area. We distinguish two types of pricing schemes: road use and parking charging. Road charges can be either area-based or point-based. In addition, road charges can be differentiated based on the amount of time or the distance a vehicle has traveled, as well as the vehicle's emission level. A last subcategory of road pricing are charges based on a permit, where the

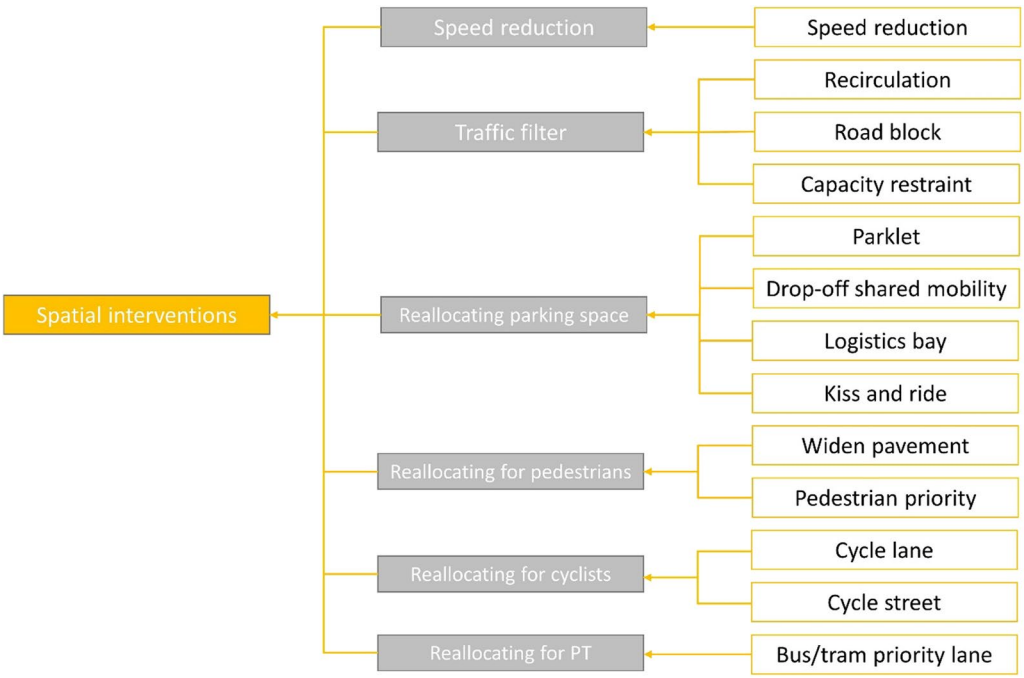

Fig. 3 Schematic for the UVAR taxonomy for the category of spatial interventions

charges are differentiated based on certain characteristics (e.g., user category, time of the day, number of vehicles).

Various types of parking and road use charging are in place in European cities, with multiple cities adopting a combination of different charging schemes. The policy decision on the type of scheme(s) to introduce is generally influenced by the main goals of the city [3, 9, 24]. Diverse road charging schemes were introduced in different European cities, such as London, UK, Stockholm, Sweden and Valletta, Malta [4, 36]. First of all, road pricing schemes can vary by place. In area-based schemes (zonal and cordon pricing), charges are levied when a vehicle enters and, in some cases, exits or travels within the boundaries of a charging zone. Point-based schemes charge vehicles when they cross specific points [13]. Secondly, road pricing charges can be differentiated based on distance or time a vehicle has traveled (e.g., distance- and time-based schemes), by vehicle type (e.g., emission-based schemes) or based on other characteristics, such as time of the day or trip purpose [13, 19]. Furthermore, numerous cities have regulated parking by introducing a parking pricing scheme [33]. Following road pricing, parking charges can be differentiated based on location (e.g., higher prices for the city center or on-street versus off-street parking), time (e.g., time of the day or day of the week), demand level, emission level of the vehicle or type of parking (e.g., workplace parking levy, a specific charge on organizations for providing off-street, private parking spaces for their employees) [32, 33].

Literature and case study analysis showed that parking charges can be differentiated based on many characteristics. We grouped them into five types: fixed prices according to areas of the city and/or time of the day, differentiated (fixed) prices between on-street and off-street, periodically updated charges to match demand levels, differentiated charges based on the emission level of the vehicle and workplace parking levies. The different overarching groups and a definition and city example of each of the UVAR measures for the category of pricing aspects are found in Table 3 and the UVAR taxonomy is represented in Fig. 4.

3.1.3 Regulatory measures

A third category of measures that cities can apply are different types of regulations to restrict access of certain types of vehicles in urban areas. Vehicular access is regulated based on many elements, one of them being vehicle characteristics. Weight, size, type, age and emission class of the vehicle are often used as determining factors [30]. The low-emission zone (LEZ) in London, UK is an example of a scheme where access is regulated based on different vehicle characteristics. Lorries and vehicles over 3.5 T that fail to meet the EURO standards are not allowed to enter the charging zone, except when paying a daily charge (Sadler [42]. Another common type of urban access control is restricting vehicle access based on trip purpose. For example, some access regulating policies include restrictions that exclusively apply for delivery vehicles [1] or specific bans that are introduced on through traffic [18]. Furthermore, vehicle access is regulated in various urban areas through the use of permits. For example, emission stickers are required to enter the

