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The atmospheric impacts of initiatives advancing shifts towards low-emission mobility: A scoping review

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Abstract

In an urban environment, people's daily traffic choices are reflected in emissions and the resulting local air composition, or air quality. Traffic contributes to the emissions of both carbon dioxide (CO₂), affecting climate, and particulate matter (PM), affecting atmospheric chemistry and human health. While the development of city infrastructure is not in the hands of individuals, it is their transport mode choices that constitute traffic. In this scoping review we analyse 108 initiatives from around the world potentially influencing individual travel behaviour and producing changes in the shares of different transport modes (modal shifts). The targets, types and techniques of initiatives are identified. Examples of economic, regulative, structural and persuasive initiatives are included. Special focus is on whether the impacts on CO₂ emissions, PM emissions and/or PM concentrations have been quantitatively evaluated, and on the quality and results of the evaluations. We observe that a variety of targets can motivate actions that lead to modal shifts and emission reductions. The results indicate that the level of atmospheric evaluations is low: absolute or relative changes in emissions and/or concentrations had been evaluated for only 31% (N=34) of the reviewed initiatives, with substantial heterogeneity in quality. Sanctions, such as congestion charge and restrictions, have more likely been evaluated in peer reviewed analyses than incentives. Evaluations of impacts on ambient PM concentrations are especially scarce (N=4), although Air Quality is the primary target of 13% of actions, and secondary target for at least 12%. We discuss the determinants of success and failure, when it comes to different types of initiatives, emission reductions and evaluations. A high-quality evaluation of atmospheric impacts captures the following: correct data about the modal shift (rate and direction), exclusion of

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external factors affecting the shift and emissions, and possible indirect impacts of the shift.

Keywords: Air Quality, Climate Change, Traffic emissions, Behaviour change, Incentives, Sanctions

1. Introduction

Urbanization, economic growth and anthropogenic carbon emissions have developed hand in hand in the past. With the majority, 55%, of the world's population now residing in urban areas, and with rapid urbanization projected for many countries by 2050 [1], it is more relevant than ever to break the connection between urban systems and their adverse environmental impacts caused by e.g. traffic emissions.

The dwellers of a city share the environment, infrastructure and rules. Traffic and mobility do not form an isolated sector but are interrelated with many aspects of urban development. Despite the fundamental role played by infrastructure, it is, ultimately, the daily decisions and transit habits of individuals that generate traffic and its emissions. Irrationality describes the nature of those decisions and habits, when they lead to outcomes that are not optimal for either the individual or the urban system as a whole: congestion, extended travel times, noise, greenhouse gas (GHG) emissions and air pollution, exposure to which has consequences to public health and mortality.

Traffic contributes to both GHG emissions affecting climate, and particulate matter affecting atmospheric processes, climate and human health. The transport sector, including passenger and freight transport, accounts for 14% of global carbon dioxide emissions [2]. 40% of the CO₂ emissions from road transport are from urban mobility. Of the primary emissions of fine particles (particulate matter with aerodynamic diameter less than 2.5 micrometers, $PM_{2.5}$) in Europe, around 11% are from road transport [3]. Looking at urban areas, the contribution of traffic to ambient concentrations of $PM_{2.5}$ is strongly dependent on the measurement point, local conditions such as vehicle fleet and road infrastructure, the presence of other sources, meteorology and atmospheric dispersion. Source apportionment of $PM_{2.5}$ indicates the traffic-originated fraction of measured concentrations, which may range from less than 10% to close to 100%, typically being between 10% and 50% in an urban environment [4]. Traffic is a multifaceted source of particles: it includes primary particle emissions from exhaust, organic and inorganic gaseous precursors of

secondary particles from the combustion of fuels and lubricants, particles that end up in the air through tyre and brake wear, and the re-suspension of depositions on the road and road wear material ([5], [6]). Car ownership and high PM concentrations are linked, and the negative impacts on human health are tangible in e.g. many Chinese cities [7].

According to projections by OECD International Transport Forum [8], the global passenger demand will more than double between 2015 and 2050, with economic development as the main driving force. How the growing demand is reflected in atmospheric emissions and air quality is dependant on how the demand is addressed: which modes are supplied and available to people, and what kind of transit habits people develop. The advent and adoption of new transport solutions or different technology could change the prevailing mobility system. Could, for example, ride-sharing become the norm and overhaul private car as the predominant transport mode? What would be the achieved change in atmospheric impacts of traffic?

In general, the preferred direction of changes in transport mode shares (*modal shifts*) is away from private cars and towards more mass transit and soft mobility (walking and cycling). From the perspective of atmospheric impacts, the key questions regarding modal shifts include: 1) What is the rejected mode, and what replaces it?; 2) How many people adopt new behaviour, how quickly and for how long?; 3) Does the modal shift lead to indirect emissions or leakage to another sector, e.g. due to more demand for energy production with fossil fuels?

Being exposed to congestion, noise and air pollution, and contributing to GHG emissions do not seem to provide enough reasons for people to shift to using more sustainable travel modes. As demonstrated by Lanzini and Khan [9], environmental values and variables play a relevant role in shaping people's behavioral intentions, but their effect on actual behaviour and choices is negligible. Psychological studies in this domain demonstrate that people's frequently repeated travel mode choices are actually habitual, script-based, which implies that the decisions are made without much deliberation ([10], [11]). When circumstances remain the same, choice-making is on "auto pilot". A context change, however, may enhance the likelihood that important values are again considered and may guide behaviour [12]. Empiric studies demonstrate this in the context of temporary structural changes, such as freeway closure or a period of free public transport ([13], [14], [15]). They argue that this kind of context changes could be efficient tools for advancing modal shifts and triggering cooperation in a social dilemma, of which using common resources such as road network and urban air is a prime example.

In the light of above deliberation, some sort of nudging or interventions seem necessary in order to break habits and advance modal shifts. Desired behavioral changes resulting in more sustainable mobility may be achieved via two avenues: by making the sustainable modes more desirable, beneficial, easy or even irresistible, and/or by making the unsustainable modes more difficult or costly. The former way refers to *incentives*, and the latter to *sanctions*, dis-incentives and punitive measures.

Possible ways to deploy incentives and sanctions are varied. Top-down approach comprises policy instruments that cover regulatory, economic and fiscal measures: fees, tolls, subsidies, restrictions, low-emission zones, bans. Structural approach and land use planning may be used for promoting access to public transport and improving biking infrastructure, or to address commuting distance. Persuasive and information instruments are about awareness and concern raising, knowledge transfer, rewarding desired choices, decision support tools and other forms of encouragement. Events (such as car-free days) and competitions represent one frontier in travel behaviour change instruments.

Some reviews of urban mobility initiatives conclude ineffectiveness. Regarding measures for reducing emissions of private cars, Nurul Amin [16] concludes that no lasting effects have been achieved, because the actions have not led to changes in attitudes or in the behavioural norms of citizens, governments and businesses. A review by Graham-Rowe et al. [17] asks "Can we reduce car use and, if so, how?": they conclude that only 6 out of 77 reviewed interventions had been evaluated, with strong methodology, to have reduced car use.

Diffusion of successful policies has been identified to be ongoing in the field of sustainable transport [18]. The ability to demonstrate effectiveness is critical. When it comes to improving air quality and mitigating climate change by reducing traffic emissions, it is invaluable for decision makers to have references for expected outcomes before adopting a new practice.

This review provides an overview of initiatives taking place all over the world with the common potential to affect individuals' transport mode choices and to advance modal shifts. Our primary goal is to shed light on the variety of approaches and their targets, and especially on the level to which the atmospheric impacts of the implemented initiatives have been evaluated and are comparable. Other reviews of interventions aiming for modal shifts have been conducted, for example the following 5 studies: Pucher et al. [19] focus on biking, Bird et al. [20] investigate controlled studies of individual-level walking and cycling interventions, Graham-Rowe

et al. [17] regard car use reductions, Martin et al. [21] look at financial incentives for more active travel from a health perspective, and Otero et al. [22] focus on health and economic impacts of bike sharing systems in Europe. Henschel et al. [23] provide a review of air pollution intervention studies, not restricted to traffic, but with focus on those that assess both improvements in air quality and associated health effects. Slovic et al. [24] present an overview of local air pollution control policies and programs that aim to reduce air pollution levels in mega cities. Our aim is to provide what is lacking: a scoping review of initiatives with potential to influence individuals' transport mode choices, focusing on their *atmospheric impacts*, i.e. the effect on CO₂ and particle emissions.

2. Methodology

2.1. Framing and research hypotheses

Our analysis focuses on initiatives that may result in modal shifts by affecting individuals' transport mode decisions. Shifts towards more sustainable transport modes, determined by atmospheric emissions, are of central interest. This framing guides to look at initiatives that may lead to a shift away from conventionally fueled private vehicles and towards increased use of public transport, ride-sharing, and soft mobility (cycling and walking). Hydrogen vehicles and electric cars form a special case. They are preferred over cars operating with fossil fuels, and incentives to increase their market penetration are generally considered beneficial to climate change mitigation and air quality, but their total atmospheric impact is conditional on e.g. energy production ([25], [26]).

The hypotheses of our study were formulated as follows:

1. Initiatives with varying motivations and targets have the potential to affect transport mode choices and emissions related to mobility;
2. The level to which individual initiatives have been evaluated is low, with respect to impacts on CO₂ and PM emissions, and PM concentrations;
3. Incentives have been less deployed for air quality improvement than sanctions, and their atmospheric impacts have been less studied.

The hypotheses were tested by collecting and analysing a database of initiatives.

The first step was to explore information and to collect a database of relevant initiatives for further analysis (section 2.2). The examined sources comprised academic papers, systematic reviews, case study reports, conference presentations, websites of city officials (e.g. transport agencies), programme websites, governmental documents and news items coupled with some external source. The reduction phase included categorization and classification of data (section 2.3). The initiatives for which an atmospheric impact evaluation was found were examined more thoroughly (section 2.4). Conclusions were drawn inductively, and reflected in the light of existing literature and previous studies (section 4).

2.2. Data collection and review

The data search and collection process included themed searches, identification of interesting items, screening of sources related to them, appraisal of eligibility and collection of specific data points using an online form connected to a spreadsheet. Searches were conducted using the following search terms and different combinations thereof: *air quality, behaviour change, congestion, cycling, emissions, fee, gamification, incentive(s), individual, modal shift, public transport, restriction, sanction, traffic, traffic mode, transit, transport, walking*.

Google Scholar and Web of Science were used for searching scholar databases with the above stated search terms. In addition, Iris.ai was used for a separate search in open access journals, by feeding the artificial intelligence (AI) tool with an abstract containing relevant terminology and research hypotheses. This was done to test whether an AI assisted search using a longer description of research topic would produce similar findings as searching scholar databases with individual keywords. Because many (local) initiatives that are interesting for our study have not gained scientific interest, we also conducted keyword searches with Google search engine. A typical search produced a list with thousands of hits. We scanned through up to 10 pages of results and narrowed the search result to include only items that we deemed usable. A flow chart of the data collection process is shown in Figure 1.

For each item that was deemed eligible based on title and content scan, new keywords (in English or local language) were identified and used for searching more information.

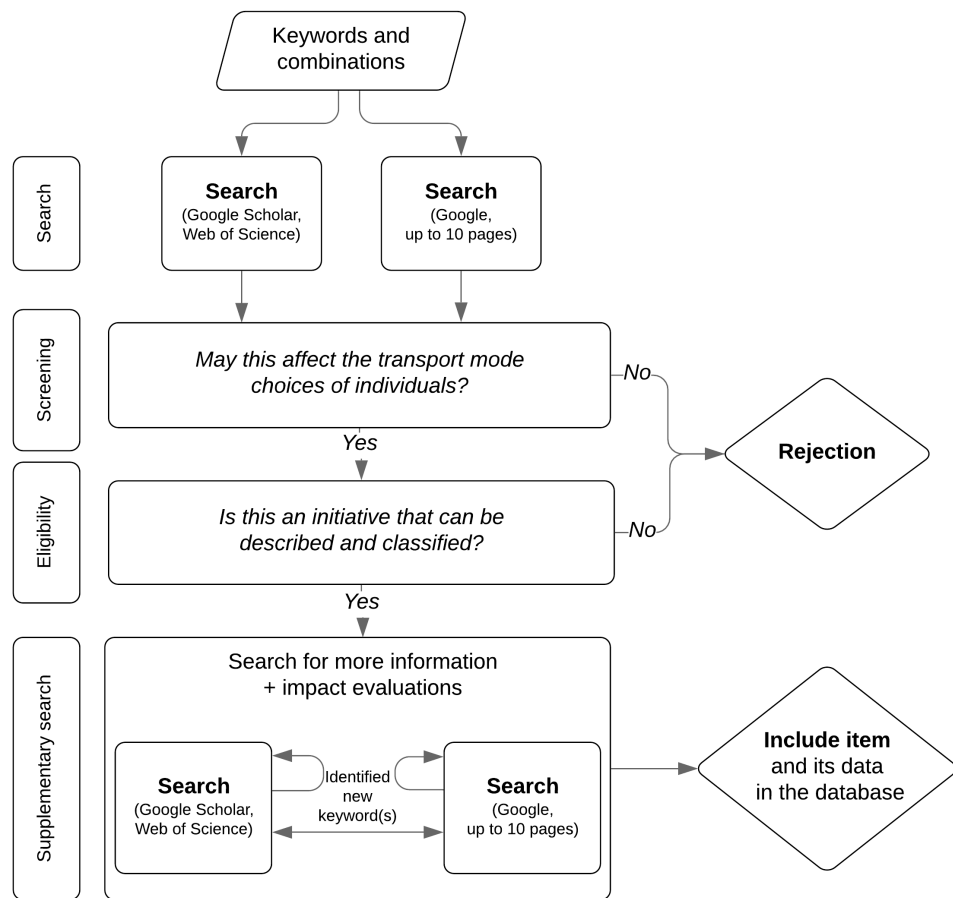


Figure 1: Data collection process.

