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A dozen effective interventions to reduce car use in European cities: Lessons learned from a meta-analysis and transition management

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ABSTRACT

Transitioning to fossil-free transport and reducing car use are necessary to meet European and national climate goals. Cities are promising leverage points to facilitate system transitions by promoting local innovation and policy experimentation. Building on transition management, we developed a knowledge base for the implementation of transition experiments to reduce city-level car use. From screening nearly 800 peer-reviewed studies and case studies, including in-depth analysis of 24 documents that met quality criteria and quantitatively estimated car use reduction, we identify 12 intervention types combining different measures and policy instruments that were effective in reducing car use in European cities. The most effective at reducing overall car use were the Congestion Charge, Parking & Traffic Congrol, and Limited Traffic Zone. Most interventions were led by local government, planned and decided in collaboration with different urban stakeholders. We evaluated the potential of the identified intervention types to be implemented in a pilot study of Lund, Sweden, using three criteria from Transition Management of novelty, feasibility, and suitability, as assessed by interviews with local experts. We recommend three transition experiments to reduce local car use in Lund: Parking and Traffic Control, Workplace Parking Charge, and Mobility Services for Commuters. We suggest practitioners follow our method to identify effective and locally suitable interventions to reduce car use, and future research quantify the effectiveness of interventions to reduce car use using the standardised outcome measure of daily passenger kilometres travelled by car.

1. Introduction

A rapid transition to fossil-free transport, including reduced car use in over-automobiled regions like Europe and North America, is necessary to avoid catastrophic climate change. Policies to reduce vehicle ownership and usage, along with a transition to electric vehicles running on zero-carbon energy, are necessary to limit warming well below 2 °C (Milovanoff et al., 2020). Transport is the second-largest source of greenhouse gas emissions in Europe (EEA, 2019), nearly three-quarters of which come from road transport (European Commission, n.d.), where current levels of car use is acknowledged as a barrier to meet existing EU (EEA, 2021) and national (Swedish Climate Policy Council, 2019) climate policy goals. Recent studies show that reducing car use has amongst the highest potential to reduce per capita emissions (Ivanova et al., 2020; Wynes et al., 2018).

Cities have increasingly been recognised as leverage points in combating global warming (Bulkeley, 2010; Bulkeley et al., 2011; Kern & Alber, 2009; Neij et al., 2015). While cities are responsible for 50-60% of global greenhouse gas emissions (UN Habitat, 2021), they also offer promising focal points for policy and societal action to lower emissions, including experimenting with new forms of policy and planning (Bulkeley et al., 2011). Reduced car use in cities is especially important to promote equity amidst limited urban space, as car users take 3.5 times more physical space than non-car users (Creutzig et al, 2020). City governments are closer to citizens than national governments and can take decisions in shorter timeframes (Bulkeley, 2010; Rotmans et al., 2001). Further, many cities possess competencies in key sectors for system transitions, such as waste, transport, and land-use planning (Bulkeley, 2010). Many cities have developed their own climate action plans and strategies - often more progressive then those of the respective nation-state – and became members of national and transnational city networks to collaboratively fight climate change (Kern & Alber, 2009; Neij et al., 2015). Alternatives emerging from the local level can inspire climate actions in other cities and even be translated into governance at higher levels, thus having a global impact (Roorda et al., 2014).

While rapid and drastic systems transitions are needed to achieve

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global climate goals (IPCC, 2018), lock-ins and path dependencies currently reinforce and stabilize unsustainable policies, institutions, infrastructure, and practices, thereby impeding necessary transitions, or fundamental, systemic changes of societal actors towards sustainability (Geels, 2011; Loorbach et al., 2015). A promising approach to promote local innovation, policy experimentation, and urban climate actions that support collective efforts for systems transitions is transition management. Transition management was developed as an instrumental, action-oriented governance framework which allows to steer and promote transitions of societal systems and sectors (Loorbach & Rotmans, 2010; Loorbach et al., 2015; Markard et al., 2012). Transition management aims to introduce a long-term perspective in policymaking, engage participation and interaction between multiple stakeholders, apply a learning philosophy (learning-by-doing and doing-by-learning), inspire new initiatives, and enable actors to address specific challenges which impede the transition process (Roorda et al., 2014; Rotmans et al., 2001). In practice, transition management is utilised to complement existing policies through the introduction of new governance activities, often with the aim to address a particular transition challenge (Loorbach et al., 2015). Usually, a transition team is formed to manage the application of transition management in the local context (Roorda et al., 2014).

To accelerate transition processes, transition management highlights the potential of so-called transition experiments: innovative, near-term interventions or initiatives that address specific challenges in the transition process on the national, regional, or city level (Loorbach & Rotmans, 2010; Roorda et al., 2014). Transition experiments emphasize accelerating the transition process by incorporating learning into policymaking, and involving stakeholders including government, public and private institutions, businesses and citizens (Loorbach et al., 2015; Nevens et al., 2013). To realise their potential to successfully accelerate a transition process, transition experiments should be 1) new approaches that differ from dominant, existing practices, 2) suitable to address the targeted societal challenge, and 3) feasible to implement in the near-term and with the available resources (Loorbach et al., 2015; Roorda et al., 2014).

Transition management has been successfully used at the city level. For example, the city of Ghent used transition management to promote its transition towards a climate-neutral city, including establishing a long-term vision, a transition team of municipal employees to identify transition challenges, and engaging stakeholder participation to implement transition experiments including car-free streets. Other examples of cities using a transition management approach include Montreuil, France achieving temporary highway closures, and experiments with remote working hubs in Aberdeen, UK (Roorda & Wittmayer, 2014).

A gap remains, however, in understanding the processes and policies that cities can adopt to reduce their reliance on cars. Such knowledge is urgently needed given the rapid decarbonization required to meet climate, sustainability, and equity targets. For example, the European Union's "Mission Cities" initiative aims to deliver 100 climate-neutral and smart cities by 2030 (European Commission, 2021), while acknowledging that the knowledge for how to make this transformation happen is unclear, and that additional innovations and learning, with cities testing and innovating, are required in real time. We have therefore selected a pilot study of potential policy feasibility and implementation in Lund, Sweden, which like many cities has clear climate ambitions but is not yet on track to meet them. Lund aims to be one of the 100 EU climate-neutral cities by 2030 (European Commission, 2020a), and is an important climate leader in Sweden, having committed to becoming climate neutral by 2030 (Viable Cities, 2020). However, to meet its 2030 climate goal, Lund's historical rate of emissions reductions is too slow; a recent evaluation by independent experts confirms that Lund municipality "needs to implement measures to reduce car use" (Neij et al., 2020). Transport emissions have declined only 10% since 1990, and today contribute 52% of emissions in Lund's geographical boundaries, 72% of which come from car use (Neij et al., 2020). Thus, Lund represents an important testing ground for applying effective car-reduction policies in practice.

In this study, we develop a knowledge base for the implementation of transition experiments to reduce city-level car use. We do so by conducting a review of nearly 800 peer-reviewed studies and case studies to identify and classify the characteristics of 12 city-level interventions that have effectively reduced car use in the EU. We further identify the stakeholder types and collaborations involved in the planning and decision-making of these interventions, in order to inform factors contributing to their effectiveness. We then use the criteria of transition experiments, as assessed by local stakeholders, to evaluate the potential of these 12 interventions to reduce car use in a pilot study of Lund, Sweden.

Table 1
Inclusion and final selection criteria for scientific articles and case-study documents included in our analysis of interventions to reduce car use. The inclusion criteria were developed during the scoping review phase of the scientific review, then applied to both peer-reviewed articles in the scientific review, and case-study reports in the document review. The final selection criteria were developed at a later stage of the scientific review to ensure data quality and utility of the selected papers for the analysis.

Inclusion Criteria
The article should:
a) be published after the year 2010
b) study an intervention to reduce car use that was conducted in a city in the EU.
c) contain an intervention in the form of a purposive attempt by an urban stakeholder to reduce local car use or to reduce car ownership, which a study of more than 100 EU cities found can be expected to reduce car use as well (Santos et al., 2013)
d) represent an ex-post analysis (not an ex-ante analysis, simulation, or model) of an intervention
e) provide quantified evidence of the intervention's effectiveness in reducing car use (or car ownership)
Final Selection Criteria
The article should include (1) *reliable data* (e.g., adequate sample size of car use group (greater than50 individuals), sound methodological description of data generation) with (2) *quantified evidence* to demonstrate an intervention's effectiveness in line with any of the following outcome measures:
• the reduction of car traffic across the cordon (border of a charged zone or restricted zone for cars)
the reduction of car traffic in the city centre
the reduction of commuters travelling by car
the reduction of share of car use among commuters to workplace
the reduction of share of car use among commuters to university
the reduction of share of car use among trips to school
the reduction of share of car use among individual residents
reduced number of trips during morning rush-hours
percentage of individuals with reduced share of car use
replaced number of private cars per car-sharing car