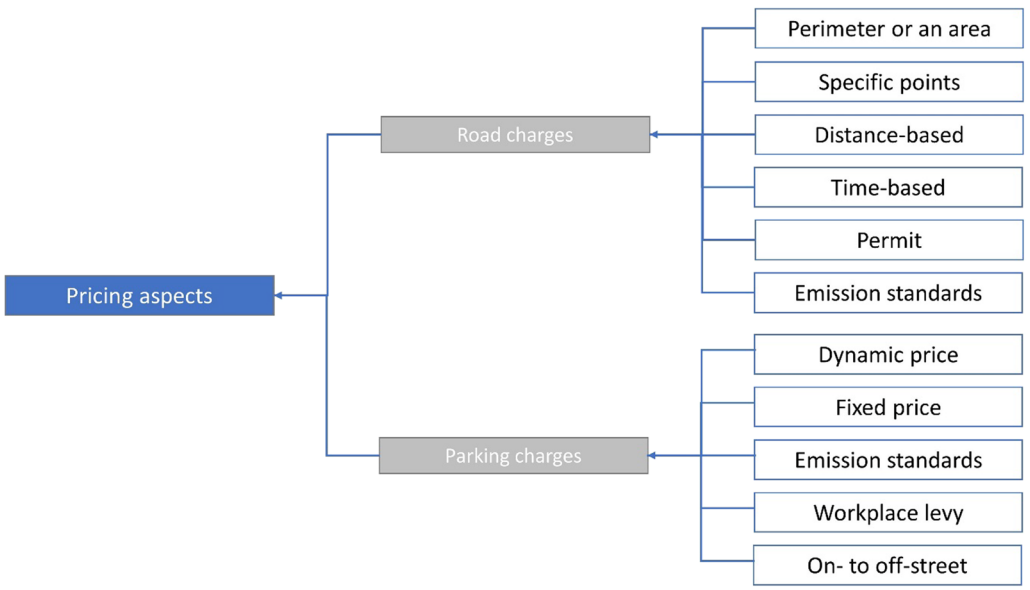

Fig. 4 Schematic for the UVAR taxonomy for the category of pricing aspects

LEZ in Madrid, Spain [44] and residents need to buy parking permits in order to legally park in Amsterdam, The Netherlands [12]. In addition, cities such as London, UK and Bremen, Germany have limited vehicle access by enforcing (maximum) parking requirements for new residential (and commercial) developments [20, 29].

We divide the vehicle characteristics into two main groups: regulations by emission (EURO standard and zero emission vehicles) and regulations by vehicle type and dimension (vehicle type and vehicle dimension). In some cases, access is regulated based on trip purpose. Two types are differentiated: vehicle access can be regulated specifically for delivery and logistics vehicles, or specifically for through-traffic. Also, permits are frequently used to regulate vehicle access to a restricted area. We distinguish three types: permits to travel, parking permits and planning permit conditions. Finally, we include vehicle safety features, representing additional safety regulations for lorries. The different overarching groups and a definition and city example of each of the UVAR measures for the category of regulatory measures are found in Table 4 and the UVAR taxonomy is represented in Fig. 5.

3.1.4 Supportive complementary measures

Most cities have adopted vehicle access regulations to reduce urban traffic and associated negative externalities. However, access regulations are often restrictive for certain types of road users and can even exacerbate inequitable situations [28, 35]. Therefore, additional, supportive measures complementing a given UVAR are introduced in most access restricting policies, with the aim to ease compliance, to counteract the restrictive nature or to address possible inequitable outcomes of access restricting measures.

Supportive measures can be categorized in three groups: financial incentives, increased mobility options and exemptions. Financial supportive measures have been introduced in several cities to ease acceptance and compliance of access regulation schemes. The launch of a support program (e.g., discounts on public transport or financial compensation to switch to cleaner alternatives) can reduce the (financial) impact of a scheme, especially for those for whom it is harder to switch to alternative vehicles or modes [43, 46]. In addition, cities may increase the sustainable mobility options to ensure access of people, goods and services, to make compliance to the scheme easier and to address possible inequitable impacts. The availability of a sufficient public transport supply can be a particular decisive factor in the accessibility and effectiveness of a scheme [25, 45]. Lastly, certain types of vehicles and road users can be exempted from the access regulating policies. For practical reasons, it is essential to exempt certain vehicles, such as waste collection, public transport, emergency vehicles, postal services or military vehicles [3, 48]. Some schemes have introduced exemptions for adapted and (in most cases) cleaner vehicles as well, such as electrical, retrofitted and hybrid vehicles [8, 34]. Depending on the type of scheme, other groups of road users can also be excluded from the regulation. Generally exempted groups are differently-abled people, residents, deliveries, motorcycles and taxis [3, 8, 48]. Exemptions can be permanent, as well as time limited, for example residents of the Area C congestion charge zone in Milan are granted 40 days of free entry per year [8]. Exempting certain road users is common and in some cases even necessary in access regulating schemes. However, the choice of the exemption groups should be

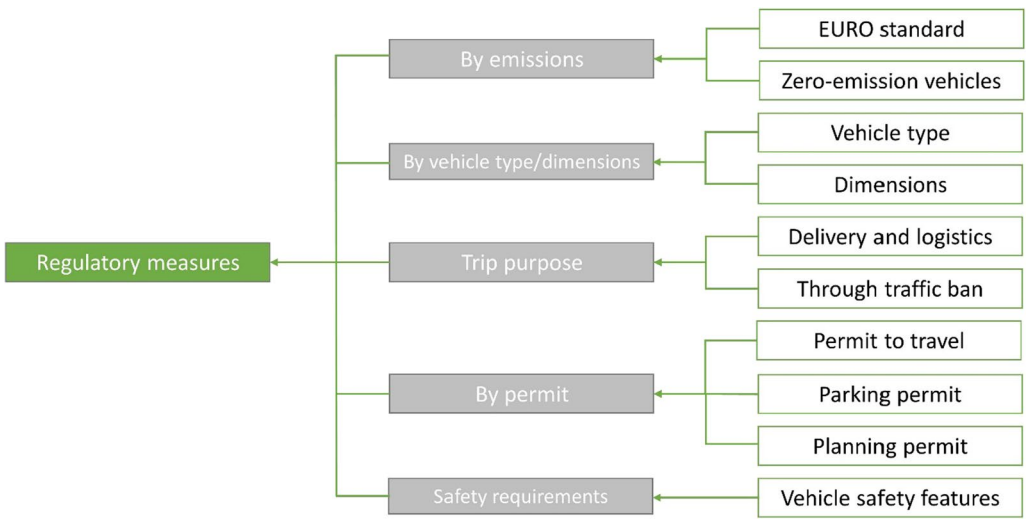

Fig. 5 Schematic for the UVAR taxonomy for the category of regulatory measures

well deliberated, as exempting certain groups can reduce or even undermine the effectiveness of the scheme [3].