Data collection was ongoing for approximately two months, meaning that sources for database items were extracted mainly within March-May 2019.

Language is one source of bias. Data searches were conducted in English, but documents in "local language" were encountered during supplementary searches. These other languages include Finnish, Swedish, German, French, Dutch, Spanish and Korean. Translations were sought whenever deemed relevant. Balance bias means that there are differences in the distributions of initiatives that have been deployed and that are covered by our collected data. This bias is caused by many factors, but it is evident that initiatives that have either caught scientific interest or gained media attention are emphasized in our data collection. Geographic bias may be influenced also by other factors than language: a systematic review by Fishman [27] observes that bike share activity is strongest in China, but there is a relative paucity of related research in Asia as compared to Europe, which results in a review imbalance. In addition, internet search algorithms make the authors relatively more exposed to information about initiatives deployed in Finland.

We acknowledge that the collected database is not, and can not be, exhaustive. Our primary goal is to cover a variety of initiatives, both incentives and sanction-based measures, with all identified categories represented, and with satisfactory geographical coverage. It is apparent that not all individual initiatives that have been deployed in cities all around the world have been found: Simply a review of bike share literature [27] reveals that there are over 800 cities with bike share schemes.

2.2.1. Omitted factors

The focus of our analysis should not be confused with the goal of finding different ways to reduce atmospheric impacts of traffic. If that were the framing, our analysis should include actions such as fuel reformulation, advancements in car technology, promoting biofuels, developing refuel station infrastructure etc. With the focus on behavioral change and modal shifts, the aforementioned actions are omitted from our analysis.

The year and speed of initiative adoption are not systematically analysed, despite the fact that the rapidity of adoption may be an indicator of success.

2.3. Categorization

For each item found in data search and deemed relevant, indicators of the following categories were sought and keyed.

2.3.1. Primary and secondary targets

The motivation, or target, behind each initiative was noted. For most initiatives they were clearly stated or were easy to deduce based on the available information. We highlight a primary target for each initiative, and list secondary targets when relevant, following the categories presented in table 1.

2.3.2. Spatial and temporal scale

The spatial scale of initiatives covers the following levels: micro, local, multi-local, city, multi-city, provincial, national and international. The target population is technically everyone in each scale, often depending on their travel mode choices (e.g. 'all who use private car'). Micro level forms an exception: it contains initiatives designed to consider only a small selected group of individuals, a pilot group, an exclusive cohort of people (e.g. obese men) or employees of a specific company or organization.

The temporal scale is tripartite: *long-term* means that the initiative spans over a year, *short-term* refers to campaigns shorter than a year, and a *trial* typically covers only a few weeks.

Our analysis considered mainly initiatives deployed in the past, but was not restricted to them. Also references proposing actions for the future and/or testing them with simulation were collected.

2.3.3. Initiative type

Type defines whether an initiative is about deploying an *incentive* or a *sanction*. This division is typically very clear. It is also possible that a single initiative is about deploying actions that fall into both classes, in which case its type is *both*.

The concrete measures - incentives and sanctions - were further classified into nests and sub-categories, listed in Table 2. Each approach is coupled with a behaviour change utility, which implies how the technique is supposed to motivate change and what it provides.

Table 1: Categorisation principles: Initiative target

Target	Abbreviation	Description
Air Quality	AQ	To reduce air pollution, i.e. emissions of particulate matter, NO _x , ground level ozone etc.
Awareness Raising	A	To raise awareness and increase knowledge about air pollution, climate change and/or the health and climate impacts of traffic.
Car Dependency	CD	To deploy changes that make people less dependent on their cars.
Climate Change Mitigation	CC	To reduce greenhouse gas emissions, CO ₂ in particular.
Economy	E	To collect city revenue in the form of taxes, fees, tolls or increased prices. Savings.
Health	H	To reduce people's exposure to air pollution and/or to encourage physical activity.
Image	I	To enhance company/city image.
Research	R	Experimental arrangements set up for research purposes: e.g. investigating the impacts of context change in people's behaviour.
Soft Mobility	SM	To advance cycling and walking specifically. Often motivated by multiple targets such as health, air quality or traffic management, but also deemed to have intrinsic value.
Traffic flow and volumes	T	To control traffic volumes, congestion and general fluency, to manage travel demand (to either reduce travel demand or redistribute it temporally or spatially).
Urban Planning	UP	To comprehensively direct the city development, e.g. to minimize urban sprawl.

Table 2: Categorisation principles: Nests and sub-categories of incentives and sanctions

Nest	Sub-category	Utility for behaviour change
<i>Incentives</i>		
Psychological, persuasive	Information, support	Knowledge, encouragement
	Benefit (non-monetary)	Persuasive reward
	Decision support tool	Knowledge
	Competition	Social force
	Event	Knowledge, social force
	Gamification, personalised rewards	Persuasive reward
Economic	Subsidy	Economic advantage
	Discount, fee/ tax exemption	Economic advantage
	Money, cash, micro-credits	Economic advantage
Promoting soft mobility	Cycling amendment	Infrastructure (e.g. bike lanes, facilities), equipment (e.g. bike-sharing schemes), safety measures, knowledge
	Walking amendment	Infrastructure (e.g. pedestrian streets), safety measures, knowledge
Mass transit development	Public transport development	Infrastructure, pricing
	Ride-sharing	Infrastructure, social force
<i>Sanctions</i>		
Regulative	Selective restriction	Disadvantage
	Restriction	Disadvantage
Economic	Fee, toll	Economic disadvantage
	Taxation	Economic disadvantage
	Pricing	Economic disadvantage

2.4. Evaluation of effectiveness

Firstly, each initiative was categorised as either having or not having been evaluated, with respect to CO₂ and/or PM emissions or impacts on the ambient concentration of PM. More specifically, CO₂, GHGs expressed as CO₂-equivalent (CO₂eq), PM₁₀ (particulate matter with aerodynamic diameter less than 10 micrometers) and PM_{2.5} were looked at. Each reported quantification was collected to the database. Their methodological quality was determined: *high* referring to peer reviewed studies, *medium* referring to documented but not peer-reviewed evaluations, and *low* referring to cases where a number was given without explaining the method, or the method was apparently deficient. Possible methods for the evaluation of changes in emissions and concentrations include measurements, numerical evaluation (calculation) and simulation. Furthermore, it was noted if the evaluation was action-specific, i.e. if the influence of other factors potentially affecting the evaluated measure were ruled out.

Substantial heterogeneity was expected in what has been reported for different initiatives. Emission reductions may be expressed as relative changes (percentage change for before vs. after) or absolute amounts (e.g. tons, kg, pounds, grams), and *per what* may be e.g. a year, a decade since initiative deployment, neighbourhood, household, person or km. It is apparent that this kind of heterogeneity brings challenges to comparability.

3. Results

3.1. Database

The data search yielded 135 unique eligible initiatives. The contents of scientific articles, reports or websites were scanned during data search, and their relevance was determined as part of data collection process. The total number of search results returned by online search rounds using combinations of keywords described in Section 2.2 was not recorded. Although originally deemed eligible, 27 items were later excluded due to being too ambiguous or general compared to others.

The final database consists of 108 unique items, each with one or more related references. Unique ID, location, a short description, spatial scale, primary target, and initiative type are shown for each item of the final database in Table 3.

A total of 83 initiatives were identified to be incentives, 16 were sanctions or restrictions, and 9 included actions from both categories. All continents and spatial scales are represented. Seven items were proposals, descriptions of future actions or simulations, and two items considered deployed initiatives but included a simulation of future scenarios as well.

Table 3: Database of reviewed initiatives. Item IDs refer to item types: *I* for incentives, *S* for sanctions, *B* for both. Target abbreviations according to Table 1.

ID	City, Country	Description	Scale	Primary target	Incentive sub-category	Sanction sub-category	Source
I1	Africa-wide	<i>Cycle out of poverty</i> -program, including micro-credits for bicycle purchase and designs for modified bicycles for small businesses. Provides access to income, education and health care, improves the socioeconomic position of African families.	continent-wide	E	Cycling amendment; Economic: micro-credits		[28]
I2	Sydney, Australia	<i>Bike bus</i> concept: timetabled route, picking up people to ride along, to increase confidence and awareness of bicycle friendly routes	local	SM	Information, support		[29], [30]
I3	Victoria, Australia	Event-based travel behaviour change: Annual ride-to-work day event with free breakfast.	provincial	SM	Event		[31]
I4	Australia	<i>TravelSmart</i> tool to assist individuals make smarter travel choices. Targeted at people with an identified willingness to consider ways of reducing their car use.	multi-local	SM	Information, support		[30]
I5	Australia	<i>Cycle100</i> program providing incentives for people to replace some of their car trips to work by bicycle. Free mountain bikes.	micro (pilot group, 160)	H	Benefit (non-monetary)		[30]
I6	Graz, Austria	A competition for companies to develop mobility management activities (to reduce car use)	micro (empl.)	T	Competition		[32], [33]
I7	Curitiba, Brazil	Transit-oriented urban planning	city	UP	Cycling amendment; Public transport		[34]
I8	Rio de Janeiro and Curitiba, Brazil	Bicycle lane provisioning	multi-city	UP	Cycling amendment		[35]
I9	Vancouver, Canada	Public bike share system	city	SM	Cycling amendment		[36]
I10	Vancouver, Canada	Protected bike lanes	city	SM	Cycling amendment		[37]
I11	Changning, China	Fare-free public transport scheme since July 2008	city	UP	Economic: discount, fee exemption		[38]
I12	Hangzhou, China	Bike-sharing: use public transit cards for bike sharing and receive a transit discount	city	SM	Cycling amendment		[39]
I13	Shanghai, China	Dockless bike-sharing scheme with 1.5 million bikes	city	SM	Cycling amendment		[40], [41]
I14	Taiyuan, China	Bike-sharing in a heavily air-polluted city (a deployed scheme + scenario simulation)	city	SM	Cycling amendment		[42]
I15	China	Promoting the electrification of traffic, subsidising electric vehicle purchases (deployed + scenario simulation)	multi-city	AQ	Economic: taxation; Economic: subsidy		[43], [44], [7]
I16	Bogotá, Colombia	Bus Rapid Transit system (<i>TransMilenio</i>) development, to substitute the existing "chaotic, uncomfortable, expensive and unsustainable" situation resulting from city extension	city	UP	Public transport		[45], [46]
I17	Arhus, Denmark	Incentivized sustainable commuting, free bike and free bus pass for motorists	micro (target group: 200)	H	Benefit (non-monetary)		[47]
I18	Copenhagen, Denmark	Increasing pedestrian-only spaces in city centre since the pedestrianization of the city's main street (Strøget street)	local	UP	Walking amendment		[48]
I19	Quito, Ecuador	Making the electric trolleybus system attractive: very low fares, a free month to test the system, feeder buses to allow passengers to reach most areas in Quito	city	T	Public transport		[49]

Table 3: Continued

ID	City, Country	Description	Scale	Primary target	Incentive sub-category	Sanction sub-category	Source
I20	Tallinn, Estonia	Fare-free public transport scheme	city	UP	Economic: discount, fee exemption		[50], [51]
I21	Espoo, Finland	Ride-sharing application	micro (pilot)	CC	Ride-sharing		[52]
I22	Helsinki, Finland	Commute vouchers for employees to be spent on public transport	micro (empl.)	E	Benefit (non-monetary)		[53], [54]
I23	Helsinki, Finland	Park-and-ride system	city	T	Public transport		[55]
I24	Hyvinkää, Finland	Bike-sharing system for company employees, initially as public-private cooperation	micro (empl.)	SM	Cycling amendment		[56]
I25	Kuopio, Finland	Electric city bikes in a hilly city	city	SM	Cycling amendment		[57]
I26	Oulu, Finland	Winter cycling made possible in a Nordic city	city	UP	Cycling amendment		[58], [59]
I27	Turku, Finland	Year-around city-bike system, integrated with the public transport fee system, winter maintenance of bike lanes,	city	SM	Cycling amendment		[56], [60]
I28	Finland	Collect biking kilometres in teams (communities, groups of friends, workplace teams), public competition	national	SM	Competition		[61], pers.comm.
I29	Dunkerque, France	Fare-free public transport scheme	city	UP	Economic: discount, fee exemption		[62], [63]
I30	Lyon, France	Bike-sharing system Vélo'v since 2005	city	T	Cycling amendment		[22], [64], [65]
I31	Lyon, France	Multimodal real-time travel information application for Smartphones (<i>Smartmoov</i>)	city	T	Decision support tool		[66]
I32	Paris, France	Large scale bike sharing system, <i>Vélib</i> , since 2007: with >23 thousand bikes and 110,000 trips per day, representing 2.04% of total trips made in the urban area of Paris	city	SM	Cycling amendment		[67], [22], [68]
I33	Munich, Germany	Pedestrian zones in downtown Munich	local	other	Walking amendment		[69]
I34	Bangalore, India	Bus transport system development	city	CD	Public transport		[70], [71], [16]
I35	Jakarta, Indonesia	Bus Rapid Transit System (<i>TransJakarta</i>) development	city	T	Public transport		[46], [72]
I36	Bologna, Italy	<i>BellaMossa</i> : Platform for collecting points with sustainable trips and getting rewards through local companies	city	CC	Gamification, personalised rewards		[73], [74], [75]
I37	Milan, Florence, Rome, Modena, Italy	Smartphone application (<i>Share'nGo</i>) to enable ride-sharing and earning incentives based on ride-share usage	multi-city	CD	Gamification, personalised rewards; Ride-sharing		[76]
I38	Italy	Future: Smartphone app, <i>Good.Go</i> , rewarding sustainable mobility practices with information and points assigned based on the emission level reached, allowing access to an awards system	national	SM	Benefit (non-monetary)		[77]
I39	Fukuoka, Japan	Car sharing system, in co-operation with an NGO, city and electric power company	city	CC	Ride-sharing		[18], [78]
I40	Kyoto, Japan	One-month free bus ticket. Research purpose: to investigate whether a temporary structural change would induce a lasting increase in drivers' public transport use	micro (pilot)	R	Benefit (non-monetary)		[14]
I41	Seoul, Korea	A weekly no-driving day, encouraged with benefits, e.g. discount on: parking fees, congestion charge, gasoline price, car maintenance cost, car washes	city	T	Economic: discount, fee exemption		[16], [79], [80]
I42	New Plymouth, Hastings, New Zealand	<i>Model Communities</i> Programme combining cycling-supportive infrastructure investments with community-wide promotion and awareness campaigns	multi-city	SM	Cycling amendment		[81]
I43	Oslo, Norway	Subsidies and incentives for increasing the volume of electric vehicles	national	CC	Economic: subsidy; Economic: taxation; Economic: discount, fee exemption		[82], [83]

