Car use budgets: Mode-specific sufficiency for cities

MyFairShare - Individual Mobility Budgets as a Foundation for Social and Ethical Carbon Reduction
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Abstract. This working paper introduces the concept of car use budgeting and its operationalisation as a mode-specific extension of mobility budgets. Motivated by the ongoing urban transport challenges of managing automobility in cities, the paper recognises the increasing political polarisation and related risks of compromising urban transport transitions. Against this backdrop, car use budgets are discussed as a concept and policy tool that may help communicate the effects of driving to the general public more effectively. They are also positioned as an invitation for residents to more proactively engage with the trade-offs and dilemmas of conventional car use in cities. The paper proposes a simple km-based metric for car use budgets and presents opportunities for these budgets to support existing policy instruments as well as to be considered as tools with direct application.

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1 Introduction

Urban car use poses a significant public policy challenge. On the one hand, the attachment to car ownership and use remains high for a considerable share of city dwellers in advanced economy countries. On the other hand, the negative externalities of driving in inner city areas further exacerbate already high social and environmental costs of automobility as a result of a mismatch between scarce road space and vast space requirements of operating private vehicles. Unsurprisingly, managing car use in cities is a major task of urban transport policy and a considerable array of instruments and tools have been developed to deal with competing street uses. Policy makers have developed incentives for modal shift, directly support alternatives to driving and also proactively discourage driving.

To date, the result has been mixed with some cities successfully taking the lead in systematically transforming transport systems and behaviours while others are still mostly catering for business-as-usual car use in cities. More recently, driving has been politicised with increasingly polarising views on the role of automobility as part of an overall urban transport mix. Car advocates often highlight the essential role of automobiles for some residents, refer to individual choice and freedom, or fundamentally object to ideas of overcoming the car-oriented city. Debates have also shifted to questions of fairness when pursuing transport transitions, often with references to procedural fairness and based on fair expectations about changes to come.

It is within this context that this paper explores the specific application of mobility budgets for the case of urban car use. Referred to as car use budgets, the paper unpacks different ways of interpreting the budgeting of automobility in cities and discusses various practical uses. The paper is structured as follows: Section 2 is dedicated to brief review of the exceptional characteristics of urban car use cutting across its popularity, negative externalities and critical technological disruptions. Section 3 introduces the broader idea of non-financial budgeting based on a more general sufficiency approach. Section 4 presents the technical details of car use budgets, identifying space as its fundamental unit, considering the combination of space and time and then introduces a simple metric. Section 5 illustrates how car use budgets can be integrated across different types of uses and differentiates a communication approach, from assisting various policy instruments and its direct application.

2 The exceptional case of urban car use

To advance the potential case for car use budgeting in cities, we must first clarify its exceptional role with far-reaching trade-offs in the context of urban development. This requires both an understanding of the popularity of car use as well as why automobility is particularly problematic for inner city areas.

2.1 Why cars are popular

Ever since the widespread introduction of automobiles, the appeal of car use and ownership has been considerable. The level of affection and central role automobiles can play in people's lives suggest that their use far exceeds a rational, utilitarian approach to transport. Three sets of functions for modal choice have been put forward: instrumental, symbolic and affective functions (Steg 2003).

But even when only focusing on objective, technical advantages of driving, a long list of advantages emerges. Among rational and economic reasons for driving are convenience, costs and safety (Hiscock, Macintyre et al. 2002, de Groot and Steg 2007, Gardner and Abraham 2007, Kent 2015). Instrumental functions also include speed, flexibility, the ease of transporting goods, and to take along passengers at no extra costs. Symbolic functions of car ownership allow individuals to express identity or social position (Sheller and Urry 2006). And car use's affective functions cut across emotions and feelings associated with owning and driving a car which may include the feeling of freedom, being in control or simply enjoying music in a private and secluded space (Wells and Xenias 2015).

At the same time, there are broader political economy effects that have ensured that car use remained popular even when challenged by various societal costs which are discussed below. Mattioli et al (2020) consider a range of factors beyond simple individual choice. First, there are structural characteristics of the automotive industry including its political clout due to sheer scale and economic significance, high capital intensity, and low profit margins. This results in continued market expansion and consumer lock-in due to rapid depreciation of the value of vehicles. Second, the provision of car infrastructure with strong political incentives for distributing road space in favour of car use and also for road network expansion. Third, the emergence of car-oriented land use patterns which reduce the viability of alternative modes of travel. In addition, it has also been pointed out that choosing to drive is a decision made at the point of purchasing a vehicle. Once this decision is made, car owners follow through and have fewer incentives to explore alternatives on a trip-by-trip basis (Simma and Axhausen 2001).

2.2 Driving troubles

The popularity of car use is challenged by a range of negative externalities. While some are being addressed, many are structurally connected with the essence of conventional motorisation. Four global concerns of driving are commonly referred to: road crashes which are estimated to account for 1.3 million deaths per year (Bhalla, Shotten et al. 2014); vehicular carbon emissions (above all from car use) which is the single largest contributor to transport carbon emissions globally (IPCC 2014); outdoor air pollution, of which much is generated by road transport, leading to an estimated 3.2 million deaths a year across the world (OECD 2011) and physical inactivity with increasing levels of motorisation leading to a reduction in total physical activity, in turn elevating risks of cardiovascular problems, cancer and diabetes (WHO 2014).

From an urban development perspective, however, it is the space consumption of car use that may be the most problematic given how difficult it is to address. Space-consuming traffic moved economic, cultural and leisure activities away from urban centres and transformed cities into nondescript agglomerations – an effect that has become known as urban sprawl. City-making in the twentieth century was dominated by a single paradigm: optimising conditions for the movement of cars. Large areas in and around the city were paved for motorways and parking in public spaces, while pedestrian space was reduced to a minimum. 'Transport' in its original and multi-modal sense lost its meaning and the quality of car traffic flows, measured in terms of 'level of service,' became the dictating parameter for planners and decision-makers. The free movement of cars was given priority over the quality of urban life.

