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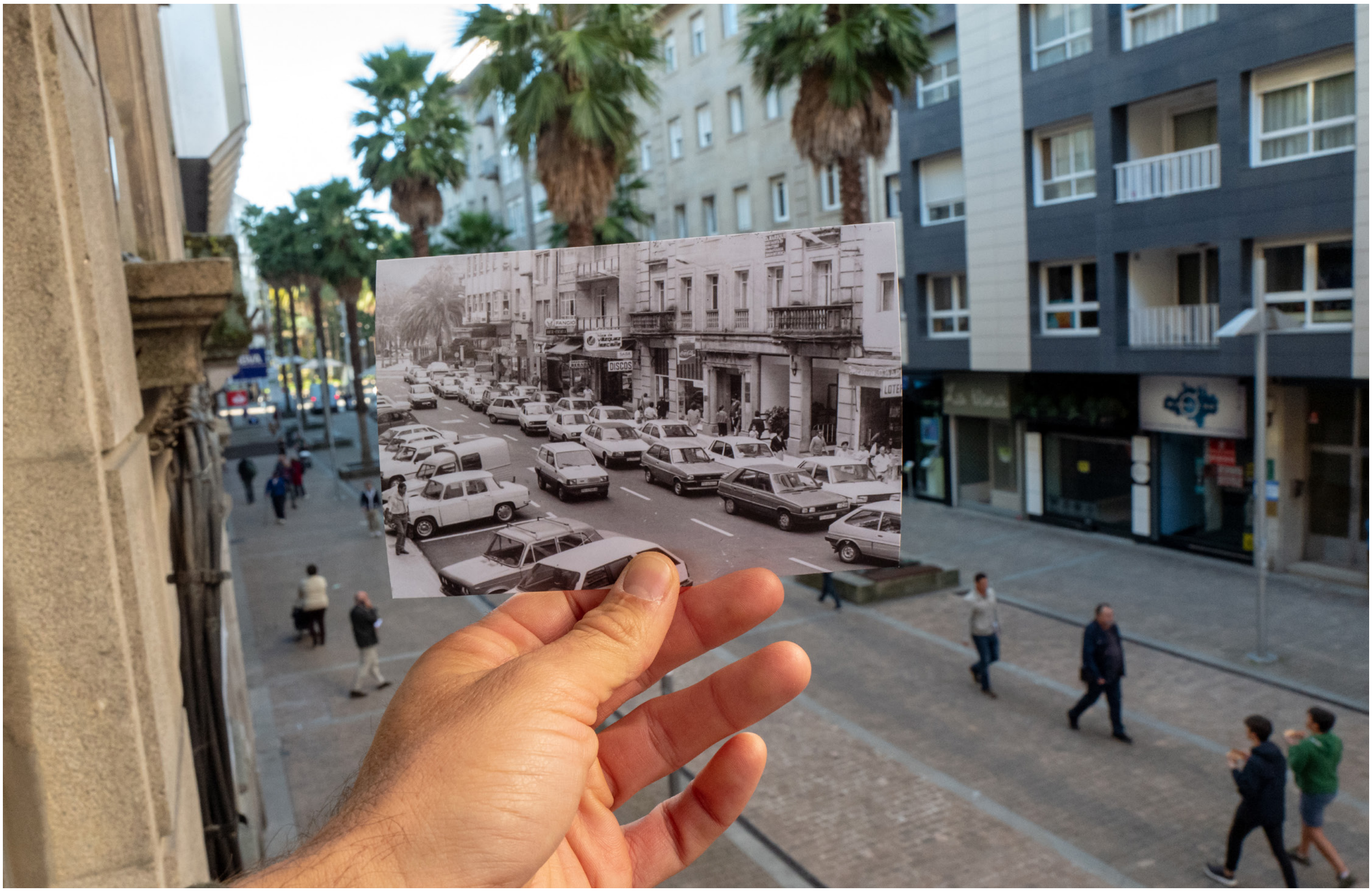

Streets That Fit

Re-allocating Space for Better Cities

Corporate Partnership Board Report

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The International Transport Forum

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Executive summary

What we did

Street space in cities is a rare resource. Much of it is currently allocated to highly space-consuming transport modes without taking into account that demands for that space vary over time. This report looks at how street space has typically been allocated in the past, examines the rationale for street space allocation and describes how to measure space consumption for mobility purposes. The study also explores by way of a simulation how new mobility services and travel modes interact when a limited, dynamic and demand-responsive re-allocation of street space is introduced in a mid-sized city. The modelling framework put people first by framing the issue around how this space serves the population and not on how the vehicles occupy the space.

What we found

The most visible infrastructure in cities is transport infrastructure. It is a necessary component of well-functioning cities but also consumes a tremendous amount of scarce and therefore precious urban space.

The allocation of urban space is fraught with inherent tension. Space-related decisions are based on improving the speed of cars and thus the travel times of their occupants to enable them to maximise what is scarce to them, namely time. For communities, the impacts of speed are less clear-cut. It contributes to improving access for those who are travelling fast but at the same time consumes a disproportionate amount of space.

This tension is exacerbated by the fact that space allocation revolves around the question of how vehicles use it and not on how well it serves people, despite the many potential and desired uses. Such an approach, however, favours car users over those who travel by other means or would use that space for other purposes.

There is an important distinction to be made between the *use* of street space versus the *allocation* of street space. On the one hand, the actual use of street space is a representation of the demand for the use of that space for travel. The demand and use vary by transport mode, by time of day and by urban zone. The use of space relates to how much physical space people and vehicles actually consume as they move.

On the other hand, the allocation of space represents the supply of street space made available for people to move or linger and for vehicles to operate, park or otherwise idle. Currently, space allocation is largely static over the course of the day. Such rigidity leads to street configurations that typically reflect the needs of the most space-consuming modes and uses allowed there. It invariably results in inefficient use of space.

Moving away from the static allocation of street space towards flexible approaches poses challenges. However, the temporary, reversible allocation of street space can make sense in specific contexts and confer considerable benefits.

The tension around street space in cities also comes from a lack of universal and comparable metrics to inform allocation choices. To serve that purpose, such metrics must incorporate both the dynamic aspect of street space consumption as vehicles move and the static consumption of public space by parked or idle vehicles. These two components can be captured in a composite indicator: square metre hours consumed (m^2.h) per traveller offers a good basis for discussing the relative space-consumption impacts of different travel modes and trips.

Together, limited and dynamic re-allocation of street space plus additional free-floating mobility services and other mobility options could significantly improve mobility outcomes. The simulations for this study suggest a performance improvement of the urban transport network of approximately 12%, measured by indicators for mobility, accessibility, environment, space efficiency and safety.

Without changes to the available mobility options and patterns, limited and dynamic space re-allocation improves network performance by 9%. Including new modes without changing to a dynamic street configuration generates only a 3% improvement.

The introduction of a wider range of generally more space-efficient modes and the limited, demand-responsive, re-allocation of street space allocation leads to a 19% reduction in the overall space consumed by all trips in the modelled city. These savings could create new opportunities for developing new uses for public city space. These benefits are not evenly distributed geographically, however. They are concentrated in the urban core, where competition for alternative uses of street space is greatest.

The combination of new mobility alternatives and limited, dynamic re-allocation of space also brings significant environmental gains. Despite increasing the number of passenger-kilometres, overall transport CO_2 emissions fall by around 5%. Particulate matter emissions drop by 4% and could fall by 23% if the shared vehicles are electric and powered using the current electricity mix.

What we recommend

Adopt meaningful indicators for how urban street space is used

No straightforward and comprehensive indicators are currently in use to assess space consumption. Traditional capacity metrics such as speed-flow relationships or other throughput measures do not capture the static and dynamic aspects of space consumed by travellers. Neither do the most common aggregate measures of transport demand such as vehicle-kilometres or passenger-kilometres travelled. An indicator that fills this gap is the square metre hour (m^2.h) occupied by a vehicle- or person-trip. This composite indicator includes the static consumption of space, i.e. the on-trip parking and idling of a vehicle, and the dynamic use of space, namely the exclusive occupation of street space by the vehicle as it moves.

Re-allocate street space to account for diverse uses and users

Prevailing road classifications are largely designed to manage the use of road space by cars, vans and trucks. Opening that space to other vehicles, users and uses – even non-transport uses – may bring benefits in many contexts. More diversity and flexibility in street space allocation requires a shift in the practice of allocating space, however. This includes aligning the legal speed of vehicle traffic with the characteristics of the street space. Which vehicles can use what street should be defined by the infrastructure's characteristics. A vehicle could access those parts of the network whose design is adapted to the vehicle's mass and dimensions. Such an approach would enable a broader range of safe uses of public space designated for mobility uses and help establish a wider variety of street uses.

Prioritise people over vehicles when allocating street space

Street space allocation should put people first. It must focus on how that space serves the population and not how vehicles occupy that space. For that, it is critical to consider how the mobility needs of people can be met and assess the access provided by the transport system. Decisions about street space allocation should, therefore, always take as their starting point the space required per person, not per vehicle.

Explore the benefits of dynamically re-allocating certain street spaces

Moving from rigid towards demand-responsive street space allocation to make it available to a wider set of users and uses can bring benefits. These accrue from a more space-efficient use of streets and the ability for people to travel safely with a wider range of vehicles and modes. Limited and dynamic re-allocation of street space also improves the resilience of the urban transport system through the ability to flexibly meet changing demand.

Adopt Safe System principles to guide the re-allocation of street space

The re-allocation of urban street space must be carefully designed and implemented to avoid negative impacts on traffic safety. Street space re-allocation should incorporate the principles of the Safe System: that humans will make mistakes, that injuries result if the human body is exposed to known levels of kinetic energy, and that all actors in a traffic system share responsibility for road safety of all, not only that of motor vehicle occupants. In a Safe System, all elements of the road traffic system combine to prevent a crash or at least prevent serious injury. Speed management and traffic separation, where necessary, are two pillars of a Safe System. Integrating Safe System thinking into decisions on street-space allocation may limit the range of potential reconfigurations achievable.

Allocating street space: How and why?

The most visible and omnipresent infrastructure in cities is related to transport – and road transport in particular. Urban motorways, boulevards, streets, parking spaces, off-road or multistorey car parks, intersections and interchanges all constitute the necessary foundation for the automotive age. However, they also consume a tremendous amount of otherwise rare (and therefore precious) urban space.

Accessibility is broadly defined as the extent to which the land use and transport systems enable individuals to reach activities or destinations (Geurs and van Wee, 2004). The spatial dimension of accessibility is linked to the interplay between its three constitutive components: available activities/opportunities, their location, and travel to them. The latter helps link the previous two – but so too does proximity. Increasing proximity (and thus density) or increasing the speed of travel increases the number of opportunities and activities that individuals can satisfy for a given period of time (Crozet, 2020).

From the perspective of travellers, increased speed is an acceptable substitute for physical proximity since it delivers the same result in terms of linking people to destinations. For individual travellers, time is a scarce resource. As such, speed delivers valuable time savings in getting from A to B, time which can be used for other things. Aggregated together, cumulative time savings represent one indicator of collective welfare and has served as the basis for measuring the impacts of transport investments and other policies (Crozet, 2020). This indicator has dominated project and policy appraisal but has also been criticised for poorly capturing certain important policy considerations and leading to unjust outcomes (Martens and Ciommo, 2017).

For communities, the impacts of speed are slightly different since travel time savings contribute to overall agglomeration benefits but consume a valuable and scarce public resource in communities – space. Consequently, there is an inherent tension between the time savings that individuals wish to maximise by their mobility behaviour and the efficient allocation and management of public space in urban areas. This tension is further exacerbated by two factors: that urban space, even space predominantly allocated to mobility, has multiple potential and desired uses, and secondly, that its allocation has largely concerned how vehicles use that space versus how well that space serves people. These factors, although different, favour the rights of those who use cars versus those who do not. The tension around urban mobility space allocation is further complicated by the lack of a universal and comparable set of metrics that can help inform choices on how this space should be allocated.

The discussion around the demand for and use of street space versus the allocation of street space should not conflate the two concepts. In the first instance, the actual *use or consumption* of street space is a representation of the demand for the mobility-related use of that space. This use/demand aspect is variable by mode, time of day and zone, and represents how much physical space is actually consumed as people and vehicles move.

The *allocation* of space represents the supply of urban road space made available for people and vehicles to move and operate. The allocation of space is largely static over the course of the day and invariable over time. It represents an investment in hard infrastructure (roadways, junctions, on- and off-street parking) and is typically dimensioned for peak demand (for roads) and to allow for generous storage of personal vehicles in residential areas and in commercial or work destinations (for a discussion of parking supply see ITF, 2021a).

Tensions inherent in road space allocation

Despite periods of relative stability, road and urban public space allocation is often contested – especially in response to broader societal changes, local demands and external events. The global Covid-19 pandemic is one example of such an external stressor. Existing trends seeking to give more space to active mobility in many cities have questioned the basis for, and practice of, allocating most road space solely to motor vehicle traffic and storage. The tension around road space allocation is typically strongest where that space is rarest – in core urban areas. But it also emerges elsewhere when existing road space allocation practices exclude other desired uses of that space. The tensions inherent in road space allocation can broadly be categorised into four areas: liveability, capacity, spatiality, and network. Liveability relates to why and under what assumptions street space is allocated. Capacity relates to how and by whom road space is allocated. Network relates to where the space is being allocated. Spatiality relates to what is being allocated.

Tensions around liveability

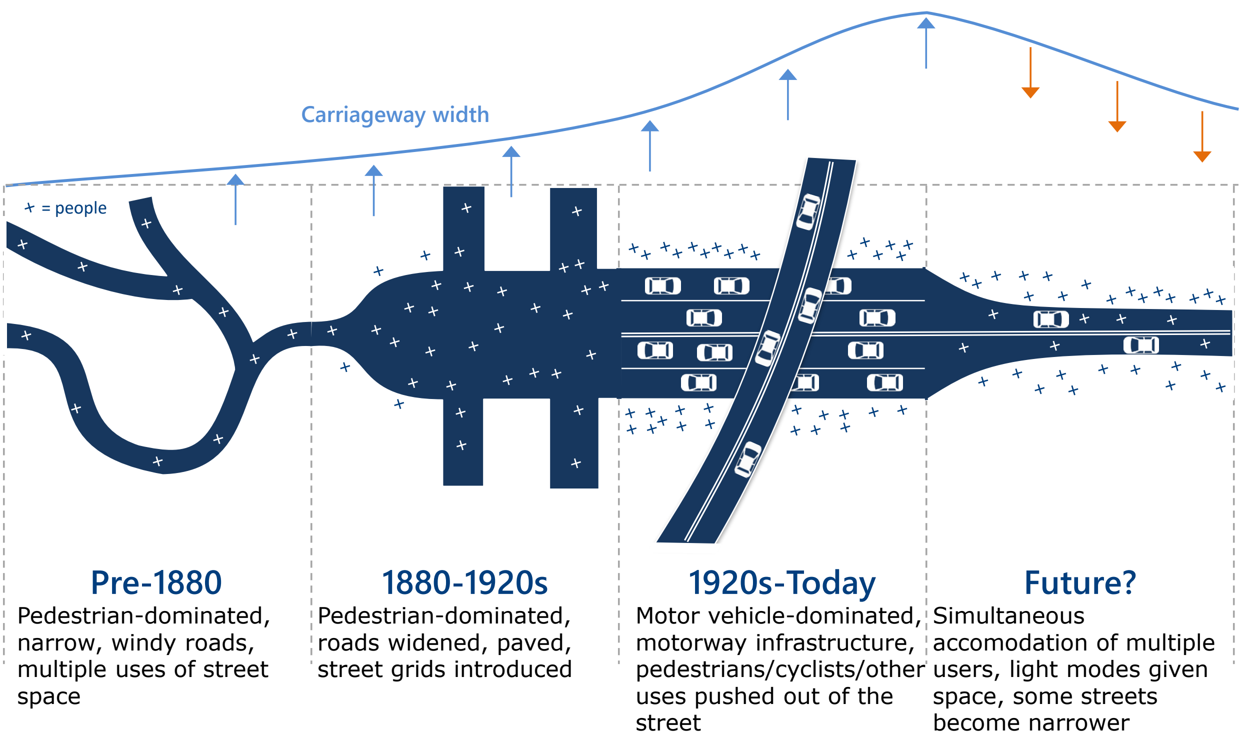
At the heart of many of the tensions around the allocation of road space are the assumptions about who should use that space and for what purpose.

Current practice regarding the allocation and supply of urban road space implicitly assumes that this space should be reserved exclusively for the movement and storage of vehicles. This stance stems from the actors and institutions that have over time defined how, by whom and to whom road space should be allocated. At its core is the shift from a broader iterative negotiation of how that space may be used, to a traffic engineering-led technical specification of how that space should be used by vehicles (Jones, 2014). Such a vehicle-oriented technical specification makes sense for major thoroughfares and urban motorways where mixing uses would prove dangerous and inefficient. However, for residential and many commercial streets, such exclusive allocation of road space is contested as there are other valuable (and valued by residents and shopkeepers) uses to which that space may be put, including children’s play, socialising, shopping and dining. These alternative uses gained attention during the Covid-19 pandemic, with the contestability of urban space sharpened in many areas around the world.

Assumptions underpinning road space allocation have emerged largely in response to the large-scale deployment of motor vehicles whose speed and mass made them unsafe for mixed uses of that space and whose economic contribution to urban areas was prioritised over contributions stemming from other uses of that space. In addition, the technical characteristics of these vehicles – especially their speed – led to them occupying an increasing share of that scarce space. Thus road space allocation has prioritised motor vehicles under the understanding that this represents the best use of that limited space while at the same time, the *amount* of space allocated to motor vehicles has increased due to their technical characteristics. This development represents a break with historic trends in street space allocation (Figure 1).