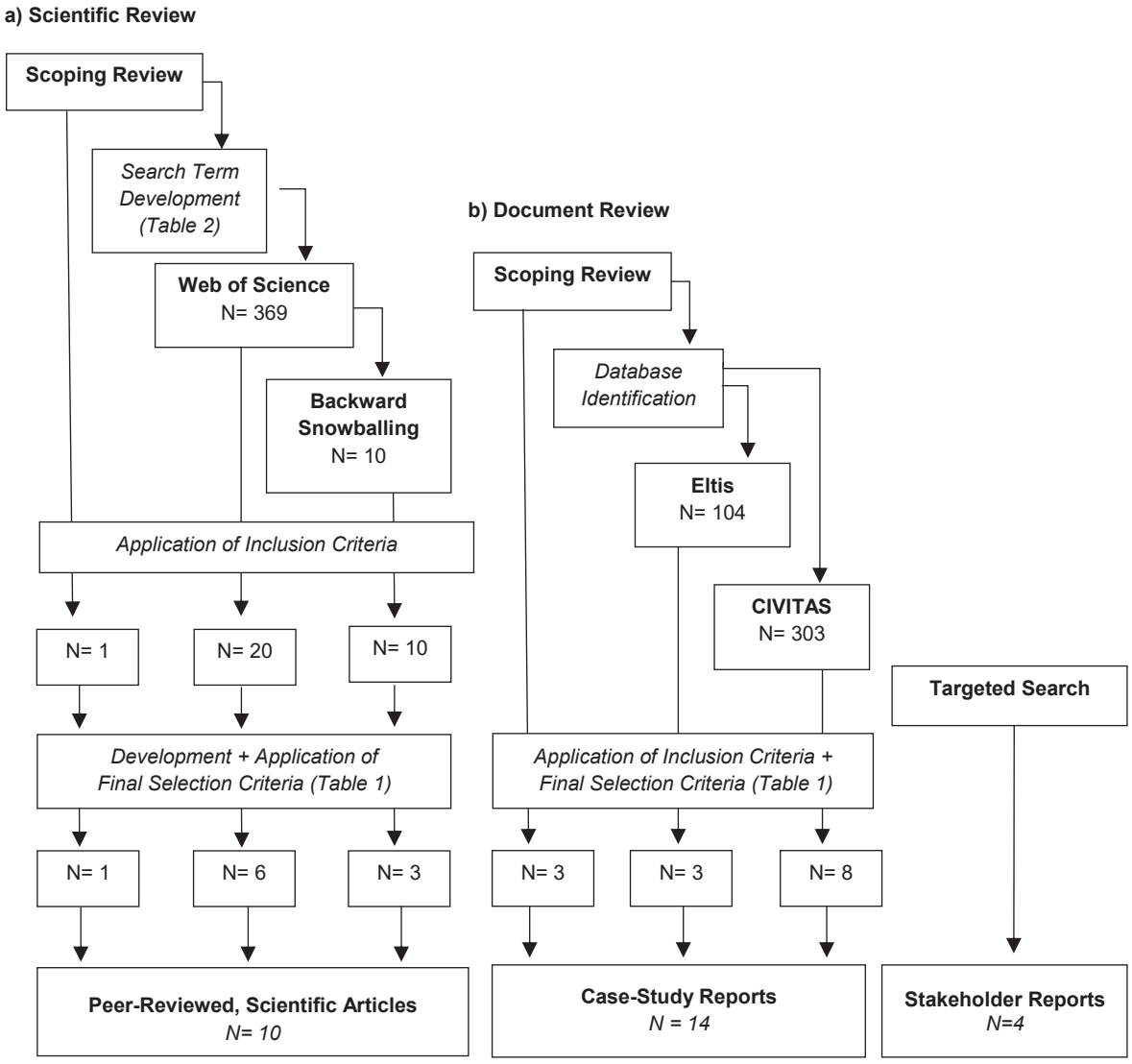

Fig. 1. Steps conducted for the systematic review of (a) scientific literature and (b) case-study reports, and the targeted search for additional reports focused on stakeholder involvement, noting the number of documents retained at each stage. See Table 1 for inclusion and final selection criteria. From left to right, the figure presents the chronological order in which the scientific and document review were conducted.

2. Methods

2.1. Systematic literature review

To identify and classify effective interventions to reduce car use in Europe, and identify the stakeholders involved in such interventions, we conducted a systematic review of both peer-reviewed and grey literature. We considered interventions from cities in EU member states, including Great Britain up until the Brexit in 2020. We initially reviewed 369 scientific articles and 407 case-study reports, of which less than 4% met our inclusion and final selection criteria (Table 1). A total of 10 peer-reviewed studies and 14 case studies of reduced car use were retained for analysis. Four of these cases did not contain sufficient information about stakeholders involved, and were supplemented with specific stakeholders reports (Fig. 1).

It is common in the field to find a small number of suitable articles: Graham-Rowe et al. (2011) reviewed 3,486 articles to find interventions related to private car use, and retained only 69.

Table 2
Search terms for peer-reviewed studies in the scientific review on Web of Science, combining aspects of reducing urban car use with policy interventions.

Database	Search Term	Number of Hits
Web of Science	reduce car use AND urban AND lessons	20
	best practice AND reduce car use AND urban	12
	restrict car use AND Urban AND policy	29
	car restrictive policy AND city	16
	reduce traffic volume AND policy AND city	27
	reduce travel distance with car AND policy AND city	29
	reduce frequency of car use AND policy AND city	19
	intervention to reduce car use AND city	61
	change car use habits AND policy	45
	modal shift from car AND policy	35
	reduce car use AND policy (reviews only)	76

For the scientific review, similar to the review conducted by Graham-Rowe et al. (2011), we began with identifying relevant search terms for case studies and reviews of car use interventions, based on a scoping review of relevant articles in *Google Scholar* and two journals for transport policy research known to the authors: *Case Studies on Transport Policy* and *Transport Review*. Such a scoping strategy is an important step to calibrate the balance between sensitivity (finding all relevant articles) and specificity (finding articles that meet criteria for relevance) (James et al., 2016). We then used the identified search terms shown in Table 2, which combine aspects of reducing urban car use with policy interventions, to identify N = 369 articles in Web of Science. The titles, abstracts and, if necessary, the results sections of these articles were screened against the inclusion criteria for relevance (Table 1). For inclusion, articles needed to study an intervention in the form of a purposive attempt by an urban stakeholder to reduce car use in an EU country; represent an ex-post analysis; provide quantified evidence of the intervention's effectiveness in reducing car use; and be published after 2010 (Table 1). The vast majority of studies in the initial review used ex-ante analysis based on simulation and models, not ex-post analysis of actual outcomes from monitoring and evaluations. Those that did report ex-post analysis primarily provided only qualitative evidence of the intervention effectiveness, such as "the intervention greatly reduced the share of car use," without reporting a measurable value of the reduction. Thus we ended up with a relatively small proportion that met our inclusion criteria.

These articles were examined for their references cited in a "backward snowballing" process (Teixeira et al., 2020), yielding N = 10 articles (Fig. 1a). All articles from the scoping review, Web of Science, and Backward Snowballing that met the inclusion criteria were subject to the final selection criteria for data quality and reporting one of our ten categories of quantified outcome measures (Table 1), resulting in a final total of N = 1, N = 6, and N = 3 studies respectively (Fig. 1a).

2.2. Systematic document review

We also conducted a systematic document review of case-study reports from public and private institutions to capture the many evaluations of interventions to reduce car use which are not published in peer-reviewed studies (Graham-Rowe et al., 2011). From an initial scoping review (Fig. 1b), we identified N = 3 reports that met the inclusion criteria (Table 1), which led us to select the databases of *Eltis* and *CIVITAS*, two EU flagship initiatives on sustainable urban mobility, each with an extensive database of reports of urban transport interventions in EU cities (European Commission, 2017). The databases include reports of cities in Great Britain from interventions conducted before the Brexit in 2020. We searched reports in Eltis using the available filters for Mobility Management and Traffic and Demand Management (N = 104 reports), and CIVITAS using the terms "reduce car use," "reduce car traffic", "reduce traffic volume", and "reduce vehicle" (N = 303) (Table 3). All articles from the scoping review, Eltis, and CIVITAS that met the inclusion criteria were subject to the final selection criteria (Table 1), resulting in a final total of N = 3, N = 3, and N = 8 studies respectively (Fig. 1b). Thus, N = 14 case-study reports were included for final analysis of interventions to reduce car use.

Across the 24 documents (10 scientific articles and 14 case-study reports), constituting the 26 cases of interventions, most but not all documents included a description of the stakeholders involved in implementing the intervention. Four cases did not include a stakeholder description in the original document (peer-reviewed study or case-study report). For each of these four cases, we identified an additional report focused on stakeholder involvement in the case through a targeted Google search (e.g., "London cordon stakeholders") (Fig. 1b).

Table 3
Search terms and filters used to identify relevant case-study reports on the site-specific search engines of Eltis (Mobility solutions) and CIVITAS (Resource Library).

Database	Filters and Search Term	Number of Hits
Eltis	Mobility Management	78
	Traffic and Demand Management	26
CIVITAS Resource Library	reduce car use	6
	reduce car traffic	4
	reduce traffic volume	0
	reduce vehicle	10
CIVITAS Mobility Solutions	reduce car use	158
	reduce car traffic	103
	reduce traffic volume	20
	reduce vehicle	54

2.3. Categorisation and classification of interventions

We classified the interventions to reduce car use along three dimensions: intervention type; intervention approach; and policy instrument used. First, we grouped the car reduction interventions from the 24 peer-reviewed studies and case study reports according to *intervention types* based on the measures used to reduce car use, such as "Workplace Travel Planning" and "School Travel Planning," which were inductively grouped into *intervention categories,* such as "Travel Planning". Second, we classified *intervention approach* according to the Push- and Pull approach (Bongardt et al., 2011; Broekhoff et al., 2018), also named Push- and Pull effect (Dijk et al., 2018). Push-measures discourage private car use, for example with charges and regulations, while pull-measures incentivise travel alternatives to the car, for example by improving public transport and bike infrastructure (Table 4). Third, we classified *policy instrument* using one of four IPCC classification of sub-national policies: regulatory instruments, economic instruments, information policies, and public goods & services (Somanathan et al., 2014). This classification was used by Moberg et al. (2019) to classify policy interventions for deep decarbonisation pathways in the transport sector. Inspired by Gärling & Schuitema (2007) who use a similar classification to distinguish measures that aim at reducing car use, the IPCC policy instrument "information policies" was expanded to "information & education policies" (Table 4). Finally, we ranked effectiveness across cases within each outcome measure used to report the reduction of car use. We use the outcome measure reported by each study, which used timeseries analysis to compare baseline and post-intervention outcomes. In such

Table 4
Classifications for intervention approach and policy instruments applied to the interventions to reduce car use identified from the systematic review. The intervention approach (push- and pull; Bongardt et al., 2011; Broekhoff et al., 2018; Dijk et al., 2018) as well as the policy instruments (regulatory approach, economic instrument, information & education policies, and public goods & services) (Somanathan et al., 2014; Gärling & Schuitema, 2007) were used to classify each of the previously identified intervention types.