3.2 Case study analysis

The UVAR taxonomy was applied to analyse sustainable mobility strategies for 12 Western-European cities. Five cases are characterized by primarily spatial strategies: Barcelona, Ghent, Mechelen, Groningen and Oslo. The scale was mostly the inner city or the neighborhood level. All cities aim to promote sustainable and active travel, and some cities additionally focus on reducing car traffic (Ghent and Groningen), increasing livability (Ghent and Oslo) and freeing up public space (Barcelona and Oslo). Some interventions are self-enforcing (e.g., speed bumps, road blocks, cycle lanes), whereas others are enforced through police control or cameras. Additionally, three cases are characterized by primarily pricing-based strategies: Milan, Greater London and Rotterdam. Here, the scale is diverse, ranging from the street to the national level, and the strategy is often scaled up in time. The main goals driving the strategies are reducing car traffic and air pollution, as well as increasing the share of sustainable and active travel. Enforcement is done through cameras, or in some cases through manual police control (e.g., parking ticketing). The case studies show that the share and number of through traffic and visitors play an important role in the acceptability of the scheme. Finally, four cases are characterized by primarily regulatory strategies: La Rochelle, Bologna, Amsterdam and Stuttgart. The scale of the implementation ranges from the street to the regional level, but most regulations focus on the city or neighborhood level. In line with pricing schemes, the borders of the regulated area have in many cases been changed (in most cases upscaled) through time. The main goal is to reduce emissions, but cities also highlight the need to reduce heavy-duty traffic, make delivery more sustainable and increase overall livability. Similar to pricing, regulatory strategies are often camera-enforced.

3.2.1 Case study lifecycles

Prior to applying the UVAR taxonomy to the sustainable mobility strategy for each case study city, the case study lifecycles allow us to get insights on the decision-making process and the evolution of the policy strategy of the cases. Figure 6, 7 and 8 illustrate the decision-making, adoption and commissioning gate, as well as the timing for the design and implementation phase for the primarily spatial, pricing or regulatory-focused mobility strategies, respectively. The design and implementation phase generally take one to five years, except for Stuttgart (a design phase of 9 years) and Rotterdam (an implementation phase of 12 years). Longer phases are primarily explained by larger participation campaigns, repeated testing and evaluation or opposition to the plan. The ideation phase and operation phase are not shown on the timeline, as they do not have a clear start or end.

The process starts with the ideation phase, which is typically characterized by the first emergence of issues related to car-based externalities. The cities start with feasibility studies and impact assessments, organize the first public hearings and end up with general plans or agreements. The decision-making gate is often a plan, act, announcement or decision that determines the course of action to be followed. In the design phase, the cities continue with more detailed studies through monitoring or evaluation of the situation as it is, in order to end up with different pathways. The adoption gate is therefore a final plan or regulation, or the introduction of a set of measures or a program. In the implementation phase, the plan is implemented and possibly updated, resulting in renewed monitoring and evaluation of the impacts of the adapted situation. The implementation of new pilots, sets of measures, complementary projects or adjustments to measures in this phase frequently result in opposition or criticism to the plans. The commissioning gate marks the end of the trial period and the start of the permanent program. In the operation phase, new or updated plans or agreements are installed, which again result in renewed but more structural monitoring and evaluation. Striking, however, is that the case studies show that participation of citizens and more extensive communication campaigns are generally only set up in the later phases of the process, when the design is already in a more final stage.

In addition, mobility strategies are characterized by different levels of phasing, scaling and timing. Strategies often progressively grow stricter over time, which underlines the importance of a well-planned communication campaign, informing citizens well in advance of the measures. This allows them to adapt their travel, organize alternatives or retrofit their vehicles, but it also paves the way for more elaborate pilots and test phases. UVAR can also be scaled, increasing the area of effect over time (e.g., the pollution charge in London or the LEZ in Amsterdam). Finally, also timing can play a crucial role in the implementation of the sustainable mobility strategy. UVAR can have a time-window, regulating access by the time of the day or week (e.g., the pollution charge in Milan) or according to the season. They can also be reactive, catering for a specific situation or event (e.g., the Feinstaubalarm in Stuttgart).

3.2.2 Applying the UVAR taxonomy: the case studies' mobility strategies deconstructed

The taxonomy of UVAR enables us to visualize the measures (planned to be) implemented in the case studies. The