Optimizing traffic flows meant not only dedicating large amounts of space to the high-speed movement of machines, often occupied by a single driver, but also adopting urban design solutions that corresponded to the new requirements of speed – linear, monotonous structures lacking any human-scale design quality. Ironically, in cities built around cars and their movement, efficient access to urban space was often drastically reduced, not only because cars require significantly more space for their movement than other modes – at 50 km/h, they require more than 160 sqm per person to operate, compared to 4 sqm for buses (Rode and Gipp 2001) – but also because of the intrinsic character of traffic flows acting as major barriers in cities.

The barrier function of roads is exemplified by the well-researched fact that increasing traffic flows significantly reduces the social interaction of residents living on opposite sides of the same street. Moreover, there is a massive storage problem for cars which, on average, sit unused for 96 per cent of the time (Heck, Rogers et al. 2014) resulting in aggregate parking space in car-oriented CBDs such as in Los Angeles of more than 80 per cent of the CBD land area (Manville and Shoup 2004).

Table 1: Space Consumption of Urban Street Use
Source: Rode and Gipp (2001)

Transport Mode	Area [m²] static	dynamic	
Pedestrian	0,25	3	
		v= 30 km/h	v= 50 km/h
Automobile	14,98	105,42	236,6
4 Persons	*3,7*	*26,4*	*59,3*
1,4 Persons	*10,7*	*75,3*	*169*
Bus (86 Pax)	35,26	140,18	298,42
100% occupancy	*0,41*	*1,63*	*3,47*
40% occupancy	*1,03*	*4,12*	*8,77*
Tram (270 Pax)	91,8	221,4	286,2
100% occupancy	*0,34*	*0,82*	*1,06*
40% occupancy	*0,84*	*2,03*	*3,9*

The space consumption concern of urban car use has been effectively introduced to the public conversation through a poster by the Dutch Cycling Federation (Fietsersbond) in 1978 (Haytsma 1978) picturing a photoshoot which has since been replicated in many cities around the world. It depicts how much space is used by cars in relation to moving individual people and contrasts this with how much more efficient their movement could be accommodated by walking, cycling or public transport. Since then, many forms of communicating this exceptional space use of cars have emerged.

2.3 Technological change

Partially in response to the above problematique of car use but also driven by wider technological advances, conventional automobility is currently confronted with three major technological changes: electrification, automation and mobility-as-a-service. In their own ways, all three add to an exceptional need and unique opportunity for policy makers and transport planners to more directly address how individual, motorised mobility in cities is managed in the future.

Electrification of road transport results in two additional agendas for cities. First, establishing the required charging infrastructure and managing parking spaces that allow for vehicle charging. Both are particularly pressing in denser urban environments where electric vehicles cannot be connected to personal household electricity and where parking is mostly provided in public streets. In these instances, typical lamppost charging times range from 8-12 hours, locking-in considerable stationary times of vehicles. Alternatively, faster charging facilities require new and dedicated infrastructure. Second, recent designs of electric vehicles have turned away from lightweight, compact cars and embraced heavy and large electric sports utility vehicles (SUVs). Due to their even greater space requirements, additional safety risks for other road users and greater wear of road surfaces, these vehicles have exacerbated the negative externalities of car use in cities (Woodward and Wild 2021, Rode 2023, Hu, Monfort et al. 2024).

Automation of road vehicles, although progressing slower than anticipated a decade ago, has already achieved various key milestones. Automation level 1 (driver assistance), 2 (partial automation) and 3 (conditional automation) are readily available and rolled-out while more widespread use of level 4 (high automation) and 4 (full automation) is anticipated for the next decade (Deichmann, Ebel et al. 2023). For cities, the latter two categories are critical. Two fundamental scenarios can be differentiated. First, shared, autonomous vehicles will substantially reduce the overall number of cars and support efforts for greater levels of urbanity in cities with increasing place functions of urban streets. Second, private, autonomous vehicles make longer journeys more acceptable as passengers can engage in other activities than having to drive which could spur suburbanisation and urban sprawl (Stead and Vaddadi 2019).

Mobility-as-a-Service (MaaS) describes the flexible bundling of transport modes which are offered as mobility services with the potential to replace ownership-based transport. Whether offered as pay-as-you-go or monthly subscription, MaaS also includes trip planning, reservation and payment through a single app (Jittrapirom, Caiati et al. 2017). MaaS would play a critical role in the first autonomous driving scenario above by fully integrating robotaxis as part of a wide range of mobility options. For cities, MaaS offers a unique opportunity to integrate a wide range of mobility services as part of a sophisticated travel demand management system. Such a system could consider travel time, route and vehicle types and operate with information provision, incentives and restrictions to adjust mobility behaviours for achieving greater efficiency and better outcomes for cities and urban life.

To summarise, the exceptionality of urban car use cuts across high levels of popularity leading to overconsumption of existing infrastructure, significant negative externalities of which excessive space use is a leading concern for urban environments, and a considerable exposure to technological change, potentially altering the trajectory of urban car use over the next decade. It is this context within which this paper presents the idea of car use budgeting.

3 From sufficiency to budgeting

Car use budgeting builds on several established concepts which this section introduces. Within the context of environmental sustainability, the sufficiency principle has recently been gaining prominence as a fundamental approach to recognising consumption ceilings. Non-financial budgeting of scarce resources directly builds on these consumption ceilings while the specific case of mobility budgeting is an example of directly interpreting sufficiency for the transport sector. This section reviews these critical concepts.