A second assumption is that the main metric for evaluating the allocation and supply of urban road space should be the space required by *vehicles* to operate safely. This is understandable since under-sized roads would lead to more inter-vehicle conflicts and increased congestion for a given level and mix of vehicular traffic. Nonetheless, the allocation of road space using vehicle space consumption requirements as its basis is highly problematic in urban areas where space is rare. It conflates social welfare outcomes with the movement of vehicles and not with the movement of people. By doing so, it excludes (or minimises) the spatial needs of people who are travelling using more space-efficient modes and favours the least spatially efficient modes – especially single-occupancy car use. It leads to a biased and inequitable allocation of space to the fastest and least space-efficient modes, contributing to overconsumption of scarce urban space and reducing overall welfare outcomes. A better metric to guide the allocation of space from a strategic perspective would relate to the amount of space required to move people, and not the vehicles in which they travel.

Figure 1. A short history of street space development



Source: Based on Ward (2018).

Alternative assumptions around uses of road space and the prioritisation of space allocation have emerged in different, largely local contexts. These assumptions give more consideration to alternative uses of road space – even beyond vehicular movement and storage – and users of road space. One of the clearest points of tension around discussions on road space allocation is the conflict between how local authorities and citizens may wish to revisit road space allocation and the planning and engineering requirements that underpin current practice (Jones, 2014; Halpern et al., 2020).

Tensions around capacity

Linked to discussions on why and to whom road space should be allocated is the question of who makes those determinations and on what basis. As noted above, road space allocation decisions are largely framed by traffic engineering considerations. Additionally, where economic appraisal is required or incorporated, transport economists provide guidance. This should not be surprising as once the assumption has been made that road space should be prioritised to the movement and storage of vehicles, it makes sense to involve traffic engineers. Given that road space is a scarce resource, it is also logical to involve economists and economic appraisal to help determine the most efficient and welfare-improving allocation of that resource. Nonetheless, because both traffic engineers and economists may work on the same set of assumptions outlined above, the outcome of their involvement may well ignore other valued uses of urban road space or exclude other, more space-efficient, uses of that space.

A second issue to consider is *how* road space provision and allocation decisions are made. This issue is linked to how transport planning and provision is carried out and has, over time, shifted from ad-hoc decision making to a more formal, plan-based and model-supported decision framework. This framework has generally focused on planning and providing for motorised vehicle demand (both private and public transport-based) under the twin assumptions of the continuation of past growth trends into the future and a stability in the way in which exogenous factors impact transport demand. The main task for public authorities in that context was to predict future demand growth and then to accommodate that growth by re-allocating existing road space or building new infrastructure. This “predict and provide” approach has served well in periods characterised by stability in demand growth and the relative impact of exogenous factors – especially during the large-scale uptake of motorised vehicles in the last century.

However, this approach has become increasingly problematic (ITF, 2021b). In many instances, future demand forecasts have failed to materialise. Where these forecasts have served as the basis for providing infrastructure, this has led to an over-allocation of space to accommodate projected growth which, paradoxically, then served to generate some of the very growth in demand it was meant to accommodate (ITF, 2021b). Thus, demand forecasts have become somewhat self-fulfilling, at least in their trajectories, if not in their levels. In addition, such “predict and provide” approaches favour existing uses of road space and are less well-suited to other users or for new, unanticipated but potentially valuable uses. Another issue is how well such aggregate projections are able to detect or accommodate more local uses of urban space and guide allocation decisions on a city or neighbourhood scale (ITF, 2021b).

For these reasons, a renewed interest has emerged in the decision-making processes that recognise agency on the part of public authorities and are based on a strategic vision for future urban mobility. These “decide and provide” approaches make explicit a vision of what the future allocation of public space should look like and how that vision should guide decisions on allocation (ITF, 2021b).

Tensions around networks

Decisions regarding road space allocation differ according to where in the network they are required and on what types of roads and public spaces they should be implemented. In urban contexts, public authorities face pressure to do more with existing (or less) space. How they solve this challenge is guided by systems of hierarchical road classifications. Even when considering the allocation of road space principally for vehicular use, it became clear early on that not all roads serve or should serve the same function. This has led to the development of road hierarchies that stipulate what kind of functions and uses should characterise different types of roads. The conventional road classification hierarchy organises the road network based on the functional characteristics of each road class, ranked by a set of normative factors relating to safety, speed and traffic volume. Different road hierarchies have emerged but they largely differentiate road function between *through use* (e.g. motorways and arterials) and *local access* functions (e.g. local and collector roads) (Levinson and Zhu, 2012; Paraphantakul, 2014).

Road hierarchies deliver several benefits from the perspective of managing motor traffic flows and access (Levinson and Zhu, 2012). By channelling the largest flows onto larger facilities, they allow economies of scale to be achieved in the construction of limited-access, regionally significant facilities. The hierarchy also avoids potentially dangerous conflicts among different road users and road uses. Designating and designing lower hierarchy links as local networks helps preserve neighbourhoods from the negative impacts of high volumes of through-traffic. Nonetheless, especially for roads in dense urban areas, the focus on functional hierarchies is problematic for several reasons.

From the moment they were originally conceived in the 1930s to the present, road classification hierarchies view road space as movement space, moderating circulation on some roads and concentrating it on others. They do not envisage non-movement uses of the space, rarely address non-motor-vehicle use of the space and almost never account for dynamic and time-variable allocation of road space. Roads and their uses are fixed and invariable and are, for all intents and purposes, set in stone. This does not reflect the historical reality of road space allocation and usage — which has changed over time and according to different technologies and prevailing uses — and prevents potential future uses of those spaces not considered in current engineering and traffic planning guidance.

Tensions around infrastructure

Inherent tensions emerge when discussing the re-allocation of built assets such as roads and other forms of mobility spaces. Roads and other forms of public space are infrastructure. They are tangible assets comprised of surface and sub-surface materials. They have set widths, turning radii, junction treatments, traffic signs and signals, on-road markings, curbs and other delimitations marking movement space and access or transaction space. They are designed for specific uses and to ensure specific outcomes (e.g. network function and safety). Decisions to re-allocate road space must necessarily contend with the physicality of the space. They must also consider expectations regarding the use of that space by those to whom it has been allocated. For this reason, discussions around the allocation of space, and especially the *re-allocation* of space are fraught with controversy and involve technical challenges. This has not prevented road space from being reimagined and re-allocated in specific instances or at a national scale in certain countries, such as the Netherlands (Oldenziel, et al, 2016; Dekker, 2021). However, in general, space re-allocation is a contested process that must overcome the inertia embedded in current practices (Mattioli et al., 2020). For these reasons, efforts to redistribute urban road space have largely focused on specific interventions or at a street level but rarely at the scale of the entire urban road network. This makes it difficult to gauge what the impacts of such a redistribution might be if it were deployed in a coherent, connected and cohesive manner at the urban scale.

How to measure space consumption

How much space does a person use when travelling? The answer to that question – differentiated by mode, travel distance and speed – can provide a good basis for discussions around the efficient allocation of urban road space. Though the tension between the *consumption* and *allocation* of space was noted early in the deployment of cars in cities, relatively little effort has been made to develop and adopt suitable metrics to measure the former compared to the latter. This is not for lack of a conceptual basis for measuring the consumption of urban space by vehicles – the framework for which is described below.

An indicator for measuring space consumption: Square metre per hour

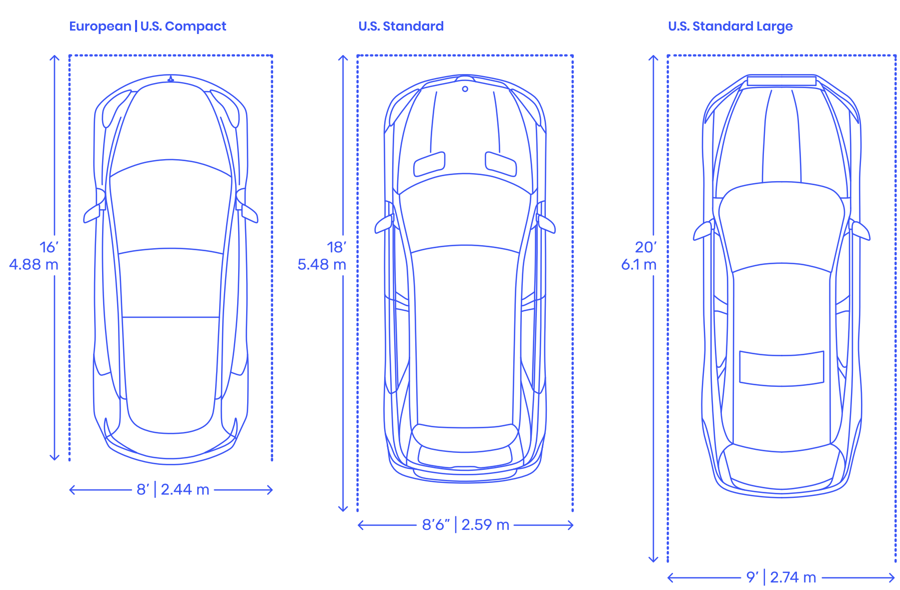
One of the difficulties in answering the space consumption question is that the amount of space consumed by a person travelling has both static and dynamic elements. It is linked to the vehicle's spatial footprint, the number of people travelling in or on the vehicle, the amount of time the vehicle is stored during a round or multi-legged trip, the trip distance and the vehicle's travel speed. These components are not captured in traditional capacity metrics such as speed-flow relationships or other throughput measures.

Similarly, they are not captured in the most common aggregate measures of transport demand such as vehicle-kilometres or passenger-kilometres travelled. Furthermore, they require a composite indicator that captures both the static (parking/vehicle storage) and dynamic (amount of space exclusively occupied while in movement) elements of space consumption. In 1973, Louis Marchand, a senior engineer at Paris's public transport operator, the RATP, developed an indicator to address this gap: the square metre hour occupied by a vehicle or person-trip (m^2.h) (Héran and Ravalet, 2008). This indicator has two components: the *static* consumption of space related to the on-trip storage of the vehicle and the *dynamic* consumption of space related to the exclusive occupation of road space by the vehicle during the trip.

Static space consumption: Parking and vehicle storage space

Trips using private vehicles involve parking the vehicle at one or several locations. This temporary storage of the vehicle requires space that may be located on the street or in off-street or multistorey car parks. The space required is proportional to the vehicle footprint, but for practical purposes, the amount of space consumed can be considered as the footprint of a standard parking space. The m^2.h for parking and vehicle storage is thus simply the amount of space consumed multiplied by the amount of time the space is occupied. This is an invariable linear relationship, although the size of a standard parking space is variable across different geographical contexts and has increased over time as vehicles have increased in size. Vehicles are stored whenever they are not used – most typically at or near the owner's residence. This storage also consumes space but is not related to the vehicle trip, per se, but rather to the storage space necessary to own a vehicle. For this reason, the rest of this report only focuses on trip-based parking space consumption.

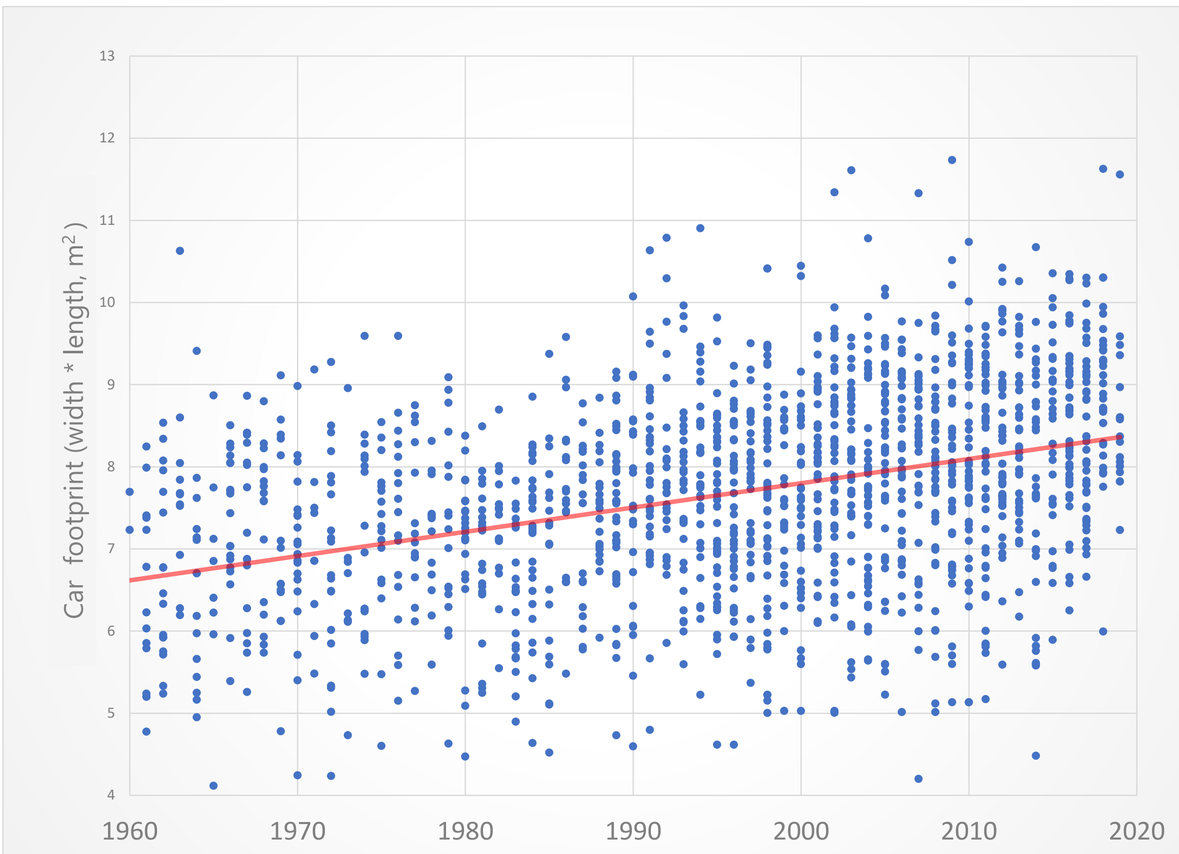
Figure 2. Different standard parking space footprints in Europe and the United States



Source: Dimensions (n.d.), www.dimensions.com.

There is no single international parking space dimension. In many cases, the size of on- and off-street parking spaces are set by traffic engineering or other bodies based on average vehicle sizes, which serve as guidance rather than a requirement. Sometimes the guidance is set at the national level and at other times by regional or local authorities. In practice, this means that these dimensions are variable across different cities, regions and countries with sometimes significant discrepancies. The most important of these discrepancies emerges in North America, where average car footprints are larger than most other regions, resulting in larger average parking space dimensions (Figure 2). The dominant share of sports utility vehicles (SUVs) and pick-up trucks in the North American fleet, alongside a car fleet that is already larger on average than other world regions, explains the shift towards larger parking space dimensions.

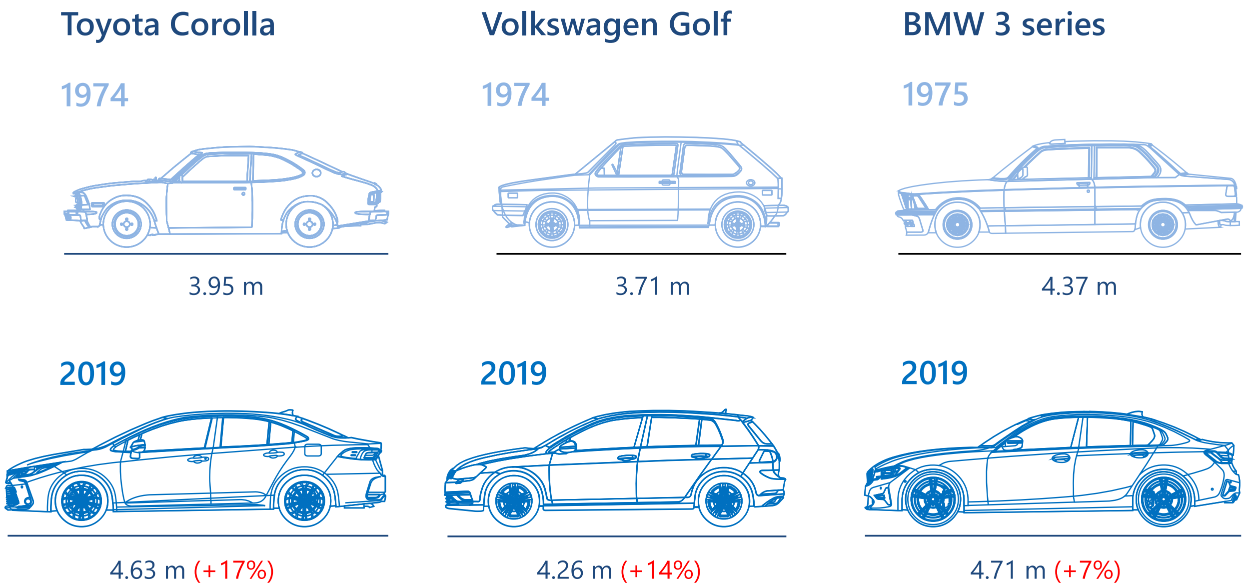
Figure 3. Vehicle footprints of cars sold in Europe by model launch year, 1960-2019



Source: Based on car dimension data from Teoalida (n.d.).