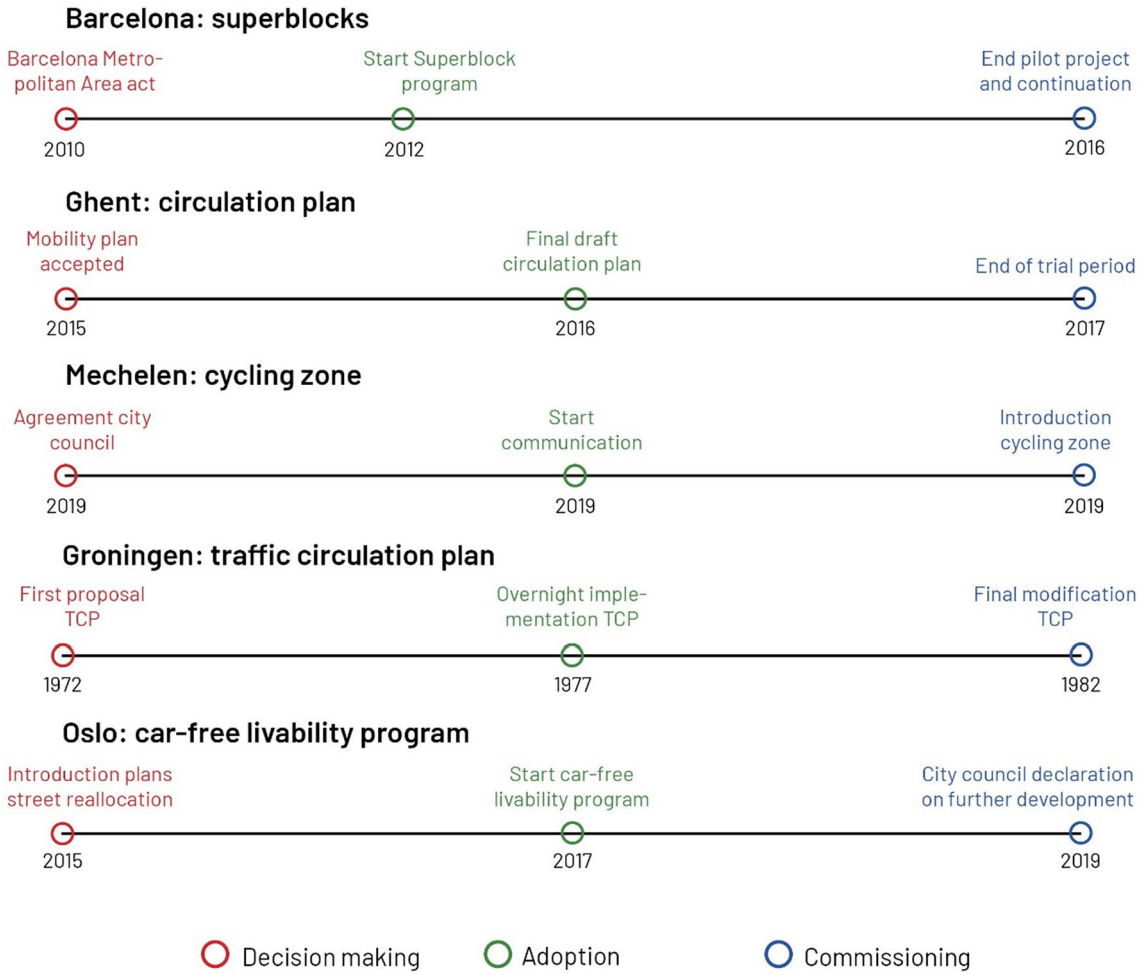

Fig. 6 Representation of case studies' timeline and main events for the decision-making, adoption and commissioning gates (primarily spatial strategies)

analysis highlights a large difference between the case studies in terms of UVAR measures, mainly due to differing mobility strategies and local contexts. The strategies are an amalgam of different UVAR and complementary supportive measures: most case studies show combinations of spatial interventions, pricing aspects and/or regulatory measures. However, some combinations prove to be more convenient (e.g., road charges are often paired with permits to travel, through traffic bans or traffic filters). The combination of the different UVAR measures are represented in circular diagrams (Figs. 9, 11 and 13) showing the combination of measures within the categories of spatial interventions (yellow), pricing aspects (blue), regulatory measures (green) and complementary supportive measures (orange). An overview of the different UVAR measures is found in Table 5. For each UVAR category, one exemplary case study is highlighted by representing the case study in the format of the UVAR taxonomy (Figs. 10, 12 and 14).

The primarily spatial strategies (in Barcelona, Ghent, Mechelen, Groningen and Oslo, Fig. 9) generally combine a large number of spatial interventions. All cases except for Mechelen have applied regulatory measures, and more specifically a permit to travel. Barcelona and Groningen have also implemented pricing aspects in the form of parking charges. Mechelen is an exceptional case, as only a small number of spatial interventions have been adopted, albeit over the whole case study area. In terms of complementary supportive measures, most cities have provided increased mobility options and tolerate exemptions (which are often linked to pedestrian priority areas). Figure 10 shows the UVAR taxonomy applied to one of the case studies, Barcelona, indicating which UVAR measures in the different UVAR categories are combined to constitute the superblock scheme. In addition to the nine spatial intervention UVARS, one pricing aspect and one regulatory measure, the strategy also applied two complementary supportive measures: exemptions and increased mobility options.

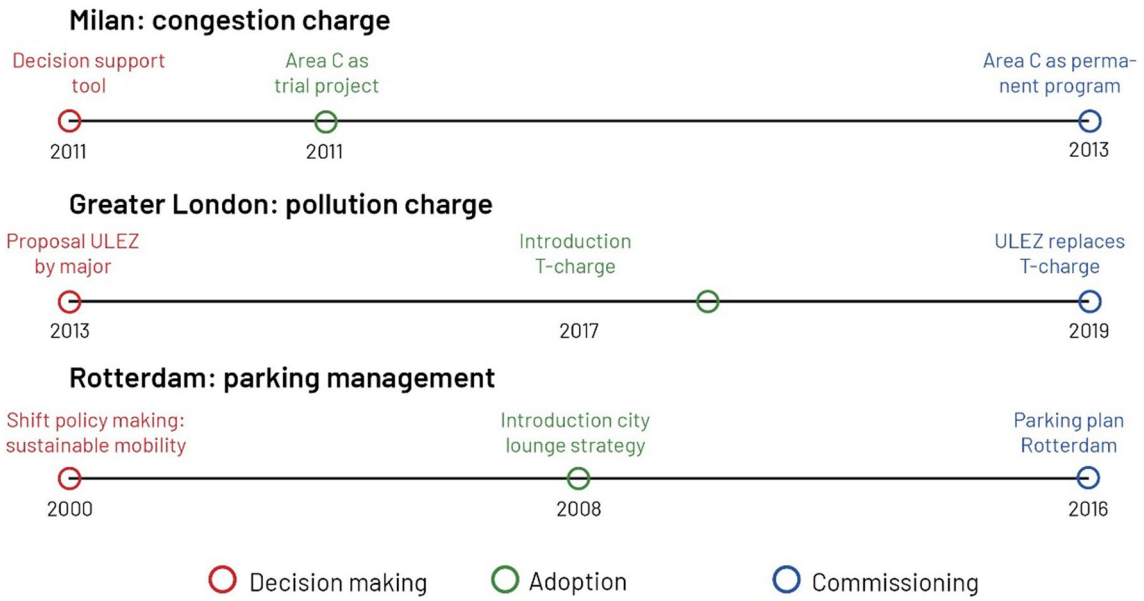

Fig. 7 Representation of case studies' timeline and main events for the decision-making, adoption and commissioning gates (primarily pricing strategies)