3.1 Sufficiency and consumption ceilings

Over the last decades, a sufficiency perspective alongside a clearer recognition of consumption ceilings has become particularly prominent in the context of sustainable development and environmentalism (Gough 2020, Jungell-Michelsson and Heikkurinen 2022). Whether expressed by a global aggregate such as the earth overshoot day (Global Footprint Network 2024), consumption ceilings for key environmental indicators (Raworth 2017) or equating risk thresholds of global temperature increase (e.g. 1.5 degrees) with carbon emissions (IPCC 2023), they all share an emphasis on either finite resources, critical natural capital, consumption limits or safe emission corridors.

For public engagement and communication, the most intuitive approach to consumption limits is the effort of translating resource requirements (at times also environmental degradation such as air, soil or water pollution) to the amount of land required to sustainably produce these resources (or to recover from environmental degradation). This effort has been led by the Global Footprint Network (2005) which publishes data for individual countries on actual vs sustainable footprints expressed in hectares of land. Still, these footprints are abstractions and require agreement on the underpinning science and calculation methods (Wiedmann and Barrett 2010, Matuštík and Kočí 2021). They may also lead to complex questions of distributional fairness, historic responsibilities and differentiating needs and wants (Vasconcellos Oliveira 2019, Lucas, Wilting et al. 2020).

One context within which consumption limits can be directly experienced is the overconsumption of land, whether in the form of congestion, overcrowding or even overtourism. Cities with their concentration of opportunities are a primary context for experiences of land overconsumption. While population density, lively streets, fully utilised public facilities and metropolitan-wide agglomeration are all critical characteristics of good cities, once threshold levels of space consumption are surpassed, urban qualities quickly deteriorate. In these instances, requests for managing demand so it stays below consumption ceilings quickly become politically acceptable.

In addition to simply making the case for recognising consumption ceilings and managing demand rather than constantly expanding supply (which the nature of cities often inherently limits), a sufficiency approach also recognises that embracing consumption corridors has many benefits and may enable better lives. A prominent example is the city of short distances (Gertz 1997) where the space consumption for travel is reduced and local accessibility caters for most daily needs. This perspective has recently been popularised by advocates for the 15-min city (Moreno, Allam et al. 2021).

The case for non-financial budgeting

At the most fundamental level, a budget refers to a stock, supply or quantity relevant for a particular situation and usually involves "an account of gains and losses of such a quantity" (Merriam-Webster 2024). Its most common use is finance-related and involves a statement of the financial position of an organisation, a plan for coordinating financial resources and expenditures or financial resources available for a particular purpose. Budgeting also refers to the management of resources beyond finance, for example, time, human or technological resources (Cetron 1969, Sword and Cutsinger 1984, Andorka 1987).

More recently, budgeting began to play an increasingly prominent role as part of managing environmental resources and transitions. In this context, two fundamental applications of environmental budgets can be differentiated. First, in relation to establishing ecological resource availability (Desing, Braun et al. 2020) with strong links to regional or planetary boundaries. Once again, these boundaries can be related to the limited availability of resources such as water, soil, or plants as well as to limits of nature absorbing various forms of pollution and greenhouse gas emissions. In the latter case, carbon budgeting has become an established terminology (Lahn 2020). Second, environmental budgeting has been interpreted "as the integration of climate and environmental perspectives into a government's budgetary processes" (Blazey and Lelong 2022,p1). These approaches typically operate with the terminology of 'green budgets' (Petrie 2021) or 'climate budgets' (Johansen 2022).

Cities and their governments can be involved in any of the budgeting examples above. In addition, they often have a particular focus on more urban specific opportunities to employ a budgeting lens. Advocates of land budgeting (Smart 1984) point out that it could assist achieving a better balance between brownfield and greenfield sites. Urban space and use allocation, zoning and planning often operate with finite land budgets around which the urban planning process is structured. Urban utilities from water to energy provision have also been identified for 'budget-based management' approaches (Sperling and Ramaswami 2018). In the context of allocating cultural resources (Landry 2012), one could also consider the relevance of cultural resource budgeting although this has not been explicitly applied in cities.

The reasons why budgeting as part of public policy at any governance level remains dominant as part of fiscal processes and marginalised for other resources are manifold. First, there are policy traditions and administrative structures that have locked-in the allocation of monetary resources as the primary form of budgeting. Second, taxing and public spending are perceived by the general public and political leaders as the most central roles of governments. Third, financial resources are easily quantifiable and can be directly tracked, evaluated and adjusted. Non-financial resources may be harder to quantify and thus more challenging to manage. Fourth, the budgeting of non-financial resources is complex, requires a nuanced understanding and often additional scientific analysis. Integrating this complexity within the budgeting process of public bureaucracies would require considerable resources and administrative change. Fifth, there is little awareness and only few tools available for administrators to advance non-financial budgeting.

At the same time, the fundamental idea of budgeting (including non-financial budgeting) is to be proactive and engaged in a planned approach to allocating limited resources while ensuring these are used in an efficient way. By budgeting beyond financial resources, governments can advance more effective and comprehensive resource management. When this includes natural, land and energy resources, it also supports a more long-term and sustainable practices. As part of government innovation, non-financial budgeting can lead to novel public policy approaches and overcome lock-in based on business-as-usual approaches. For communicating with the general public, any non-financial budgeting approach also accepts that a resource may be desirable but that its overconsumption would eventually result in a significant problem affecting most people.

Put differently, non-financial budgeting can be motivated by avoiding having to ration these resources to cope with their eventual scarcity. Rationing would involve a far more restrictive practice of controlling resource distribution usually only acceptable during emergencies and times of crisis.