Over time, the growth in average vehicle size has also placed upward pressure on parking size dimensions. Car footprint dimensions for new models sold in Europe (by launch year) have increased by approximately 18% from the 1960s to the 2010s (Figure 3). This increase has been even larger in North America due to the rapid penetration of SUVs in the market (US EPA, 2019). Launch year dimension statistics hide growth within each car model over its production lifetime. Here too, dimensions have increased over time, reflecting the generalised trend in the growth of vehicle footprints (Figure 4). Parking space dimensions include additional space for accessing the vehicle and manoeuvring in and out of the parking space. The growth in vehicle size creates pressure to increase the storage space allocated to vehicles, just as discussions are underway in many cities to re-allocate that space to other uses.

Figure 4. Change in dimensions of selected vehicle models from launch year to present



Source: Based on data and drawings from The Blueprints (n.d.).

The footprint of on-street parking varies according to its configuration. Parking parallel to the curb consumes the least space but other on-street parking arrangements (e.g. angled parking) consumes more space. Off-street parking consumes even more space as the auxiliary space required to access and manoeuvre in standard or multistorey car parks must also be included. The differences are significant and should be accounted for in space consumption calculations. In a comprehensive study looking at space consumption in the Ile-de-France region of France, Frédéric Héran compiled a set of "standard" European parking space use values based on an empirical review (Table 1). The values in this table serve as a good starting point for calculating the static space required to store various vehicles. In other regions, and particularly in North America, they should be adjusted to reflect prevailing dimensions. The values are adjusted by typical load factors to give per-person static space consumption values.

The values for the static consumption of space by buses is based on observed values in bus depots in the Ile-de-France region. This space is analogous to the space required for home parking by vehicles in residential areas and as such, it is not clear whether this space should be considered trip-based parking since buses do not park on-trip. Buses do, however, temporarily occupy space at bus stops — approximately 24 linear metres for a 12-metre bus accounting for manoeuvring space (Héran and Ravalet, 2008). Because of its short-term nature, the exclusive use of space by buses can be subsumed into the dynamic aspect of the m^2.h indicator and is related to the bus's average commercial speed. In practice, because of the need to keep stops accessible to buses, space at bus stops is often exclusively allocated to buses and is thus not available for other uses. So, while the bus's consumption of space is limited, the allocation of space to buses is more extensive.

Table 1. Static space consumption per person by mode and configuration

Mode and configuration	Parking space per vehicle (m^2)	Ancillary and manoeuvring space (m^2)	Space consumption per vehicle (m^2)	Average load factor per vehicle (persons/vehicle)	Static space consumption per person (m^2)
Car (on-street, parallel)	10		10	1.3	7.7
Car (on-street, angled)	12		12	1.3	9.2
Car (car park)	10	15	25	1.3	19.2
Car (multistorey car park)	15	10	25	1.3	19.2
Motorised two-wheeler (on-street)	1.5		1.5	1.05	1.4
Motorised two-wheeler (car park)	1.5	1.0	2.5	1.05	2.4
Bicycle (stand)	0.8		0.8	1	0.8
Bicycle (two-level rack)	0.4	0.2	0.6	1	0.6
Bus (12-metre)*	42	28	70	17	4.1
Bus (12-metre, peak period)*	42	28	70	50	1.4
(pedestrian)					(0.25)

* For an 18-metre articulated bus, multiply by 1.5
Source: Héran (2012).

Dynamic space consumption: Movement space

The exclusive occupation of space by vehicles in movement is a function of vehicle size, inter-vehicle spacing, the amount of lateral space consumed in normal operation and the amount of time the space is occupied – itself a function of vehicle speed. Therefore, a large car travelling fast requires more space and exclusively occupies a greater linear and lateral spatial footprint in traffic. However, because it travels through that space at greater speed, it occupies that space for less time. A bicycle, on the other hand, takes little space, has a smaller spatial footprint as it moves but occupies that space longer due to its lower speed. Speed consumes space as it increases the vehicle's dynamic spatial footprint, but speed also means that vehicles occupy that space for less time. However, of the two effects, the speed effect is the greatest – on balance, the faster a vehicle travels, the more space it consumes.

The relationship between space consumption and throughput is an inverse one. For any given width of carriageway, the more space consumed by a vehicle, the less throughput is achieved. Table 2 shows maximum vehicle and person throughput values for different modes and carriageway widths. For public transport services, it accounts for standard service-related headways and peak hour load factors.

Table 2. Maximum vehicle and person throughput by mode for different carriageways

Mode	Vehicles per hour and direction	Inter-vehicle headway for public transport (minutes)	Average load factor (persons per vehicle)	Hourly throughput of people per direction	Width of carriageway	Hourly throughput per metre of carriageway width
Walking				9 000	3	3 000
Bicycle	9 000		1	5 000	3	1 667
Bus (12-metre in traffic)	20	3.0	70	1 400	3	467
Bus (18-metre, dedicated lane)	25	2.4	100	2 500	3.5	714
Tramway	30	2.0	300	9 000	3	3 000
Subway	40	1.5	800	32 000	3.5	9 143
Commuter rail	20	3.0	1 000	20 000	4	5 000
High-speed commuter rail	30	2.0	2 000	60 000	4	15 000
Car (motorway)	2 400		1.25	3 000	3.5	857
Car (urban street)	900		1.25	1 125	3	375

Source: Héran and Ravalet (2011).

Strictly from a throughput perspective, the potential for public transport and active mobility is orders of magnitude greater than that of cars – these modes simply can convey more people per unit of space available. However, they are unable to serve all parts of the urban region (for rail-based modes), nor can they offer the same travel speeds (for active and bus-based modes) – though at peak hours, this differential decreases significantly in urban centres. Further, the arrival of new modes such as electric kick scooters and electric bicycles have increased achievable speeds and ranges for light mobility modes.

Throughput metrics only indirectly reflect dynamic space consumption. Marchand's early work at the RATP sought to capture this dimension more explicitly and accurately with the notion of the *dynamic surface,* which captures the exclusive occupation of space by a vehicle as it travels.

The dynamic surface is calculated by multiplying the sum of the length of the vehicle (in metres) and the inter-vehicle spacing (in metres) by the average lane width per direction of travel (also in metres). Because vehicle size plays a minimal role in inter-vehicle distancing (this distance is a factor of vehicle mass and speed) and because lateral width necessary for safe operation (allowing for natural weaving and sufficient separation from other vehicles) is also a factor of vehicle speed, there is little difference in the dynamic surface of small versus large vehicles operating at the same speed and what difference there is relates more to the mass of the vehicle rather than their footprint (Héran and Ravalet, 2011).

Inter-vehicle spacing is a function of reaction time and stopping time – both, in turn, are a function of speed. Reaction time for a normal driver is approximately one second – this must be multiplied by the speed to obtain the reaction distance component of the dynamic surface. Stopping time is the amount of time it takes from the moment the vehicle starts braking to the moment it stops moving. This time must also be multiplied by speed (and adjusted for the rate of deceleration for the vehicle's mass and coefficients for surface friction and gravity) to obtain the stopping distance. However, (Héran and Ravalet, 2011) note that inter-vehicle distances are, in practice, much shorter than the theoretical function would predict and have decreased over time (with, for example, the introduction of ABS). For this reason, he suggests basing the inter-vehicle distance component of the dynamic surface equation on observed values on crowded urban roads (e.g. the Paris ring road). This results in the following function to calculate the inter-vehicle distance component of the dynamic surface (Héran and Ravalet, 2011):

$IVD = V + 0.01371\ V^2$

Where:
IVD=Inter-vehicle distance in metres, and
V=Speed in metres per second

The lateral component of the dynamic surface calculation is comprised of the width of the vehicle, an additional width necessary for the safe operation of the vehicle in traffic (due to natural weaving and lateral separation from other vehicles) and an additional adjustment for the space required to operate the vehicle on a roadway (junctions, shoulders, etc.). The average space consumed per lane of travel can be simplified based on observed values (again from the Paris region) such as speed and the number of junctions. Thus the lateral component of the dynamic surface is represented in the following formula (Héran and Ravalet, 2011):

$ALS_L = 2.2 + 0.0052\ V^2$

Where:
ALSL= Average Lateral Space consumption per lane in metres, and
V= Speed, in metres per second

The combination of the inter-vehicle and lateral components gives the dynamic surface function:

$DS = (L + IVD) * ALSL$

Where:
DS = Dynamic Surface
IVD = Inter-vehicle distance in metres
V = Speed, in metres per second

The dynamic surface increases with the square of speed which explains the preponderant weight of speed in the overall calculation of space consumption. However, as noted, speed also means that as a vehicle travels faster, it occupies that space for less time. Thus Marchand's specification for the m^2.h indicator also accounts for travel speeds and trip lengths. The resulting function for calculating m^2.h/km is (Héran and Ravalet, 2011):

$DSC = DS * T_k$

Where:
DSC = Dynamic space consumption per vehicle per kilometre travelled in m^2.h
DS = Dynamic Surface
T_k = Time it takes to travel one kilometre

Since $T_k = 1/(3.6\ V)$ and given that V is expressed in metres per second, the dynamic space consumption formula can be simplified as (Héran and Ravalet, 2011):

$DSC = SD / (3.6\ V)$

The above formula reflects a theoretical basis for approximating the consumption of space by mode. In practice, it must be adjusted to reflect differences between modes. Héran and Ravalet (2011) note that urban traffic speeds are highly variable and cars and other motorised vehicles may travel at anywhere between 15 km/h (and slower) to 50 km/h (or faster) during the same trip. To account for this variability, he recommends adjusting the dynamic space consumption resulting from average speeds upwards by 50%. The same adjustment should be applied to motorised two-wheelers who have limited opportunities to bypass other vehicles in dense urban traffic. Pedestrians, cyclists and e-push scooters experience much more even travel speeds – especially where dedicated infrastructure is available (pavements and light mobility lanes).

Combining the dynamic and static space consumption functions outlined above and applying different specific trip characteristics and speeds provides insight (and data) on the actual space consumed by different transport modes per trip and, when trip distances and numbers are available, in aggregate. Figure 5 shows the space consumed per person for two different trips. The first is comparable to a shopping trip with a 6 km round-trip distance and a two-hour dwell time. The second is comparable to a typical work trip with a 10 km round-trip distance and an eight-hour dwell time.

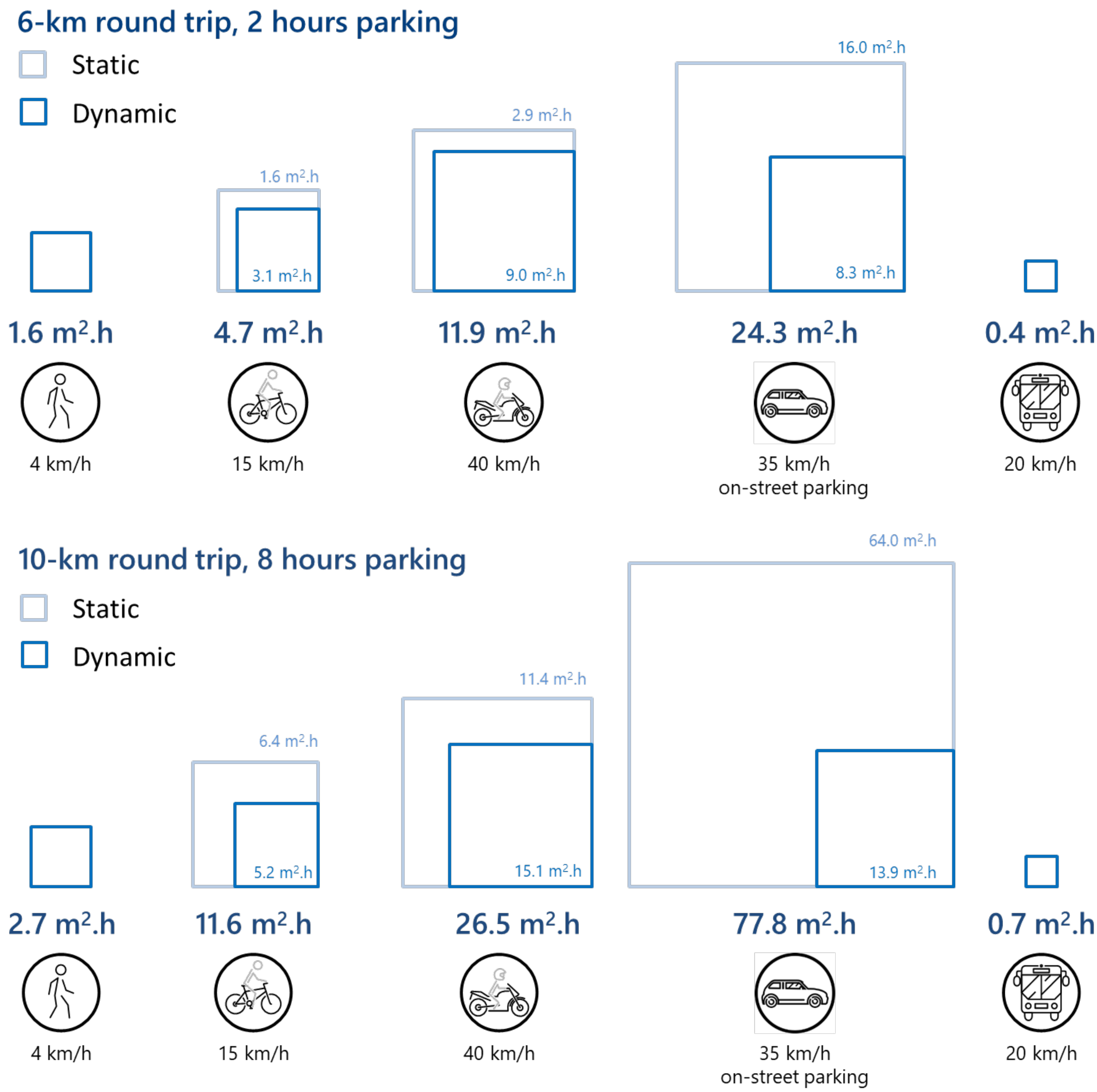
What these examples (and others based on the functions outlined here) show is that the consumption of space varies by mode but that the most space-intensive by far is the car. It also shows the spatial efficacy of public transport in comparison to all other modes (at sufficient load factors) and underscores the impact that speed plays since the 5 km/h difference in speeds between motorised two-wheelers and cars is sufficient to raise the dynamic space consumption of the former over the latter.

Figure 5 shows the impact that parking plays on space consumption, since as dwell time increases, so too does the space exclusively occupied by vehicles. Finally, load factors play an important role in influencing space consumption per person. Increasing the load factor of cars to three people per vehicle would almost equalise the dynamic consumption of space between cars and bicycles. Likewise, decreasing the load factor of buses to ten people per bus (not unusual in off-peak hours) would triple its dynamic spatial footprint (although it would still consume less than half the space of a car occupant at typical load factors).

The m^2.h indicator serves to better differentiate modes by their actual consumption of space. As noted earlier, in urban areas, especially in core and other locally dense areas, this space is rare and so it makes sense to prioritise the most space-efficient modes and uses. However, the optimisation of the use of space, although important, is only one factor to consider when allocating space.

From a societal perspective, it makes sense to give space to active modes as these provide significant health benefits on top of their mobility benefits (ITF, 2013). From a physical accessibility perspective, it makes sense to give space for those who may require a car or another vehicle to get around due to their mobility impairments. Finally, as noted earlier, individuals value the use of the car not only because it allows them to access numerous destinations relatively quickly, but also because they derive other amenity values such as carrying loads, giving others a ride and enjoying a private space in which to travel. In many circumstances, some of these amenities could also be delivered by other modes (cargo bikes can carry many typical carloads; cycling side-by-side on safe infrastructure provides an analogous level of privacy as travelling within a car; travelling by public transport allows people to read or interact with internet-based services and social media) but these practices have rarely been facilitated by the provision of car-based infrastructure.

Figure 5. Space consumed per person per trip for different trip characteristics



The relatively recent arrival of different new mobility services, including shared micromobility, carsharing, ridesourcing and on-demand van services, all display slightly different spatial footprints. These were modelled in the work described later, but the main differences relate to the way in which the static footprint is defined. On a per-trip basis, shared cars, shared bicycles and shared e-push scooters have the same static spatial footprint as their non-shared analogues (and shared e-push scooters have similar dynamic spatial footprints as bicycles). However, if a "trip" for shared vehicles is based on each vehicle's daily service cycle, then the relative share of the static component decreases in line with how long the vehicle is stopped between uses (and almost disappears for shared rides and ridesourcing) while the dynamic component of the spatial footprint increases. Seen this way, each trip can be considered one segment of a daily composite trip chain.

New frameworks to characterise street space

Most frameworks used to characterise street spaces and their functions emerged from the need to manage motor vehicle flows and avoid conflicts with other uses. While it is natural that these frameworks prioritised motor vehicle flows, as they were designed to do, these road classification hierarchies do not allow for new possibilities around the use and allocation of road space.

As a response, alternative street hierarchies and methods for organising urban road space have emerged. These include frameworks such as London's Street Families that differentiate the use of streets according to their movement or link functions as opposed to their place-making functions. The former relates to how people, goods and services get from one place to another by using a range of different travel modes. The latter relates to the use of streets for living and unlocking or accessing opportunities in areas adjacent to the movement space and to ensure essential urban functions (TfL, 2013). This approach allows for more flexibility in how street space could be used but does not directly address issues relating to the specific allocation of street space to competing uses. For instance, streets may be designated as principally having a movement or link function and thus favour motor vehicle use, however, allocating space to separated light mobility infrastructure may also extend the link function to bicycles and other forms of micromobility. Likewise, designating a street as having primarily a place function does not preclude it also serving as a link for bicycles and other forms of micromobility (Aldred, 2014).