Table 3: Continued

ID	City, Country	Description	Scale	Primary target	Incentive sub-category	Sanction sub-category	Source
144	Marikina, Philippines	Marikina Bikeways Network: bikeway construction with road improvements & widenings; bicycle safety education; information, dissemination and advocacy campaigns; recovering public places to increase mobility and green spaces	local	UP	Cycling amendment; Walking amendment; Information, support		[84], [85], [86]
145	Singapore	Pedestrian streets	local	UP	Walking amendment		[87]
146	Barcelona, Spain	Bike sharing system, <i>Bicing</i> , since 2007	city	H	Cycling amendment		[88], [89]
147	Stockholm, Sweden	Incentivized active commuting, clinical trial targeting obese women	micro (target group: 120 women)	H	Benefit (non-monetary); Information, support		[90]
148	Sweden	Electric bike purchase subsidy. The subsidy corresponds to 25 percent of the purchase price including VAT, but can be max. SEK 10 000.	national	CC	Economic: subsidy		[91], [92]
149	Dar es Salaam, Tanzania	Bus Rapid Transit System development	city	UP	Public transport		[93], [94], [95]
150	Bangkok, Thailand	Van Transit System, demand-supply principle, promoting ride-sharing	city	T	Ride-sharing		[96]
151	Enschede, The Netherlands	Smartphone app to monitor and to reward reduction in the use of conventionally fuelled vehicles with points, discounts, information, games, community support	city	CD	Gamification, personalised rewards		[97], [98]
152	Maastricht, Sittard-Geleen, The Netherlands	Employers offering pilot deals for public transport, bikes and carpooling to encourage sustainable commuting	micro (empl.)	CD	Economic: subsidy		[32]
153	The Netherlands	Future: Compensation scheme: companies paying people to cycle to work, a tax-free mileage allowance of up to 19 cents per km	micro (empl.)	SM	Economic: subsidy; Cycling amendment		[99], [100]
154	The Netherlands	An incentive program to stimulate the shift from car commuting to e-cycling in the Netherlands	provincial	CD	Economic: subsidy		[101]
155	The Netherlands	<i>Spitsmijden</i> : Rewards (money or credits for obtaining a Smartphone) to participants who avoid rush-hours and/or switch to other modes of travel or remote working. To reduce rush-hour congestion.	multi-city	T	Benefit (non-monetary); Economic: money		[102], [103], [104], [105], [106]
156	The Netherlands	Promoting cycling with incentives: tax free bicycle for employees, bicycle parking facilities, providing a public bicycle, campaigns to promote shopping and commuting by bike, promoting electric bikes	national	SM	Economic: taxation; Cycling amendment; Information, support		[107]
157	Cambridge, UK	New transport infrastructure (Cambridgeshire Guided Busway)	local	UP	Public transport		[108]
158	Cardiff, Kenilworth, Southampton, UK	Walking and cycling infrastructure programme <i>Connect2</i>	multi-local	SM	Cycling amendment		[109], [110]
159	Portsmouth, UK	<i>Big Green Commuter Challenge</i> (BGCC) competition and incentives provision to increase the number of commuters that use active and sustainable modes of transport, and to publicise the social, personal and environmental benefits of sustainable commuting. 928 participants.	micro (empl.)	AQ	Competition		[111]
160	Hertfordshire, UK	Measures to encourage cycling in employer travel plans	micro (empl.)	AQ	Information, support; Benefit (non-monetary)		[112]
161	London, UK	Year-around bike sharing scheme since 2010	city	T	Cycling amendment		[22], [113], [114]
162	Many locations, UK	<i>Green Commuter Plan</i> , a set of employer level initiatives to encourage the use of alternatives to the car and to manage car-use, in order to influence the travel behaviour of the employees, suppliers, visitors and customers of the company and to reduce the environmental impacts of transport	micro (empl.)	other	Cycling amendment; Economic: discount, fee exemption; Information, support; Decision support tool; Ride-sharing, Benefit (non-monetary)		[115]

Table 3: Continued

ID	City, Country	Description	Scale	Primary target	Incentive sub-category	Sanction sub-category	Source
163	many cities and towns (6 in 2005-2011, 12 in 2008-2011), UK	Cycling Demonstration Towns and Cycling Cities and Towns: a programme of town-level initiatives aiming to get more people cycling, more safely, more often. Implemented in urban areas of England outside London. Initiatives were tailored for each setting. Each town spent a mixture of capital investment (e.g. building cycle lanes, creating cycle parking) and revenue investment (e.g. promotional activities, cycle training). Commuter cycling was a central component of most initiatives. Also included: <i>Bikeability</i> cycle training in schools, general infrastructure improvements, cycling to stations made possible	multi-city	SM	Cycling amendment		[116]
164	Birmingham, Huntsville, Montgomery, Mobile, USA	Smartphone app, <i>Commutesmart</i> , to earn rewards for using alternative commuting modes (carpool, transit, bike, walk) or remote working	multi-city	AQ	Economic: discount, fee exemption		[117]
165	California, USA	Cash instead of parking subsidy to commuters	micro (empl.)	CD	Economic: discount, fee exemption		[118]
166	California, USA	Testing the efficacy of financial versus social incentives to reduce driving and parking	local	R	Economic: subsidy; Benefit (non-monetary); Information, support		[119]
167	Los Angeles, USA	A system, <i>Metropia</i> , to incentivize people to avoid congestion. System predicts future traffic conditions, applies a routing algorithm to find time-dependent shortest paths for different departure times, and, based on user request, provides automobile travelers with multiple departure times and route choices	micro (pilot)	T	Decision support tool		[120]
168	Los Angeles, USA	Simulation: AI based travel assistant to achieve energy & delay reductions	city	E	Decision support tool		[121]
169	Los Angeles, USA	Compressed work week to reduce commuting	micro (pilot)	T	Benefit (non-monetary)		[122]
170	Los Angeles, USA	Information provision about mode selection for the "first-last mile" (access and egress) when using public transit.	city	CC	Public transport		[123]
171	New York, L.A. Miami-Beach, USA	Hybrid-only parking	multi-city	CC	Benefit (non-monetary)		[16]
172	Oregon, USA	<i>Curb Your Car</i> project. Government offices offered the program to their employees. The program offered free bus passes and rewards for the use of alternative modes (other than cars).	micro (empl.)	CD	Information, support; Benefit (non-monetary)		[124]
173	San Diego, USA	<i>Compass + Pass</i> Programme. Participants are provided with unlimited transit system access and monthly car-sharing privileges.	micro (pilot)	CD	Benefit (non-monetary)		[125]
174	San Francisco, USA	<i>City CarShare</i> , providing ride-sharing	city	other	Ride-sharing		[126]
175	Stanford University, USA	Incentive program, CAPRI, to reward commuters for driving during off-peak hours, walking or biking	micro (pilot)	R	Economic: money		[127]
176	Washington State, USA	Community-based social marketing, <i>In Motion</i> programme, to provide neighborhood residents with incentives to try driving less, raise individual awareness of alternative travel options, and help break the automatic reflex to drive for all trips. Rewards to those who pledge. The program was designed to be easily adapted to other neighborhoods with minor modifications in message and tailored materials.	local	CD	Information, support; Benefit (non-monetary)		[128], [129]
177	Washington D.C., Baltimore, USA	Gamification application, <i>incenTrip</i> . To get personalised rewards for "greener and more efficient modes and routes"	multi-city	E	Gamification, personalised rewards		[130], [131]
178	Washington D.C., USA	<i>Capital Bicycle</i> : bike sharing system since 2008	city	SM	Cycling amendment		[132], [133]
179	Yolo County, California, USA	Incentive Program to incentivize and reward commuters for trying other means of commuting than single occupant vehicle and changing daily commute habits	multi-city	T	Benefit (non-monetary); Economic: money		[134]
180	USA	Simulation: Motivating urban cycling through a blockchain-based financial incentives system	national	T	Economic: subsidy		[135]

Table 3: Continued

ID	City, Country	Description	Scale	Primary target	Incentive sub-category	Sanction sub-category	Source
I81	USA	Corporate Bike-to-Work Incentives; companies give benefits to people who cycle to work.	micro (empl.)	CC	Economic: subsidy		[136]
I82	North America	Car-sharing programmes in North America	national	CD	Ride-sharing		[137]
I83	United States, Canada, Australia	Promoting walkable neighbourhoods and helping to find a walkable place to live through giving walk scores to areas in the context of house search engines	multi-country	SM	Decision support tool		[138]
B1	Brussels, Belgium	Low Emission Zone in the city centre, incentives for people to cancel their car registration plates and to favor sustainable mobility	city	AQ	Benefit (non-monetary)	Selective restriction	[139], [140]
B2	Vancouver, Canada	Short- and long-term street closures to encourage pedestrians	local	SM	Walking amendment	Selective restriction	[141]
B3	Beijing, China	Substituting for private travel through parking management and intelligent transport systems	city	T	Public transport	Economic: fee, toll	[142]
B4	Bogotá, Colombia	<i>Ciclovía</i> , a weekly 121-km street-closure program since 1974. Blocking off main streets to cars, opening them for bicyclists and recreational walking.	local	SM	Cycling amendment	Selective restriction	[143]
B5	Paris, France	To reduce acute air quality problems, e.g. smog, by a temporary driving restriction + making public transport free	city	AQ	Economic: discount, fee exemption	Selective restriction	[144]
B6	Paris, France	Pedestrianisation of a busy motorway	local	AQ	Walking amendment	Restriction	[145], [146]
B7	France	Taxation and subsidies to guide new car purchases based on CO ₂ emissions	national	CC	Economic: taxation; Economic: subsidy	Economic: taxation	[147], [148], [149]
B8	Bangkok, Thailand	Walking street programme, street closure campaign with activities and awareness raising	local	A	Walking amendment	Selective restriction	[150]
B9	organisations and employers in any city, UK	Travel plans for reducing employee travel by car	micro (empl.)	CD	Cycling amendment; Benefit (non-monetary)	Economic: fee, toll; Selective restriction	[151]
S1	Beijing, China	Vehicle labelling (green, yellow, red) indicating emission standard, restrictions according to the label	city	AQ		Selective restriction	[152]
S2	Shanghai, China	A mixture of actions including implementing emission limit for vehicles, forbidding the operation of motorcycles and controlling the number of vehicle licenses for private use.	city	AQ		Restriction	[153]
S3	Beijing, China	Traffic control during the Olympic Games. Restricted operation for private vehicles, allowed on odd or even days depending on the last digit of their license plates.	city	other		Selective restriction	[154], [155]
S4	Paris, France	Banning cars built before 1997 (approximately 10% of registered cars) from driving within the city on weekdays	city	AQ		Selective restriction	[156]
S5	Delhi, India	<i>Odd/even</i> license plate based driving restriction periods since 2016, typically 2 weeks at a time. Ban does not apply to women or the Prime Minister and his ministers. Also auto-rickshaws, taxis, scooters and motorcyclists are excluded.	city	AQ		Selective restriction	[157], [158], [159]
S6	Milan, Italy	Milan Ecopass scheme, congestion charging within a specified zone	city	AQ		Economic: Congestion charge	[160], [161], [32]
S7	Seoul, Korea	Congestion pricing scheme since 1996; exemption if 3+ people in a car.	local	T		Economic: Congestion charge	[162], [163]
S8	Mexico City, Mexico	<i>Hoy No Circula</i> : Banning drivers from using their vehicles one weekday per week + Saturdays based on the last digit of the license plate	city	AQ		Selective restriction	[164], [165]
S9	Oslo, Norway	Eliminating parking spots within city centre	local	UP		Restriction	[166], [167]
S10	Singapore	Part of the central business district made into a restricted zone with entry fee, Electronic Road Pricing (ERP), raised parking charges. Revenue directed at the development of a rapid transit system.	city	T		Economic: fee, toll; Economic: taxation; Selective restriction	[168], [169], [170]
S11	Singapore	Vehicle Quota System to reduce the number of private vehicles in operation	national	T		Economic: taxation	[171], [172], [173]

Table 3: Continued

ID	City, Country	Description	Scale	Primary target	Incentive sub-category	Sanction sub-category	Source
S12	Madrid, Spain	Banning cars built before 2000 from driving into the city	city	AQ		Selective restriction	[174], [175]
S13	Stockholm, Sweden	Congestion charging, a road toll scheme: formally a tax decided by the national parliament, supplemented by extension of public transport services	city	T		Economic: Congestion charge	[176],[161], [177]
S14	Bristol, UK	Removing the right to park at a university campus	local	UP		Restriction	[178]
S15	London, England	Congestion charge since 2003, changed in 2008 to CO ₂ charge	city	T		Economic: Congestion charge	[161], [177], [179]
S16	Birmingham, Chicago, Minneapolis and Oakland, USA	Gasoline price increase; focus on the impact on cycling	local	n/a		Economic: gasoline price	[180], [181]

Both scientific and other sources were utilised for finding information about initiatives that may advance the shift to low-emission mobility. For 54 items out of 108, no scientific source was found. Sanction-type initiatives are more often analysed by peer-reviewed analyses than incentives: 64 % of items considering sanctions included a scientific reference, while the fraction of incentives with peer-reviewed sources was 46 %. Non-scientific references are emphasized in the most recent data. The majority of sources are from year 2010 or later. A slight trend in what type of initiatives have gained interest over the years may be observed based on our database: sanctions and restrictions have been focused at in relatively earlier studies than incentives. Gamification and ways to personalise rewarding represent the newest frontier.