Intervention Approach	
Push - approach	Discouragement of private car use by increasing the costs of car use or imposing regulations to control or prohibit car use e.g., charges, taxes, fees, regulations, rules
Pull - approach	Incentivising the use of low-carbon or non-motorised modes of travelling as alternatives to the car e.g., monetary incentives, improvement of public transport, improvement of walking and biking infrastructure
Policy Instrument	
Regulatory Approach	Rules, Standards, Prohibitions
Economic Instrument	Taxes, Subsidies, Charges
Information & Education Policies	Information Campaigns, Marketing, Persuasion, Feedback
Public Goods & Services	Physical Infrastructure, Planning, Provision of Services

"real-world experiments," it is not possible to attribute causality of the entirety of emissions reductions to specific, individual measures, and indeed most policy interventions consisted of a "package" of several combined measures (see Chapter 3.1.1). However, we believe this approach provides the best available evidence of emissions reductions in practice, at least until large-scale randomized controlled trials would be undertaken.

2.4. Classification of stakeholder types and collaborations

We identified and classified stakeholder types and collaborations following the approach of Castán Broto & Bulkeley (2013) and Bulkeley & Castán Broto (2013), who identified and classified stakeholders involved in urban climate change experiments as one of five types: National government, regional government, local government, civil society, and private sector. First, we identified the stakeholders involved in the planning and decision-making of the car reduction interventions from the full set of 28 peer-reviewed studies, case study reports, and stakeholder reports. Stakeholders who solely implemented or financed an intervention were not included.

Second, we further classified stakeholders as either *Leading Stakeholders* (that initiate and lead interventions) or as *Partner Stakeholders,* that work in close collaboration with the Leading Stakeholders to support their work. Third, the Leading Stakeholders were further classified into *Single Leading Stakeholders*, when only one Leading Stakeholder initiates and leads an intervention, and *Multiple Leading Stakeholders*, when several leading stakeholders together initiate and lead an intervention. Fourth, we counted the number of Leading and Partner Stakeholders involved in each case.

2.5. Pilot study interviews

The purpose of identifying successful "bright spots" where reductions in car use have been achieved through the systematic review of the literature is to allow these innovations to take root elsewhere, to scale up, out, and deep (Bennettet al., 2016). Therefore, we conducted a pilot study to operationalize transition management principles and assess suitability of the identified highly effective interventions, to inform scaling our results to other cities going forward. For this pilot we selected Lund, Sweden, a municipality of 126,000 inhabitants (Statistics Sweden, 2020) hosting a large international university in the region of Skåne in southern Sweden. Three-quarters of the population live in the main city of Lund, with the remainder in eight outlying villages (Lunds Kommun, 2021). Lund was selected as a pilot study due to its strong climate progress to date, having successfully cut its emissions by half in 2020, compared to 1990 (Lunds Kommun, 2020b), as well as its established climate goal aiming to become climate-neutral by 2030 (Lunds Kommun, 2020a). With this, Lund's current climate goals are more progressive than Swedish and EU climate goals. Sweden aims for zero net greenhouse gas emissions by 2045 and the EU has the goal to become a climate neutral continent by 2050 (European Commission, 2020b; Ministry of the Environment and Energy, n.d.). This makes Lund an important leader for urban climate actions. Lund was the first municipality in Sweden to introduce a climate policy council in 2018, consisting of local scientific experts who evaluate the compatibility of Lund's politics with their climate goals in form of an annual report (Neij et al., 2019). Lund is also a leader in stakeholder collaboration, working with Lund University and local companies that are part of the local climate alliance *Lund Klimatallians* (Viable Cities, 2020) as well as the Swedish city network *Klimatkommunerna (Climate municipalities)* (Lunds Kommun, 2020a).

To evaluate the potential of the effective city-level interventions to function as transition experiments to reduce car use in the case of Lund, we conducted qualitative, semi-structured interviews with local experts of Lund's transport transition, as recommended by transition management to introduce stakeholder knowledge and competencies throughout the transition process (Loorbach & Rotmans, 2010). The interview questions applied the criteria of effective transition experiments to the car reduction interventions identified from the systematic review, namely asking if the interventions would be 1) new measures for Lund, 2) suitable to reduce local car use, and 3) feasible to implement. Thereby, all interventions were tested against the three criteria which transition experiments require to fulfil their potential. We interviewed two local practitioners who work with transport as employees of Lund municipality (abbreviated: E1 and E2 [E = Expert]) and two researchers from Lund University who closely studied Lund's climate work in the transport sector (abbreviated: E3 and E4) on Zoom. Each interview lasted 45–60 min and was recorded with consent by the interview partner.

We assessed the potential of the interventions identified to function as transition experiments to reduce car use in Lund using thematic analysis on verbatim interview transcripts using MAXQDA based on transcription rules proposed by Kuckartz & Rädiker (2019). We used three themes drawn from the criteria which should be fulfilled for a transition experiment to realise its potential: novelty (a new approach that differs from dominant, existing practices), suitability (to reduce car use), and feasibility (to implement in the near-term with available resources). Each of the three themes was coded as fully, partly, or not fulfilled, based on the interview partners' response. If the answers of more than two experts within a theme were coded with the same code (e.g., three times "fully fulfilled" for the theme "suitability"), then this code determined the evaluation of the theme. If the answers of two or less experts were coded with the same code (e.g., two times "fully fulfilled" and two times "partly fulfilled"), then the lower ranking (partly fulfilled) was chosen. The overall potential for an intervention to reduce car use was assessed based on how well it fulfilled each of the three criteria. The potential was classified as high with at least two fully fulfilled criteria and at most one partly fulfilled; moderate if two or more criteria were partly fulfilled; and low if at least one criteria was unfulfilled.

3. Results

3.1. Effective city-level interventions to reduce car use

3.1.1. Classifying intervention types, measures, approaches and policy instruments

Overall, we identified seven intervention categories based on the cases' *main* measures (e.g., charging and pricing, access limitation, etc.), which were further sub-divided into 12 intervention types (e.g., congestion charges vs. workplace parking charges). These 12 intervention types were classified according to their intervention approach (push, pull, or both) and which of four possible policy instrument(s) were used. In total, we found 26 cases of effective city-level interventions to reduce car use or car ownership (Norwich, Brighton & Hove, and San Sebastián conducted two interventions each) (Table 5, Appendix A). In terms of specific policy instruments, we found Public Goods & Services was part of almost every intervention type, most often in combination with economic or regulatory instruments (Table 5). The policy instrument Information & Education was part of every intervention type that follows a pull-approach to reduce car use.

Of the seven categories of interventions we identified, the most widely studied were charging and pricing, and travel planning (Table 5). Charging and pricing consisted both of interventions to charge for cars crossing the border of a defined charging zone, with revenues used for infrastructure or public transport investments (Beria, 2016; Börjesson & Kristoffersson, 2015; Eliasson, 2014; Metz, 2018), as well as parking fees

Table 5
Interventions shown to effectively reduce car use or ownership in Europe. The interventions are grouped in seven categories, which are further sub-divided to 12 types of intervention based on their approach (push, pull, or both) and the policy instrument(s) used (regulatory, economic, information & education, public goods & services). The categories were derived from analyzing the 26 city cases identified from the systematic review shown in Fig. 1, using the literature listed.

Intervention Category	Intervention Type	Intervention Approach	Policy Instrument(s)	Main Measures	Cities (*treated as cases of effective interventions)*	References	Stakeholder References
1) Charging & Pricing	1) Congestion Charge	Push & Pull	Economic, Public Goods & Services	- Daily/ time-dependent charges for cars in defined charging zone, roughly city centre (cordon-based system) - Revenues for public transport or infrastructure investments	1) Gothenburg (SE) 2) London (GB) 3) Milan (IT) 4) Stockholm (SE)	1) (Börjesson & Kristoffersson, 2015) 2) (Metz, 2018) 3) (Beria, 2016) 4) (Eliasson, 2014)	1) (Börjesson & Kristoffersson, 2015) 2) (Centre for Public Impact, 2016) 3) (Beria, 2016) 4) (Eliasson, 2014)
	2) Workplace Parking Charge	Push & Pull	Economic, Public Goods & Services	- Charges for car parking spaces at workplace - Cash-out scheme for employees to use public transport (Rotterdam) - Revenues for public transport expansion (Nottingham)	5) Nottingham (GB) 6) Rotterdam (NL)	5) (Dale et al., 2019) 6) (Strompen et al., 2012)	5) (Nottingham City Council, 2008) 6) (Strompen et al., 2012)
2) Access-Limitations	3) Limited Traffic Zone	Push & Pull	Regulatory, Public Goods & Services	- Time- and weekday dependent access restrictions in city centre -Access only with special entrance permit for residents or with an annual fee - Revenues from entrance permit + violation fines for public transport investments	7) Rome (IT)	7) (CIVITAS, 2013c)	7) (DeRobertis & Tira, 2016)
3) Parking & Traffic Control	4) Parking & Traffic Control	Push & Pull	Regulatory, Public Goods & Services	- Removal of parking spaces in + around city centre - Introduction of car-free streets - Alteration of traffic routes - New bike lanes + pedestrian-friendly infrastructure	8) Oslo (NO)	8) (Modijefsky, 2021)	8) (Modijefsky, 2021)
4) Mobility Services	5) Mobility Services for Commuters	Pull	Economic, Public Goods & Services, Information & Education	- Free public transport pass for employees - Private Shuttle Bus from local companies to Park' n' Ride stations, train stations, etc. - marketing of measures + communication plan	9) Utrecht (NL)	9) (Stumpel-Vos et al., 2013)	9) (Stumpel-Vos et al., 2013)
	6) Mobility Services for University	Pull	Economic, Public Goods & Services	- Fare-free public transport for (Erasmus, Ph.D.'s) students - Bus Rapid Transit and a metro-shuttle bus to campus site outside the city centre	10) Catania (IT)	10) (Inturri, 2019)	10) (Inturri, 2019)
5) Car Sharing	7) Integrated Car-Sharing Action Plan	Pull	Public Goods & Services, Information & Education	- Increase of number of car-sharing cars + stations - Introduction of car-sharing service for employees - Integration of car sharing into residential areas, public transport, bike infrastructure, parking spaces - Awareness-raising for car-sharing services	11) Bremen (DE) 12) Genoa (IT)	11) (Glotz-Richter, 2016) 12) (CIVITAS, 2013a)	11) (Glotz-Richter, 2016) 12) (CIVITAS, 2013a)