Other frameworks such as the superblock model (Ajuntament de Barcelona, 2016; Mueller et al., 2018) base urban space allocation and function on the network permeability for certain modes (primarily walking, cycling and micromobility) and segregation for faster, motorised modes. The superblock model is comprised of a higher speed link-oriented network for cars and public transport and a local, access-restricted and speed-managed network that services active modes and residential access by motorised vehicles. This approach is also reflected in the Street Design Principles developed by Sidewalk Labs (Ng and Doyle-Wiese, 2019).

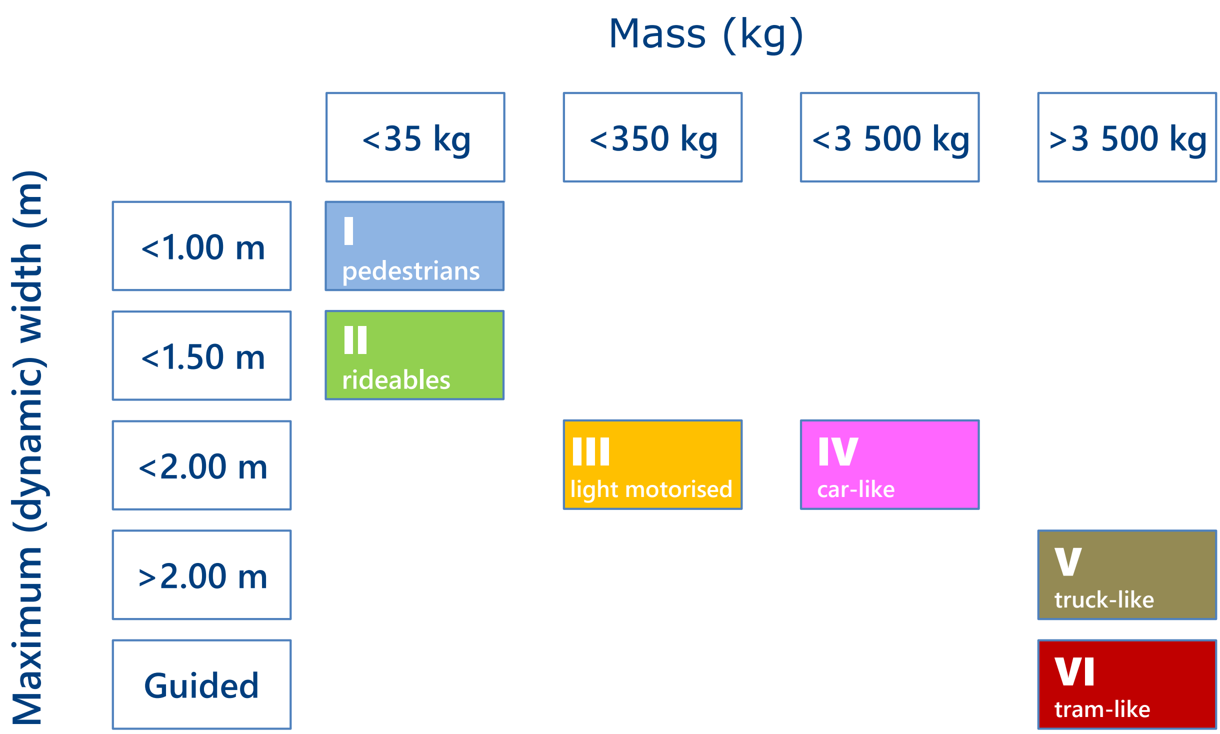
The modelling work undertaken for this report was informed by another framework, commissioned by the Royal Dutch Motoring Club (ANWB). This framework – the "Good Street" framework (Immers et al., 2020) – seeks to "develop a generically applicable design methodology with which urban public space (including traffic infrastructure) can be reconfigured, while simultaneously considering quality of life, safety and accessibility demands and requirements" (Immers et al., 2016; 2020).

This framework is based on two fundamental principles:

1. The legal speed of vehicular traffic is linked to the design and characteristics of the infrastructure and not, as currently is often the case, to vehicle type. Vehicle access is thus based on infrastructure design and characteristics.
2. The mass and dimensions of vehicles will determine on what parts of the network vehicles are permitted or not.

Taken together, these two principles ensure that differences in speed between vehicles are minimised by design (the first principle) as are inter-vehicle differences in mass and size (the second principle). Reducing differences in speed, mass and size are at the core of the Safe System[1] approach for road safety (ITF, 2016a; 2016b) and are a highly effective strategy to improve road safety. They also contribute to ensuring that a wider variety of street functions and uses can emerge.

Figure 6. The Good Street vehicle families, classified by weight and dimension



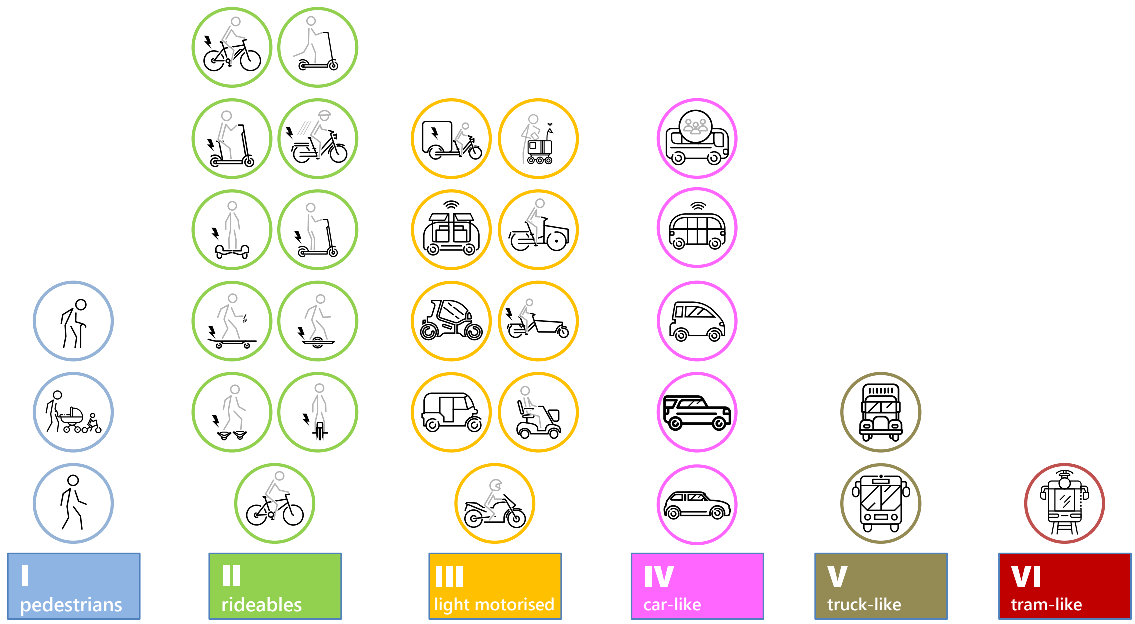
Source: Adapted from Immers et al. (2016; 2020).

At the core of the framework is the classification of vehicles into six different vehicle families, as shown in Figure 6 (Immers et al., 2016; 2020). These families were adapted for this study to reflect different forms of micromobility and, in particular, integrate the four classes of micromobility vehicles established in the ITF's work on Safe Micromobility (ITF, 2020b). The vehicle families are as follows:

- Vehicle family 1: Pedestrians. This family acknowledges the place of all persons walking, both as users of public space and as a standalone mode of transport, or as a way of accessing other modes of transport.
- Vehicle family 2: All "cycle-like" modes of transport that are lighter than 35 kg and no wider than 1.5 m. These can be considered as "rideables". This family includes bicycles, e-bikes, e-push scooters and other like vehicles. It covers ITF Micromobility types A and D (ITF, 2020b).
- Vehicle family 3: Small yet heavier vehicles, including ITF Micromobility type C and D (ITF, 2020b). This comprises heavier cargo bikes, small urban goods distribution vehicles, motorised wheelchairs, rickshaws and heavier mopeds and other motorised two or three-wheelers.
- Vehicle family 4: All car-like vehicles, including vans and SUVs.
- Vehicle family 5: All truck-like delivery, service or work vehicles, including buses.
- Vehicle family 6: On-street guided vehicles such as trams and streetcars.

This set of vehicle families provides a simple basis to classify any number of existing or new vehicles according to mass and size (Figure 7).

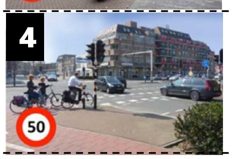
Figure 7. Indicative classification of various vehicles into six vehicle families



As with other approaches, the Good Street framework seeks to address the balance between place-specific attributes of networks (i.e. the identity of the city, identity and function of the neighbourhood, alternative uses of urban space, desired land use characteristics and density) and traffic-related functions (i.e. access to activities, trip-making, desired transport network structure and decisions to mix or separate users). This approach recognises that people both live and use spaces just as they use these spaces to travel.

To help achieve this balance, the Good Street framework proposes four archetypal traffic environments characterised by the maximum legal operating speed for vehicles in each environment and primarily designed for a normative vehicle family (Figure 8). In this framework, lighter and smaller vehicles than the normative design family always have access. Vehicles larger and heavier than the normative family may be admitted within each environment but only as guests and under certain conditions – the first of which is that they respect the design speed and predominant traffic behaviour.

Figure 8. The Good Street archetypal urban traffic environments, corresponding normative vehicle family and access rules

Urban traffic environment.	Maximum permissible speed	Normative vehicle family for design	Lighter vehicles (always permitted)	Heavier vehicles (excluded or guest)
1 	10 km/h	I pedestrians		(II, III, IV, V, VI)
2 	20 km/h	II rideables	I	(III, IV, V, VI)
3 	30 km/h	III light motorised	I, II	(IV, V, VI)
4 	50 km/h	IV car-like	I, II, III	(V, VI)

Source: Adapted from Immers et al. (2016; 2020).

The Good Street framework addresses multiple uses of the same street space by defining when and under what conditions vehicle families may operate in the same space or "domain", and when they should be separated. Generally, vehicle families that are no more than one category lighter than the normative design family may be allowed (but not required) to share that domain or road space. Vehicle families that are two or more categories lighter and smaller than the normative design family must be accommodated in other domains either by separation in the same road space or by rerouting to other domains.

These principles and the Good Street framework served to inform the modelling work undertaken in the second part of this report.

Modelling mobility and space consumption

To assess alternative space allocation options, the ITF developed a detailed simulation and optimisation approach that could simultaneously test dynamic management of street space allocation, and the deployment of new private ownership and shared mobility solutions.

The modelling for this study has two new features compared to previous ITF urban modelling work. The first is that it incorporates a wider range of mobility options and services than previous work and addresses these at a more detailed level within the urban core. The second is that it allows for limited, dynamic, demand-responsive re-allocation of street space according to street type. A pre-existing shared simulation model for the Greater Dublin Area (ITF, 2018a) was used as the basis for testing the measures and policies discussed in this report. However, rather than depend on observed data, a plausible characterisation of shared or free-floating transport supply, as well as detailed parking availability, was generated synthetically. For this reason, the results of this report should not be used to assess the results or impacts specifically in the case of Dublin.

The pre-existing simulation was adapted by adding multiple free-floating modes (including shared cars and micromobility, i.e. e-kick scooters and free-floating shared bicycles), pedestrians, and private bicycles. These modes are incorporated either as a principal travel mode or an access or egress mode (i.e. first and last kilometre) for public transport. Furthermore, a new and more detailed routable street network was created within the core urban area covered in the model to more finely capture detailed non-motorised vehicle flows. This network was then consolidated with the pre-existing network outside the city core.

More details about the simulation architecture of the shared component and optimisation services approach can be found in ITF (2018a). The present report focuses on capturing the impacts of adding more, largely free-floating, shared mobility services that are directly operated by customers than were investigated in ITF (2018a). It also seeks to capture the effects of more dynamically managing street space allocation and use. The simulation does this by running an optimisation process every 30 minutes. This enables configuring streets that are theoretically adjusted to the observed or predicted demand.

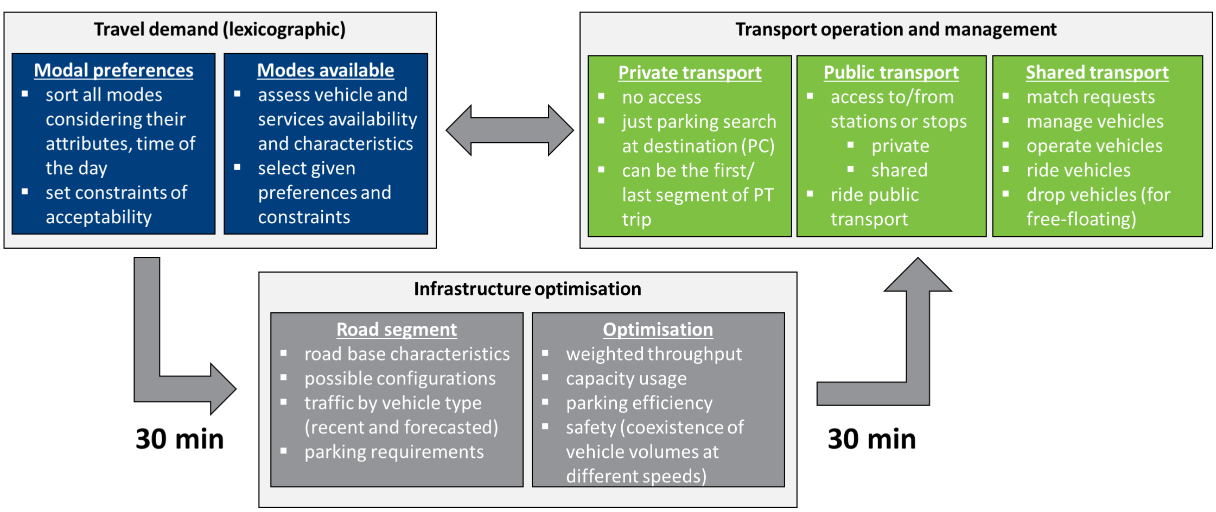
The optimisation objective function minimises space consumption (both in its static and dynamic components). The objective function includes: travel time by vehicle type (weighted by the flow and corrected by a factor of two for pedestrians and one point five for bicycles so as to not overly represent cars that may present higher travel time savings by circulating at higher speeds), parking capacity usage (i.e. estimated parking search time and unused spare capacity of reserved parking spaces) and traffic safety (i.e. number of potential conflicts between vehicle types and their difference in flee flow speeds). For this, all components of the function are converted into time.

Figure 9 presents the adjusted model framework. It has three key components: a lexicographic travel demand framework, an infrastructure optimisation framework and a transport operation and management framework. The model simulates how users make mode-choice decisions given available options, the modal attributes that are expected given the operational layout and the expected travel time given the street specifications in terms of capacity and speed for each vehicle type.

The model is conceived as a sorting utility-based algorithm derived from the Outlook 2021 Global Urban Model (ITF, 2021b) and constraints are set to trigger potential modal switches (i.e. the conditions under which one mode can be replaced by another). Specific modal availability and/or suitability depends on the time of day and trip purpose. In practice, all travellers and vehicles operating in the city simultaneously send and receive information to a centralised dispatch algorithm that optimises vehicle usage and plans for subsequent periods. Finally, every 30 minutes an optimisation algorithm runs based on the registered dynamic and static (i.e. parking) demand on each street segment. This algorithm enables changes in the capacity reserved for each vehicle type (moving or standing) to be captured, as well as the allowed free flow speed given the combination of flows expected in the next 30 minutes.

The optimisation objective function minimises space consumption (both in its static and dynamic components). The objective function includes: travel time by vehicle type (weighted by the flow and corrected by a factor of two for pedestrians and one point five for bicycles so as to not overly represent cars that may present higher travel time savings by circulating at higher speeds), parking capacity usage (i.e. estimated parking search time and unused spare capacity of reserved parking spaces) and traffic safety (i.e. number of potential conflicts between vehicle types and their difference in flee flow speeds). For this, all components of the function are converted into time.

Figure 9. Updated model framework to account for space allocation and use



The optimisation of each street segment accounts for 19 different road typologies. It uses a "greedy optimisation" approach, where each link is optimised individually and co-ordinated with the neighbouring segments. Each road type has a predefined set of compatible conversion options. Table 4 and Figure 10 present the different street typologies used, their nomenclature, and the conversion compatibilities among them. There are different flow capacities and free-flow speeds for each vehicle type (depending on whether the infrastructure is shared or not), and parking capacity is allocated for every linear 10-metre street segment. The values are separated for motorised-based modes and vehicles (car/bus/motorcycle), pedestrians, and bicycle-based modes. In each street configuration solution, the infrastructure devoted to each of these groups can be shared – which requires lower speeds (especially for the fastest modes) – or segregated. In the following section, each transport mode considered is attributed to one of these groups. Each street has an initial typology that is revised every 30 minutes during the simulation.

More details about the simulation architecture of the shared component and optimisation services approach can be found in Martinez and Viegas (2017) and ITF (2018b). The current report will focus on discussing the modelling approach and the results of adding more shared mobility services that are directly operated by customers and are usually free-floating, and the dynamic management of the street network configuration.

Scenario definitions

Four different space allocation scenarios are assessed. They include variations in terms of the network (static or dynamic), the demand (static or dynamic) and the mode choice (existing or including new shared modes). This approach allows for the impacts of these different components to be disentangled.