The geographic distribution of analysed items (Figure 2) shows that Europe is strongly represented in our data, with action examples from all nests of incentives and sanctions. For both Europe and North America, most initiatives fall into the nest of psychological and persuasive measures. Promoting soft mobility (cycling and walking amendments) is the only nest with examples from all over the world. Sanctions are relatively prominent in the data from Asia. Persuasive incentives (psychological, economic) are more prevalent in the Western world than in Asia or South America, where the focus is more on infrastructure and the provision of new means of transport. Data from Africa is scarce.

Figure 3 depicts counts of initiative types with different primary targets. The most common primary target is to promote soft mobility: 21.3 % (N=23) of the database items. None of the

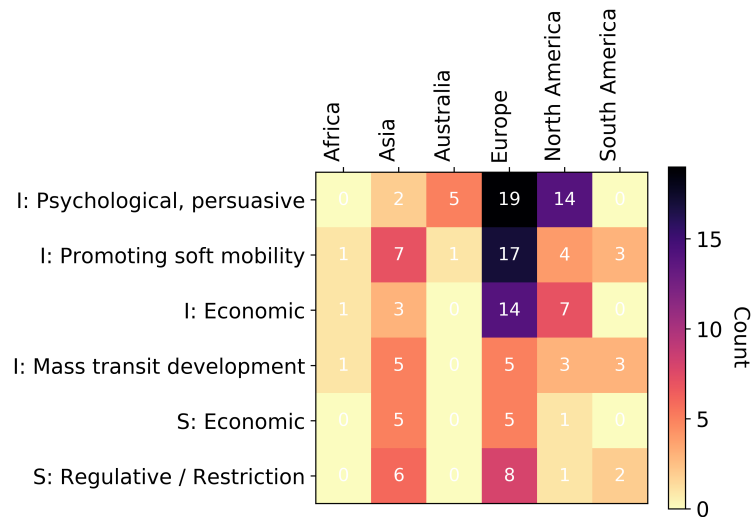


Figure 2: Counts of reviewed items categorized based on geographic location (continent where deployed) and the nest(s) to which the initiatives were labelled.

initiatives with this target are about deploying only a sanction. When the identified primary target is air quality, 71.4% of initiatives include sanctions or restrictions. For research purposes and health promotion, only initiatives relying on incentives were identified. The target category "other" includes initiative motivations such as business, company image and "being able to host the Olympic Games".

Urban planning or urban development is mentioned (or inferred) as a secondary target in connection to almost all primary targets. Climate change mitigation is most commonly paired with the primary target 'Traffic', referring to the fact that congestion alleviation, reduced traffic volumes and better traffic flow are associated with potential to reduce the number of private vehicles and related GHG emissions. The primary target 'Health' is not once coupled with 'Air Quality'. It reflects that physical activity, rather than exposure to traffic originated pollutants, is viewed as the determinant for health in the context of those initiatives.

A diagram of item counts in each initiative nest and sub-category (Figure 4) shows that psychological / persuasive incentives form the largest nest (27.7% of the techniques used in

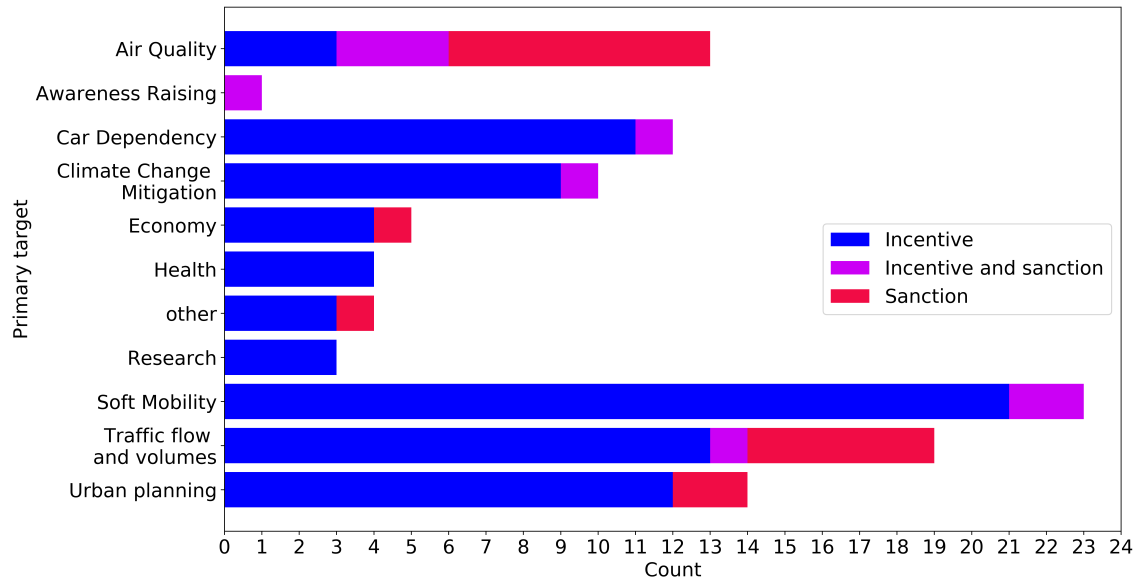


Figure 3: Counts of reviewed items categorised based on initiative type and the primary target of each item.

analysed initiatives). *Non-monetary benefits* are the most common technique in this nest, with 43.9% share of the nest and 12.2% of total identified techniques. The most common sub-category is 'Cycling amendment', with a share of 17.6% of total. Of the reviewed sanctions, *Selective restriction* is the most common sub-category (46.4% of sanction-type items and 8.8% of total identified techniques).

Table 4 shows database clustering based on sub-category and spatial scale. Starred ID's refer to items for which there exists an evaluation of atmospheric impacts. City scale is the most common (N=46, 42.6%), and includes the largest variety of incentive and sanction sub-categories. Persuasion by rewarding with non-monetary benefits is mostly deployed at micro-level. On the other hand, the examples of gamification approaches with personalised rewards are city scale initiatives.

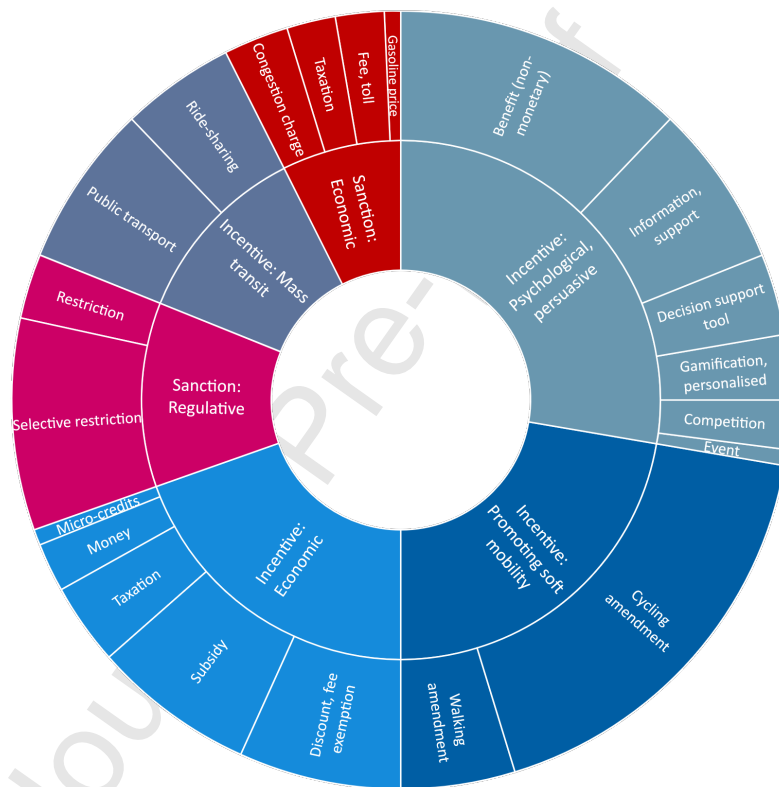


Figure 4: Distribution of incentive and sanction nests and their sub-categories. Diagram section widths are relative to item counts.

Table 4: Reviewed items clustered based on type, sub-category and spatial scale. For starred (*) items, an evaluation of CO₂ and/or PM emissions was found.

	International	National	Pro-vin- cial	Multi-city	City	Multi- local	Local	Micro (Pi- lot or tar- get group)	Micro (Em- ployer)
INCENTIVES									
Benefit (non-monetary)		I38		I55, I71, I79	B1*		I66, I76*	I5, I17, I40, I47, I69*, I73	I22, I60, I62, I72, B9
Information, support		I56				I4	I2, I44, I66, I76*	I47	I60, I62, I72
Decision support tool	I83				I31, I68			I67	I62
Gamification, personalised rewards				I37, I77	I36*, I51				
Competition		I28*							I6, I59*
Event			I3						
Cycling amendment	I1	I56		I8, I42*, I63	I7, I10, I9, I12, I13*, I14, I25, I26, I27, I30*, I32, I46*, I61, I78	I58*	B4, I44		I24, I53, I62, B9
Walking amendment							I18, I33, I44, I45, B2, B6, B8*		
Subsidy		I43*, I48, I80, B7*	I54	I15*			I66		I52, I53, I81
Discount, fee exemption		I43*		I64	I11, I20, I29, I41*, B5				I59*, I62, I65*
Taxation		I43*, I56, B7*		I15*	B1*				
Money				I55, I79				I75	
Micro-credits	I1								
Public transport					I7, I16*, I19, I23, I34, I35*, I49*, I70*, B3		I57*		
Ride-sharing		I82*		I37	I39*, I50, I74*			I21	I62
SANCTIONS									
Congestion charge					S6*, S13*, S15*		S7		
Fee, toll					B3, S10*				B9
Taxation		B7*, S11			S10*				
Gasoline price							S16		
Regulation									
Restriction					S2		B6, S9, S14		
Selective restriction					B1*, B5, S1*, S3*, S4, S5*, S10*, S8*, S12*		B2, B8*, B4		B9

3.2. Evaluation of atmospheric impacts

All database items with an evaluation of atmospheric impacts (CO₂, PM_{2.5}, PM₁₀) are listed in Table 5 (N=34, 31.5 % of database). We specify the measure (absolute or relative change during what period) and type of approach (measured, evaluated / calculated, simulated), and if

the evaluation was action-specific. A short description of methods and results based on available information is attached to each item. For further details, we guide the reader to investigate the item-specific references.

Relative change in either CO₂ or PM emissions evaluated for conditions before and after initiative deployment is the most comparable measure for the impacts of different initiatives (Figure 5), assuming that evaluation framing is clear. Regarding methodological quality, 12 out of 17 (70.6 %) relative evaluations were defined as 'high'. When looking at absolute change in either CO₂ or PM emissions or PM concentrations, there was more variation in the methodological quality. Four had low methodological quality due to either unrealistic assumptions or lacking documentation of the approach.

A typical problem is about reporting "saved" emissions in the context of increased cycling take-up (e.g. I28, I30), while unfoundedly assuming that all observed cycling replaces trips with private vehicles. Fishman [27] state that actually no evidence of bicycle sharing replacing car use in a large scale exists. Rather, it has been shown that the majority of bicycle sharing users are substituting from other sustainable modes of transport, such as walking or public transportation. The fraction of modal shift to bike sharing from private car is, indeed, rather low: London 2%, Lyon 7%, Barcelona 9.6%, Washington D.C. 7%, Melbourne 19% [132].