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Table 5 (*continued*)

Intervention Category	Intervention Type	Intervention Approach	Policy Instrument(s)	Main Measures	Cities (*treated as cases of effective interventions)*	References	Stakeholder References
6) Travel Planning	8) Workplace Travel Planning	Push & Pull	Information & Education, Regulatory, Economic, Public Goods & Services	- Travel plans + advice for companies and employees - Parking management (Norwich, 20 cities in GB) - Company shuttle busses (Norwich, 20 cities in GB) - Discounts for public transport (Nantes, 20 cities in GB) - Improved bike infrastructure (B&H, Norwich, 20 cities in GB)	13) Brighton & Hove (GB) 14) Graz (AT) 15) Nantes (FR) 16) Norwich (GB) 17) 20 cities in GB (GB)	13) (CIVITAS, 2013g) 14) (ITL, 2018) 15) (CIVITAS, 2013b) 16) (CIVITAS, 2013f) 17) (Cairns et al., 2010)	13) (CIVITAS, 2013g) 14) (ITL, 2018) 15) (CIVITAS, 2013b) 16) (CIVITAS, 2013f) 17) (Cairns et al., 2010)
	9) School Travel Planning	Pull	Information & Education, Public Goods & Services	- Travel plans + advice for pupils and their parents - Promotion of walking + biking + car-pooling - Improved bike infrastructure - Promotional events + awareness-raising	18) Brighton & Hove (GB) 19) Norwich (GB)	18) (CIVITAS, 2013g) 19) (CIVITAS, 2013f)	18) (CIVITAS, 2013g) 19) (CIVITAS, 2013f)
	10) University Travel Planning	Push & Pull	Information & Education, Regulatory, Economic, Public Goods & Services	- Travel plans + advice for staff and students - Promotion of car sharing, walking, biking, public transport - Parking management on/ around the campus - Improved bike infrastructure (Bristol) - Discounts for public transport (Bristol) - Information + awareness-raising (San Sebastián)	20) Bristol (GB) 21) San Sebastián (ES)	20) (University of Bristol, 2018) 21) (CIVITAS, 2013d)	20) (University of Bristol, 2018) 21) (CIVITAS, 2013d)
	11) Personalised Travel Planning	Pull	Information & Education, Economic	- Personal travel analysis and plans for individuals - Public transport discount offers (San Sebastián, Munich, Maastricht)	22) Marseille (FR) 23) Munich (DE) 24) Maastricht (NL) 25) San Sebastián (ES)	22) (Thaler et al., 2018) 23) (Bamberg & Rees, 2017) 24) (Modijefsky, 2019) 25) (CIVITAS, 2013e)	22) (Thaler et al., 2018) 23) (Bamberg & Rees, 2017) 24) (Programme office Zuid-Limburg Bereikbaar, 2021) 25) (CIVITAS, 2013e)
7) Gamification	12) App for Sustainable Mobility Competition	Pull	Information & Education, Economic	- App for individual users + teams of local companies - Collection of points for sustainable mobility behaviour through mobility tracking of the app - Rewards from local businesses for the achievement of a certain point threshold	26) Bologna (IT)	26) (ITL, 2018)	26) (ITL, 2018)

for workplace parking, combined with either a cash-out scheme for local employers (Strompen et al., 2012) or with investments in the local public transport system (Dale et al., 2019). Access limitations introduce restrictions for cars in a defined zone during certain hours (CIVITAS, 2013c), while Parking & Traffic Control includes parking space removal, traffic route alteration, introduction of car-free streets, as well as the extension of pedestrian-friendly infrastructure and bicycle lanes (Modijefsky, 2021). Mobility Services consisted of both services for commuters to local workplaces and university students to provide free public transport passes, a private shuttle bus, and marketing and awareness-raising measures (Stumpel-Vos et al., 2013, Inturri, 2019). Car Sharing expanded car-sharing stations and cars for both private households and as employees, integrating car sharing into the urban transport system (CIVITAS, 2013a; Glotz-Richter, 2016). Travel Planning was carried out extensively by workplaces, schools, and universities, as well as for private citizens, combining personalized planning and advising with improved infrastructure, public transport discounts, and awareness-raising. Finally, Gamification used an app competition to track trips and award points for trips made by foot, bike, public transport, and car sharing (ITL, 2018).

3.1.2. *Comparing intervention effectiveness*

All 26 cases of interventions effectively reduced urban car use (or car ownership) either by reducing the overall car use in a certain geographical area of the city, among a certain car user group, related to a certain institution, or at a specific time of day (Table 6). Across studies, we identified ten different categories of quantified outcome measures of effectiveness for reducing car use (Table 1), which we grouped under six scopes: within a geographical area; for commuters; for universities, schools, and residents; and others (four studies each reported a unique

Table 6
Effectiveness of interventions shown to reduce car use in Europe. Ranking of the effectiveness of the 26 cases of interventions to reduce car use identified from the systematic review (Fig. 1), ordered from the most to least effective across intervention types for the same scope and category of outcome measure.

Scope of outcome measure	Categories of outcome measures	Intervention Type	Cities *(cases of interventions)*	Effectiveness	References
Geographical Area	Reduction of car traffic across the cordon to the charging zone (city centre)	Congestion Charge	London Milan Stockholm Gothenburg	33% 31.1% 22% 12%	(Metz, 2018) (Beria, 2016) (Eliasson, 2014) (Börjesson & Kristoffersson, 2015)
	Reduction of car traffic in the city centre	Parking & Traffic Control	Oslo	11% (in first two years) 19% (in third year)	(Modijefsky, 2021)
		Limited Traffic Zone	Rome	10% (during unrestricted hours) 20% (during restricted hours)	(CIVITAS, 2013c)
Commuters	Reduction of commuters travelling by car	Mobility Services for Commuters	Utrecht	37%	(Stumpel-Vos et al., 2013)
		Workplace Parking Charge	Rotterdam Nottingham	20–25% 8.6%	(Strompen et al., 2012) (Dale et al., 2019)
	Reduction of share of car use among commuters to workplace	Workplace Travel Planning	20 cities in GB Norwich Graz Nantes Brighton & Hove	18% 17.7% 12–14% 12% 3%	(Cairns et al., 2010) (CIVITAS, 2013f) (ITL, 2018) (CIVITAS, 2013b) (CIVITAS, 2013g)
University	Reduction of share of car use among commuters to University	University Travel Planning	Bristol	27% (*only* staff)	(University of Bristol, 2018)
		Mobility Services for University	Catania	24% (*only* students)	(Inturri, 2019)
		University Travel Planning	San Sebastián	7.2% (staff *and* students)	(CIVITAS, 2013d)
School	Reduction of share of car use among trips to school	School Travel Planning	Norwich Brighton & Hove	10.9% 5%	(CIVITAS, 2013f) (CIVITAS, 2013g)
Residents	Reduction of share of car use among individual residents	Personalised Travel Planning	San Sebastián Marseille Munich	8–12% 6% 5.6%	(CIVITAS, 2013e) (Thaler et al., 2018) (Bamberg & Rees, 2017)
Others	Number of private cars replaced per car-sharing car	Integrated Car-Sharing Action Plan	Bremen Genoa	15 12	(Glotz-Richter, 2016) (CIVITAS, 2013a)
	Reduced number of trips during morning rush hours	Personalised Travel Planning	Maastricht	3.800	(Modijefsky, 2019)
	Percentage of app-users with reduced share of car use	App for Sustainable Mobility Competition	Bologna	73%	(ITL, 2018)

outcome measure) (Table 6). The most commonly reported measures were reduction in car traffic in a geographic area, reported by six cities; and reduction of car commuters, reported by eight studies (one of which included 20 cities in Great Britain, for a total of 27 cities) (Table 6). The large variety in the scope and structure of outcome measures unfortunately prevents creating a single, definitive metric of overall effectiveness across all measures, but it is possible to judge effectiveness at reducing car use within each scope.

Overall, the largest reductions in car use came from the Congestion Charge; with a reduction of 33% (Metz, 2018), the Congestion Charge in London was the most effective in reducing car traffic across the cordon of a charging zone (Table 6). Since the charging zones of all congestion charges roughly covers the city centre, we concluded that London's congestion charge was also most effective in reducing car traffic in the city centre. For non-geographical outcome measures looking at reduced car use for a subset of the population, we find that the Mobility Service for commuters in Utrecht was the most effective at reducing the *number* of a specific population of car users (in this case, commuters travelling by car) (Table 6) with an achieved reduction of 37% from providing and marketing free public transport and private shuttles (Stumpel-Vos et al., 2013).