The scenarios are defined as follows:

1. **Baseline scenario:** This serves as the departure point. The network remains static (i.e. without temporal configuration and street space allocation changes), as does the demand. No additional modes are included in the supply.
2. **Full implementation scenario:** Incorporates a dynamic network, dynamic demand, and the implementation of new transport alternatives (e.g. free-floating micromobility, shared modes). It is a combination of scenarios 3 and 4.
3. **Dynamic network scenario:** Incorporates a dynamic network, but the transport supply and mobility alternatives remain unchanged from the baseline.
4. **New mobility paradigm scenario:** Incorporates new modal alternatives, including a dynamic demand where users can switch between modes, depending on the current supply at any moment in time. However, the road network remains unchanged and static.

Modal alternatives

As noted earlier, the simulation covers 19 different travel modes. These were categorised according to several variables and are outlined in Table 3 below. To help define the rules for re-allocating street access and use in the model, these modes were mapped to the Good Street vehicle families described earlier (Figure 6). The modes include active, electric and internal combustion (IC) alternatives. In addition to walking, a range of low-capacity (i.e. cars, motorbikes) and micromobility (i.e. bikes, e-bikes, e-scooters) alternatives are included in their private and shared variants. Mass public transport (i.e. bus, car + public transport [CPT], light rail, heavy rail) is also considered, as well as on-demand services of different capacities (i.e. taxis, on-demand buses designated here as TaxiBus, shared vehicle options, feeders). The 19 modes were finally divided into five classes for modelling purposes:

- private non-motorised and micromobility
- shared non-motorised and micromobility
- private motorised transport
- public transport
- shared transport.

The model is implemented for the whole of the urban region, but free-floating shared micromobility modes are included only within the core, where the resolution of the street network for this purpose was also increased.

Table 3. Description of modal alternatives included in the simulation exercise

Mode in model	Description	Active or motorised?	Private self-owned or shared?	Sharing type	Good Street vehicle family*	Modelling analysis group
Walking	Walking as access or full mode from origin to destination	Active	Private		I	Private non-motorised + micromobility
Owned bicycles	Private non-electric bicycle as access or full mode from origin to destination	Active	Private		II	Private non-motorised + micromobility
Owned e-bicycles	Private electric bicycle as full mode from origin to destination	Active	Private		II	Private non-motorised + micromobility
Owned e-scooters	Private electric scooter as full mode from origin to destination	Motorised	Private		II	Private non-motorised + micromobility
Shared bicycles	Free-floating shared-bicycle service	Active	Shared	Free-floating or station-based	II	Shared non-motorised + micromobility
Shared e-bicycles	Free-floating electric shared-bicycle service	Active	Shared	Free-floating or station-based	II	Shared non-motorised + micromobility
Shared e-scooters	Free-floating electric scooter sharing service	Motorised	Shared	Free-floating or station-based	II	Shared non-motorised + micromobility
CPT	Car + public transport (e.g. park and ride)	Motorised	Private/ shared		IV/VI	Private motorised transport
Car (driver)	Car driver from origin to destination	Motorised	Private		IV	Private motorised transport
Car passenger	Car passenger from origin to destination	Motorised	Private		IV	Private motorised transport
Motorcycle	Motorcycle from origin to destination	Motorised	Private		III	Private motorised transport

Mode in model	Description	Active or motorised?	Private self-owned or shared?	Sharing type	Good Street vehicle family*	Modelling analysis group
Bus	Bus as single-use or part of multimodal trip	Motorised	Shared	Mass Public Transport	V	Public Transport
Rail	Rail as single-use or part of multimodal trip	Motorised	Shared	Mass Public Transport		Public Transport
LRT	Light rail as single-use or part of multimodal trip	Motorised	Shared	Mass Public Transport	VI	Public Transport
Taxi	Taxi passenger from origin to destination	Motorised	Shared	On-demand	IV	Shared transport
Carsharing	Free-floating carsharing service	Motorised	Shared	Free-floating or station-based	IV	Shared transport
Ridesourcing	App-based ridesourcing service with professional driver	Motorised	Shared	On-demand	IV	Shared transport
Taxi-bus	App-based on-demand bus (route and schedule) from origin to destination	Motorised	Shared	On-demand	IV/V	Shared transport
Feeder	App-based on-demand bus (route and schedule) to access heavy public transport station (rail or LRT) directly to destination	Motorised	Shared	On-demand	IV/V/VI	Shared transport
Shared motorbike	Free-floating motorcycle sharing service	Motorised	Shared	Free-floating or station-based	III	Shared transport

* See Figure 6 for an explanation of the vehicle families.

Street space functions and configurations

The simulation model developed for this report adjusts the allocation of street space to expected demand every 30 minutes. To enable this, different road classification categories were defined based on a characterisation of the Dublin road network (OpenStreetMap, 2021). Rules relating to how and under what circumstances these road classes could switch were also built into the model. The linkage between road classes (and their use) and vehicle classes was roughly based on the street space classifications developed for the Good Street framework as seen in Figure 6 (Immers et al., 2016; 2020).

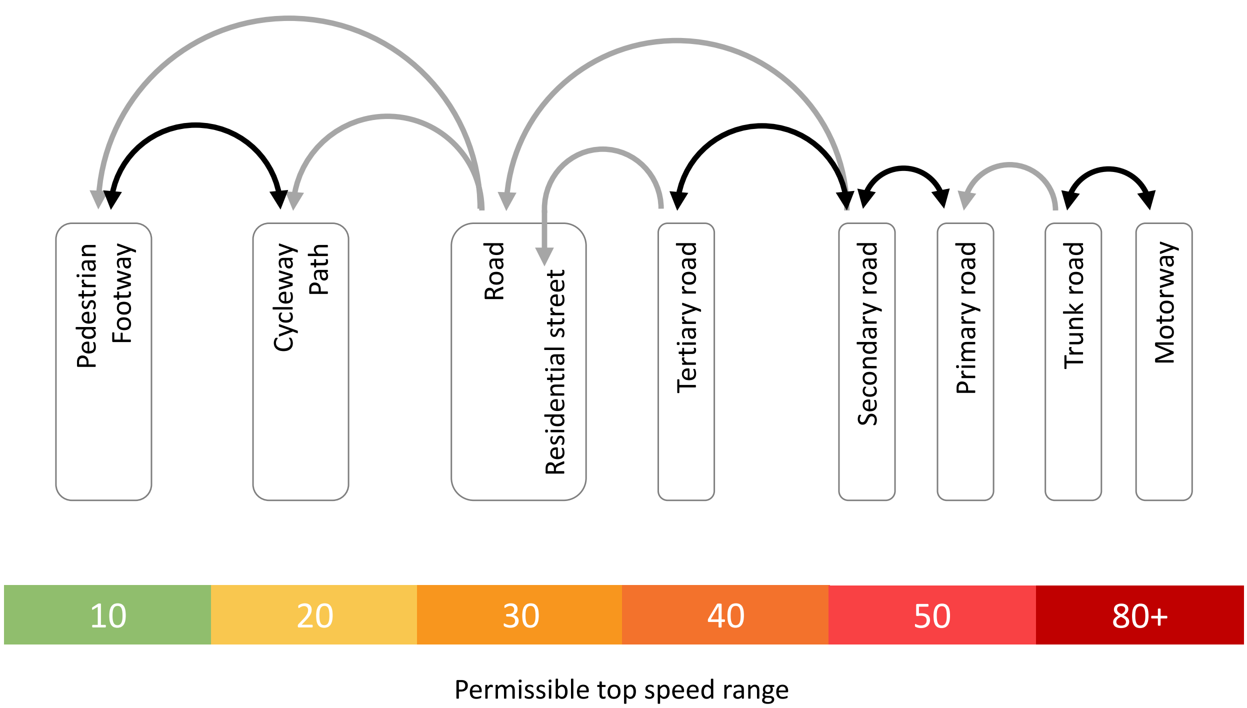
Table 4. Street space functions and configurations

Road category	Pedestrian		Cycling		Car		Parking	Traffic segregation (%)
	Speed (km/h)	Capacity (person/h)	Speed (km/h)	Capacity (vehicle/h)	Speed (km/h)	Capacity (vehicle/h)	(vehicle/10 m)	
Steps	3	500					0	100%
Pedestrian	5	3 000	12	500			0	0%
Cycleway	3	100	27	2 000			0	0%
Footway	5	4 000	12	500			2	0%
Path	5	2 000	27	800	20	400	1	10%
Track	5	2 000	27	500	20	250	0	0%
Service	5	1 000	12	500	30	600	3	25%
Residential	5	1 000	12	500	30	600	4	50%
Roads	5	1 000	12	500	30	600	3	75%
Tertiary entry	5	1 000	12	500	30	600	2	50%
Unclassified	5	750	12	500	40	600	1	25%
Secondary entry	5	1 000	12	500	40	800	2	80%
Tertiary	5	750	12	500	40	800	4	50%
Secondary	5	750	12	500	50	1 400	2	80%
Primary	5	500	12	200	50	1 800	0	100%
Trunk entry			8	1	50	1 400	0	100%
Motorway entry					50	2 200	0	100%
Trunk			8	1	80	3 000	0	100%
Motorway					90	4 400	0	100%

Characteristic road performance values for the different road categories (i.e. capacity, speed and traffic segregation or reserved right of way) are defined and used as attributes in the optimisation exercise. Additionally, for each road category, the car-equivalent parking capacity was defined for every 10 metres of road length (e.g. a bus occupies three times more space than a standard car). The values for these categories can be found in Table 4. It is important to note that this table represents the speed and capacity performance per mode *if the street configuration is changed in the model*. Thus, there are some vehicles that can never occupy some types of street space in the model – e.g. a car will never operate on steps and a pedestrian or bicycle will never be present on a motorway. The table does indicate how infrastructure built for one use may handle different vehicles under a temporarily changed configuration. For example, in the model, a pedestrian zone that is temporarily redesignated to accept bicycle use could see up to 500 bicycles operating per hour at a maximum speed of 12 km/h. Similarly, a tertiary road that is temporarily redesignated as a secondary road in the model will not see more than 800 vehicles per hour operating at a maximum speed of 40 km/h (as opposed to a "native" secondary road that can handle 1 400 vehicles per hour at a maximum speed of 50 km/h).

These categories also act as constraints in the model in terms of the geometrical changes that can be introduced to alter the original road space configuration. Each road category has a predefined set of other possible categories to which it can be converted based on the original geometry (Figure 10). For example, a motorway cannot become a pedestrian area in the model.

Figure 10. Dynamic reconfiguration of road space:
Possible in-model conversion pathways of road classifications



Note: the grey arrows represent one-way or uni-directional change of road typology, whereas the black arrows represent two-way or bidirectional potential road typology changes. Grouped road typologies imply interchangeability among them. Arrows to/from groups indicate potential changes of road typology to any road type in the group.

It is important to stress that the potential street-use conversion pathways discussed in this report are theoretical in nature and serve to help understand what potential efficiencies could be achieved with more dynamic adjustments of physical street space. In reality, such adjustments would have to be carefully designed and implemented to avoid any negative safety outcome. This may limit the range of potential reconfigurations that this report investigates, even under the constraints imposed in the model. At a minimum, such dynamic re-allocation of space would require a very different road management paradigm than exists today.

Assessment indicators of model outputs

To assess the results of the simulation exercise, two main types of indicators are used: space consumption measures and accessibility-like measures. These are described in more detail below.

Space consumption indicators

The mobility patterns (pertaining to the number of trips, modes and their duration) resulting from the different simulations were used to calculate space consumption based on the approach and equations from (Héran and Ravalet, 2011) described earlier.

The space consumption measure incorporates four main components. The first two comprise (1) the static space consumed when vehicles are not in use (e.g. parking) and (2) the dynamic space consumed by vehicles while travelling. Additionally, when considering public transport or shared modes, the space used by travellers (3) while waiting for the vehicles to arrive and (4) while travelling to and from public transport, are also included. The space consumption indicator assesses two key aspects: (1) the total stock of space consumed while travelling, and (2) the space efficiency per traveller and by passenger-km.

Accessibility-like indicators

Two different types of accessibility-like indicators were developed for the current study. The first is a cumulative travel isochrone and the second is an indirect measure of spatial accessibility that accounts for the propensity for each traveller to use a travel mode based on the accessibility benefits it confers (i.e. availability, travel time/range and affordability).

Both indicators explore the accessibility provided by different transport modes based on mobility patterns observed in the simulation exercises. Unlike more commonly used accessibility measures, they do not consider the potential ability to reach specific opportunities (based on the temporal or distance-based proximity, and network and transport services performance).

The decision to define the indicators in this way stems from the fact that the simulation framework used in this study measures the effects of the dynamic activity of users, who have a predefined location and time for the activities they want to perform throughout the day. A different activity-based and land-use integrated transport (LUTI) model would be required for the more common approach to accessibility.

The first indicator is a cumulative travel isochrone. This is an aggregate indicator for the entire region which measures the share of all the realised travel that could have been performed by each mode within 30 minutes. The indicator estimates the percentage of recorded trips that could have been made by a particular mode. This calculation accounts for the availability of the mode at any given time and how that mode may perform at that time given the current operational and network characteristics. It considers the origin and destination locations, as well as the time of the day the trip is expected to take place. This allows the model to assess the potential of each mode to be used as an option for the intended travel. The performance of each modal option in terms of travel times and cost is also estimated to allow for a richer comparison between the different modes. Additionally, an analysis by departure area is performed to analyse the geographical distribution of the resulting access indicator.

The second set of indicators explores the potential willingness of travellers to use each mode for their travel based on the attributes of distance and expected travel time. It is a variation of the travel decay functions, which are used in potential accessibility measures. To estimate the willingness to travel by a particular mode, the statistical distribution of choices from the synthetic mobility dataset was used as a reference for the potential interest. The result is a distance and time probability density function that reduces the probability of interest in using a particular mode as the distance and/or travel duration increases. For modes not normally used for very short trips, it also reduces the probability of using a particular mode as travel time decreases.

Two variations of this indicator are calculated. The first considers only the ability and willingness to travel between a particular origin and destination at a particular time of the day and using a particular mode, given the spatial and temporal attributes of that trip choice. The second incorporates an additional travel cost component that considers the cost of accessing the mode (if applicable), the cost of travel, and the cost of ownership (if applicable). More details on the cost component can be found in the following section.

The mobility costs for each mode or potential mode are computed for each trip. The cost calculations include the following components:

- **Ownership cost** is calculated when travellers use vehicles they have purchased or leased. It includes the cost of vehicle acquisition, parking, maintenance and insurance. The parking cost includes parking permits or the cost of home garages.
- **Vehicle acquisition costs** were computed and derived from new vehicle sales, vehicle age and vehicle residual values. Parking costs were estimated based on a review of the current costs of parking permits and the acquisition of new off-street parking spaces in different parts of the modelled urban area. Insurance and maintenance costs were added as additional percentages to the acquisition costs. These costs are annualised and then converted into an average commuting day (220 days in the model).
- **Cost of using alternatives** was calculated for each mode on a per-trip, per-hour or per-kilometre basis. These costs include vehicle energy consumption (petrol or electricity), mobility service subscriptions, tickets, distance or time-based fees, minimum fares and parking costs (on- and off-street during the activity duration). Each mode has a specific fare structure and parking requirement.

These costs are attributed to the main mode of travel and to the access and egress segments of the trip, if applicable (e.g. shared bicycle to reach a metro station).

This final set of indicators also provides an estimate of potential demand and thus the market each service provider may tap into given current operating characteristics. Like the isochrone indicator, it can be estimated as an aggregate indicator for the entire region or disaggregated by departing geographical location, showing the suitability of each mode to satisfy the local demand in each city area.

New mobility and dynamic street space allocation: The impact on space consumption

The modelling undertaken for this report has resulted in the following iterative outputs:

- The network-wide impacts of including new modes, with limited dynamic re-allocation of the network.
- The modal impacts of these changes and space consumption (i.e. total stock of space consumed while travelling and space efficiency per traveller and by passenger-km travelled)
- Analysis of modal potential to better understand the likelihood that specific modes could serve current mobility needs.
- Environmental impacts of the applied scenarios, including the environmental performance of the modes in terms of emissions, and the environmental implications of the operational performance of shared micromobility alternatives, including rebalancing impacts.

Overall, limited and dynamic re-allocation of street space and adding new free-floating and other mobility service options (full implementation scenario) could potentially improve network performance by approximately 12% (a weighted measure as described above that combines mobility, accessibility, environment, space efficiency and safety). Enacting variable and demand-responsive street reconfiguration alone, without changes to baseline modal options and mobility patterns (dynamic network scenario) improves network performance by 9% and finally, the inclusion of new modes without the accompanying dynamic changes to network (new mobility paradigm scenario) improves network performance by 3%.

As highlighted in

Figure 11 and Figure 12, the temporal dynamics of these improvements vary throughout the day. The results show that the reduction in car use and parking requirements are almost entirely absorbed by the need for more infrastructure diversity and greater space for pedestrians, bicycles and scooters. Furthermore, from a safety perspective, having more vehicles circulating at very different speeds decreases the safety component of the performance function.

What emerges from the comparison of the various scenarios is that limited dynamic re-allocation of street space has the potential to improve network performance, especially in conjunction with the introduction or accelerated uptake of non-individual car mobility options (including owned and shared bicycles and other forms of micromobility, shared rides and carsharing). Conversely, introducing these mobility options without re-allocating street space (dynamically or statically) does not significantly improve network performance in the scenarios modelled.