Table 5: Reported evaluations of reductions in CO₂ emissions, PM (PM₁₀ or PM_{2.5}) emissions, and the ambient PM concentration

ID	PM emissions	Ambient PM concentration	CO ₂ emissions	Source	Methodological quality	Evaluation details
I13	n/a	n/a	-25 240 t	[40]	high	Measure: absolute change in CO ₂ emissions in 2016 Action specific: yes Type: evaluation Description: Big Data analysis utilizing a service providers Internet of Things data, covering 56% of total trips. Analysis of vehicle km travelled, considering that shortest trips (less than 1km) do not substitute car but walking. Sample ratios and market shares of bikeshare companies are considered so that the result represents one year and all bike-sharing in Shanghai.
I15	n/a	n/a	max. -17%	[43]	high	Measure: hypothetical relative change in annual CO ₂ emissions Action specific: no Type: simulation Description: Well-to-wheels analysis of CO ₂ emissions for 4 scenarios of promoted electric vehicle penetration during 2010-2030, in different developed regions in China. Reduction by 2030 as compared to internal combustion engine vehicles, considering different scenarios of power generation mix and light duty passenger vehicle fleet.
I16	-8-11%	-9.20%	-246 563 t	CO ₂ : [182], PM: [183]	medium (CO ₂), high (PM)	Measure: relative change in emissions and ambient concentration of PM, absolute change for CO ₂ eq emissions yearly. Action specific: yes Type: measured (PM), evaluation (CO ₂) Description: For PM, a difference-in-differences analysis for 2000-2002. Comparing readings from a monitoring station located near the bus rapid transit (BRT) corridor to readings at a baseline monitoring station. The baseline monitoring station has two characteristics: (i) similar PM readings to the corridor monitoring station before entry into operation of the system; and (ii) location near a non-BRT corridor without negative spillovers from relocation of buses. For CO ₂ , using UNFCCC CDM Tool03 guidelines for calculating emissions from fossil fuel combustion; no details for project specific parameters.
I28	n/a	n/a	-5 024.690 t	[61], pers.comm.	medium	Measure: absolute amount of "saved" CO ₂ emissions during 5 months Action specific: yes Type: evaluation Description: Calculated for 2018 competition based on total biking kilometres and petrol CO ₂ emission factor.
I30	n/a	n/a	-18 600 000 pounds (8 437 t)	[64]	low	Measure: absolute amount of "saved" CO ₂ emissions Action specific: yes Type: evaluation Description: Coarse estimate of emissions saved during 2005-2009, assuming that all bike share trips were replacing car use.
I35	n/a	n/a	-54000 t	[46]	high	Measure: absolute change in yearly GHG emissions Action specific: yes Type: evaluation Description: Reduction in 2012. (-125 000 t due to modal shift, +71 000 t due to the Bus Rapid Transit system)
I36	n/a	n/a	-711 t	[74]	low	Measure: absolute amount of "saved" CO ₂ emissions during 6-month campaign Action specific: yes Type: evaluation Description: Evaluation for the 6-month programme in 2018, no reference emission level given in order to estimate a relative change

Table 5: Continued

ID	PM emissions	Ambient PM level (conc.)	CO ₂ emissions	Source	Methodological quality	Evaluation details
139	n/a	n/a	-5 174.6 kg	[78]	low	Measure: absolute amount of "saved" CO ₂ emissions Action specific: yes Type: evaluation Description: CO ₂ emissions when compared to standard gasoline vehicles driven the same distance.
141	n/a	-3.5 mg/m ³ (reported units suspected to be wrong, probably should be $\mu\text{g}/\text{m}^3$)	-10%	CO ₂ : [80]; PM: [16]	low	Measure: relative change in yearly CO ₂ emissions of transport sector, absolute change of PM ₁₀ concentration Action specific: yes / no Type: evaluation Description: For CO ₂ , reduction of yearly vehicle emissions evaluated. For PM, no information.
142	n/a	n/a	-3 514 t / emissions from passenger vehicles: -1% compared to control cities	[81]	high	Measure: absolute amount of "saved" CO ₂ emissions in 3 years, change relative to control cities Action specific: yes Type: evaluation Description: Comparing levels of cycling and walking in the intervention cities with the control cities spanning the period of the intervention, and quantifying changes attributable to the intervention rather than to a wider trend. Data: VKT + government estimates of emissions from fossil fuel consumption.
143	-10.9% (2016-2017); -43.4% (2012-2017)	n/a	-7.8% (2016-2017 passenger cars); -9.8% (2012-2017 road traffic)	[184]	medium	Measure: relative change in total CO ₂ eq and PM _{2.5} emissions from road traffic Action specific: no Type: Measured Description: Change in road traffic or passenger car emissions during one year 2016-2017 and period 2012-2017. Calculated from national statistics of absolute emissions.
146	n/a	n/a	-9 062 344 kg	[89]	high	Measure: absolute change in annual average CO ₂ emissions Action specific: yes Type: evaluation Description: Evaluated emission savings achieved by using bike sharing instead of car. Emission factors of cars calibrated to represent the Barcelona vehicle fleet.
149	n/a	n/a	-69 182.67 t	[93]	medium	Measure: absolute amount of "saved" CO ₂ emissions Action specific: yes Type: evaluation Description: expected estimate for 2019
157	n/a	n/a	the likelihood of an increase in commuting CO ₂ emissions was approximately half for those living 4 km from the busway than for those living 9 km from the busway	[185]	medium	Measure: likelihood to increase CO ₂ emissions Action specific: yes Type: evaluation Description: n/a

Table 5: Continued

ID	PM emissions	Ambient PM level (conc.)	CO ₂ emissions	Source	Methodological quality	Evaluation details
158	n/a	n/a	no statistically significant changes	[110]	high	<p>Measure: absolute change in CO₂ emissions</p> <p>Action specific: yes</p> <p>Type: evaluation</p> <p>Description: One- and two-year follow-ups after taking new infrastructure in use. To investigate the extent to which any travel behaviour change was attributable to the new infrastructure, they defined individuals whose modal split for active modes increased, and whose modal split for car driving decreased, as having shifted their mode of travel as intended. Travel activity data to derive CO₂ emissions, with different methods for car and non-car modes. For cars and vans, the self-reported data on weekly travel activity, vehicle fuel, size and age allowed for the use of a dis-aggregate method including the estimation of hot CO₂ emissions, which are a function of distance travelled, mean speed, fuel type, size and age.</p>
159	n/a	n/a	-5 777 kg; -49%	[111]	high	<p>Measure: absolute and relative change in CO₂ emissions of participants</p> <p>Action specific: yes</p> <p>Type: evaluation</p> <p>Description: Self-reported miles travelled by mode during a typical week prior to the BGCC and during the BGCC week. Mileage per mode combined with mode-specific Passenger Road Transport Conversion Factors for CO₂ (by Defra).</p>
165	-500 g	n/a	-367 kg; -12%	[118]	high	<p>Measure: absolute change in yearly CO₂ and PM₁₀ emissions per employee, relative change in CO₂ emissions from commuting</p> <p>Action specific: yes</p> <p>Type: evaluation</p> <p>Description: Reductions calculated to reflect the impact of the measure.</p>
169	-81 lb of "pollutants"	n/a	-2 185 lb (991 kg)	[122]	medium	<p>Measure: absolute change in weekly CO₂ and "pollutant" emissions</p> <p>Action specific: yes</p> <p>Type: evaluation</p> <p>Description: Weekly reduction of miles converted into annual emissions. Pollutant, CO₂ and fuel use factor data are from Division of New Technology, Materials and Research, California Department of Transportation.</p>
170	n/a	n/a	-10%	[123]	high	<p>Measure: hypothetical relative change in CO₂ emissions</p> <p>Action specific: yes</p> <p>Type: Simulation</p> <p>Description: Analysis based on an environmental life-cycle assessment of transit and automobile travel in the greater Los Angeles region to evaluate the impacts of multimodal transit trips by utilizing existing transportation life-cycle assessment methods. The evaluated reduction of transit system GHG emissions requires a shift of 23 to 50% of automobile first-last mile trips to a neutral emissions mode.</p>
174	n/a	n/a	-0.76 lb / member (vs. +0.25 lb for non-members)	[126]	medium	<p>Measure: absolute change in average daily CO₂ emissions from transportation per City CarShare member</p> <p>Action specific: yes</p> <p>Type: evaluation</p> <p>Description: Evaluation for the first two years. Average daily vehicle kilometres travelled fell slightly for members yet increased for non-members. While factors like changing fuel prices (which rose) and rainfall (which was much lower during Survey #4 than Survey #1) might have impacted travel habits during survey periods, these potential confounders affected both members and non-members equally, meaning their influences are netted out when comparing trends.</p>

Table 5: Continued

ID	PM emissions	Ambient PM level (conc.)	CO ₂ emissions	Source	Methodological quality	Evaluation details
176	n/a	n/a	-35 t / neighbourhood	[129]	low	Measure: absolute change in average CO ₂ emissions per neighbourhood during the 10-16-week programme Action specific: yes Type: evaluation Description: n/a
182	n/a	n/a	-0.84 t / household	[137]	high	Measure: absolute change in yearly average GHG emissions per household Action specific: yes Type: evaluation Description: An online survey (asking respondents about past and current vehicle holdings, as well as shifts in travel patterns) with members of major car sharing organizations was used to evaluate the change in annual household emissions. The results show that a majority of households joining car sharing are increasing their emissions by gaining access to automobiles. Individually, these increases are small. The remaining households are decreasing their emissions by driving less. The collective emission reductions outweigh the collective emission increases, which implies that car sharing reduces GHG emissions as a whole.
S1	-42%	n/a	n/a	[152]	medium	Measure: long-term (10 years) relative change in total PM ₁₀ emissions of Beijing's vehicle fleet Action specific: no Type: evaluation Description: Reduction in total emissions evaluated for Beijings vehicle fleet. The evaluation includes the impact of all deployed measures and other factors.
S3	-51.6%	n/a	n/a	[154]	high	Measure: relative change in PM ₁₀ emissions Action specific: Yes Type: measured, simulated Description: PM ₁₀ emissions from urban traffic during Olympics vs before. Bottom-up methodology with traffic monitoring has been used to develop grid-based emission inventories with micro-scale vehicle activities and speed-dependent emission factors.
S5	n/a	$\pm 0 \mu\text{g}/\text{m}^3$	n/a	[159]	high	Measure: absolute change in ambient PM _{2.5} concentration Action specific: Yes Type: measured Description: Analysis of data collected by Continuous Ambient Air Quality Monitoring Systems and manual stations.
S6	-23% (exhaust emissions in charge area), and -18% of total	n/a	-14%	[160]	high	Measure: relative change in yearly CO ₂ and PM ₁₀ emissions Action specific: yes, but not controlled Type: evaluation Description: Estimates are based on the difference between the number of vehicles entering the charge area before and after the Ecopass implementation. They are not controlled for any additional factor that could have influenced them (seasonal variations, fuel prices variations, public transit variations, other changes in traffic management policies).
S8	n/a	$\pm 0 \mu\text{g}/\text{m}^3$	n/a	[165]	high	Measure: absolute change in air pollution concentrations Action specific: yes Type: measured, numerical analysis Description: Air quality is compared before and after the restrictions were implemented using high frequency measures of five major air pollutants from monitoring stations. Other factors than Hoy No Circula were factored out.

Table 5: Continued

ID	PM emissions	Ambient PM level (conc.)	CO ₂ emissions	Source	Methodological quality	Evaluation details
S10	n/a	n/a	-0.14% (-56 kt) in 1975; -0.02% (-9 kt) in 1998; The cumulative CO ₂ emission reduction from 1975 to 2008 is 1 907 kt, and as a result of ERP from 1998 to 2008 about 103 kt.	[170]	medium	Measure: absolute and relative change in CO ₂ emissions Action specific: yes Type: evaluation Description: Emission reductions due to reduced traffic in the restricted charging zone. Two one-step reductions in traffic volumes (1975 when the restriction was established and 1998 for start of ERP) regarded separately.
S12	n/a	n/a	-14.2%	[175]	not confirmed, study referred by news item not found	Measure: Relative change in CO ₂ emissions after 3 months Action specific: - Type: Evaluation Description: Reference to "a study by the Technical University of Madrid", which looked at both traffic flow and car types in the restricted area: emission reduction in city centre after 3 months of start of ban.
S13	-10-14%	n/a	-14%	[176]	high	Measure: relative change in yearly CO ₂ and PM emissions("air-borne pollutants") Action specific: yes Type: measured, evaluation Description: The evaluation is based on traffic analyses carried out in connection with the trial together with the Stockholm and Uppsala county Air Quality Associations emissions databases. The action specific CO ₂ reduction corresponds to traffic emission reduction of 23% in the whole metropolitan area (the county of Stockholm).
S15	-16%	n/a	-16%	[161]; [179]	high	Measure: relative change in yearly PM ₁₀ and CO ₂ emissions Action specific: yes Type: measured Description: Change in emissions 2002-2003, "scheme-attributable", from all road traffic sources, on an annual total basis.
B1	-0.074 t or 6.4%	0 %	n/a	[140]	high	Measure: absolute and relative change in PM2.5 emissions and concentrations Action specific: yes Type: evaluation (emissions) and measured (conc.) Description: Based on camera data, and assuming that the number of km travelled has remained constant, difference between emissions from cars in circulation in the representative week of June 2018 and December 2018 is evaluated.
B7	n/a	n/a	-7.95 g CO ₂ /km (= -5.4%)	[147]	medium	Measure: absolute change in average CO ₂ emissions per km driven Action specific: yes Type: evaluation Description: How much the average emissions rate declined during 2007-2008. According to the author, "mostly explained by the initiative".
B8	n/a	-51.6%	n/a	[150]	medium	Measure: relative change in average ambient PM ₁₀ concentration during project weeks compared to pre-initiative level Action specific: yes Type: Measured Description: n/a

Figure 5 indicates that the reported CO₂(eq) and PM emission reductions achieved by implementing different types of initiatives are typically less than 20% compared to levels prior to initiative implementation. There is variation in what is reported, and what is the control level: some studies look at emissions from all road traffic, some at personal vehicles only, some at participating individuals before and after initiative deployment, and some at measurement data without controlling for any additional factors that could have influenced the measured values (e.g. seasonal variations, fuel prices variations, public transit variations, other changes in traffic management policies). This variety undermines the possibility to conduct a proper meta-analysis.