Geographical area measures are especially notable, because they indicate reducing the *overall* car traffic within the *entire centre* of a city. The greatest car use reduction within a geographical area came from the Congestion Charge (up to 33% for London), followed by the Limited Traffic Zone in Rome restricting car entry and funding public transport (reduced car traffic in the city centre by 10–20%; CIVITAS, 2013c) and Parking & Traffic Control in Oslo to reduce space for cars and increase

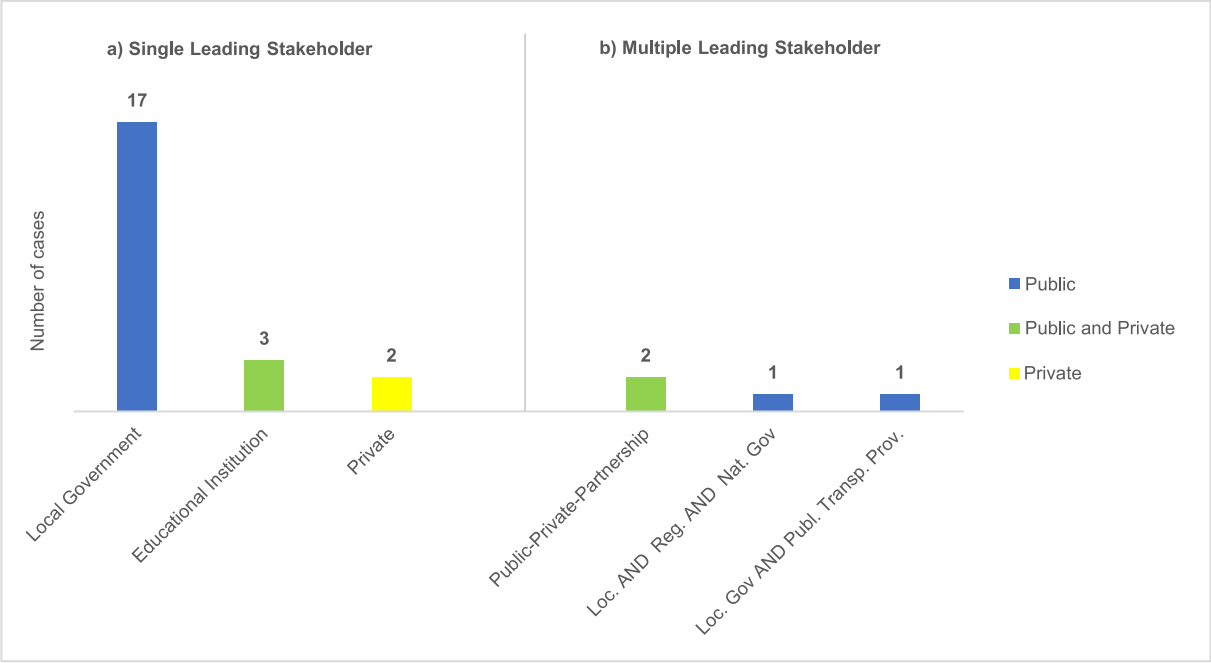

Fig. 2. Classification of Leading Stakeholders initiating and leading the planning and decision-making from 26 cases of effective interventions to reduce car use (Table 5). Most cases (N = 22) had a Single Leading Stakeholder, primarily local government (a), while four cases featured Multiple Leading Stakeholders (b). See Appendix B for a detailed list of all Leading Stakeholders.

infrastructure for walking and biking (11–19%, Modijefsky, 2021) (Table 6).

Measures to reduce car use by a specific population included those targeted at commuters, where the Mobility Service for Commuters was most effective as noted, followed by the Workplace Parking Charge (Table 6).

However, in reducing the *share* of car use among commuters, the Workplace Travel Plans of the 20 different British cities were most effective: on average across all cities, car use was reduced by 18% from a combination of parking management, company shuttle buses, public transport discounts, and improved bike infrastructure (Cairns et al., 2010).

When it comes to reducing the share of car use specifically among commuters to a University, comparing the intervention types University Travel Planning with the Mobility Services for University is difficult since their effectiveness is measured for different target groups: the University Travel Planning in Bristol reduced the share of car use among *staff* by 27%, the University Travel Planning in Catania reduced the share of car use among *students* by 24% and the University Travel Planning in San Sebastian reduced the share of car use among staff *and* students by 7.2% (Civitas, 2013d; Inturri, 2019; University of Bristol, 2018).

In reducing private car use for trips to school, the School Travel Planning in Norwich was the most effective (Table 6) with an achieved reduction of 10.9% (CIVITAS, 2013f).

The Personalised Travel Plans in San Sebastián was the most effective in reducing the share of car use among individual residents (Table 6), with a reduction between 8 and 12% (CIVITAS, 2011). In reducing the overall number of private cars in a city, the Integrated Car-Sharing Action Plan in Bremen was the most effective (Table 6). It replaced 15 private cars per car-sharing car (Glotz-Richter, 2016).

The effectiveness of the Personalised Travel Planning in Maastricht and the App for Sustainable Mobility Competitions in Bologna could not be compared since both are the only intervention types in their respective category of outcome measures (Table 6). It was also not possible to assess the overall effectiveness of the App, which reduced car use among 73% of app users (Table 6), but *how much* they reduced car use was not reported.

3.2. Involvement of stakeholder types and collaborations

Local Governments were the most important type of Leading Stakeholder to initiate and lead effective city-level interventions to reduce car use. Most cases (22 out of 26) had a single Leading Stakeholder, of which over three quarters were Local Government (17 out of 22) (Fig. 2a, Appendix B). The remaining single-led cases were led by Educational Institutions or Private Stakeholders alone (N = 3 and 2 respectively), while 4 of the 26 cases were initiated and led by Multiple Leading Stakeholders, two of them Public-Private-Partnerships (Fig. 2b, Appendix B).

Collaborations with Partner Stakeholders were important to support the planning and decision-making of the Leading Stakeholder: 20 cases involved a collaboration between the Leading Stakeholder with between one to four Partner Stakeholders, with only six cases involving only a Single Leading Stakeholder with no collaboration (Fig. 3a, Appendix B). In total, 37 Partner Stakeholders were involved in the 20 cases where collaboration occurred, most often Private Stakeholders (local companies and businesses), followed by the Public Transport Provider and Civil Society (Fig. 3b, Appendix B).

3.3. Potential of interventions as transition experiments

We identified four intervention types as high-potential transition experiments to reduce car use in Lund: an App for Sustainable Mobility Competition, Integrated Car-Sharing Action Plan, School Travel Planning, and Workplace Parking Charge (Table 7, Appendix C). All four experts considered the App for Sustainable Mobility Competition and the Workplace Parking Charge as new approaches to reduce car use in

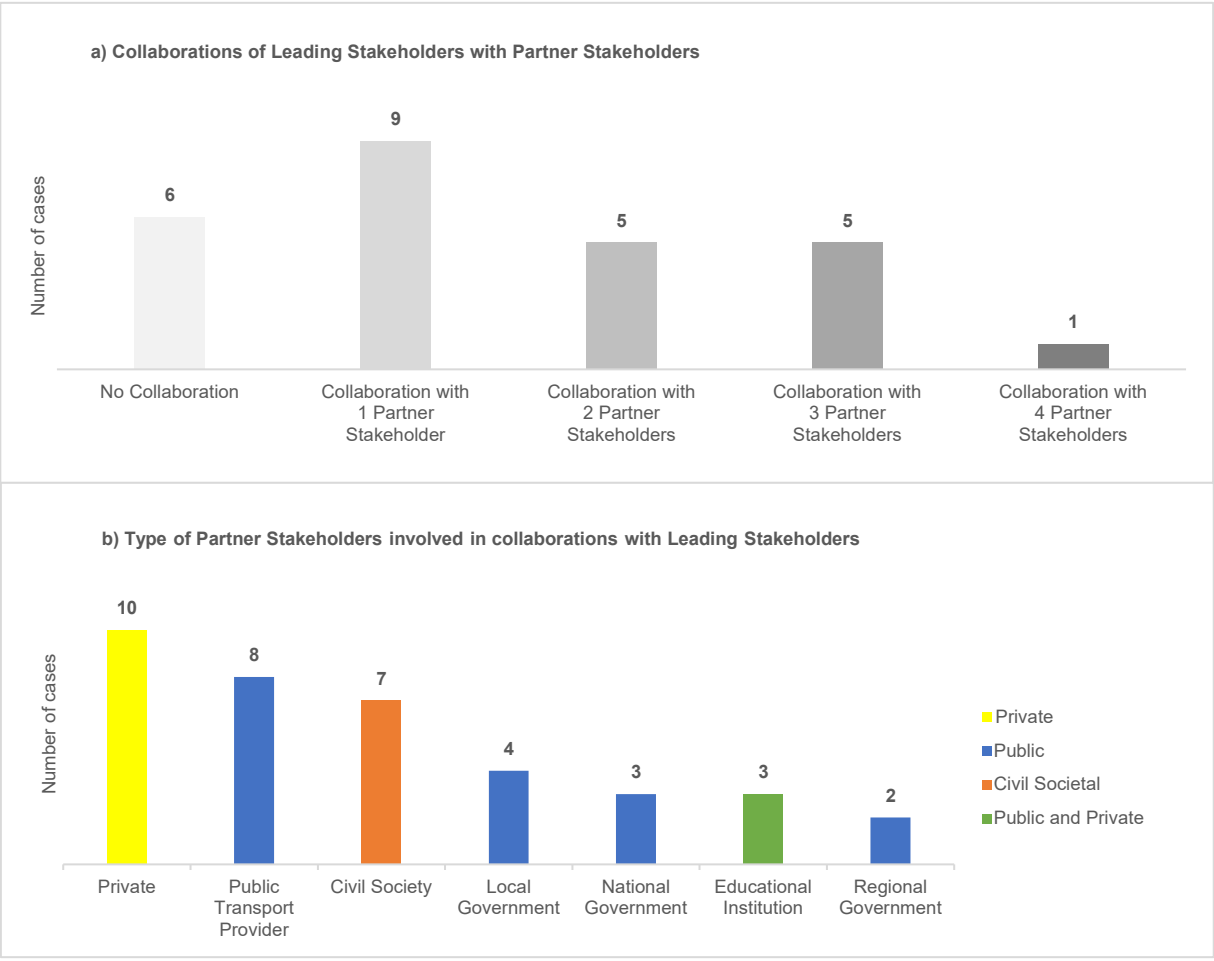

Fig. 3. Collaborations and Partner Stakeholders from 26 cases of effective interventions to reduce car use (Table 5). All but 6 cases involved collaboration between Leading and Partner Stakeholders (a), while the most common Partner Stakeholders were private collaborators, public transport providers, and civil society (b). See Appendix B for a detailed list of all collaborations and Partner Stakeholders.