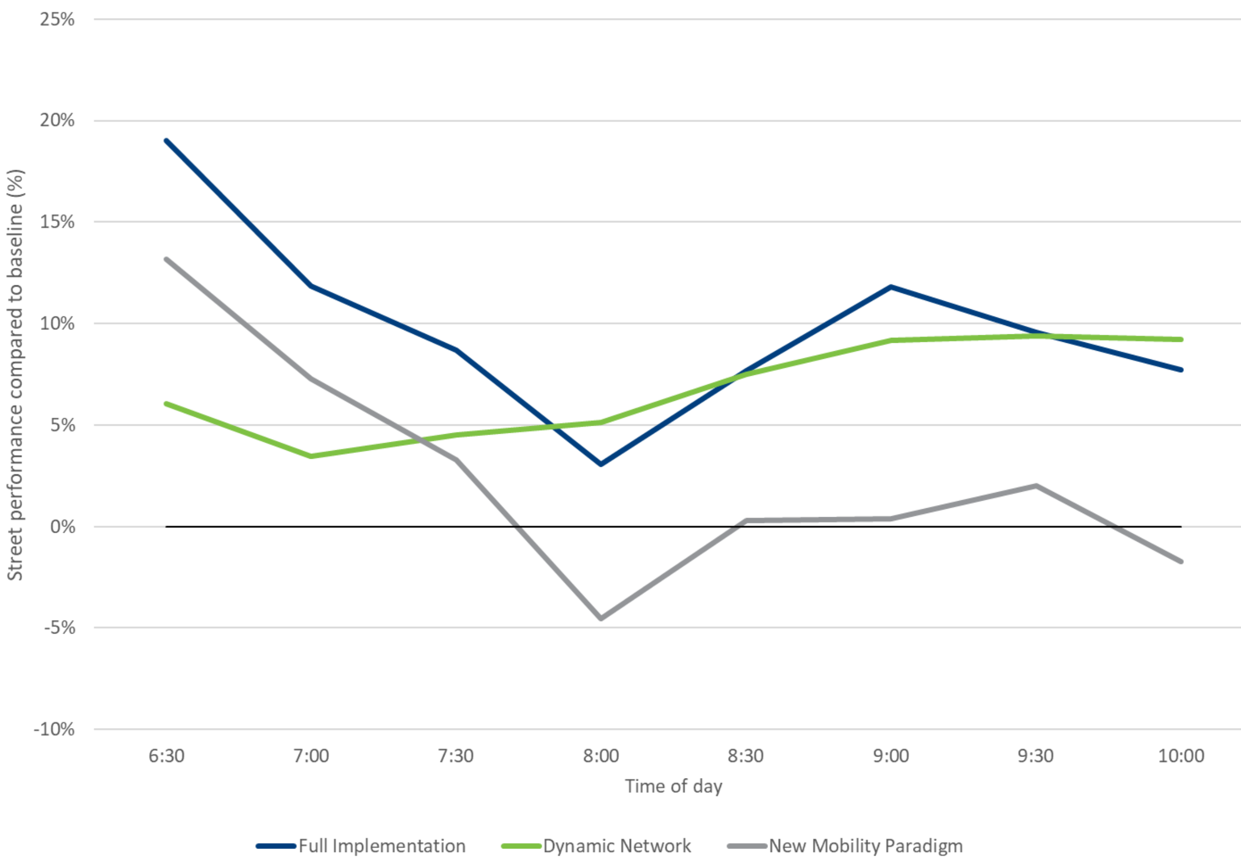
However, the introduction of limited dynamic re-allocation of street space would also come with challenges. First among these are how to address the mix of different road users safely and how to ensure high levels of predictability in the face of the dynamic re-allocation of space.

The former concern reinforces the need for speed management approaches consistent with the Safe System approach (ITF, 2008) or, alternatively, where this is not possible, with hard separation which limits the opportunity to re-assign the street space dynamically.

The second concern reinforces the need to explore new road use paradigms that could deliver elevated and safe levels of predictability under changing road use conditions. Here too, default low and safe speeds could go a long way to managing this dynamic use of space. Providing more efficient parking solutions during low demand periods when vehicles are mostly idle is also an important consideration.

Figure 11. Street performance compared to baseline over 24 hours

Figure 12. Street performance compared to baseline in the morning peak



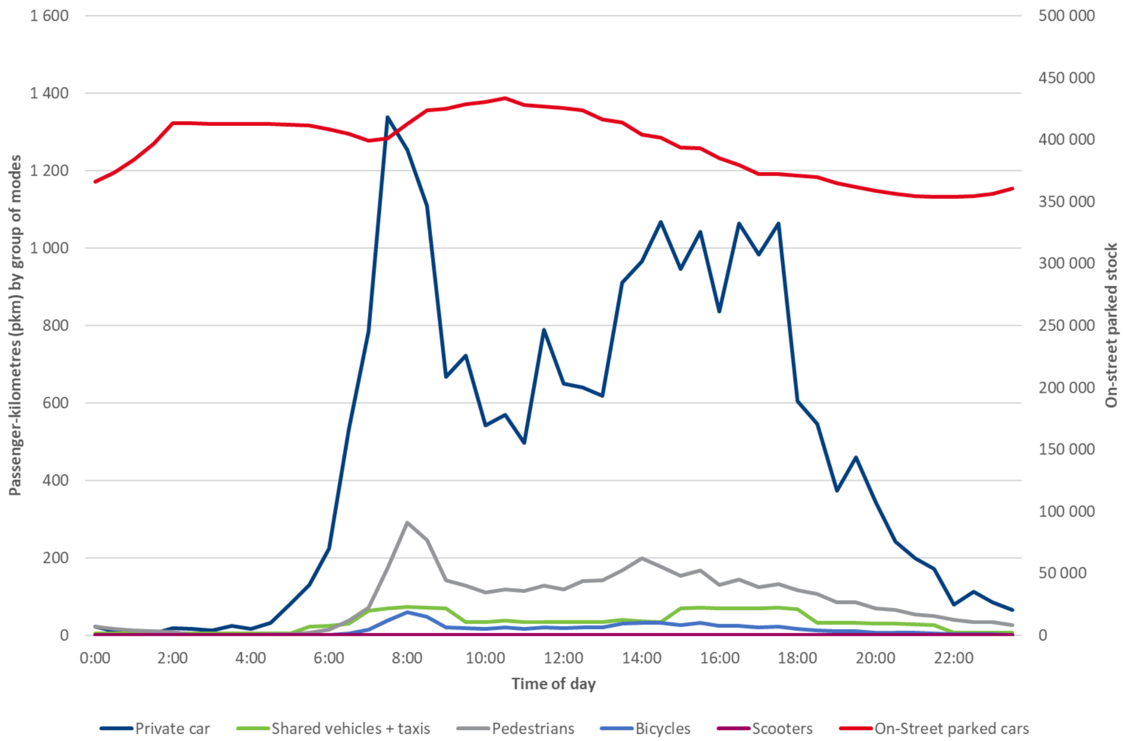
Activity in the network and modal shift

The uptake of non-individual car-based modes and limited, demand-responsive, re-allocation of street space has a significant impact on passenger-kilometres per mode (see Figure 14 and Figure 15). The use of shared vehicles and taxis (green in Figure 14 and Figure 15) more than doubles, with a 278% increase, and bicycle kilometres (light blue in Figure 14 and Figure 15) also see a significant increase of 114%.

In contrast, there is a slight decrease of 4% in pedestrian travel (grey in Figure 13 and Figure 15), although the spatial distribution of this decrease is very uneven. In the centre, some pedestrian access trips to public transport and short to medium-length travel by foot are replaced by micromobility or other forms of shared travel. Walking increases in the suburbs with more people leaving their car at home and walking to access-shared modes. Travel by private car (dark blue in Figure 13, and Figure 15) decreases the most (-22% passenger-kilometres). Furthermore, as a result of these induced changes in mobility, there is a 9% decrease in on-street parking capacity requirements.

Figure 13. Passenger-kilometres by mode

(A) Baseline scenario



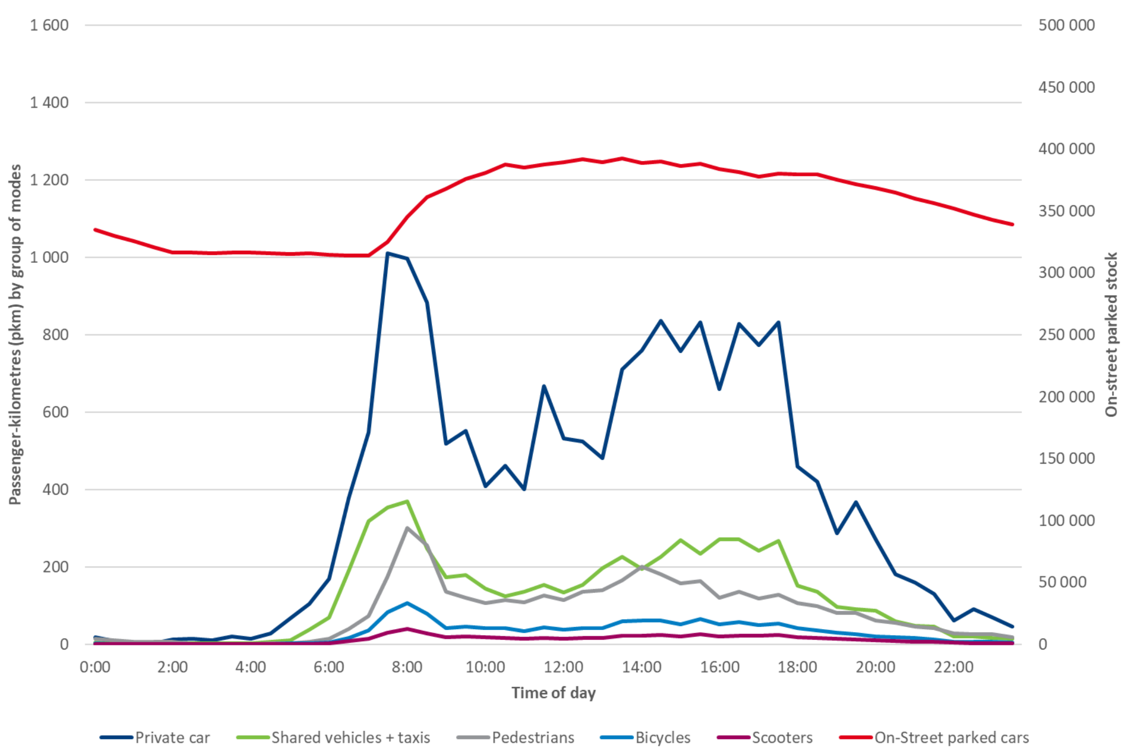
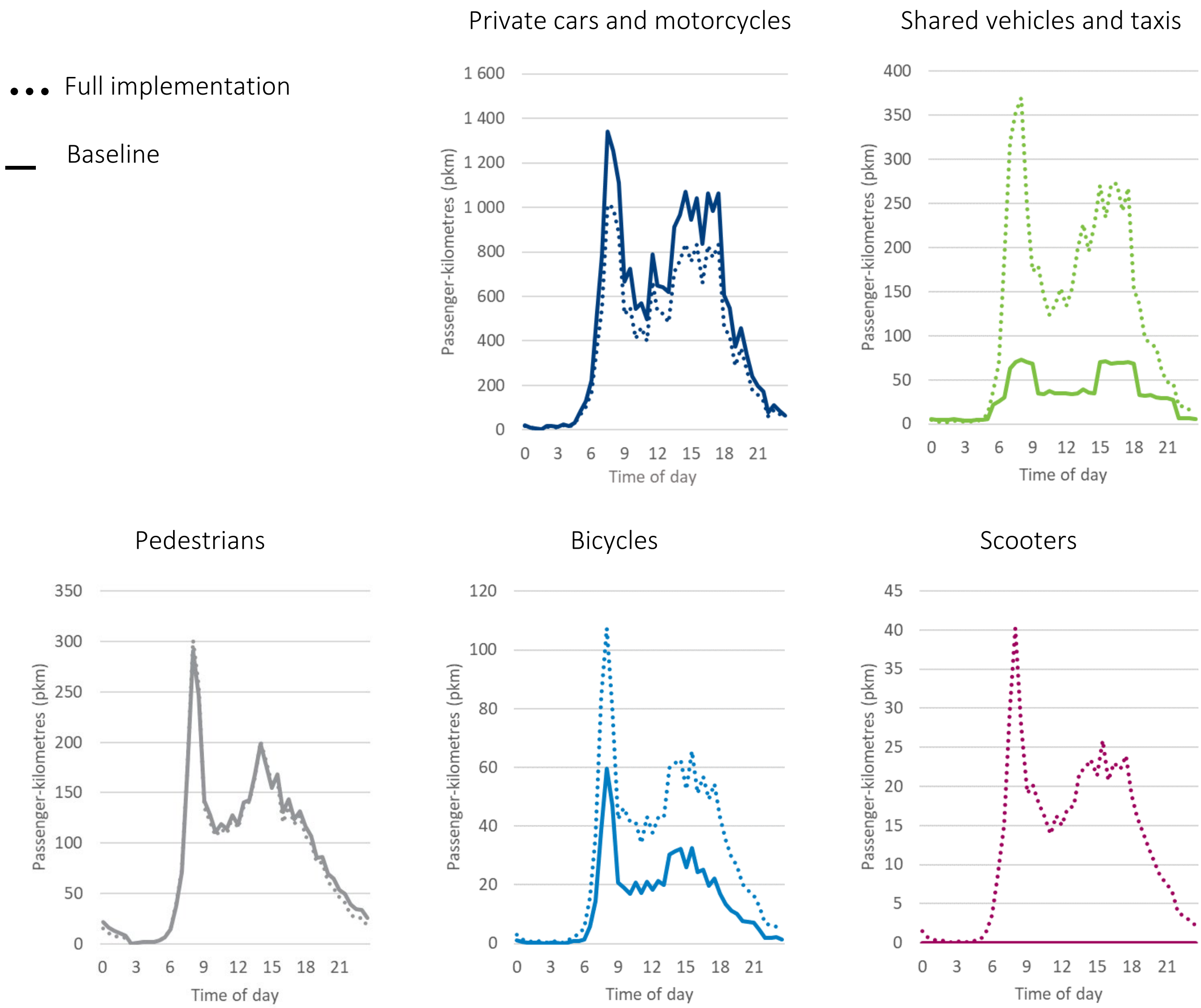


Figure 14. Changes in activity between baseline and full implementation scenarios by mode

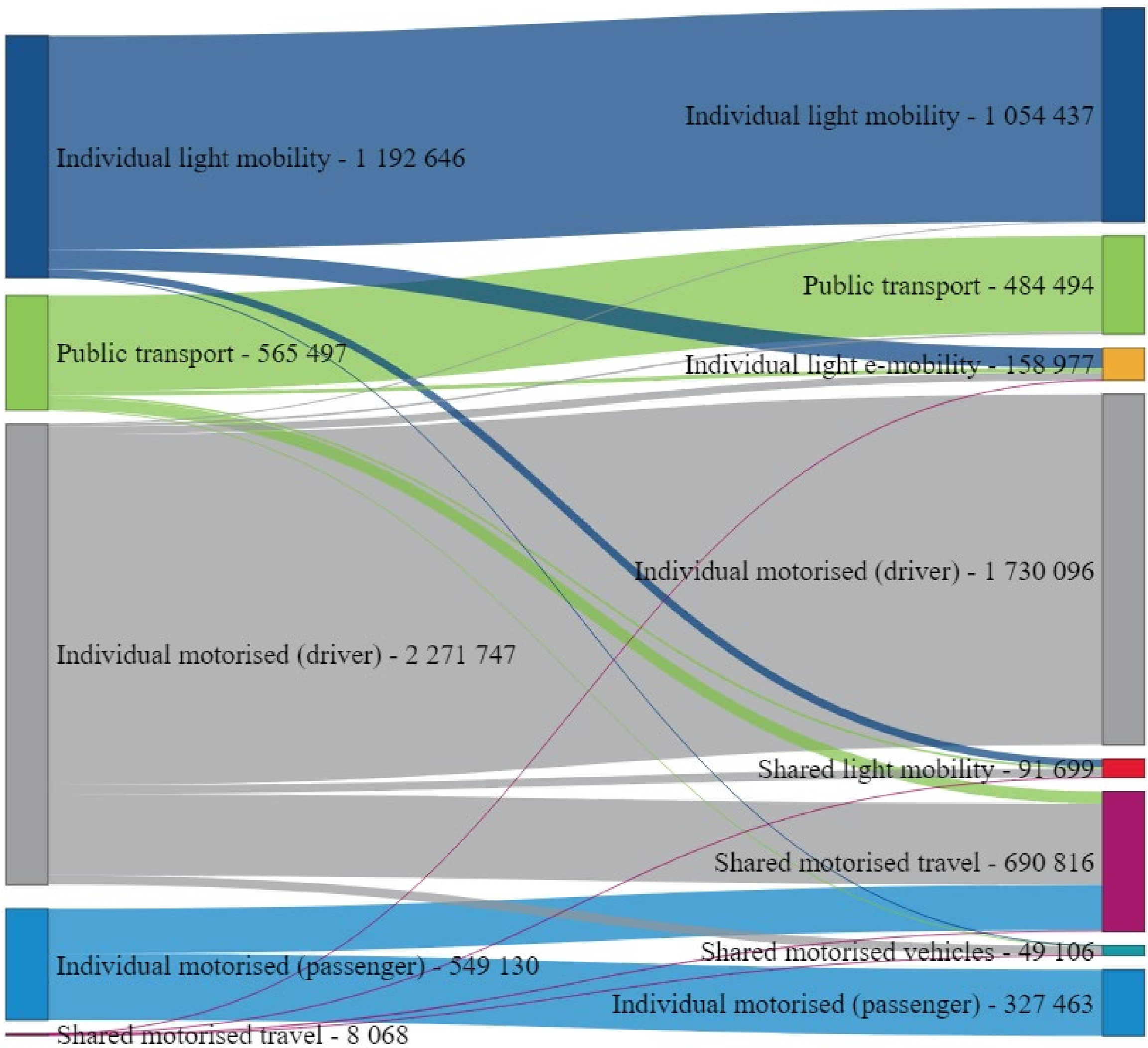


Note: The Y-axis (passenger-kilometres) varies between sub-figures.