Traffic control before and during the Beijing Olympic Games (S3), is a special case. More than 4 million people are reported to have switched from driving vehicles to taking the public transport during the restriction period. On the other hand, rule-breaking behaviour was constant and pervasive, with 47.8% of the regulated car owners not following the rules. The documented reduction in traffic-related PM₁₀ emissions is 51.6%, but this number is not controlled for all the other actions and measures taken to control air quality during the Games, and the reduction was not permanent.

Congestion charges are one of the most studied categories in traffic control. The cases in our database (London S15, Milan S6 and Stockholm S13) exhibit very similar reductions in CO₂ and PM emissions: all within 14-16%. These values correspond to traffic reductions of 20-30% in the controlled area. For Stockholm, it is reported that virtually all evicted car trips were replaced by using public transport. In Milan, public transport use increased by 9.2%.

Examples of subsidising electric vehicles are from Norway (I43) and China (I15). For Norway, the reported PM emission reduction (10.9% / y, 43.4% / 5y) and CO₂ emission reduction (9.8% / 5y) are based on national statistics of road traffic emissions, and not controlled for other factors. During the 5 years, the market share of electric vehicles has been steadily growing, with market penetration attaining 10% in 2018 [186]. The analysis of electric vehicles in China is based on scenarios for 2010-2030, including a well-to-wheels evaluation of emissions. According to these simulations, the achievable CO₂ emission reduction is strongly dependant on region and their electricity production. Maximum reported reduction is 17%, assuming an

increase in vehicle volumes and electric vehicle fraction, and a significant shift towards more production of renewable energy.

Only a few (N=6) analyses of impacts on ambient particulate matter concentrations were found. Four were associated with high methodological quality. Bangkok's walking street programme (B8) was reported with medium quality to have achieved a concentration reduction of 51.6%. The initiative included a selective restriction (some streets banned for cars on selected days), improved pedestrian conditions, and walking street activities supported with awareness raising about air quality. Over a million people joined the activities on the streets, and surveys indicate successful awareness raising about vehicular air and noise pollution. On the selected days, there were over 300 000 people using the Mass Rapid Transit instead of cars. Sanctions-only initiatives, *Hoy No Circula* in Mexico City (S8) and *odd/even* in Delhi, India (S5), are reported with high methodological quality to not have had any significant impact on ambient PM concentrations. Evidence for S8 indicates that the restrictions actually led to an increase in the total number of vehicles in circulation, as well as a change in operating fleet towards high-emissions vehicles. Mohan et al. [159] conclude in the context of S5 that a single factor or action, such as the odd/even scheme, cannot substantially reduce air pollution levels in Delhi. According to them, the odd/even could achieve a maximum reduction of 2.3% in $PM_{2.5}$, if the reduction in cars was 50%. The actual reduction in cars being less than 25%, the expected PM reduction due to the odd/even policy would have to be less than 2%.

In Brussels, Belgium, a Low Emission Zone (LEZ) has been implemented in the city centre, coupled with incentives for people to cancel their car registration plates and to favor sustainable mobility (B1). A reduction of 6.4% in particulate matter emissions during six months has been reported, but no evidence of reductions in ambient PM concentrations exists. Many LEZs that have been deployed are targeting heavy traffic, and are thus not included in this review. But to compare, Jones et al. [187] report a 30% reduction in particle number concentrations in London over a period of few months after the introduction of LEZ targeted at heavy vehicles, and the deployed regulation for sulphur free diesel fuel. Also Fensterer et al. [188] demonstrate an up to 19.6% reduction in PM_{10} levels as the impact of LEZ and heavy traffic ban in Munich, Germany. Boogaard et al. [189] discuss the effectiveness of LEZs on ambient air pollution concentrations

based on measurements of $PM_{2.5}$, PM_{10} , soot, NO_x and NO_2 in different urban areas in the Netherlands. They conclude that with the exception of one urban street where traffic flows were drastically reduced, the LEZs have not been effective enough to produce significant decreases in traffic-related air pollution concentrations. The same conclusion is drawn by Hooftman et al. [5] evaluating LEZs in Europe.

Figure 6 depicts the initiatives for which absolute reductions in CO_2 emissions as tons of CO_2 or CO_2eq have been reported.

Development of a bus rapid transit system from scratch, and thus offering a new transit mode for people to consider, in Bogotá, Colombia (I16), Jakarta, Indonesia (I35) and Dar es Salaam, Tanzania (I49) are associated with carbon emission reductions of more than 50 kt a year. For I16, the demand of public transport is reported to have increased from 14 000 passengers per day to 1.7 million. However, Echeverry et al. [183] argue that the development may not have reduced the problem of polluting emissions but simply displaced it to other areas. For I35, only 14% of the passengers of the new bus system were former car or motorcycle users.

Bike sharing schemes in Shanghai, China (I13), Barcelona, Spain (I46) and Lyon, France (I30) are reported with evaluated CO_2 emission savings achieved by using bike sharing instead of car. For I46, the applied emission factors of cars are calibrated to represent the Barcelona vehicle fleet, and the evaluation of I75 relies on Big Data analysis, whereas I30 is an example of low quality analysis with coarse assumptions. In the context of e.g. London bike sharing (I32), an evaluation of the impact of the observed modal shift on people's exposure to $PM_{2.5}$ has been analysed, but not the impact that the scheme itself has had on PM emissions [190].

The persuasive measures with gamification approach (I28, I36) are reported, with low methodological quality, to reduce CO_2 emissions by approximately 1 000-5 000 t in a year. Yet, they have been deemed successful in the extent to which they have mobilized people. It is reported for I36 that over 20 000 people claimed rewards for sustainable trips, and 47% of the participated daily car users showed some form of maintained engagement and behavioural change throughout the project.

The walking and cycling infrastructure programme in many cities in the UK (I58) is reported to not have had statistically significant changes in CO₂ emissions. According to Brand et al. [110], people's journeys involved marginally more active travel and less car driving at follow-up than they did at baseline. About 21-25% of respondents were identified as having made a shift from driving to active modes, but the inverse shift was observed as well (20%). It can not be concluded that the observed changes reflected anything other than random variation or were causally related to the provision of the new infrastructure.

Shaheen and Cohen [191] have documented significant reductions in vehicle kilometres travelled and vehicle ownership as a result of ride/car sharing. In our database, the only reported CO₂ emission reduction is for Fukuoka, Japan (I39), and it is modest: approximately 5 t, evaluated with low methodological quality.

The only sanction-type initiative with evaluated absolute emission change is the long-term road pricing scheme in Singapore (S10). The depicted number, 103 000 t, is for a 10-year period, when the electronic road pricing has been in force. The observed change is a drop of 22% in weekday traffic flow into the restricted zone and increased use of car-pooling and public transport (+20%).

A metric that repeatedly occurs in the context of traffic mode studies is Vehicle Kilometres Travelled (VKT). When investigating the atmospheric impacts of modal shifts, it is relevant to look at changes in VKT by personal vehicles. Instead of comparable quantifications of carbon or PM emissions, many references in our database report reductions in VKT by car. For I65 (cashing out parking subsidies), a -12% reduction in VKT by car for commuting is reported, while car sharing increased by 64% and walking and cycling by 39%. For I42 (cycling-supportive infrastructure with awareness campaigns), a 30% increase in the rate of active trips corresponded to a 1.6% reduction in average annual VKT per passenger vehicle. For I82 (car sharing in North America), the average observed VKT by car per year was found to decline by 27% among participants. These numbers could be converted into emission reductions by utilizing statistics of vehicle fleet and corresponding emission factors.

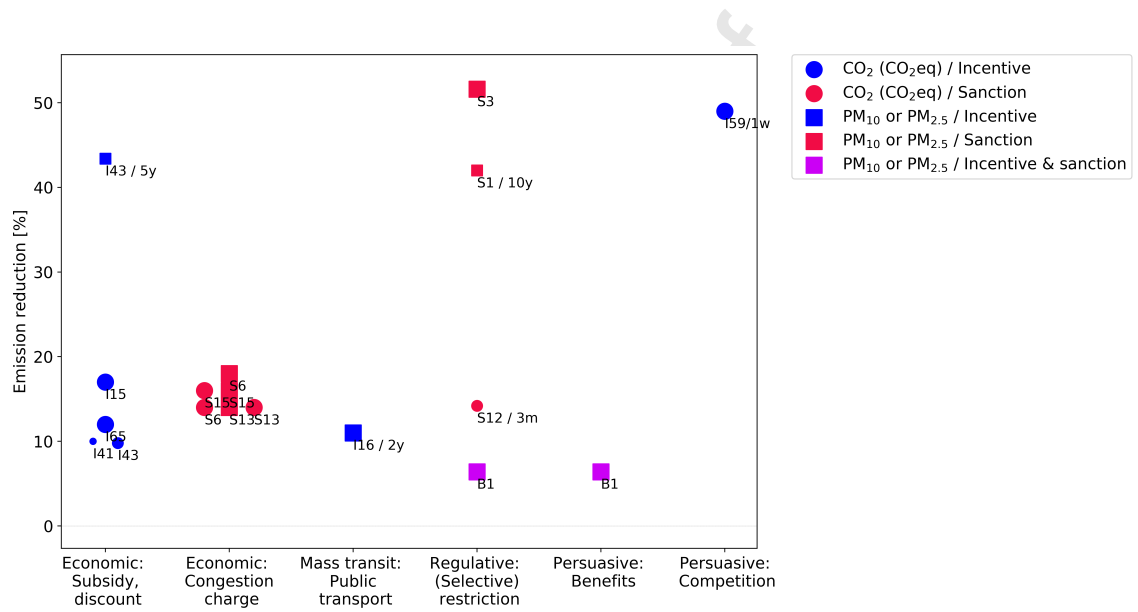


Figure 5: Reported relative change in CO₂ or PM emissions as a result of incentives or sanctions from different categories. All values regardless of evaluation time frames or methodological quality are presented. Item IDs are depicted, as well as the evaluation time frames when they are not "per year". Marker sizes (3) indicate the quality of evaluation methods, described in Section 2.4: the largest referring to high quality, middle-size to medium and the smallest to low.

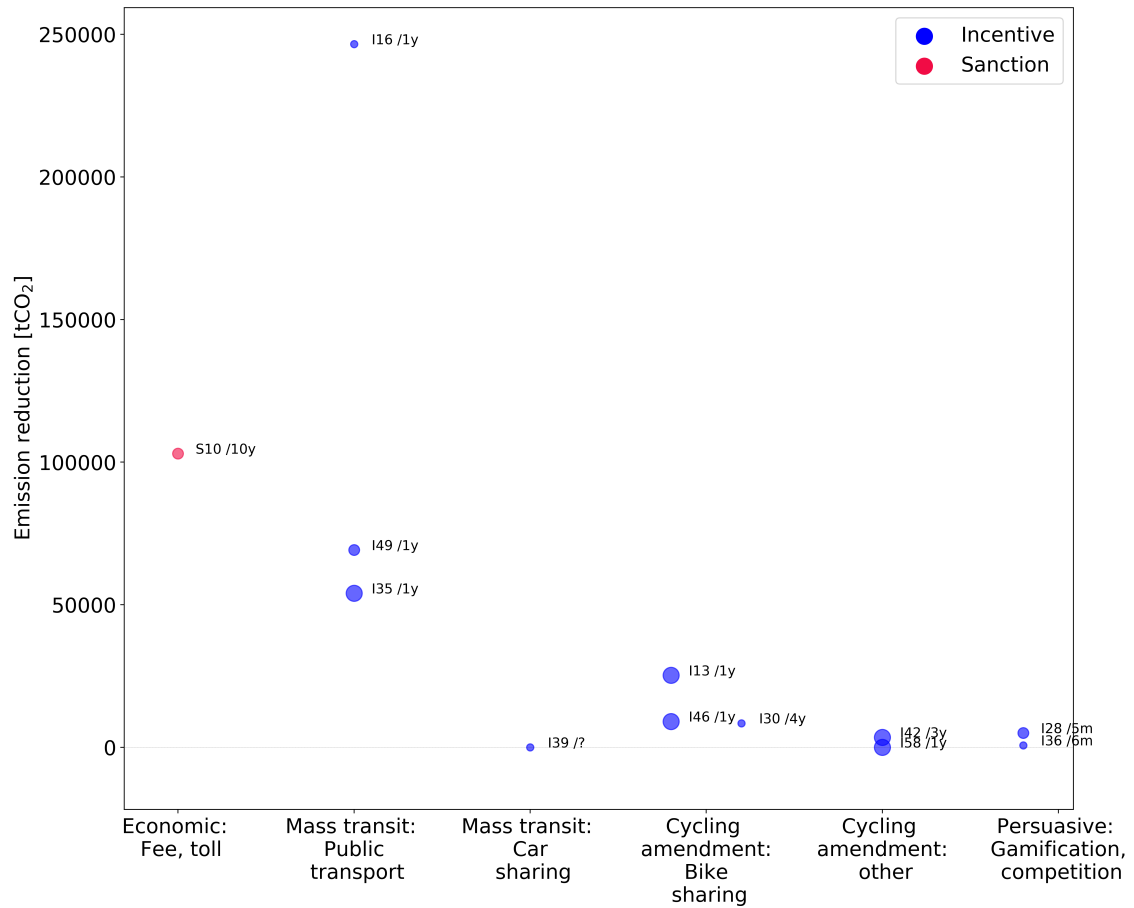


Figure 6: Reported absolute change in CO₂ emissions as a result of incentives or sanctions from different categories. All values regardless of evaluation time frames or methodological quality are presented. Item IDs are depicted, as well as the evaluation time frames. Marker sizes (3) indicate the quality of evaluation methods, described in Section 2.4: the largest referring to high quality, middle-size to medium and the smallest to low.