Lund. The Integrated Car-Sharing Action Plan and the School Travel Planning were assessed as partly new, as three experts reported isolated existing cases of car sharing and support for School Travel Planning in Lund. All four intervention types were overall viewed as suitable to reduce car use in Lund by three experts, who also considered three interventions feasible to implement (the App for Mobility Competitions, the Integrated Car-Sharing Action Plan and School Travel Planning). The last expert mentioned available municipal resources as a possible constraint to feasibility for these three. A Workplace Parking Charge was only considered feasible with strong municipal leadership, as two experts expected opposition from local employers.

Two intervention types were evaluated as transition experiments with moderate potential: the Mobility Services for Commuters and the Parking & Traffic Control (Table 7, Appendix C). We assessed both intervention types as partly new approaches. According to two experts, free public transport trials for employees in Lund have once been tested, and shuttle busses are offered by a few local companies. Besides, three experts mention the existence of car-free streets exist in Lund's city centre. Considering the suitability of the Mobility Services for Commuters, one expert questioned if fare-free public transport offers might be used by pedestrians and cyclists rather than car users. Two experts considered a Parking & Traffic Control intervention suitable if extended to outer areas of Lund, as only a small share of local car use is produced in Lund's city centre. However, most experts expected a lack of support for parking and traffic control measures from incumbent politicians.

We evaluated six intervention types as transition experiments with low potential (Table 7, Appendix C). The Workplace and Personalised Travel Planning were not considered new approaches to reduce car use in Lund by three experts who also did not view the Mobility Services for University suitable to reduce local car use. Besides, most experts did not regard the Congestion Charge, University Travel Planning, Mobility Services for the University, or the Limited Traffic Zone as feasible to implement. The suitability of university-related interventions was questioned by three experts, since students were not judged as a major contributor to local car use. One of the experts further perceived the University as reluctant to work on reducing car trips of employees. The Limited Traffic Zone was not regarded as feasible to implement; one expert expected a lack of support from incumbent politicians regarding the restriction of car use.

Table 7
Potential of 12 interventions to reduce car use (Table 5) to function as transition experiments for the pilot study in Lund, Sweden, as assessed by four expert interviews using the three Transition Experiment Criteria.

Intervention Type	Evaluation of Transition Experiment Criteria based on the Expert Interviews (E1, E2, E3, E4)	Potential of Intervention Type as a Transition Experiment to reduce car use in Lund
App for Sustainable Mobility Competition	new ✓ suitable ✓ feasible ✓	High
Integrated Car-Sharing Action Plan	partly new ✓ suitable ✓ feasible ✓	High
School Travel Planning	partly new ✓ suitable ✓ feasible ✓	High
Workplace Parking Charge	new ✓ suitable ✓ partly feasible ✓	High
Mobility Services for Commuters	partly new ✓ partly suitable ✓ feasible ✓	Moderate
Parking & Traffic Control (City Centre)	partly new ✓ partly suitable ✓ partly feasible ✓	Moderate
Workplace Travel Planning	not new ✗ suitable ✓ feasible ✓	Low
Congestion Charge	new ✓ partly suitable ✓ not feasible ✗	Low
Personalised Travel Planning	not new ✗ partly suitable ✓ feasible ✓	Low
University Travel Planning	new ✓ partly suitable ✓ not feasible ✗	Low
Mobility Services for University	new ✓ not suitable ✗ not feasible ✗	Low
Limited Traffic Zone (City Centre)	partly new ✓ partly suitable ✓ not feasible ✗	Low

4. Discussion

We identified 26 cases of effective city-level interventions to reduce car use in Europe, which we grouped into 12 intervention types in seven categories. All 12 intervention types entail multiple measures and apply at least two different policy instruments, predominantly combining either Public Goods & Services or Information & Education with an Economic or Regulatory instrument. Half of the intervention types apply a Pull-approach to reduce car use; the other half combine a Pull- and Push-approach. No intervention type only applied a Push-approach. Different measurement indicators complicated direct comparison, but we conclude that the Congestion Charge, Parking & Traffic Control, and Limited Traffic Zone were the most effective to reduce car use since all three significantly reduced the *overall* car use in a city and not only the car use of a specific car user group. Most interventions were initiated and led by local city governments, often in collaboration with private stakeholders (e.g., local companies) as well as local public transport providers and civil society.

Using interviews to elicit local expert knowledge on three criteria for transition experiments (novelty, suitability, and feasibility) for the pilot study of Lund, Sweden, we identified four intervention types as having high potential as a local transition experiment: an App for Sustainable Mobility Competition, an Integrated Car-Sharing Action Plan, School Travel Planning, and a Workplace Parking Charge. Two interventions, Mobility Services for Commuters and Parking & Traffic Control, were identified as moderate potential transition experiments. Combining criteria for effectiveness (Table 6) and transition experiments (Table 7), we recommend a portfolio of three transition experiments to reduce car use and greenhouse gas emissions in Lund, Sweden: Parking & Traffic Control, Workplace Parking Charge, and Mobility Services for Commuters.

4.1. Comparisons with previous literature

4.1.1. Effective interventions to reduce car use

We found that all effective city-level intervention types to reduce car use combine between two and four different policy instruments; none of them relies on a single policy instrument (Table 5). This provides empirical support for recent discussions suggesting packages of different policy instruments might be more effective than a single policy instrument to shift urban travel away from car use to other transportation modes (Buehler et al., 2017; Dijk et al., 2018; Givoni, 2014; Glazener & Khreis, 2019; Scheepers et al., 2014). Transition studies also suggest so-called policy mixes of different policy instruments stimulate innovations and support sustainability transitions (Kivimaa & Kern, 2016; Nykamp, 2020; Rogge & Reichardt, 2016). A US study found that the combination of "carrots and sticks" (expanding public transport, walking, and pedestrian networks, while implementing restrictions or disincentives for car use) are most effective to reduce car use and encourage active travel modes (Piatkowski et al., 2019). Further research is needed to determine under which conditions Car Sharing reduces emissions. A study from the Netherlands found car sharing is effective in reducing car ownership and use (Nijland & van Meerkerk, 2017). However, a recent report on low-carbon lifestyles emphasises that car sharing entails the risk of rebound effects when previously car-free residents start using car sharing and increase their car use (Lettenmeier et al., 2019).

4.1.2. Stakeholder involvement and collaborations

Our stakeholder analysis found that collaborations between different types of urban stakeholders, including government, private sector, and civil society, were relevant for the planning and decision-making of most city-level interventions to reduce car use in Europe, with the local city government the most important stakeholder. This parallels findings from two global surveys of urban climate change experiments, which found collaborations between different urban stakeholders were a key characteristic of such urban experiments, and suggest that collaborations between multiple actors benefit the introduction of different interests and values in urban climate change governance (Bulkeley & Castán Broto, 2013; Castán Broto & Bulkeley, 2013). These surveys also confirm that local governments are the most prominent Leading Stakeholders for interventions that promote systemic change and greenhouse gas emission reductions on the local level (Bulkeley & Castán Broto, 2013; Castán Broto & Bulkeley, 2013). On a broader level, the findings represent the increasing shift of urban climate politics from mere top-down approaches to "collaborative and communicative planning" (Neij et al., 2015).

4.1.3. Potential of interventions as transition experiments

Tensions between the three elements of successful transition experiments (novelty, suitability, and feasibility; Loorbach et al., 2015; Roorda et al., 2014) need to be addressed to give the experiments the best chance of success in practice. The degree of novelty in transition experiments can vary, with some more far-reaching and a bigger change from existing practices, and therefore considered more radical (Bertolini, 2020). The balance between radicality and feasibility when developing transition experiments can be difficult (Roorda et al., 2014). Our interviews with experts showed they viewed completely new and thus more radical intervention types, such as the Congestion Fee, as not feasible to implement near-term and with the available resources, while less radical and more familiar interventions, such as School Travel Planning, were considered more feasible.

Suitability focused on the geographical extent of interventions, where experts emphasized the need for measures to reduce car use not only the city centre, but also address the transport demands of surrounding residential areas and from commuting to peripheral employment centres, as noted by Lund's Climate Policy Council (Neij et al., 2020).

Finally, feasibility concerns included stakeholder support and currently available resources. Local experts expect opposition from local employees and incumbent politicians for more restrictive intervention types to reduce car use, such as the Workplace Parking Charge or Parking & Traffic Control (Table 7, Appendix C). Both interviewed practitioners named the currently available financial and human resources as a potential constraint to the near-term implementation of interventions, in line with cost constraining transition experiments' feasibility found by Wittmayer et al. (2018). We further detected tensions between the feasibility and effectiveness of intervention types. Two of the three most effective intervention types (Congestion Charge, Limited Traffic Zone) were not regarded as feasible to implement by the experts (Table 7). This tension may also be reflected in the findings of our literature search, namely that far more studies focus on hypothetical, ex-ante projections of possible measures, rather than reporting ex-post evaluation of actually implemented policies.

To develop stakeholder support and commitment and address resource constraints, transition management suggests setting up a transition team with three to five employees of the municipality to develop a process plan, budget, and communicate the experiment internally and externally (Roorda et al., 2014; Wittmayer et al., 2018). Given long-term economic planning, generally decided four years in advance for Lund municipality, transition experiments should ideally be planned early to introduce them into the municipal budget plans as soon as possible.

4.2. Policy implications for reducing car use

Transition management suggests developing a portfolio of different transition experiments that collectively support the achievement of transition goals (Loorbach et al., 2015). We suggest five steps to plan and decide on a portfolio of transition experiments to reduce local car use in European cities, drawing on the principles of transition management and our research findings: (1) establish a transition team, (2) engage Partner Stakeholders, (3) decide on a portfolio of transition experiments, (4) develop a process and budget plan as well as an internal and external communication plan, and (5) develop a monitoring and evaluation plan.