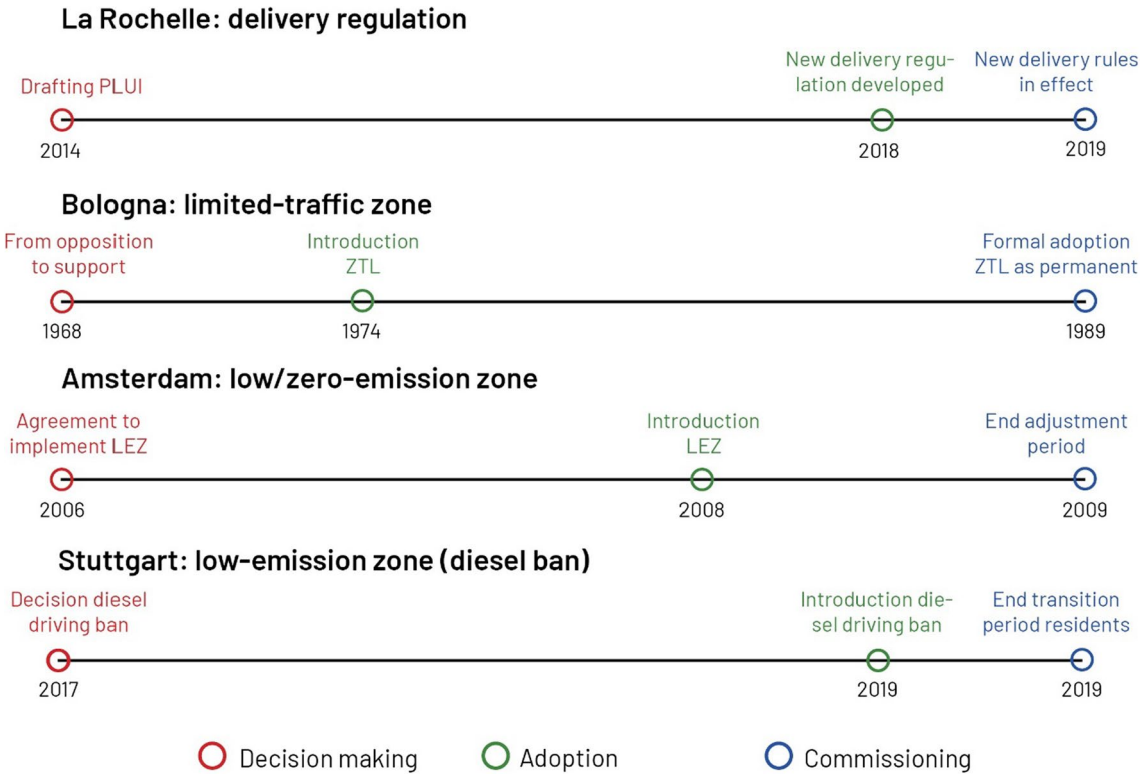

Fig. 8 Representation of case studies' timeline and main events for the decision-making, adoption and commissioning gates (primarily regulatory strategies)

Fig. 9 UVAR measures implemented in the primarily spatial strategies

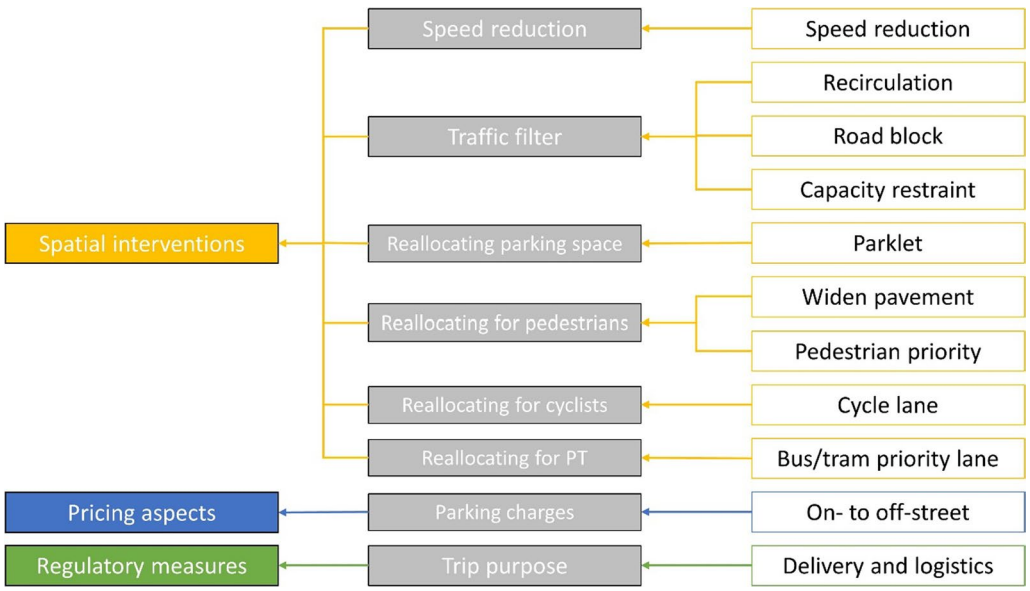

Fig. 10 Schematic representation of the UVAR taxonomy applied for the case study of Barcelona (implementation of a superblock scheme)

The primarily pricing-focused strategies (in Milan, Greater London and Rotterdam, Fig. 11) show a wide range of UVAR combinations. In Milan and Greater London, the strategy primarily revolves around a congestion or pollution road use charge, but also combines a large number of regulatory measures. Most of these, however, are directly linked to the pricing scheme (e.g., regulating access based on emission levels, differentiating charge based on vehicle type and dimensions, permit to travel). Spatial interventions are mainly used to

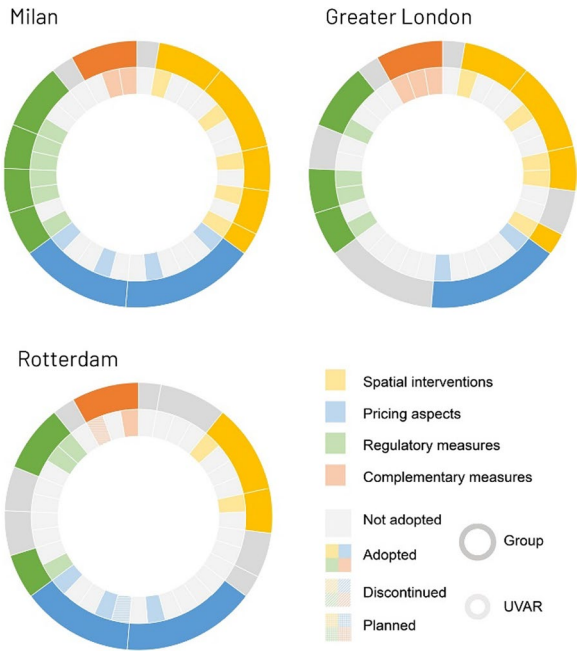

Fig. 11 UVAR measures implemented in the primarily pricing-focused strategies

complement the charge, as such having a twofold aim: reducing the number of (polluting) cars as well as enabling the shift to more sustainable, alternative transport modes. In Rotterdam, UVAR are aimed at parking management. Different parking charges are paired with specific parking regulations and spatial interventions focused on reallocating parking or road space. Figure 12 shows the UVAR taxonomy applied to one of the case studies, Greater London, indicating which UVAR measures in the different UVAR categories are combined to constitute London's pollution charge. In addition to the five spatial intervention UVARS, two pricing aspects and four regulatory measures, the strategy also applied three complementary supportive measures: financial incentives, exemptions and increased mobility options.