3.2 From mobility budgets to mode-specific budgets

Transport policy has a long history of navigating tensions between infrastructure supply, managing demand (particularly car use demand) and proactively shifting away from certain modes (Goodwin, Hallett et al. 1991, Litman 1999, Banister 2002, Whitelegg and Low 2003). While most transport management does not operate with a direct budgeting reference, the principle of adjusting demand to supply is well established and includes take-off/landing slots for airplanes, train path allocation, berth allocation for ships and various forms of road transport demand management (parking and congestion fees, licence plate restrictions, entry permits, etc.). Explicit references to mobility budgets only emerged over the last couple of decades in response to increasingly flexible work patterns, environmental awareness and sustainability requirements, technological innovation (new vehicles, mobility services and mobility apps), and cost saving needs in corporate mobility management.

Most prominently, corporate or employee mobility budgets have begun substituting company cars with mode-agnostic travel budgets (Zijlstra and Vanoutrive 2018, Schlegel and Stopka 2022). A further variant of individual mobility budgets is based on carbon budgets which are translated to an allocation of budgets for personal travel (Millonig, Rudloff et al. 2022, Arhipova, Bumanis et al. 2023). And mobility coins have been proposed as mobility budgets, allocated through a multi-modal tradeable credit scheme (Hamm, Weikl et al. 2023). For a broader public policy application, they could also underpin a fairer design of established policy instruments such as road pricing. Across these applications, the mobility budget concept remains ambiguous and can be interpreted as voluntary tracking, allowances for travel expenses, or potentially even as direct rationing.

Employing an urban lens, this paper discusses a mode-specific interpretation of mobility budgets in the form of car use budgets. Above all, this considers the considerable space consumption and consumer preferences of car use leading to a pronounced pattern of overconsumption of available infrastructure in cities (i.e. congestion). Unlike rail, aviation, or shipping where demand and supply are more finely tuned and often involve ticketing or direct demand management, the choice of driving where, when and with what type of vehicle is mostly left to individuals.

4 Car use budgeting

This section presents an approach of translating mobility budgets to the specific case of urban car use. It proposes different approaches to car use budgets, discusses its communication, and considers the integration with other policy instruments and direct application.

4.1 Space as fundamental urban unit

Conventional car use can be considered an exceptional transport mode as discussed above. Arguable, this exception is most profound in relation to its space use or ground area consumption in cities. As shown above, a factor difference of well above 40 between walking and public transport on the one hand and driving by car with a typical occupancy rate on the other hand is not uncommon. For parking, a factor difference of 6 to 20 for storing bicycles has been observed (Rode and Gipp 2001, Litman 2013). There are no other externalities in urban transport, where the differences between motorised road transport modes are likely to be that profound, including air pollution, carbon emissions and road safety.

Given the magnitude of difference in space use between cars and other transport modes, the traditional response in urban planning aiming to enable car use has been one of complete re-design of urban environments. To accommodate full car mobility in urban areas, the combination of urban motorways, vast areas of land dedicated to parking, and suburban (typically detached housing) development has been the pre-dominant urban development trend during the post-war area and until the 1990s. In many parts of the world, the legacy of this urban sprawl, car use nexus continues to be embraced and leads to rapidly increasing ground area use by private vehicles.

By contrast, established urban areas and cities have stopped a cycle of accommodating car use by changing the physical characteristics of cities and adjusting road infrastructure. Here, adjusting car use to existing capacities through demand management has evolved as the primary logic. With urban population growth, new demands for public street use (including expanding green infrastructure, opportunities for children to play, and other social and place functions of streets) questions of street use intensities for different purposes will become more important. This fundamental shift in land use and transport norms establishes a concern about space consumption as a further rational for prioritising space use as the fundamental unit of analysis.

4.2 Time-space considerations

Most discussions and analysis of space consumption in the urban transport sector focuses on static, instantaneous requirements of space use or the allocation of public street space to different modes (at times differentiated by velocity or vehicle density). Prominent examples for the first, are calculations of parking space requirements or comparisons between space use of different transport modes (Topp 1987, Brilon, Grossmann et al. 1994). Much attention has also been given to the latter which typically utilises a street cross section perspective, detailing how the share of a total street width given to different street functions.

What any of these calculations do not consider is that the requirements of street use not only differ with regards to the static space demand but in terms of the temporal length of usage. The availability of street space therefore needs to reflect both, the available static space as well as the time period over which the space is available. This is the fundamental idea behind the notion of time-space which expresses space availability or space use over a specific period of time.

While time-space is at times associated with the mapping of geographies that are accessible within a certain time (Ficzere, Ultmann et al. 2014), the focus here is on the consumption of space (s) over a specified time period (t). Real estate and particularly the rental sector maybe the context within which time-space is fully incorporated with references to a certain amount of living, retail or office space that can be rented over a certain time (typically weeks, months or years). Within the transport sector, it features most directly for parking fees to be paid again for a specific period. Here, it is one parking lot (e.g. 12 sqm) that is rented for a few hours (e.g. over 3 hours), so a possible time-space can be calculated (e.g. 36 h*sqm) for which a fee of x is being charged.

This understanding of time-space aligns with Bruun's and Vuchic's (1995) review of the time-area concept. They note "The concept of time-area occupancy by vehicles captures in the same unit not only the quantity of ground area (or space) that is required for safe vehicle movement or for storage but the period of time for which the area is occupied as well" (p94). Linking static and dynamic features of transport units, they consider its main advantage to more directly evaluate the efficiency of transport systems' consumption against available time-area (Figure 1). They note three advantages of this concept:

- a metric for area and time consumption which can be used across transport modes
- a metric combining moving and stationary transport units (car use and parking)
- a metric that allows for comparison of different transportation modes.