Figure 15 shows the changes in mode choice observed between the baseline and full implementation scenarios. The simulation indicates that car drivers and passengers generally select other motorised transport modes, in particular shared motorised travel, if they switch mode choice between the baseline and full implementation scenarios.

In line with other recent studies on e-bike substitution effects (e.g. de Haas et al., 2021) the largest share of new users of electric micromobility alternatives are those that would otherwise use non-electric micromobility alternatives in the baseline scenario. This underscores the embeddedness of current travel choices in a system of provision that largely incentivises single-use automobile travel (Mattioli et al., 2020). Reversing this or deviating from that trend will require creating comfortable and compelling enough travel experiences and incentives, including infrastructure provision, to induce larger numbers of private car users to other, less impactful, modes.

Figure 15. Modal switch (baseline vs. full implementation scenario)



Space consumption

All trips in the baseline scenario consumed 512 km^2 for a modelled day. Implementing the limited and demand-responsive re-allocation of street space and broadening the number of new mobility options for travellers reduced the overall consumption of space to 429 km^2 – a 19% reduction (see Figure 17). This is a very significant reduction considering that only 27% of car occupants switched to alternative modes (mostly to shared, motorised modes).

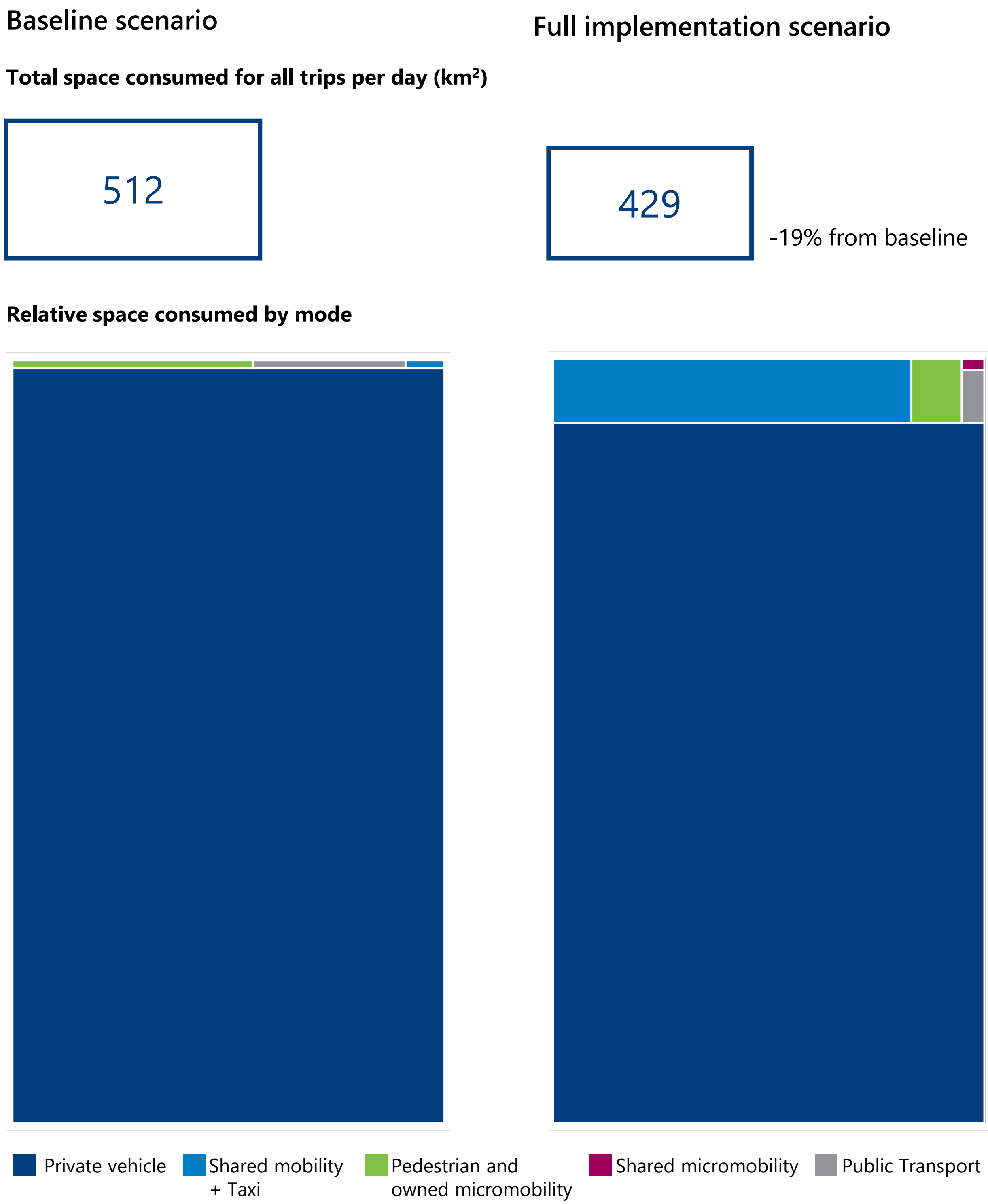
The private car consumes more space per day than any other mode as measured by total square kilometres under the baseline scenario (see Figure 16). On average, private motorised transport has the highest space consumption per trip (189.66 m2/trip) and per kilometre travelled (24.35 m2/pkm). These values are several orders of magnitudes larger than any other reported transport mode (see Table 5).

Table 5. Space consumption by mode

Mode	Baseline scenario				Full implementation scenario			
	Dynamic space	Static space	Space consumed (m^2/trip)	Space consumed (m^2/pkm)	Dynamic space	Static space	Space consumed (m^2/trip)	Space consumed (m^2/pkm)
Walking	100%	0%	0.41	0.37	100%	-	0.43	0.37
Cycle	14%	86%	14.73	4.35	14%	86%	14.63	4.28
Owned e-bikes	-	-	-	-	15%	85%	14.3	3.8
Owned e-scooters	-	-	-	-	25%	75%	7.72	2.05
Owned micromobility	**78%**	**9%**	**1.81**	**0.73**	**81%**	**19%**	**3.3**	**1.11**
Shared bike	-	-	-	-	77%	23%	1.62	0.84
Shared e-bike	-	-	-	-	83%	17%	2.36	0.72
Shared e-scooter	-	-	-	-	91%	9%	0.95	0.62
Shared micromobility	**-**	**-**	**-**	**-**	**83%**	**17%**	**1.8**	**0.74**
Bus	55%	45%	1.31	0.36	56%	44%	1.38	0.37
Rail	72%	28%	2.2	0.26	72%	28%	2.33	0.28
LRT	57%	42%	1.31	0.35	58%	42%	1.38	0.37
Public transport	**61%**	**39%**	**1.62**	**0.32**	**61%**	**38%**	**1.7**	**0.34**
Car driver	4%	96%	229.66	29.51	4%	96%	232.46	29.74
Motorcycle	25%	75%	31.88	3.98	25%	74%	32.52	4.01
Car + public transport	35%	65%	25.4	3.02	50%	49%	14.2	1.65
Car passenger	100%	-	0.31	0.62	100%	-	0.31	0.62
Private motorised transport	**20%**	**80%**	**187.36**	**24.17**	**20%**	**80%**	**189.66**	**24.35**
Carsharing	-	-	-	-	14%	86%	91.07	9.37
Ridesharing	-	-	-	-	72%	28%	33.63	5.67
Taxi bus	-	-	-	-	42%	58%	1.53	0.66
Feeder	-	-	-	-	29%	71%	1.56	1.03
Shared motorbike	-	-	-	-	87%	13%	5.38	1.13
Shared transport	**-**	**-**	**0.22**	**0.04**	**53%**	**47%**	**20**	**3.26**

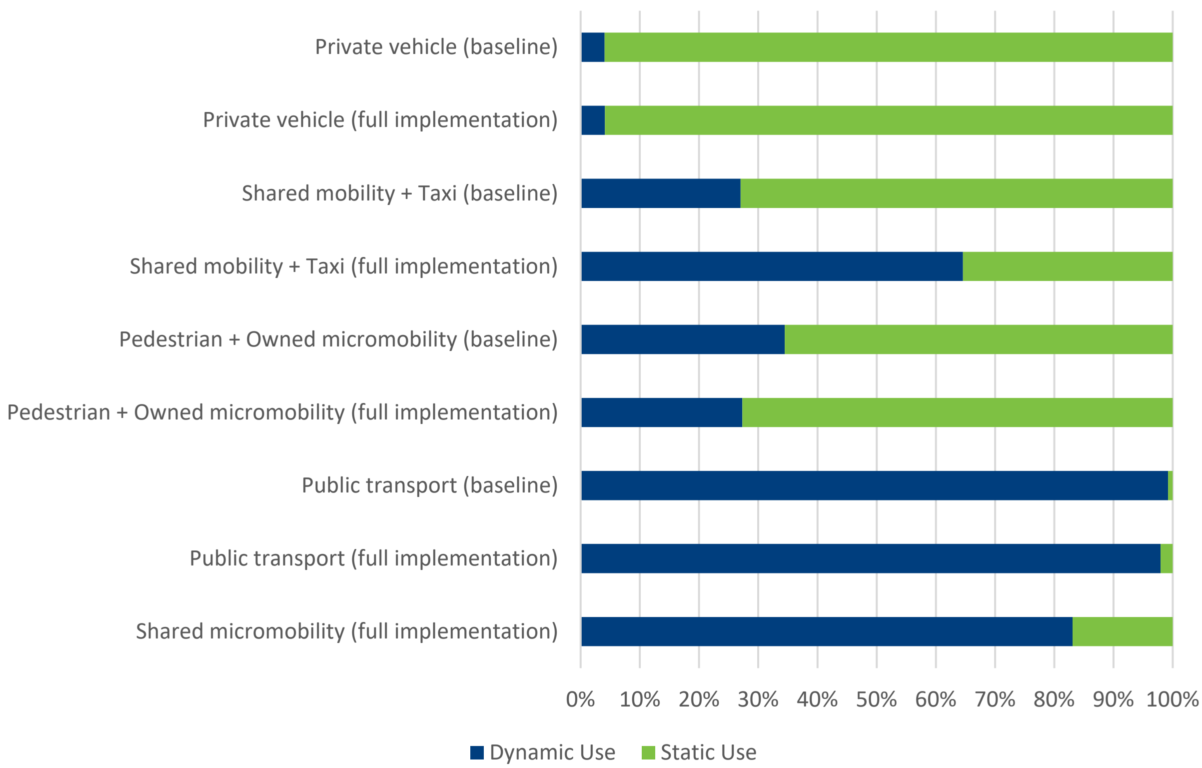
The ratio between dynamic and static space usage for all considered modes can be found in Figure 17. Importantly, 80% of the space consumed by private vehicles relates to parking. As a result, shared motorised transport performs much better, and has a much better ratio between dynamic and static space usage consumption (53:47). Specifically, space consumption by shared motorised modes per trip and per kilometre travelled is only 11% and 13% respectively of that of individual motorised transport.

Figure 16. Total and share of space consumed by mode per day



Of note is that the space consumed by shared motorised transport remains significantly higher than that of public transport and shared and private micromobility in terms of total space, space consumed per trip, and space consumed per passenger-kilometre (see Figure 16 and Table 5). Among these three better-performing alternatives, public transport performs particularly well on a per-kilometre basis because public transport trips are more likely to be longer when compared to trips using micromobility alternatives.

Figure 17. Relative space consumption: Dynamic versus static space



Modal accessibility: What modes can be used to perform current trips?

Indicator 1: Potential travel isochrone

As described in the methods section, this indicator is an aggregate isochrone for the entire region which measures the share of all the realised travel that could have been performed with each mode in a 30-minute period.

As summarised in Table 6, shared transport modes (which are not included in the baseline scenario) are theoretically able to realise the largest share of trips (69%) in the full implementation scenario. This is followed by private motorised transport, which is still a viable option for 59% of the trips in this scenario. However, this represents a 6% decrease from baseline scenario levels. On the other hand, the number of trips that could be performed using non-motorised and micromobility alternatives increases by a third from 27% to 36%. Finally, as expected, there is no change in the trips which can be made using public transport. This is because no increases in service or coverage were modelled.

Table 6. Potential travel isochrone indicator:
Modal shift with Full implementation scenario

Group	Baseline scenario			Full implementation scenario		
	Urban core	Rest of urban area	Overall urban region	Urban core	Rest of urban area	Overall urban region
Non-motorised + micromobility	42%	26%	27%	46%	36%	41%
Private motorised transport	68%	58%	65%	63%	54%	59%
Public transport	13%	4%	8%	13%	4%	8%
Shared transport	-	-	-	75%	61%	69%

Indicator 2: Traveller modal choice propensity

Unlike the first indicator, the second set of accessibility indicators consider not only the characteristics of the mode itself, but the perception of the trip makers and their willingness to travel a particular distance or time using a particular mode. This is measured according to a basic configuration relating only to the modal and trip characteristics (e.g. availability, speed, distance) and in a full configuration in which costs are factored. Table 7 summarises these two versions of the traveller modal propensity indictor for both the baseline and full implementation scenarios.

In contrast to the potential travel isochrones (Indicator 1) where it was found that 69% of current trips could be potentially replaced by shared transport (in the full implementation scenario), the propensity to use these modes for these trips is not nearly high enough. When considering only the modal and trip characteristics in the basic traveller modal propensity indicator, the share of replaceable trips by shared modes is reduced to 46%. When the cost is also considered, this share is reduced to only 15% of the total trips.

Non-motorised and micromobility trips are also affected. Using Indicator 1, 41% of trips could be potentially made using non-motorised and micromobility modes in the full implementation scenario. However the propensity of users to make these trips using these modes is such that it becomes a viable alternative for only 18% of the total trips when cost is not considered, and 22% of trips once cost is accounted for.

Table 7. Traveller modal propensity indicator: Willingness to use different modes

	Baseline scenario		Full implementation scenario	
Mode	Basic travel propensity indicator	Full travel propensity index	Basic travel propensity indicator	Full travel propensity index
Non-motorised + micromobility	13%	23%	18%	22%
Private motorised transport	48%	11%	46%	11%
Public transport	12%	9%	11%	7%
Shared transport	-	-	46%	15%

In terms of cost, under the full implementation scenario, among the micromobility alternatives, shared bikes (EUR 0.05 per km) and shared e-bikes (EUR 0.11 per km) provide the most value for the user, at even lower costs than the per kilometre cost for an owned bicycle (EUR 0.18 per km). This reveals the benefits of shared assets in reducing ownership costs, which in individual transport vehicles with little to no energy (e.g. fuel) costs, are the largest cost component.

At the other extreme, this report finds that the cost of shared e-scooters is particularly high. It is more than twice the cost per km (EUR 0.86 per km) than any other micromobility alternative (owned or shared). This cost brings it closer to the costs of motorised alternatives such as ridesharing (EUR 0.92 per km) private motorcycles (EUR 0.95 per km) and carsharing (EUR 1.13 per km).

Additionally, as shown in Table 8, impacts vary between the centre and the periphery. In the urban core, as expected, more residents are willing to travel by non-car modes as compared to inhabitants of the rest of the wider urban area. This is a result of more travel options being available in the core as well as the density of potential travel destinations resulting in shorter overall trips that are amenable to non-car modes. Even in the wider urban area, factoring in the cost of ownership and use of cars decreases the propensity for travellers to choose this mode even if it could meet their travel needs. Furthermore, examining the differences between the baseline and full implementation scenarios shows that shared transport (which includes a variety of different services including taxi buses and ridesourcing) can be an attractive and cost-effective option for many users in both the core and extended urban area, although the attractiveness of these modes remains highest in the urban core.

Table 8. Traveller modal propensity indicator: Willingness to use different modes (by location)

	Basic travel propensity indicator		Full travel propensity index	
Group	Urban core	Rest of urban area	Urban core	Rest of urban area
Baseline scenario				
Private non-motorised + micromobility	0.15	0.09	0.25	0.16
Private motorised transport	0.66	0.34	0.19	0.07
Public transport	0.23	0.06	0.17	0.04
Shared transport	-	-	-	-
Full implementation scenario				
Private non-motorised + micromobility	0.26	0.16	0.29	0.16
Private motorised transport	0.64	0.32	0.18	0.07
Public transport	0.21	0.05	0.14	0.03
Shared transport	0.63	0.32	0.19	0.11

Environmental considerations

Changes in mode choice and travel activity will have a knock-on effect on environmental impacts – which are important to consider when evaluating different scenarios. These impacts are linked to the operational performance of new shared modes including the positioning and relocation dynamics of shared micromobility modes which are a non-negligible source of generated travel (ITF, 2020a).

Operational performance of shared mobility and micromobility

Table 9 presents an overview of the operational performance of shared mobility and micromobility modes included in the simulations. Shared taxis have a very high share of empty kilometres (30.4%). This is in contrast to carsharing (10.9%) and taxi-buses (8.3%) which show a very different profile. It should be noted, however, that the in-model specification of taxi-bus services is expressly designed to minimise low efficiency (from a load factor and empty travel perspective) operation. When certain efficiency thresholds cannot be met, the model re-allocates taxi-bus trips to shared taxis. This reassignment of taxi-bus trips is captured in the percentage of reassigned trips (54.6% for taxi-bus trips while shared taxis do not lose any trips) and in the load factors (where the taxi bus has the highest load factor among all shared alternatives at 9.14).