Also indirect impacts matter, and they may change the overall atmospheric impact of the deployed action to either direction. For example, bike sharing has been reported to increase the use of public transport by providing a solution to the "first/last-mile" dilemma, and on the other hand, the emissions saved through using a bike sharing system may be partly cancelled out by the vehicles that are used for redistributing the bicycles back to the docking stations [88]. Evidence from London [132] shows that when looking at car travel reduction versus motor vehicle support required, the net effect of the bike sharing scheme is actually an increase in vehicle kilometres travelled.

4. Discussing the determinants of success and failure

4.1. Longevity

A temporary incentive program may not be effective in producing sustained long-term change in travel mode choices, although they have proven to be effective during the actual reward period. In the case of Spitsmijden in the Netherlands (I46), people reverted to their pre-reward period behaviour within a week of the program termination, although their driving habits had changed significantly. Also competitions (such as I59) may be very effective in changing the participants' behaviour and reducing their emissions in short-term. But it is unclear how long an incentive has to be sustained so that new behaviour would stick.

4.2. Individualization and incentive compatibility

On a smaller scale, such as local level or individual employees, tailored incentives may be the most effective. A subsidy for electronic cycles may be the key for one employer, resulting in a significant modal shift of commuters, whereas cashing out parking may work better for a certain segment of people. For larger scales, heterogeneity starts to characterize the situation, and analysis plus tailoring becomes more difficult to deploy.

Individuality is central in travel plans (I60, B9). Their aggregate impacts depend on the combination of individual effectiveness and overall level of take-up. At employer level, effectiveness may be high. At network level, the situation becomes more complex. Private vehicle trips removed by travel plans may be replaced by other traffic that, e.g., was previously

suppressed by congestion. That traffic could counterbalance the reduction achieved with travel plans or any other initiative. A review by Rye [151] shows evidence that travel plans have their intended effect, which is to reduce the number of employees commuting alone by car, but larger scale impacts and ripple effects have not been analysed.

The provision of personalized rewards and individual level incentives can be made possible with modern technology, including Internet of Things (IoT), Big Data analysis tools, smart phones and applications. Poslad et al. [192] provide a proof-of-concept analysis of an Intelligent Transport System approach combining traffic sensors and targeted travel incentives (related to I51). They emphasize the necessity of rewards to be individualized.

Effective persuasive applications provide useful information, customizable goal setting, feedback and rewards [193]. These success factors are present in the BellaMossa gamification project (I36). Emission reductions are not enough to motivate the majority of people, but a game with tangible and personalized rewards works. The applications could also give feedback about monetary and health impacts of an individual's travel mode choices, and refer to patterns of other users to foster social force.

4.3. Awareness

Awareness raising may contribute to modal shifts, but is not likely to produce them without any other measures. Campaigns (I2), walking street programs with information booths (B8), and travel plans (I60, B9), for example, serve the purpose of raising awareness regarding alternative traffic modes, traffic related air pollution and ways to mitigate it. Although being informed and considering alternatives is the first step towards actual behaviour change, concrete interventions seem to be required when it comes to mobility and modal shifts. Coupling awareness raising with other incentives or sanctions (such as in B8) is a promising avenue.

4.4. Economic tools

Counter-intuitively, fare-free public transport has failed its goal of attracting more people to use it in many places, e.g. in Rome, Tallinn and many U.S. cities. The outcome of analyses is that fare free public transport mostly entices people who would otherwise walk, not those who would drive [38]. Reports analyzing the case of Tallinn (I20) identify the same problem of modal shifts

occurring mostly from soft mobility. They also highlight the risk that people tend to underappreciate things that they get for free, and that the absence of a direct cost may lead to over-utilization and eventually to fewer investments in public transport due to the lack of direct income gathering.

Economic incentives may be useful in establishing interest. Norway (I43), with increasing market penetration of electric vehicles and decreasing traffic emissions, is a promising example of successful subsidy policy.

Congestion charging and its impacts have been studied relatively well, and with relatively uniform results from European cities. This is helpful for policy agents planning to deploy a congestion charging scheme by enabling grounded predictions about the outcomes. In Seoul (S7), the congestion charging scheme targeting selected arterial roads is evaluated to be effective in reducing traffic volumes in the entire road network. Despite this example, leakage of traffic to other areas is a potential problem that needs to be addressed when planning an initiative of this kind. Furthermore, when the system includes fees and tolls, it is relevant what this generated revenue is used for. At best, it will be spent on developing the transportation infrastructure towards environmental sustainability.

4.5. Infrastructure

Provision of better cycling infrastructure and related facilities (part of sub-category 'Cycling amendment' in our study) is a common approach to promote soft mobility. The atmospheric impacts of these initiatives have been poorly evaluated (2 out of 13 in our database). Wardman et al. [194] present a mode choice model to predict the impacts of different measures to encourage cycling. Their result is that even an unfeasible scenario of a universally provided and completely segregated cycleway would increase cycling by only 55%, and, importantly, result in just a slight reduction in driving. Real-life cases I42 and I58 are in line with this simulation. For I42, cycling-supportive infrastructure investments with community-wide promotion and awareness campaigns resulted in a 30% increase in the rate of active trips, but only 1.6% reduction in average annual VKT per passenger vehicle, corresponding to a decrease of 1% in CO₂ emissions. For I58, there was no impact at all on emissions during 2 years. Payments for cycling were found to be highly effective in the simulation by Wardman et al. [194], but no real

life cases of this were found.

Developing public transport, especially in a way that provides people with a new alternative traffic mode, has the potential to be very effective in reducing emissions and improving air quality. The preconditions for success are that the modal shift is from private vehicles, that the volumes of private vehicle traffic are not just displaced to e.g. the outskirts of the city, that travel times are reasonable and that peoples perception of the new mode is positive. Bus Rapid Transit system in Jakarta (I35) has reduced emissions, but not as much as expected due to significant challenges stemming from passengers poor attitudes towards the service [46]. Also in Bogotá, people had negative stereotypes about bus travel, and no real system for public transport to serve as an alternative to private vehicle, before the TransMilenio (I16) was deployed and branded. The model with demonstrated tangible reductions in air pollution, fatalities and travel time has been replicated in many cities, and TransMilenio was approved by the United Nations to generate and sell carbon credits under the Kyoto Protocol mechanisms.

4.6. Providing choice and alternatives

Restricting the use of private cars may be necessary in order to control the atmospheric impacts of traffic, but an intervention alone, without the provision of viable alternatives, may fall short of target. Vehicle Quota System (VQS) in Singapore (S11) has gained public acceptance, but mostly because there exists an efficient public transport system providing an alternative to the car. With the VQS, road pricing (S10) and other measures, the number of vehicles in Singapores urban area has been growing slower than predicted, and the trend of air pollution levels has been stable or declining. The provision of choice is reported as the key success factor: As part of the Electronic Road Pricing, commuters can choose to either pay a charge and drive smoothly, change their time of travel and pay a lower charge, use an alternative road and not pay the charge, use public transport, or use schemes such as park-and-ride.

Weekly car-free days coupled with economic and non-monetary incentives in Seoul (I41) have proven to be a rather successful combination with participation rate of 30%. Coupling the restriction with incentives may be the key, because experiences from other cities having deployed only restrictive measures, e.g. Mexico City (S8) and Beijing (S3), have not shown similar longevity. Users of private vehicles have a revealed preference for fast and convenient

mobility, and will find ways to circumvent selective restrictions ([165], [155]).

Ride sharing is a potentially disrupting service in mobility sector. The case from Fukuoka (I39) demonstrates that a big motivator is the ability to observe individual economic benefits as compared to owning a car. Social acceptance is an essential element for large scale adoption, and it can be advanced by providing enough flexibility (for e.g. driving range, capacity, docking).

4.7. Sustainability nexus

In African countries, and Global South in general, the discourse surrounding travel is very different than in Global North. Reducing emissions may not be a central motivation, and the nexus of economy, poverty, food, health and environment is rather complex. Sustainable solutions must be promoted with other arguments than simply the potential to reduce emissions. The Cycle Out Of Poverty programme (I1) has offered several practically feasible solutions with underemployed entrepreneurs, especially women, in the centre. In this case, the modal shift may be from nothing to bicycle, but it is more about advancing many aspects of sustainability simultaneously.

5. Conclusions

Changing people's travel behaviour and affecting their transport mode choices is a difficult task. The constraint of daily activity scheduling combined with strongly habitual "auto-pilot" behaviour makes modal shifts a challenge that requires thought-out multilevel measures. The measures should help to overcome barriers of low-emission transport options and to avoid future lock-in effects related to e.g. infrastructure. As stated in the fifth Assessment Report by the IPCC [2], "changing behaviour of consumers and businesses will likely play an important role [for achieving emission reductions in transport sector] but is challenging and the possible outcomes, including modal shift, are difficult to quantify."

Based on the results of this review, it is evident that high quality quantifications of the atmospheric impacts of individual mobility and mode choice initiatives are not common. This may be partly because emission reductions are often not the primary goal of those initiatives: urban planning, congestion reduction and increase of soft mobility are more typical targets.

When targeting air quality, most initiatives include sanctions, while other targets are addressed with incentives. Sanctions have also more likely been scientifically evaluated, whereas more than half of incentive evaluations were non-scientific. These findings support our three original hypotheses.

The difficulty to evaluate the impacts may arise from the multitude of factors affecting people's behaviour and the emissions of CO₂ and PM plus their dispersion in the atmosphere. Studying control cities and executing surveys with follow-ups would alleviate the problem of ruling out other factors than the impacts of the deployed initiative, but evaluations with these approaches are scarce. The majority of initiatives lack a flow of dynamic data that would enable initiative-specific evaluation of the impacts on multiple levels. The initiatives that typically have this are built on smart or intelligent systems, and include the use of smart phones and applications, collecting data from the user and reciprocally providing the user with useful information. The incentive schemes leaning on gamification are an example of this, but the four initiatives belonging to this sub-category in our database have not fully utilized the potential of the data for the purpose of evaluating the atmospheric impacts.

Cycling amendment, including cycling infrastructure provision, awareness raising and bike-sharing schemes, is the most common initiative sub-category in our database. The atmospheric impacts of these initiatives have been rather poorly evaluated. The coarse and misleading method of calculating "saved emissions" with the assumption that all of the observed increase in biking is due to a modal shift from private vehicles, is common. For the evaluation of the atmospheric impacts of a modal shift, it would be essential to know and consider both the new mode with its adoption rate and the substituted mode, the emission factors of the modes and also the indirect impacts of the shift that may change the overall atmospheric impact of the deployed action to either direction.

The evaluated impacts of congestion charge schemes are rather coherent, whereas the evaluations of restrictive schemes and their ripple effects vary significantly. The outcomes of some type of actions are thus more predictable than others. Behavioral psychology speaks for positive enforcement when it comes to change effectiveness, on which many incentive-type

initiatives are based, but with varying and partly unanalysed outcomes. It would be extremely useful to be able to diligently compare the atmospheric impacts of different incentive- and sanction-based initiatives. Unfortunately, the level of and heterogeneity in the quality of existing evaluations do not allow this.

Only a few reviewed cases address the impact of an individual initiative on ambient PM concentrations. Using a dispersion model to analyse the comprehensive effects of mobility changes on air quality is rare, although it would help to apportion the contribution of traffic in the measured concentrations, and reveal changes in the spatial distribution of dispersed traffic-originated concentrations.

Effective practices could be better diffused and disseminated, if the already deployed initiatives were better evaluated with respect to their atmospheric impacts - even if their original motivation was not climate change mitigation or air quality improvement. The questions of impact permanence and indirect effects are also raised by looking at the data collected in this scoping review. They remain for further research to answer, and could be the key for crafting effective schemes leading to genuinely sustainable mobility shifts.