The primarily regulatory-based strategies (in Bologna, La Rochelle, Amsterdam and Stuttgart, Fig. 13) combine different regulatory measures. Spatial interventions and pricing aspects are not part of the strategies (apart from Bologna, which implemented a pedestrian priority street with speed reduction and a permit charge). For the regulatory measures, phasing plays an important role, as restrictions grow stricter over time. As such, polluting vehicles are progressively banned by, for example, changing EURO standards or reducing the time window of delivery. Moreover, regulatory measures such as LEZ or LTZ are often considered as a pathway to ZEZ. Figure 14 shows the UVAR taxonomy applied to one of the case studies, Bologna, indicating which UVAR measures in the different UVAR categories are combined to constitute a limited traffic zone. This strategy combines two spatial intervention UVARS, one pricing aspect and five regulatory measures, with two complementary supportive measures: financial incentives and exemptions.

4 Conclusion and discussion

Although there is a clear consensus on the merits of urban vehicle access regulations (UVAR), literature shows that only a limited number of studies have defined

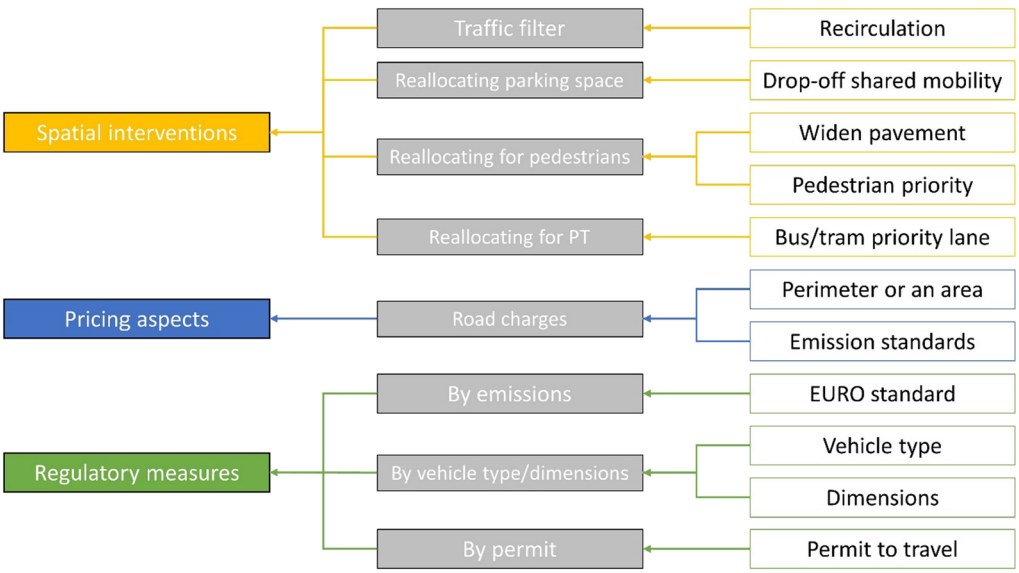

Fig. 12 Schematic representation of the UVAR taxonomy applied for the case study of Greater London (implementation of a pollution charge)

Fig. 13 UVAR measures implemented in the primarily regulatory-based strategies

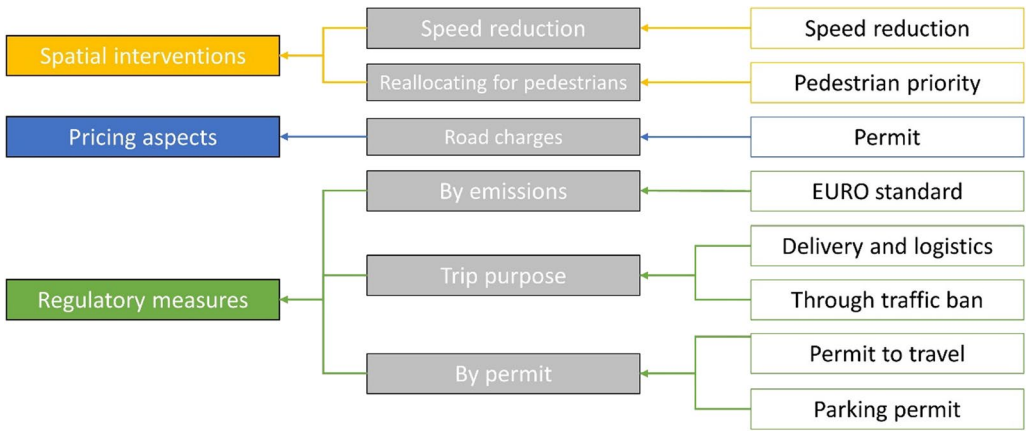

Fig. 14 Schematic representation of the UVAR taxonomy applied for the case study of Bologna (implementation of a limited traffic zone)

a distinct UVAR categorization, and that information on specific measures is scattered and inconsistent. However, a thorough understanding of the way in which UVAR are combined into robust strategies can be valuable for the replicability of these strategies in other urban contexts. Through literature and case study analysis, this paper has therefore examined the wide range of measures that cities can apply, in order to establish a more harmonized and coherent approach of enabling and accelerating sustainable urban mobility transitions.

Through a literature review, urban vehicle access regulations (UVAR) are categorized in spatial interventions, pricing aspects and regulatory measures. These categories were differentiated in a taxonomy of 34 UVAR (in 13 overarching groups), as such covering the wide range of options that cities can choose from to mix and match

to formulate, design and implement a robust mobility strategy. The spatial interventions are often small scale measures that are easy to adapt and differentiate according to the local context. These interventions are primarily focused on traffic calming (e.g., speed reduction or traffic filters) or redefining road or parking space (e.g., cycling streets, pedestrian zones). The pricing aspects are mainly aimed at restricting vehicles or road users to access or park in a certain regulated area. Pricing is divided into road use (e.g., area or time-based) and parking charges (e.g., fixed or dynamic charging), and can be differentiated based on many characteristics, such as the location, the time of day or the vehicle's emission levels. The regulatory measures are aimed at regulating access through various vehicle dimensions. Regulations can focus on emission levels, vehicle type and dimensions, trip purpose, permit or safety requirements. Additionally, complementary supportive measures such as financial incentives, increased mobility options or exemptions are generally adopted to counteract the often restrictive nature of UVAR.