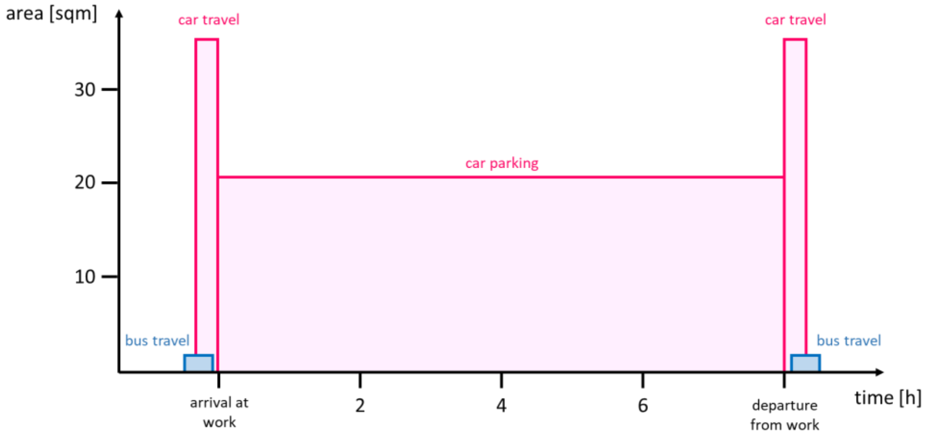

Figure 1: Time-area consumed per passenger on an 8-km round-trip commute by car vs bus
Source: based on Bruun and Vuchic (1995)

Following the time-area concept, Rode (2001) presents an analysis of time-space supply and demand for an inner-city area considering all main street uses based on their spatial and temporal use patterns. The *time-space supply* is defined as the product of the available land area (e.g. overall public space or space dedicated to specific uses) within a given territory and the chosen time intervals over the analysed time period (e.g. day, week or year). The time interval is chosen at the required level of granularity (e.g. minutes or hours) so that the analysis can be conducted appropriately. The *time-space demand* is established by the product of the use-specific space requirement and the time needed to conduct the respective activity. Again, it is calculated for the given territory and based on appropriate time intervals and period used for the supply calculation.

The modelled time-space supply and demand for a hypothetical urban area considers [1] available area, [2] area structure and uses, [3] external visitors, [4] local population, [5] time-space dimensions of individual street uses, and [6] temporal patterns of individual street uses. The result of this analysis presented in Figure 2 considers a period of a weekday (24 hours) and a time interval of one hour.

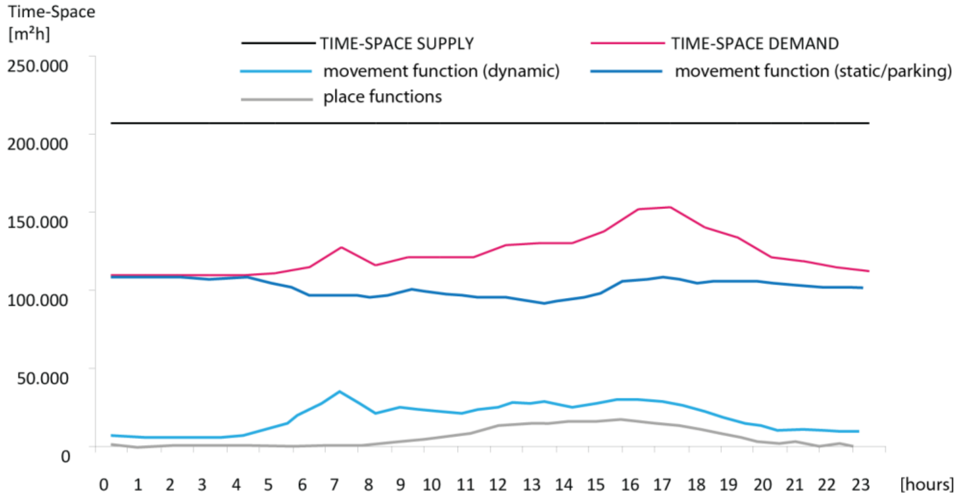

Figure 2: Hourly time-space supply and demand of urban street uses in a hypothetical urban area over a period of one day
Source: based on Rode (2001)

More recently, time-space analysis has been considered in the context of technological changes, for example, for identifying efficient last-mile delivery options (Schnieder, Hinde et al. 2020).

Utilising the time-space concept for car use budgeting could result in the following approach. The time-space supply TS_s [m²h] considers all available road space for driving and street parking within an urban area based on hourly intervals over a 24h period. The time-space demand TS_d [m²h] is the sum of all individual car use occurrences each calculated as the product of the space requirement of car use (e.g. 105 m² at 30 km/h) or car parking (e.g. 12 m² per vehicle) and the duration of use.

Time-Space Supply TS_S (over 24 hour period):

$$TS_s = \sum_{h=1}^{24} (S_s * t_s)$$

S= space (availability)

t_s= duration of supply

Time-Space Demand TS_d (over 24 hour period):

$$TS_d = \sum_{h=1}^{24} (\sum_{i=1}^{x} S_{m,h} * t_{m,h} + \sum_{i=1}^{y} S_{p,h} * t_{p,h})$$

S= space (requirement)

t= duration of use

h= hour over 24 hour period

i = individual occurrences

x= total number of car use occurrences

y= total number of car parking occurrences

m = moving vehicle

p= parking vehicle

While a time-space approach to car use budgeting most directly engages with consumption ceilings and appropriate consumption corridors, its technical nature makes it less suited for public communication and engagement. What follows is the introduction of a simple metric that indirectly incorporates the time perspective as well as individual budgeting.