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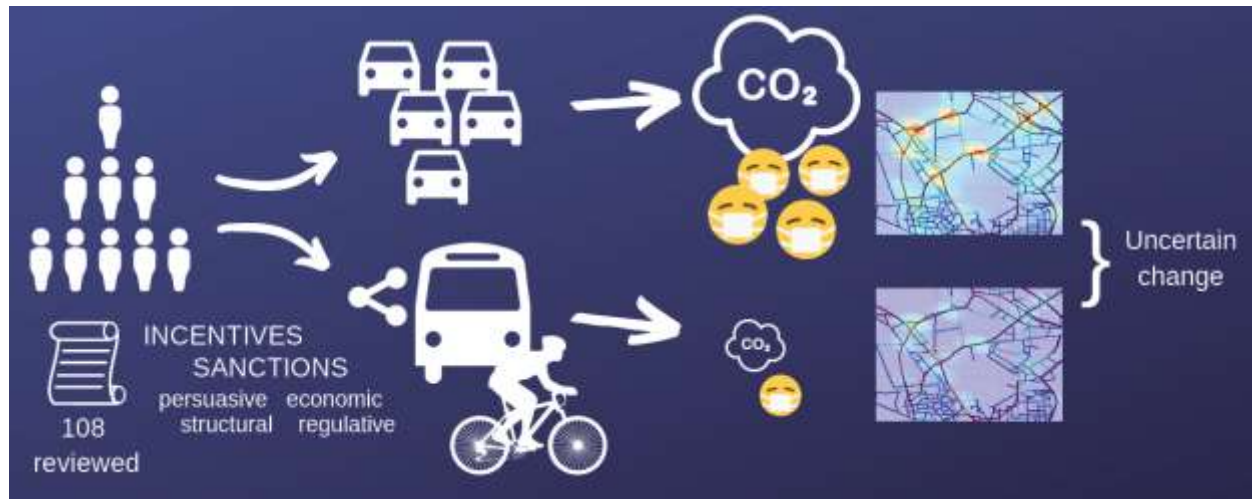
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Graphical abstract



Highlights

- Urban mobility initiatives and their atmospheric impact evaluations under scrutiny
- We reviewed 108 persuasive, economic, regulative and structural initiatives
- We break down the approaches to evaluating achieved emission reductions
- High-quality atmospheric impact evaluations of incentives are scarce
- Longevity of incentivized shifts to low-emission mobility is the key to real impacts

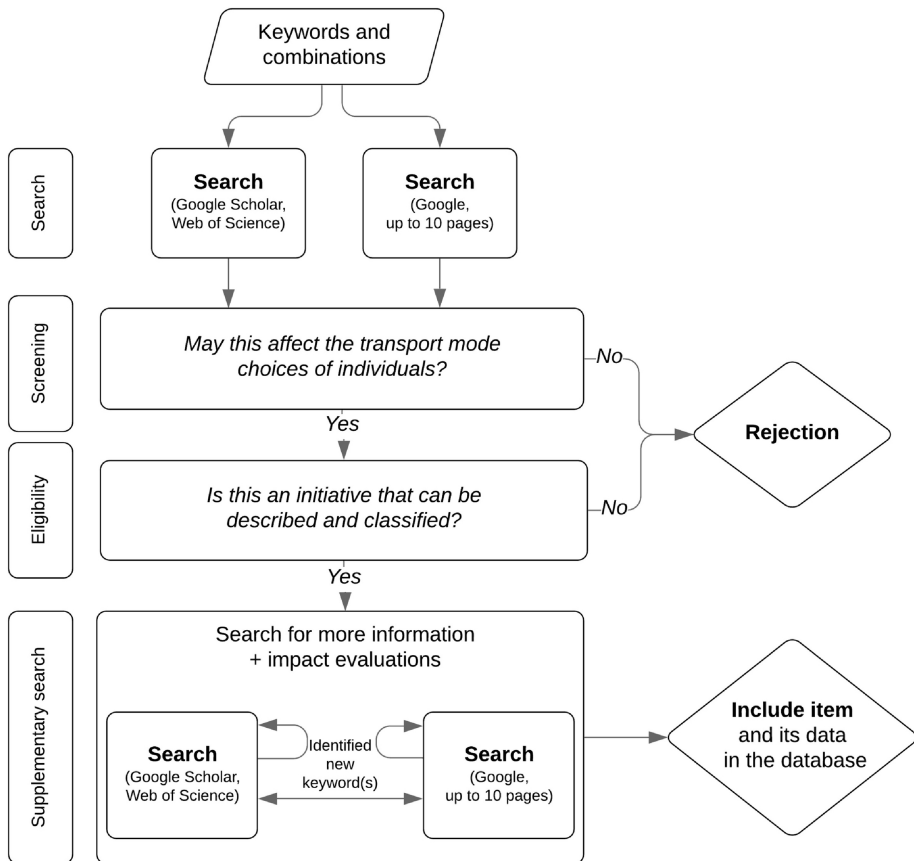


Figure 1

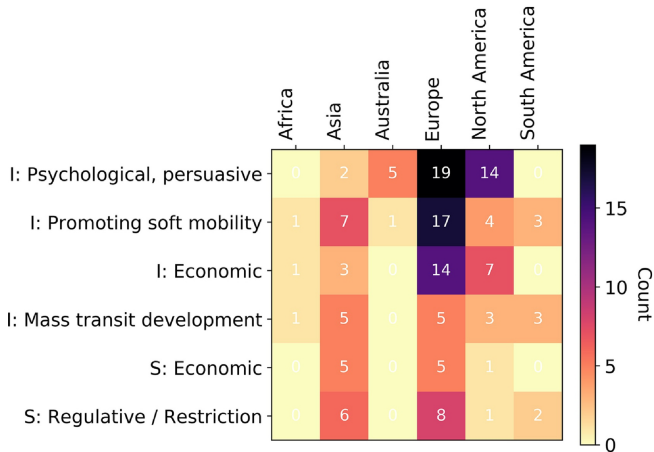


Figure 2

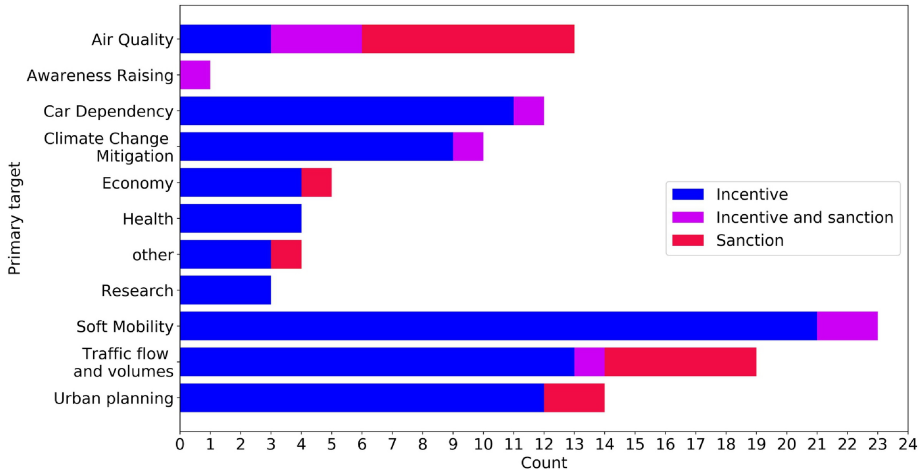


Figure 3

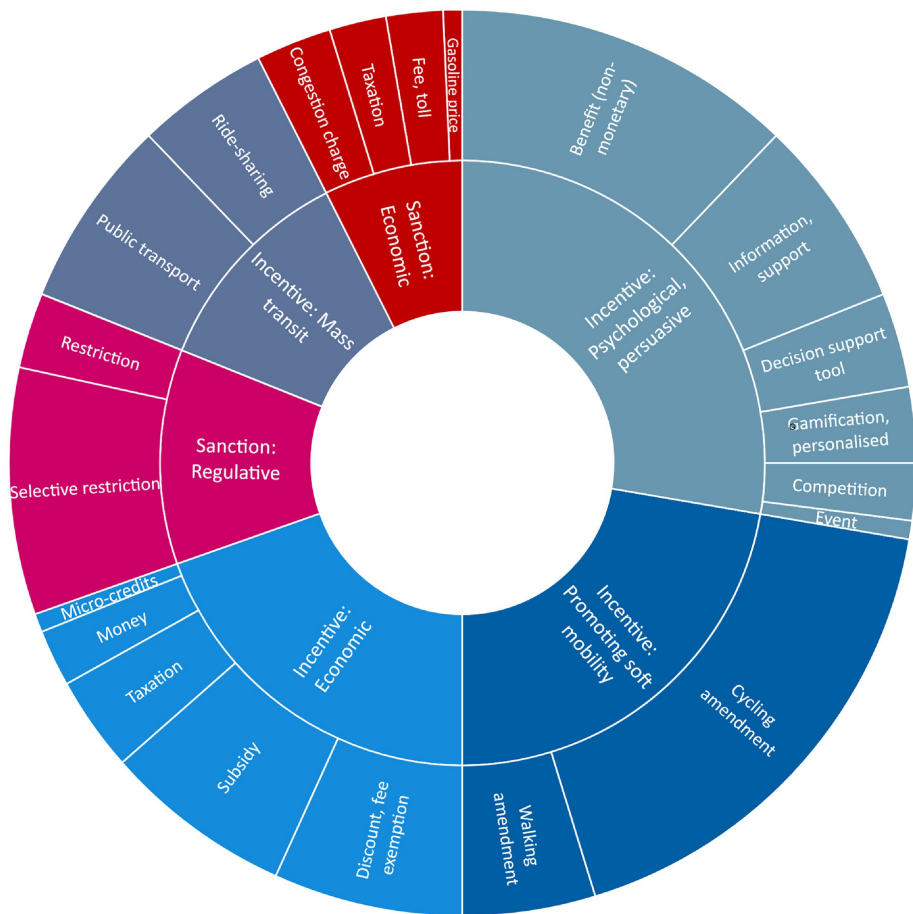


Figure 4

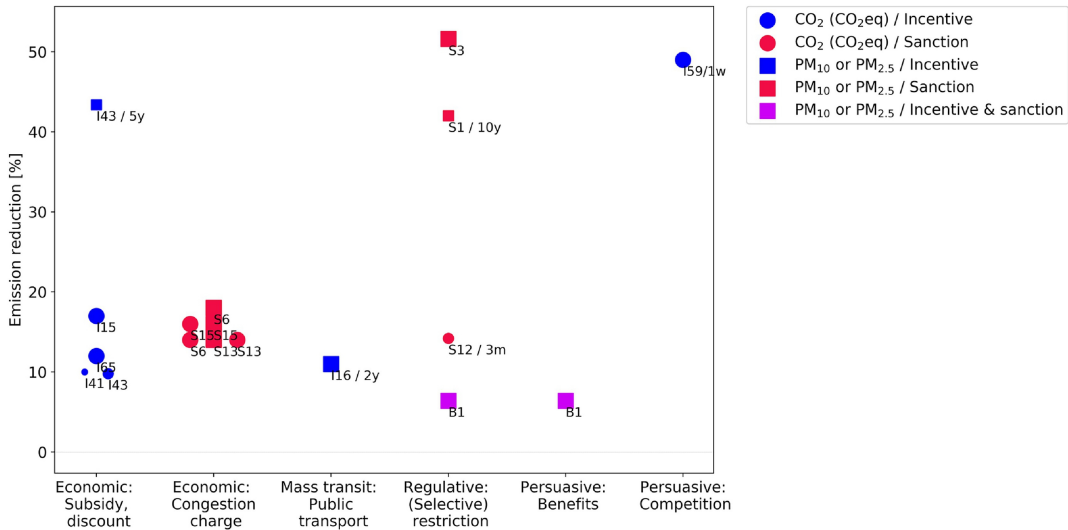


Figure 5

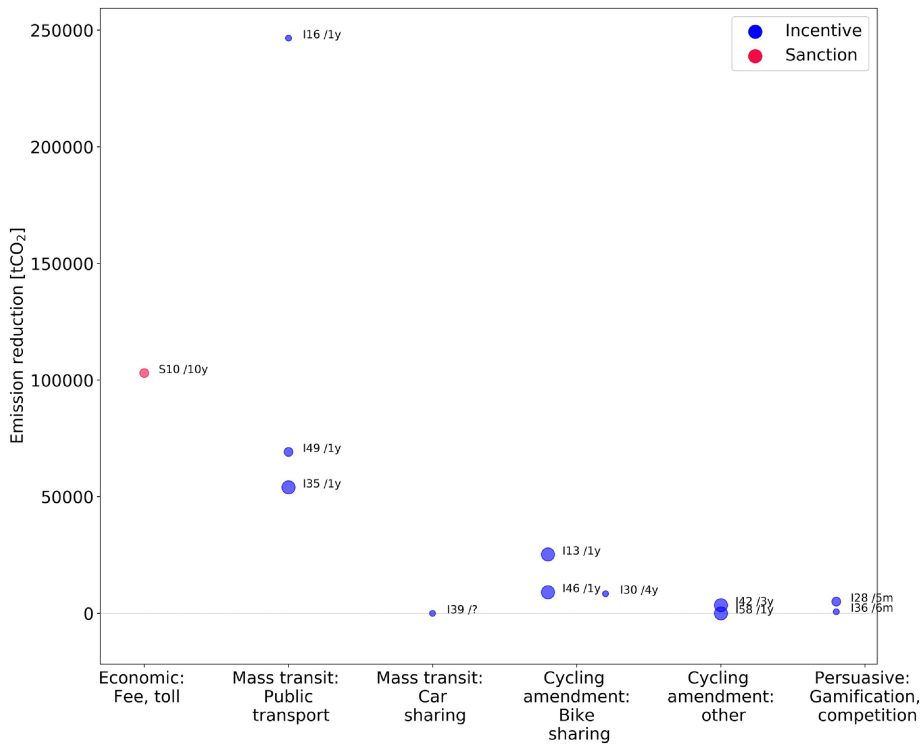


Figure 6