The taxonomy of UVAR was applied to examine the implementation of various mobility strategies for 12 Western-European cities, more specifically by focusing on what characterized the implementation process and how different UVAR options were combined. The case study lifecycles illustrate the decision making process from decision making over adoption to commissioning. This process is mostly context specific and is characterized by different levels of phasing, scaling and timing. In addition, the case study analysis shows that cities often adopt an amalgam of different UVAR and supportive measures. For the 12 case studies, five were characterized by primarily spatial (Barcelona, Ghent, Mechelen, Groningen and Oslo), three by primarily pricing (Milan, Greater London and Amsterdam) and four by primarily regulatory mobility strategies (La Rochelle, Bologna, Amsterdam and Stuttgart). Although spatial, pricing, regulatory and supportive measures are often combined together, some combinations occur more frequently.

Although the literature review and case study analysis provide valuable insights into the UVAR implementation process, there are some limitations to take into account. First, we acknowledge that the UVAR taxonomy is a snapshot of the currently available UVAR options and that its quality is based on our interpretation of case studies discussed in the literature review. The UVAR option 'Reallocating parking space—Kiss & Ride', for example, is to our knowledge not mentioned as access regulating intervention in academic literature, but was added to the taxonomy because it is an integral part of sustainable mobility strategies in various European cities. Moreover, other future options such as geofencing or dynamic traffic management might not be considered within the standard range of UVAR yet, but they could be in the (near) future. Therefore, a continued assessment of existing and new mobility options can further expand and improve the UVAR taxonomy in the future. Second, the case study analysis was limited to Western-European cities due to language barriers and ease of access to information. The authors (and affiliated project partners) were able to assess policy documents and have interviews with policymakers in languages that they master well enough to capture all aspects and nuances of the process. Although the cities examined in this paper are quite diverse, a follow-up research on the UVAR implementation process in other cities in Europe—or even worldwide—can provide valuable insights in the transferability of the results to completely different cultural, geographic or social contexts. In Latin America and Asia, for example, various cases of access regulation based on vehicles' license plate number exist [22, 52]. Third, it is important to note that all information on the process phases and gates was collected through a review of policy documents, websites and papers, and interviews with policy makers. In addition, interviews with stakeholders were limited to one stakeholder per case and were only held for the case cities Ghent, Mechelen and La Rochelle. As such, the case study lifecycles are subject to the authors' or interviewee's interpretations of important events, start and end dates or expected outcomes. For example, there might be UVAR options that were considered throughout the process, but that were not referred to in policy documents. Moreover, it is difficult to define what aspects are part of the strategy and, as such, limit its scope to a scale and timeframe that is analyzable. In Ghent, for example, the circulation plan was actually part of a broader mobility plan, which also encompassed a parking scheme and many other specific interventions (that were not part of the case study analysis). Fourth, mobility strategies can lead to unwanted inequitable effects and, therefore, are not inherently socially sustainable. We have examined the implementation of supportive measures and the involvement of citizens and stakeholders throughout the different phases of the processes. However, we did not critically examine the impact of stakeholder involvement on the success of the implementation. De Vrij and Vanoutrive [14] illustrate that stakeholder participation can alleviate inequitable effects, especially when experiences of the most vulnerable are taken into account. It is crucial to highlight that the suggested UVAR options are not a one-size-fits-all solution. They are part of a wider strategy that encompasses different scales, domains and perspectives.

Appendix

See Tables 2, 3, 4 and 5.

Table 2 UVAR for the spatial interventions category, showing the overarching group, definition and a city example where the measure is implemented

UVAR group	UVAR	Definition	City example
Speed reduction	Speed reduction	Variation in road design to indicate that road use is different and/or speed is limited (e.g., lane narrowing, chicanes, speed cushions)	Vitoria-Gasteiz, Spain
Traffic filter	Recirculation	Change in the traffic circulation for motorized vehicles in a specific area	Groningen, The Netherlands
	Road block	Barrier to disable motorized vehicle access or to indicate restricted access for motorized vehicles that do not have a destination in the designated area	Bielefeld, Germany
	Capacity restraint	Barrier to limit the volume of (a certain type of) motorized vehicles passing through (and stopping in) the designated area	Bern, Switzerland
Reallocating parking space	Parklet	Parking space is converted to a small, public space or green space created as a public amenity on or alongside a pavement	Paris, France
	Drop-off zone shared mobility	Parking space is converted to a space for dropping of vehicles of shared mobility systems (e.g., micromobility, public transit, car-sharing, etc.)	Lisbon, Portugal
	Logistics bay (mini-hub)	Parking space is converted to a designated parking space for logistics	Oslo, Norway
	Kiss and ride (K&R)	Parking space is converted to an area where the time motorized vehicles can stop is limited (to the time needed to drop off children, hospital patients, …)	Mol, Belgium
Reallocating road space for pedestrians	Widen pavement	Road space is converted to pavement to allow for a wider area designated to pedestrians	Barcelona, Spain
	Pedestrian priority street or zone	Road space is converted to a street or zone allocated and designed for pedestrians, allowing for mixed-use where pedestrians have right of way and other modes are allowed as guests, or where only resident (or other specific group) access by motorized vehicle are allowed. Motor traffic is regulated through a required change in driving behaviour and/or by changes in the spatial road layout. Examples are school streets, pedestrian streets, home zones or play streets	York, UK
Reallocating road space for cycling	Cycle lane	Part of the road is converted to space fully dedicated to cyclists (or other types of micromobility, such as (e-)scooter)	Sevilla, Spain
	Cycling street	Road space is converted to a non-segregated street with right of way for cyclists, who are the priority users. Cars are guests and can be forbidden or discouraged to overtake cyclists. Cycling streets are characterized by a custom (often red) coloured surface and/or road marking at the entrances of the street	Cologne, Germany
Reallocating road space for public transport	Bus or tram priority lane	Road space is converted to a lane designated for bus or tram movement, resulting in priority for public transport (ensuring that traffic delays do not impact public transport circulation)	Bordeaux, France

Table 3 UVAR for the pricing aspects category, showing the overarching group, definition and a city examplewhere the measure is implemented