4.3 Towards simple metrics

Establishing a simple metric for car use budgets could consider the following:

(1) not only the static but dynamic component of space use and thereby integrate the length of usage
(2) understandable by drivers, ideally having an intuitive sense of how the budget relates to actual and individual car use patterns;
(3) recorded at any point so that drivers as well as public agencies have a clear picture of real-time car use compared to budgets;
(4) possible to integrate the metric as part of accessible and clear political communication;
(5) an intuitive proxy for space use by automobiles so that the central concern of urban car use remains the overarching focus.

Based on these criteria, what follows below is an introduction to distance related *car use budgets* based on kilometres travelled per day and a space related *car parking budgets* based on sqm per year. While the car use budgets integrate the temporal aspect through the distance travelled and an average speed assumption, the car parking budgets directly incorporate time-space for an annual period.

The underlying logic of establishing car use budgets (CUB) is the relationship between the road infrastructure capacity (supply side) and the demand for car use (demand side). For the aggregate *infrastructure supply side*, the basic approach of calculating car use budgets considers the total lane length of all major access roads (l_r) (e.g. A-roads in UK cities) within an urban area. The boundary for this area should consider a perimeter within which road space demand exceeds supply. The network lane length would have the maximum carrying capacity if it was one single, linear road. An additional coefficient δ accounts for a lower traffic flow capacity of a more complex urban street grid rather than that of a linear road.

For individual car use budgets, the point of departure for the *car use demand* are all people that need/want to be driven in cars (n_c). All automobiles that regularly drive or are registered within the chosen urban area may be a possible proxy for this. For an assumed and ideal urban cruising speed of 30 km/h, this may translate to dynamic space requirement (S) of about 30 m of linear lane length (l_c) or between 90 and 110 sqm per car (see Box 1). In addition to the area occupied by the vehicle itself, this includes buffer space around the car and a so-called 'shadow area' – the reaction and breaking distance to the next vehicle travelling in front. It is further assumed, that people are not travelling equally distributed across a 24-hour period. Instead, a 3-hour core mobility period (t_m) is suggested during which all of these vehicles would like to travel, ideally congestion-free at 30 km/h.

Box 1: Assumptions for car use density and car use space consumption

(1) The maximum theoretical capacity of one driving lane can be calculated based on a 2-seconds safe driving distance requirement between two cars. This translates to 30 cars per minute or 1,800 cars per hour. Moving at a speed of 30 km/h, a vehicle covers 1 km in 2 minutes which translates to a car density of 60 vehicles per kilometre.
(2) The maximum empirical capacity of one driving lane is documented in the fundamental diagram of traffic flow (Brilon, Grossmann et al. 1994). According to this, at 30 km/h there is a capacity of 600 cars per hour (10 cars per minutes, one car every 6 seconds). The car density is 30 vehicles per kilometre which translates to one car every 33.33m (Brilon, Grossmann et al. 1994, Rode and Gipp 2001).
(3) This empirical capacity is aligned with Lehner (1961) who calculates for a speed of 30 km/h a space consumption of about 105 sqm per car (considering a lane width of about 3 m). At 50 km/h this increases to 240 m² (Topp 1987).

The individual *car use budget (CUB)* is then calculated based on the available infrastructure and the number of vehicles that want to travel congestion-free at 30 km/h. It is expressed in km travel distance over the chosen period of time and for one user/vehicle. Once average travel speeds within urban areas can be guaranteed, it is also possible to consider a simple time metrics of e.g. minutes of use as a car use budget.

$$CUB\ (km) = \frac{l_r(m) * \delta}{l_c(\mathrm{m}) * n_c} * v_c\left(\frac{km}{h}\right) * t_m(h)$$

l_r= lane length of all major access roads
δ= urban street grid coefficient
l_c= linear lane length requirement per car
n_c= automobiles that regularly drive within the chosen urban area
v_c= average vehicle speed (set at 30 km/h)
t_m= core mobility time

Alternatively, and to allow for different average road traffic speeds, car use budgets can be calculated based on this formula (see Appendix for a detailed breakdown of a 5-step approach):

$$CUB\ (t) = \frac{D_{max}\left(1 - \frac{v}{v_f}\right) * L * v * (1 - a * J) * u * g}{(R * m_{rc} + V * m_{vc})/o} * t$$

D_{max} = The maximum density of vehicles where speed is zero (jam density). This is assumed to be 130 vehicles per kilometre given the mix of shorter and longer vehicles in urban traffic.
v = actual speed [km/h]
v_f = free flow speed [km/h] which is set at 30 km/h (considered most appropriate gradient for urban streets)

L = total lane length [km]
a = reduction coefficient per junction (typically between 0.08–0.12)
J = number of junctions per km

u = network utilisation factor (0.5 for inner city areas)
g = capacity reduction factor due to freight (0.7 for inner city areas assuming that about 30% is typically non-car and non-taxi traffic, e.g. UK average share of non-car/taxi traffic is about 25% (DfT 2024))

R = number of mobile residents
V = number of visitors
m_{rc} = share of residents using cars/taxis [%]
m_{vc} = share of visitors using cars/taxis [%]
o = average car occupancy rate

t = core mobility time (1h, 3h or 12h)

Car parking budgets (CPB) are considered separately. On the *parking supply side*, the basic approach reflects the total public car parking area (e.g. all parking on public land) available within the same urban area chosen above (a_r).

$$CPB\ (sqm) = \frac{a_r(sqm)}{n_c * 12(\text{sqm}) * \alpha * \beta * \mu}$$

a_r= available public parking area
n_c= number of automobiles requiring parking
α= parking access and circulation coefficient
β= parking time coefficient
μ= private car parking coefficient

For the *parking demand side*, the point of departure are all people that need/want to be driven in privately owned cars (n_c). Once again, all automobiles that regularly drive or are registered within the chosen urban area may be a possible proxy for this. For road-side parking, this area can be calculated directly (12 sqm per car), for dedicated parking lots, an access and circulation co-efficient (α) needs to be considered alongside which may almost double-parking space requirements per car (up to 22.5 sqm per car). It is further assumed that privately owned cars require parking for at least for 95%, to what extent this occurs within the boundary area is captured by the co-efficient (β). To account for car drivers with access to private parking, a co-efficient (μ) reduces the space need.