First, a *transition team* of municipal employees should be established to represent the municipality as the Leading Stakeholder to initiate, lead, and facilitate the experiments. Our work shows that local governments are the key actor to promote urban transport transitions; however, not by enforcing top-down decisions, but by initiating and facilitating climate actions and actively engaging in collaborations with other local stakeholders.

Second, the transition team can *engage and involve different Partner Stakeholders* to ensure the inclusion of different interests, values, and competencies in the planning, decision-making, and implementation of the experiments. We found that especially private stakeholders such as local companies and businesses, as well as local transport providers and civil society, are relevant partner stakeholders for collaboration.

Third, the transition team and partner stakeholders can select a *portfolio of transition experiments,* starting with the twelve effective intervention types identified here (Table 5), and assessing how the main measures and policy instruments contained in the selected intervention types can be translated into local, context-specific transition experiments which comply with the city's overarching, long-term sustainability vision.

Fourth, the transition team can *develop a process and budget plan* for the transition experiments, to be incorporated in the next municipal budget plan. To develop support from relevant political, municipal, civil, and private stakeholders, it is important to have strong *internal and external communication* of the transition experiments.

Fifth, the transition team should develop a *monitoring and evaluation plan* to assess both the effectiveness of the experiments in reducing transport emissions (recommended measurement unit: kilometres-per-person-travelled-per-day by each travel mode) and ensure the coherence of the experiments with the city's long-term sustainability vision and goals. This approach to identify challenges and opportunities as they emerge enables a "learning-by-doing" process where insights can be translated into strategic, long-term policies to support the sustainable transition of the local transport sector.

For a portfolio of transition experiments for our pilot study in Lund, Sweden, we suggest a combination of *Parking & Traffic Control* as one of three intervention types which we found to be most likely to reduce local car use, with *Mobility Services for Commuters* and a *Workplace Parking Charge* to tackle commuting as a main contributor to high car use in Lund, including beyond the city centre. A comparison of the potential of the 12 intervention types to function as transition experiments to reduce car use in Lund (Table 7) with their potential in reducing overall car use and its associated greenhouse gas emissions (Table 6), revealed tensions between feasibility and potential effectiveness. The three suggested intervention types offer a good trade-off between having a high or moderate potential as transition experiment as well as having a great potential to reduce local car use and emissions.

5. Research limitations and future research

Our review of nearly 800 documents on reduced car use (369 scientific articles and 407 case-study reports) found only 24 that adequately quantified reduced car use, of which only 10 were peer-reviewed studies. The current shortcomings in research design and reporting limit actionable knowledge for informing policies to effectively reduce car use. This is especially concerning as the lack of quantified evidence in evaluations of interventions to reduce car use was already reported by Graham-Rowe et al. (2011) and Scheepers et al. (2014). Hence, the evidence basis of effective interventions to reduce car use has not improved notably in the past 10 years.

We suggest that future research (1) focus on ex-post analysis to evaluate interventions' effectiveness based on observed car use reductions, which are more valuable for policy learning than estimated or simulated reductions (Dijk et al., 2018); and 2) report standardized, quantified outcome measures for car use reduction, to allow accurate comparison and ranking of effectiveness. We suggest future research should report transport interventions in terms of kilometres-per-person-travelled-per-day, which is the outcome measure suggested by Graham-Rowe et al. (2011). This measure would allow estimating the greenhouse gas emissions reductions achieved by an intervention, which is essential to inform policy, but rarely reported directly or possible to calculate from reported outcome measures (Wynes et al., 2018). Future research should also report implementation cost, which we have seen is important for stakeholder support, but was not reported by the studies we identified. Finally, future research could add reduced car *ownership* as well as car use to their search terms, to explicitly focus on this car-reduction pathway.

Our pilot study of Lund only included a small number of interviews, although it benefitted from being able to draw from existing transport policies and a comprehensive assessment of transport needs to meet Lund's climate goals (Neij et al., 2020). Future research assessing the dynamics of the 26 cases where effective interventions were undertaken, including interviewing relevant stakeholders, would be useful to inform successful transition experiments. It is particularly important to gain insight into how support was developed for the more radical and more effective transition experiments to reduce car use, as radical emissions reductions are needed to avoid catastrophic warming.

6. Conclusion

We have identified 12 intervention types that are effective in reducing urban car use, which is important to meet urban climate goals. This menu of interventions can be used to inform city-level efforts to reduce car use, following our approach to apply transition management to identify interventions viewed as novel, suitable, and feasible by local experts in order to support successful local transition experiments. Such approaches are needed to gain public and policymaker support for the radical policy and behavioural changes needed to rapidly reduce greenhouse gas emissions and limit global warming near 1.5 °C.

CRediT authorship contribution statement

Paula Kuss: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Kimberly A. Nicholas:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Overview of the effective city-level interventions to reduce car use

The table presents a detailed list of *all* measures introduced by each of the 26 cases of effective interventions to reduce car use. While Table 5 presents a summary of the *main* measures (bold in this table) introduced by the cities (cases) that were classified as one intervention type, this table presents *all* measures each city (case) within an intervention type introduced when implementing the intervention.

Intervention Category	Intervention Type	Cities *(treated as cases of interventions)*	Measures a city (case of intervention) introduced when implementing the intervention	References
Charging & Pricing	***Congestion Charge***	(1) Gothenburg (SE)	• introduced 2013 (after referendum) **congestion pricing in defined charging zone (cordon-based system)** **co-funding of large infrastructure package with revenues of the charges** time-of-day dependent charges (charging from 6.00 to 18.30; costs between 8SEK-18SEK in both directions)	(Börjesson & Kristoffersson, 2015)
		(2) London (GB)	• introduced 2003 **congestion pricing in defined charging zone (cordon-based system)** **80% of revenues used for public transport investments** fixed daily charge (initial charge 5£ per day, price raised in 2005 (to 8£/day) and 2011 (10£/day) and in 2014 (11.50£/day)) discounts + exemptions for certain groups + vehicles	(Metz, 2018)
		(3) Milan (IT)	• introduced 2011 (after referendum) **congestion pricing in defined charging zone (cordon-based system)** **reinvestment of charge in public transport** fixed daily charge discounts + exceptions for certain groups + vehicles	(Beria, 2016)
		(4) Stockholm (SE)	introduced in 2007 (after referendum) **congestion pricing in defined charging zone (cordon-based system)** **revenues of congestion fee as part of infrastructure package** weekday and time-of-the-day dependent charge	(Eliasson, 2014)
	Workplace Parking Charge	(5) Nottingham (GB)	• introduced 2012 **workplace parking fee** for car parking spaces used by major employers within city boundaries that have more than 10 workplace parking spaces **revenues from parking fee used to part-fund transport initiatives** (e.g., expansion of tram line) public consultation process before introduction	(Dale et al., 2019)
		(6) Rotterdam (NL)	• introduced 2004 **workplace parking fee** for Erasmus Medical Centre (approx. 10.000 employees) parking fee according to arrival time and living distance to hospital **cash-out scheme:** credit for employees for every km not travelled by car	(Strompen et al., 2012)
Access-Limitations	***Limited Traffic Zone***	(7) Rome (IT)	• **restricted zone for cars in city centre** (electronic gates at entry points) introduced 2001, expansion of size in 2007 time-of-the-day and weekday dependent restrictions (restrictions between 6.30 and 18.00 on weekdays and between 14.00 and 18.00 on Saturdays) access for residents and other users who pay an annual fee for the entry permit **revenues from entrance fee + violation fines for investments in public transport services**	(CIVITAS, 2013c)
Parking & Traffic Control	***Parking & Traffic Control***	(8) Oslo (NO)	• implementation between 2015 and 2019 **Removal of on-street parking spaces in + around city centre** **Introduction of car-free streets** **Alteration of traffic routes** **New bike lanes + extension of pedestrian-friendly infrastructure** (pedestrian network, terraces, playgrounds etc.)	(Modijefsky, 2021)

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(*continued*)

Intervention Category	Intervention Type	Cities *(treated as cases of interventions)*	Measures a city (case of intervention) introduced when implementing the intervention	References
Mobility Services	***Mobility Services for Commuters***	(9) Utrecht (NL)	• launched 2008–2012 based on Public-Private Cooperation "Foundation Utrecht Accessible" **free public transport pass (UB pass) for employees in Utrecht** (since 2011 companies from the whole region could by the pass); pass for local buses and trams in the region as well as for a bicycle rental service **Green Shuttle Bus: private bus which transfers between train stations, park'n'ride facilities and business areas** (must be paid extra) **marketing + communication plan**, awareness-raising of companies for urban mobility (e.g., creation of website)	(Stumpel-Vos et al., 2013)
	Mobility Services for University	(10) Catania (IT)	• **Bus Shuttles**: Bus Rapid Transit to Campus (2013) + Metro-Bus-Shuttle (2017) **free access to all public transport** (2018) for students, Ph.D., trainees, Erasmus students etc.	(Inturri, 2019)
Car-Sharing	***Integrated Car-Sharing Action Plan***	(11) Bremen (DE)	• launched in 2009 **increase of car-sharing cars + stations** (city-centre + residential areas) **car-sharing services for private households + employees** (e.g., municipality) bicycle stands at car-sharing station **proximity of car-sharing stations to public transport nods (e.g., train station)** **awareness-raising + PR campaigns**: billboards, media reports, campaigns etc possibility to purchase Public Transport Season Ticket in combination with Car-Sharing Card	(Glotz-Richter, 2016)
	Integrated Car-Sharing Action Plan	(12) Genoa (IT)	• launched 2005–2008 **increase of car-sharing cars + stations** (city centre + residential areas) **car-sharing service for private household + employees** (e.g., municipality) **proximity of car-sharing to public transport nods (e.g., train station)** **promotion + awareness-raising** activities for car-sharing: media coverage (local radio, newspaper), direct marketing campaigns, street events	(CIVITAS, 2013a)
Travel Planning (TP)	***Workplace TP***	(13) Brighton & Hove (GB)	• **development of travel plan for local companies + businesses** **improvement of bike infrastructure at workplaces (e.g., bicycle storage)** promotion + awareness-raising events: Bike + Walking promotion events, Bike Maintenance Workshops Social Media engagement on different platforms to promote the travel plans and encourage participation	(CIVITAS, 2013g)
		(14) Graz (AT)	• **travel advice + development of travel plans for small + medium-sized local companies** (information handbook, free consultation, individual support etc.) monetary awards from municipality for five best travel plans which can be used by companies to implement travel planning	(ITL, 2018)
		(15) Nantes (FR)	• **travel advice + development of travel plans for companies** (analysis of mobility needs + habits and accessibility of public transport, advice for alternative travel modes) **discounts of public transport ticket for employees** follow-up assessments	(CIVITAS, 2013b)
	Workplace TP	(16) Norwich (GB)	• **travel advice + development of travel plans for local companies + businesses** **support for improving bicycle infrastructure** **parking management at workplaces (e.g., restricted car parking)** introduction of **company shuttle busses** annual travel plan awards promotion + awareness-raising: events, flyer, newsletter, development of website to guide travel plans	(CIVITAS, 2013f)
		(17) 20 cities in GB (GB)	• **development of travel plans for local companies** **parking management at workplaces (e.g., restricted car parking)** introduction of **company shuttle busses** **discounts of public transport ticket for employees**	(Cairns et al., 2010)