UVAR group	UVAR	Definition	City example
Road charges/tolls	Charge applied to a perimeter or an area	Road charges for a perimeter or an area are a daily charge to be paid for driving through a designated boundary and/or within the restricted area	Milan, Italy
	Charge applied to specific points	Road charges for specific points are applied to vehicles that travel through a given location or series of locations on the road network	Oslo, Norway
	Distance-based charge	Distance based road charges are proportional to the distance travelled. This is calculated via a GPS that is installed inside the vehicle	Brussels, Belgium
	Time-based charge	Time-based road charges are based on the amount of time a vehicle is inside the regulated zone. When a vehicle leaves the area, the system calculates the time the vehicle remained inside the boundary and computes the fee due for access (and parking)	Valletta, Malta
	Permit charge	In an UVAR scheme based on permits (e.g., LTZ), drivers/owners may be required to pay a fee for a vehicle-specific permit. Fees may be differentiated according to user categories (e.g., residents pay less than delivery companies), the total number of vehicles (the second or third permitted vehicle is charged more than the first) or the time window (some slots cost less than others)	Siena, Italy
	Based on emission standards (pollution charge)	High-polluting vehicles are charged when they enter or circulate within the designated area	London, UK
Parking charge	Dynamic price (real time)	Pricing of parking spaces is updated periodically during the day to match demand levels	San Francisco, USA
	Fixed price	Vehicles are charged to occupy parking spaces. Prices are fixed for the specific area of the city and/or time of the day	Amsterdam, The Netherlands
	Based on emission standards	Vehicles are charged to occupy parking spaces. Prices are based on the vehicle's emission levels	Madrid, Spain
	Workplace levy	Charge on employers and educational institutions (schools, universities) for the number of parking places they provide to be used by employees, students or others	Nottingham, UK
	From on-street to off-street parking	Vehicles are charged to occupy parking spaces. Prices are higher on-street than in parking infrastructure facilities to gradually reduce the presence of cars in the city and improve the quality of public spaces (e.g., free/cheaper Park and Ride facilities)	Rotterdam, The Netherlands

Table 4 UVAR for the regulatory measures category, showing the overarching group, definition and a city example where the measure is implemented

UVAR Group	UVAR	Definition	City example
Regulation by emissions	EURO standard	Vehicle access is regulated by their EURO standard emissions. This is usually phased and differentiated by vehicle type, trip purpose, locality or fuel type. It can be part of a LEZ, LTZ (including delivery scheme) or charging scheme, and can be extended to a ZEZ	Brussels, Belgium
	Zero-emission vehicles	Vehicle access is regulated, only allowing (or giving advantages to) zero-emission vehicles, as opposed to segmenting vehicles into different emission categories	Krakow, Poland
Regulation by vehicle type and dimensions	Vehicle type	Vehicle access is regulated by vehicle type, such as heavy duty, light duty, car, van, lorry, coach, minibus, special, etc	Paris, France
	Dimensions	Vehicle access is regulated by the physical vehicle attributes, such as weight, length, width, number of axles	Prague, Czech Republic
Regulation by trip purpose	Delivery and logistics	Vehicle access is regulated for delivery and logistics vehicles. The rules or permits given can be phased, time limited, permanent or can provide more (or less) freedom for those with 'desirable behaviour'. They focus on emissions, vehicle size or other requirements (e.g., delivery type, delivery time, …)	Strasbourg, France
	Through traffic ban	Vehicle access is regulated for through traffic (e.g., 'access only' via road sign to prevent through traffic). It enables a scheme to be focused on or away from certain vehicle uses (by inclusion or exclusion), for example affecting through traffic or not affecting residents or those who are accessing these streets. The rules or permits given can be phased, time limited or permanent	Milan, Italy
Regulation by permit	Permit to travel	Vehicle access is regulated by a permit that has been granted before entry into the area. This can happen through a windscreen sticker or letter and/or be done 'virtually' through registration of the vehicle plate in a database (e.g., whitelist)	Siena, Italy
	Parking permit	Vehicle access is regulated by a permit required in order to be legally able to park a vehicle within the area or to drive to the parking space	London, UK
	Planning Permit Conditions	Vehicle access is regulated by planning permit conditions, which are used to affect the number or impact of vehicles. This can be used to specify how many parking spaces (on or off street) are permitted per dwelling. Planning permit conditions can also be used to place requirements on the (on and off-road) vehicles that are used during the operation of the site (perhaps specifying the parking permits) or during the building phase (e.g., emissions of vehicles used)	Helmond, The Netherlands
Regulation by safety requirements	Vehicle Safety features	Vehicle access is regulated by additional safety features required for lorries to improve safety for sustainable mobility modes (particularly cycling)	London, UK

Table 5 UVAR taxonomy structure for the case study analyses, indicating the possible UVAR measures in the UVAR categories (spatial interventions, pricing aspects and regulatory measures) and the complementary supportive measures

UVAR group		UVAR	
Spatial interventions			
1	Speed reduction	a	Speed reduction
2	Traffic filter	a	Recirculation
		b	Roadblock
		c	Capacity restraint
3	Reallocating parking space	a	Parklet
		b	Drop-off zone shared mobility
		c	Logistics bay (mini hub)
		d	Kiss and ride (K & R)
4	Reallocating road space for pedestrians	a	Widen pavement
		b	Pedestrian priority street zone
5	Reallocating road space for cycling	a	Cycle lane
		b	Cycling street
6	Reallocating road space for public transport	a	Bus/tram priority
Pricing aspects			
7	Road charges/tolls	a	Charge applied to a perimeter or an area
		b	Charge applied to specific points
		c	Distance-based charge
		d	Time-based charge
		e	Permit charge
		f	Charge based on emission standards (pollution charge)
8	Parking charge	a	Dynamic price (real time)
		b	Fixed price
		c	Charge based on emission standards (pollution charge)
		d	Workplace levy
		e	From on-street to off-street parking
Regulatory measures			
9	Regulation by emission	a	EURO standard
		b	Zero-emission vehicles
10	Regulation by vehicle type and dimensions	a	Vehicle type
		b	Dimensions
11	Regulation by trip purpose	a	Delivery and logistics
		b	Through traffic ban
12	Regulation by permit	a	Permit to travel
		b	Parking permit
		c	Planning permit conditions
13	Regulation by safety requirements	a	Vehicle safety features
Complementary measures			
14	Complementary supportive measures	a	Financial incentives
		b	Exemptions
		c	Increased mobility options

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Author contributions
All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Koos Fransen and Jente Versigghel. The first draft of the manuscript was written by Koos Fransen and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript. The paper was revised by Koos Fransen.

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Availability of data and materials
Not applicable.

Declarations

Competing interests
On behalf of all authors, the corresponding author states that there is no conflict of interest.

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