To communicate, *car parking budgets* alongside car use budgets, their time intervals are considered on a daily basis. Their overall time period is annual as it has to be assumed that these are demands that are fairly static over periods of longer than one year (unlike demands for car use budgets which are more flexible over the short time).

Annual car parking budgets below the value of 4,380 m^2days (12 m^2 * 365 days) imply that there is not enough space for car parking needs to be accommodated and that only a proportion of residents can have full access to car ownership or that cars are shared instead.

In summary, the logics behind even a simple metric for ground-area related car use budgets which also consider time-space can be difficult to intuitively understand. Particularly the identification of time intervals and time periods which underpin the analysis is open for discussion and contestation. However, a more prominent use and awareness of a kilometres-per-day metric of urban car use may have considerable benefits and opportunities. In urban areas where road-based travel speeds can be reliably managed, a shift to pure time-budgets (minutes of use over specified period) may be the easiest solution as this is already part of many Mobility-as-a-Service solutions (scooter and bike sharing) and prominently used for car parking charging.

Below follows a discussion of the potential applications of car use budgeting.

5 Applying car use budgets

The potential application of car use budgeting can take on various forms and where possible can be informed by pilots, trials and experiments. Three fundamental approaches to car use budgets are discussed in this section: First, a communication support approach, second an approach for supporting established policy instruments and third, a dedicated and direct application of car use budgeting as stand-alone policy tool.

5.1 The communication approach

Utilising car use budgets for a communication approach, above all, targets a better understanding of individual spatial implications of driving and parking in inner city areas. While the general public may have good knowledge of the overall issue of limited street space and parking in cities, there is arguable less understanding of how such limitations relate to individual car use. Many drivers in inner city areas often may not even be aware of how many (or how few) people actually drive and may falsely equate a privileged use of a significant amount of urban space for driving and parking as average or normal.

For residents in urban areas reliant on public, on-street parking, the priority consideration are car parking budgets. While area-based metrics allows for direct comparison with other uses and a time-space perspective would further emphasise the length of parking use, the most basic communication approach for resident street parking could be based on parking slots per locally registered vehicle, household and/or resident. Certainly, for the latter two, this ratio will be well below one, clearly communicating that not everyone can expect to have access to on-street parking which then naturally leads to questions of who should be granted public parking, who not and what price may be appropriate. Parking slot figures could be complemented by actual space use over time to compare the individual use of public space for different purposes.

For driving in inner city areas, the above introduced km-per-day car travel budgets may be a sound basis for communicating how a ceiling of available road space would translate to average car use budgets. Once again, these could be calculated based on all drivers/vehicles that frequently use the defined urban area or for all its local residents and frequent visitors. In the latter case, once again the figure would be surprisingly low for most drivers and as a starting point of any public debate on transport policy clarifies the level of privilege driving in cities implies.

The importance here is to stick to individual budgets and area-based metrics (which always convey the opportunity for alternative use) or kilometres driven (potentially even driving time as long as average speeds can be guaranteed) over a specific time period rather than vehicle counts and vehicle capacities which do not communicate space consumption. The relatability of distance travelled per day is critical to engage with drivers who are usually aware of the amount of driving they do.

5.2 Assisting other policy instruments

For exploring the role of car use budgeting in support of established transport policy instruments, this section differentiates between information-based, economic and regulatory instruments. *Information-based instruments* build on the communication approach above, e.g. as part of awareness campaigns, and may then also assist a city or urban area establish voluntary car use budgets. Above all, such efforts would require establishing the required data and statistical analysis embedded as part of urban transport policy. Targeting a new comparative urban transport metric such as kilometres driven per resident may be a critical complementary measure for cities alongside modal share information not only assisting knowledge creation but educational efforts. Once a more established urban transport category, car use budgets can also be communicated by city leaders in reference to their own travel behaviour and assist various opportunities of signalling desirable choices.

Supporting economic instruments, car use budgets may be particularly useful for a range of pricing tools. On the one hand, time-space analysis lends itself to establishing prices for driving and parking as it makes car use relatable to other urban space uses and associated costs. On the other hand, car use budgets can underpin fairness considerations for road pricing and parking fees. They could, for example, establish a baseline of usage available to everyone for free (in line with given space consumption ceilings) and consider progressive pricing for every additional unit thereafter. This may be particularly relevant for the political debate associated with cities shifting to km-based road pricing. Beyond fees and pricing, car use budgets could also underpin fairness tests of subsidies and non-financial resource provision (above all land) for different transport uses.

Finally, car use budgets could assist various *regulatory instruments*, above all vehicle access restrictions that are triggered above a certain level of usage. Sophisticated forms of car use budgets that incorporate vehicle size may help establishing upper limits of compliance for vehicle standards. The implied tracking of car use which related budgeting may require also supports a range of regulatory enforcement tools, from speed limits to access restrictions. For planning and infrastructure design, public debate and agreement on car use budgets and ceilings can also inform the provision of infrastructure and a fair distribution of assigning street use to different functions.

Across all these policy instruments, a fundamental role of car use budgeting is a more direct engagement with fairness aspects of urban car use. As car use budgeting relates abstract transport planning KPIs to individual consumption, it makes discussions about appropriate levels of car use and the distribution of related transport resources more accessible and intuitive. By doing so, it addresses a fundamental critique of certain sustainable transport schemes about being perceived as or being objective examples of regressive and unjust policy interventions.