Additionally, the simulation tracks when a traveller's first choice for a travel mode cannot be fulfilled due to lack of availability or other constraints and re-assigns these trips to other modes. – e.g. 'frustrated' modal choices. For example, in the simulation, only 30 out of 100 travellers who wanted to ride a shared electric bike were able to do so. Sixty-eight of the remaining travellers had to use a conventional shared bike and two used another mode completely.

Table 9. Load factor by mode and use rate in full implementation scenario

Mode	Fleet/1 000 inhabitants	Trips/vehicle day	Km/vehicle day	Load factor	% share of empty km	Reassigned or frustrated trips
Carsharing	4.04	7.73	73.41	0.92	10.9%	1.9%
Shared taxi	16.22	24.75	203.52	1.16	30.4%	0.0%
Taxi-bus	3.07	4.79	240.16	9.14	8.3%	54.6%*
Shared bicycles	31.64	8.14	9.67	0.89	12.4%	13.5%
Shared scooters	17.06	4.99	10.00	0.86	16.3%	4.6%
Shared-motorcycles	4.04	1.44	6.75	0.75	47.1%	1.6%

*Trips switched to taxi to preserve higher load factors for the taxi-bus category.

Fleet relocation and rebalancing dynamics

The operation of shared micromobility modes requires fleet rebalancing to ensure vehicles are where they are most needed and will be most frequently used. Fleet rebalancing creates additional environmental (and monetary) costs. To this end, the movements per hour for each "station" (i.e. area of the city as modes are free-floating) were analysed in the simulations with 72% of rebalancing movements happening after the morning peak hours and before the afternoon peak, compensating for commuting flows to and from the suburbs to the city centre.

Bikesharing has the greatest number of trips per hour per station (area) of 4.7 while e-push scooter sharing averaged 3.5 moves per hour per station (area). This performance is more than two times better than carsharing (1.4) and motorbike sharing (0.1). The number of trips observed has a natural rebalancing effect on the demand, avoiding artificial vehicle repositioning.

The temporal dynamics of rebalancing operations are illustrated by taking a closer look at a representative station (area) in the centre of the city (Figure 18). While there is a natural rebalancing throughout most of the day, there are significant changes between 08:00 and 08:30 and again between 17:30 and 18:00 for bikesharing, implying the need for operational rebalancing. Shared e-push scooters follow a similar pattern morning and evening in the urban core. Stations in the periphery, on the other hand, display opposite patterns to those experienced in the core (Figure 19). There is significant movement earlier in the morning (06:00), highlighting an earlier commuting wave not present in the centre.

Figure 18. Fleet relocation dynamics in a central urban area

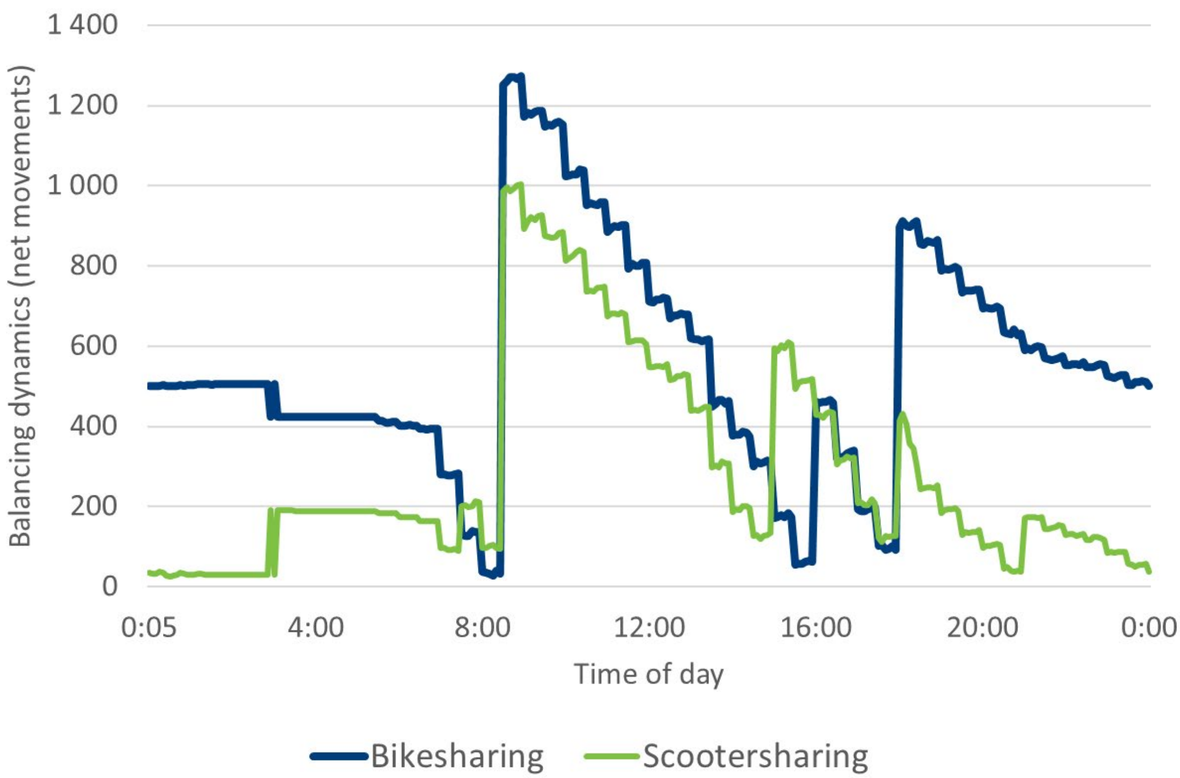
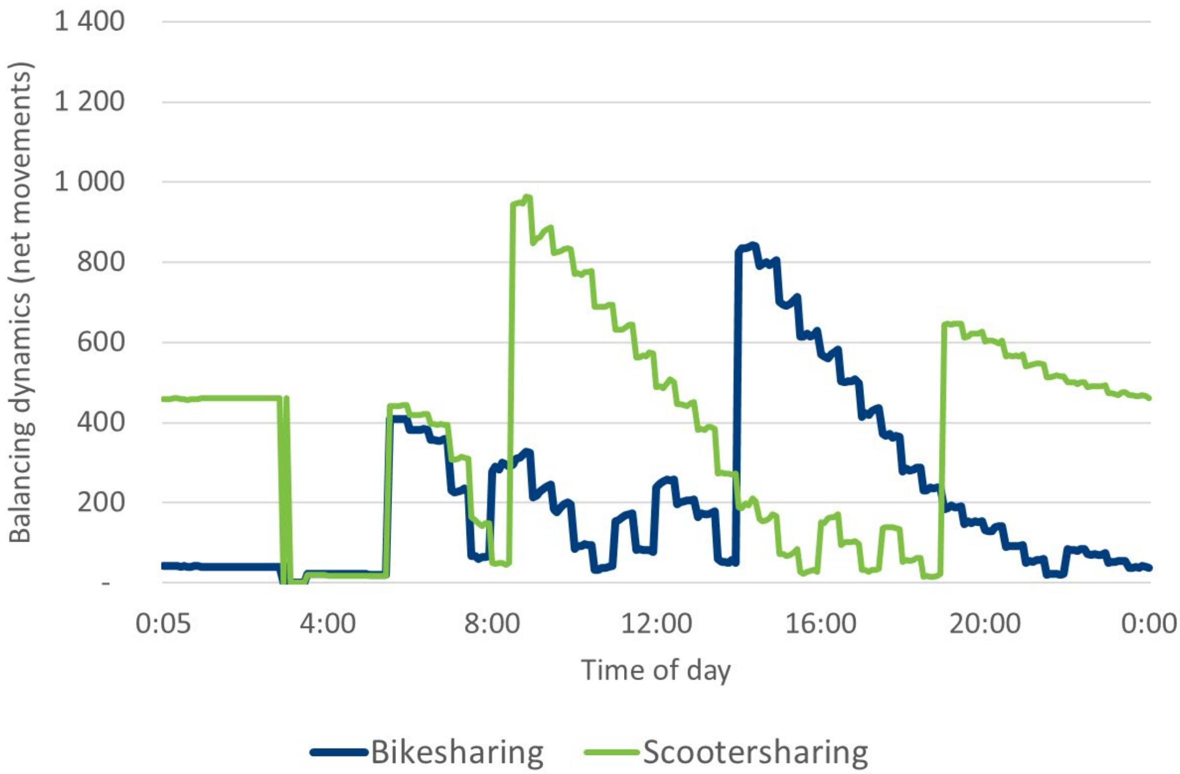


Figure 19. Fleet relocation dynamics in an outer urban area



Environmental performance

The full implementation scenario delivers modest but significant improvements in terms of lifecycle CO_2, NOx, SO_4 and fine particulate emissions, despite increases in overall vehicle and passenger-kilometres travelled (+4% and +7%, respectively). Tank-to-wheel and well-to-tank CO_2 emissions are reduced by 6% and 5%, while particulate matter emissions drop by 4%.

Given the fact that the increases in travelled kilometres, as shown in Table 10, are entirely due to the newly implemented shared transport and micromobility alternatives, the full implementation scenario was recalculated with one additional condition: the electrification of the shared vehicle stocks (i.e. electric cars for ridesharing and taxi-buses). The full electrification of these fleets leads to further significant emissions reductions – up to -23% each for all measured pollutants. This highlights the importance of not only updating and improving the alternatives available for the users but also strengthening the electrification of all shared mobility vehicle stocks.

Table 10. Environmental impacts and travel volumes by mode

Scenario	Variable	Transport mode					
		Public transport	Private transport	Shared transport	Micro-mobility	Total	Variation from baseline
Baseline scenario	CO_2 TTW	250.6	2280.7	0.0	0.0	2531.3	-
	CO_2 WTT	144.7	497.0	0.0	0.0	641.6	-
	NOx	0.7	4.1	0.0	0.0	4.8	-
	SO4	0.0	0.0	0.0	0.0	0.0	-
	PM25	0.0	0.1	0.0	0.0	0.1	-
	PKM	6.5	17.7	0.0	0.0	24.2	-
	VKM	0.3	14.8	0.0	0.0	15.2	-
Full implementation scenario	CO_2 TTW	200.6	1754.5	428.4	1.6	2385.1	-6%
	CO_2 WTT	124.6	382.3	93.3	6.9	607.1	-5%
	NOx	0.6	3.2	0.9	0.0	4.7	-4%
	SO4	0.0	0.0	0.0	0.0	0.0	-1%
	PM25	0.0	0.1	0.0	0.0	0.1	-4%
	PKM	5.4	13.6	5.7	1.1	25.8	7%
	VKM	0.3	11.4	2.9	1.1	15.7	4%
Full implementation scenario + electric ridesharing and taxi-bus	CO_2 TTW	200.6	1754.5	0.0	0.0	1955.1	-23%
	CO_2 WTT	124.6	382.3	163.3	5.2	675.5	5%
	NOx	0.6	3.2	0.0	0.0	3.7	-23%
	SO4	0.0	0.0	0.0	0.0	0.0	-23%
	PM25	0.0	0.1	0.0	0.0	0.1	-23%
	PKM	5.4	13.6	5.7	1.1	25.8	7%
	VKM	0.3	11.4	2.9	1.1	15.7	4%

Conclusions

This report assesses street space allocation, accounting for new mobility alternatives. It explores street configurations, space allocation and the potential of dynamically managing the use of this space to deliver more just outcomes. It considers modal shifts, environmental impacts, mobility and accessibility impacts, and safety considerations. It builds upon previous work in earlier CPB reports on shared mobility and the ITF case-specific study for the region of Dublin, Ireland (ITF, 2018a).

Street space is a scarce commodity in dense urban settings and serves a broad range of purposes. Its allocation is inherently contentious and has significant impacts on the population. The allocation of this contested space constrains potential accessibility and limits how citizens can effectively move. Traditionally, the design of public spaces has too often favoured highly space-consuming transport modes, such as private automobiles, even though the space consumed by a driver in a car by kilometre is several orders of magnitude larger than by any other mode.

This tension around space allocation and usage is further reinforced by the rise of new motorised shared modes and private and shared micromobility alternatives. To address this, the methodology was expanded to include a wider range of emerging urban mobility modes which required more detailed modelling. These modes include other private mobility options for door-to-door travel, and shared vehicles, either docked or free-floating, used for door-to-door travel or as part of a longer trip chain in combination with public transport. Furthermore, the urban infrastructure reserved for transport use, which is key to ensuring well-functioning cities, is evaluated and optimised.

Attention must be paid to the distinction between the *use* of street space versus the *allocation* of street space to better understand the tension inherent to space allocation. The actual *use or consumption* of street space is a representation of the demand for the mobility-related use of that space. This use/demand feature is variable by mode, time of day and zone. It equates to the physical space that is actually consumed as people and vehicles move. The *allocation* of space is a representation of the supply of urban road space made available for people and vehicles to move, operate and park.

The model focuses on guaranteeing equitable, accessible and efficient mobility for all users. It puts people first, framing the issue around how this space serves the population, and not on how vehicles occupy the space. To this end, it is important to consider how the mobility needs of the population can be met, and the potential accessibility provided by the system. This is very much related to the option values concept which highlights that people value not just the actual use they make of the transport system (mobility) but the availability of alternatives. Three key considerations are included: the trips and trip purposes that can be effectively served by different modes, the space needed to deliver that mobility and the environmental impacts of moving using a particular mode.

Omitting or improperly accounting for space in transport appraisals can have significant negative outcomes. Space allocation and consumption is rarely considered when discussing transport, despite being so central to the amount of accessibility provided by a system. There is an underlying trade-off between the dynamic consumption of space and vehicle speed. Vehicles moving at greater speeds increase the accessibility provided by a mode but come with an associated increase in space usage. However, focusing only on vehicle throughput is flawed because it only addresses the dynamic component of mobility space use, while ignoring the static space consumed as vehicles idle or park. This has resulted in the outsized concession of space to automobile mobility, at the expense of all other road users, often without considering the significant amount of public space needed for these vehicles to stand idle for more than 90% of the time or the impacts to the safety or wellbeing of citizens.

To ensure more just outcomes, appropriate space consumption indicators need to be incorporated into policy and appraisal assessments. These metrics need to incorporate the temporal component of space consumption. They should include the dynamic consumption of street space as vehicles move and the static consumption of public space when vehicles are parked or idle. These two components can be captured in a composite indicator – m^2.h – which, when calculated per traveller, gives a good basis on which to discuss the relative space-consumption impacts of different travel modes and trips.

Street space allocation tends to be static and quasi-permanent despite the temporal variation in the spatial requirements of different modes. By better fitting infrastructure to the needs of the different modes at different points of the day, it is possible to better address the needs of the population. The simulation results indicate that there are added benefits to having dynamic and demand-responsive re-allocation of street space. Importantly, this re-allocation can help compensate for the additional dynamic space consumption needs of slower vehicles, preserving the levels of efficiency and enhancing the accessibility provided by these modes while promoting better equity and environmental performance.

Dynamic re-allocation of space alone would be associated with a 9% improvement in network performance but would be further enhanced by the inclusion of new mobility alternatives resulting in an improvement of approximately 12%. More specifically, the introduction of more space-efficient modes and the demand-responsive re-allocation of space leads to a 19% reduction in the space consumed to perform all modelled trips.

These benefits are not evenly distributed. They concentrate in the urban core where a greater number of modes are viable alternatives for travel. In the urban core, 46% of the simulated trips could be performed by active and micromobility alternatives and 75% by shared modes if taking account of theoretical door-to-door travel time alone. In the rest of the urban area, these values are 36% and 61% respectively. When considering the potential propensity to travel by a particular mode, and in particular accounting for the associated costs, the potential willingness to travel using different modes also shows significant differences between the core and the periphery. All modes are much more attractive in the urban core than in the rest of the urban area. However, in the urban core, the population is more likely to travel by shared modes and non-motorised micromobility alternatives than by private car, and public transport also remains a viable option.

The combination of new mobility alternatives and limited dynamic re-allocation of space is also associated with significant environmental gains. Despite increasing the number of passenger-kilometres, tank-to-wheel and well-to-tank CO_2 emissions are reduced by 6% and 5% respectively, while particulate matter emissions drop by 4%. These improvements could be even more significant, reaching 23% if the shared vehicle stocks were electrified.

Finally, the allocation of space should always consider the safety of all. Default low speeds for all modes would allow the system to meet the mobility needs of the population more effectively, increasing accessibility while providing a diverse set of safe and effective transport alternatives. More modes travelling at different speeds and sharing the same space increases the likelihood of conflicts and crashes. Dynamically changing the use of the space makes the need for safety even more salient. By relying on safe-system principles for any dynamic re-allocation of space and minimising the differences in speeds at which vehicles sharing the same space can travel, the transport system can become safer and more accessible to all.

Notes

1 A Safe System recognises that humans will make mistakes, and that the human body has a limit to which it can absorb crash forces without suffering injury. It posits that safety is a shared responsibility of all actors in a traffic system, not only that of a road user. Thus, all elements of the road traffic system should come together in an integrate safety chain in which the elements will combine to prevent a crash, or at least prevent serious injury, even if one or more elements fail (ITF, 2016b).

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Streets That Fit

Re-allocating Space for Better Cities

Street space in cities is a rare resource. Much of it is currently allocated to highly space-consuming transport modes without taking into account that demands for that space vary over time. This report looks at how street space has typically been allocated in the past, examines the rationale for street space allocation and describes how to measure space consumption for mobility purposes. The study also explores by way of a simulation how new mobility services and travel modes interact when a limited, dynamic and demand-responsive re-allocation of street space is introduced in a mid-sized city.

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