(*continued on next page*)

(*continued*)

Intervention Category	Intervention Type	Cities *(treated as cases of interventions)*	Measures a city (case of intervention) introduced when implementing the intervention	References
			improvement of bike infrastructure + services at workplaces awareness-raising + promotional events	
Travel Planning (TP)	***School TP***	(18) Brighton & Hove (GB)	• **travel advice + development of travel plans for local schools** **improvement of bicycle + scooter storages at schools** **promotion of walking + biking + car-pooling** scooter training for school children, support of School Travel Teams promotion + awareness-raising events: Bike + Walking promotion events, Bike Maintenance Workshops Walk to School Event Social Media engagement on different platforms to promote the travel plans and encourage participation	(CIVITAS, 2013g)
		(19) Norwich (GB)	• **travel advice + development of travel plans for local schools** **promotion of walking + biking + car-pooling** **improvement of bike infrastructure** promotion + awareness-raising: promotional events, flyer, newsletter, development of website to guide travel plans	(CIVITAS, 2013f)
	University TP	(20) Bristol (GB)	• launched by and for University of Bristol in 1998 (targeted at staff + students) **parking management**: limiting parking spaces + conditions for parking permits on University Campus, and surrounding areas of University, increased parking charges **promotion of car-sharing, car-pooling, biking, public transport** **discounted season ticket for public transport** **improved bicycle infrastructure + services** (e.g., improving changing facilities for walkers + cyclists; new, secure cycling storage)	(University of Bristol, 2018)
		(21) San Sebastián (ES)	• launched 2008–2012 **promotion public transport, bicycle, walking, carsharing and carpooling** **information + awareness campaigns for students + staff** inclusion of sustainability mobility in university learning processes	(CIVITAS, 2013d)
	Personalised TP	(22) Marseille (FR)	• **travel advice + plans for individual residents of the city** individualised mobility assessment personalised advice formal commitment to travel plan	(Thaler et al., 2018)
		(23) Munich (DE)	• **travel advice + plans for new residents of the city** (information package for new residents with information about public transport, walking, cycling, city map etc.) one-week **free public transport pass** follow-up assessment via phone to report about mobility experience	(Bamberg & Rees, 2017)
Travel Planning (TP)	***Personalised TP***	(24) Maastricht (NL)	• launched 2012–2017 **travel advice + plans for residents of the city** (analysis of mobility patterns, route planning, travel information) **mobility pass offers (includes public transport)** target groups: individual residents from different population groups (commuters, students, visitors, logistics service providers etc.) marketing + communication tools (e.g., financial incentives, gamification, off-peak points saving system etc.) branding of project with own portal, identity, communication channel, etc.	(Modijefsky, 2019)
		(25) San Sebastián (ES)	• launched 2010–2011 **personalised travel advice plans for thousands of households** in 2 city districts 3 months **free public transport pass** promotion + awareness-raising: newspaper coverage, mails, phone calls, etc.	(CIVITAS, 2013e)
Gamification	***App for Sustainable Mobility Competition***	(26) Bologna (IT)	• **App** (BetterPoints) for individual users + teams of local companies App facilitates **mobility competitions between individuals as well as between companies**: app gives scores for trips made by foot/bike/ public transport → **collection of points for sustainable mobility behaviour** collected data can be used by public administration for planning purposes	(ITL, 2018)

Appendix B. Detailed Stakeholder classification

The table presents the type and number of Leading Stakeholder and Partner Stakeholder involved in each of the 26 cases of effective interventions to reduce car use. Thus, the table presents the Stakeholder Types and Collaborations involved in the effective interventions to reduce car use.

Leading Stakeholder	Partner Stakeholder	Intervention Type	Cities *(treated as cases of interventions)*	References
Single Leading Stakeholder				
Local Government	No Partnership	Limited Traffic Zone	Rome	(DeRobertis & Tira, 2016)
	No Partnership	Personalised TP	Marseille	(Thaler et al., 2018)
	No Partnership	Personalised TP	San Sebastian	(CIVITAS, 2013e)
	Private	App for Sustainable Mobility Competition	Bologna	(ITL, 2018)
	Private	Workplace TP	Graz	(ITL, 2018)
	Private	Workplace TP	Norwich	(CIVITAS, 2013f)
	Educational Institution	School TP	Norwich	(CIVITAS, 2013f)
	Civil Society	Congestion Charge	Milan	(Beria, 2016)
	Public Transport Provider	Congestion Charge	London	(Centre for Public Impact, 2016)
	National Government, Regional Government	Congestion Charge	Gothenburg	(Börjesson & Kristoffersson, 2015)
	Civil Society Private	Workplace Parking Charge	Nottingham	(Nottingham City Council, 2008)
	Civil Society Private	Parking & Traffic Control City Centre	Oslo	(Modijefsky, 2021)
	Private Public Transport Provider	Integrated Car-Sharing Action Plan	Bremen	(Glotz-Richter, 2016)
	National Government Civil Society Private	Integrated Car-Sharing Action Plan	Genoa	(CIVITAS, 2013a)
	National Government Private Public Transport Provider	Workplace TP	Nantes	(CIVITAS, 2013b)
	Civil Society Private Public Transport Provider	Workplace TP	Brighton & Hove	(CIVITAS, 2013g)
	Civil Society Educational Institution Public Transport Provider	School TP	Brighton & Hove	(CIVITAS, 2013g)
Educational Institution	Local Government	University TP	Bristol	(University of Bristol, 2018)
	Local Government Public Transport Provider	Mobility Service for the University	Catania	(Inturri, 2019)
	Local Government Regional Government Public Transport Provider	University TP	San Sebastian	(CIVITAS, 2013d)
Private	No Partnership	Workplace Parking Charge	Rotterdam	(Strompen et al., 2012)
	Local Government Public Transport Provider Civil Society Private	Workplace TP	20 cities in UK	(Cairns et al., 2010)
Multiple Leading Stakeholder				
Local Government Public Transport Provider	University	Personalised TP	Munich	(Bamberg & Rees, 2017)
National Government Regional Government Local Government	Civil Society	Congestion Charge	Stockholm	(Eliasson, 2014)
Public-Private-Partnership: (Local Gov., National Gov., Regional Gov., Private)	No Partnership	Mobility Service for Commuters	Utrecht	(Stumpel-Vos et al., 2013)
Public-Private-Partnership: (Local Gov., Private, Public Transport Provider)	No Partnerships	Personalised TP	Maastricht	(Programme office Zuid-Limburg Bereikbaar, 2021)

Appendix C. Coded themes (Transition Experiment Criteria) of expert interviews

The table presents the colour-coded themes (Transition Experiment Criteria) for each intervention type from all four expert interviews as well as the evaluation of the Transition Experiment Criteria based on the coded themes as explained in the Methods.

Intervention Type	Coded Themes (Transition Experiment Criteria)	Expert 1 (E1) *Practitioner*	Expert 2 (E2) *Practitioner*	Expert 3 (E3) *Researcher*	Expert 4 (E4) *Researcher*	Evaluation of the Transition Experiment Criteria
App for Sustainable Mobility Competition	*Novelty*					new ✓
	Suitability					suitable ✓
	Feasibility					feasible ✓
Integrated Car-Sharing Action Plan	*Novelty*					partly new ✓
	Suitability					suitable ✓
	Feasibility					feasible ✓
School Travel Planning	*Novelty*					partly new ✓
	Suitability					suitable ✓
	Feasibility					feasible ✓
Workplace Parking Charge	*Novelty*					new ✓
	Suitability					suitable ✓
	Feasibility					partly feasible ✓
Mobility Services for Commuters	*Novelty*					partly new ✓
	Suitability					partly suitable ✓
	Feasibility					feasible ✓
Parking & Traffic Control (City Centre)	*Novelty*					partly new ✓
	Suitability					partly suitable ✓
	Feasibility					partly feasible ✓
Workplace Travel Planning	*Novelty*					not new ✗
	Suitability					suitable ✓
	Feasibility					feasible ✓
Congestion Charge	*Novelty*					new ✓
	Suitability					partly suitable ✓
	Feasibility					not feasible ✗
Personalised Travel Planning	*Novelty*					not new ✗
	Suitability					partly suitable ✓
	Feasibility					feasible ✓
University Travel Planning	*Novelty*					new ✓
	Suitability					partly suitable ✓
	Feasibility					not feasible ✗
Mobility Services for University	*Novelty*					new ✓
	Suitability					not suitable ✗
	Feasibility					not feasible ✗
Limited Traffic Zone (City Centre)	*Novelty*					partly new ✓
	Suitability					partly suitable ✓
	Feasibility					not feasible ✗

new / suitable / feasible

partly new / partly suitable / partly feasible

not new / not suitable / not feasible

uncertainty of expert / no suitable answer of expert

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