5.3 Direct application

To date and as part of transport policy in cities, there is no direct application of car use budgeting. Yet, there are related approaches which indicate that policy contexts can change rapidly and potentially lead to the introduction of more radical measures. Road pricing, licence plate-based driving restrictions, and related road space rationing are among the more common ones. There are various factors that could potentially create the political circumstances under which a more direct interpretation of car use budgeting may become more likely. These include, technological change, shifting public attitudes, emergency measures, *Technological change* could create a context for car use budgeting in two ways. First, the change in vehicle technologies (electrification, automation, diversification) will overwhelm existing transport infrastructures and policy tools, requiring a more direct intervention through demand management. Second, new forms of demand management instruments which operate reliably and with significant levels of data privacy can bring together user details, vehicle types, time and geography of use. On top, such technologies may fully and automatically integrate cap-and-trade approaches for mobility budgets as part of mobility service apps. These systems could build on early experiments such as mobility coins and multi-modal tradeable credit scheme (Hamm, Weikl et al. 2023).

In terms of *shifting public opinion*, some cities are currently close to or have already surpassed social and political tipping points which make it acceptable to prominently position the reduction of car use within inner city area a key objective of urban policy. In these cities, including Paris, London, Milan and Brussels, the political leadership have advanced related agendas over several electoral cycles and were able to expand their political capital in support of transport transitions. It is in these contexts, where novel transport policy instruments may emerge as part of new experiments and could potentially include at least voluntary forms of car use budgeting.

There are various reasons why *emergency measures* may require the rationing of car use in cities. These could be triggered by direct spatial requirements in circumstances when available street space has to be radically redistributed (distribution for essential goods like water and food, establishing green corridors in existing streets to mitigate extreme heat, various types of flood events and disasters restricting road use, etc.) or in instances where car use is a proxy of using other scarce resources or negative externalities that need to be dramatically reduced (air pollution emergencies, climate emergency measures, fuel shortages, etc.).

6 Conclusion

While many urban transport policy instruments clearly acknowledge car use consumption ceilings in inner city areas, a mode-specific sufficiency approach in transport policy has so far not been considered. This working paper presented an overview on interpreting the sufficiency principle in urban transport through car use budgeting. The fundamental idea of this type of budgeting is motivated by relating society-wide, collective action to individual behaviours. Building greater public awareness in this way may facilitate greater acceptance for sustainable transport objectives and help overcoming polarisation based on better presented evidence on fairness.

Discussing various options for developing such budgets, the paper suggests that for an early and simple public policy adoption, these budgets could be structured around individual kilometre-based budgets over a 24-hour period. At a later stage and when average travel speeds can be guaranteed, these budgets could also be expressed in time of use over the same period. Car parking budgets may initially best operate with a units per resident approach and should eventually be complemented by a time-space analysis to compare parking requirements with other, alternative street uses in urban areas.

This paper intends to open-up a discussion and motivate further research. Above all, it would be important to test the idea of car use budgeting with the general public and to better understand whether it can assist a better communication of urban transport policy. Alongside, such tests should consider questions of transport fairness and equity which car use budgeting could be a helpful tool for.

Appendix – 5-Step Car Use Budgeting

1. *Basic urban area and road system characteristics*

The starting point is to determine the *land surface area* of the city, urban area, district or neighbourhood in question.

Based on this we can either extract the typical *kilometres of major roads* (link length) based on what is most common in other cities or, if known, use the number of actual road kilometres (link length).

The link length of major roads then needs to be converted to the actual number of *lane kilometres (L)* within the identified area by multiplying link length with the average number of lanes per major road within the given area.

2. *Theoretical lane capacity*

The theoretical *linear lane capacity* (C_{lin}) of these lane kilometres is then initially calculated for a single circular street that equals this lane length and has no intersection. This capacity is expressed by the total number of kilometres that can be driven by all vehicles within one hour.

This lane capacity is calculated in two steps. First by calculating the *vehicle density (D)* as a function of the *actual vehicle speed (v)* which can be calculated based on the so-called Greenshields' model (for urban speeds between 10 and 30 km/h this simple model is a good enough approximation).

$$D\ (v) = D_{max}\left(1 - \frac{v}{v_f}\right)$$

D_{max} = The maximum density of vehicles where speed is zero (jam density). This is assumed to be 130 vehicles per kilometre given the mix of shorter and longer vehicles in urban traffic.

v = actual speed [km/h]

v_f = free flow speed [km/h] which is set at 30 km/h (considered most appropriate gradient for urban streets)

With speeds between 10 and 30 km/h, this formula can easily be verified based on a typical lane capacity of 1,000 vehicles/hour divided by the actual speed. E.g. for 20 km/h this would result in a vehicle density of 50 vehicles/km.

Second, the *linear lane capacity* (C_{lin}) expressed by the total vehicle kilometres travelled per hour is then calculated based on the vehicle density (D) multiplied the total lane length (L) of the road and the *actual vehicle speed (v)*.

$$C_{lin}\ (v) = D(v) * L * v$$

C_{lin} = linear lane capacity [vehicles km/h]

L = total lane length [km]

3. *Urban grid capacity*

The *urban grid capacity* (C_{urban}) converts the capacity of the single road to that of an urban street grid of the same length. It makes use of the number of intersections of major roads within the given area which establishes a street grid capacity reduction factor. The capacity of a street grid system is significantly lower compared to that of a linear road of similar length to due vehicle interactions at intersections.

$$C_{urban}\,(v) = C_{lin}(v) * \delta$$

C_{urban} = urban grid capacity [vehicles km/h]
v = actual speed [km/h]
δ = urban street grid capacity reduction factor (between 0 and 1)

$$\delta = 1 - a * J$$

J = number of junctions per km
a = reduction coefficient per junction (fixed at 0.1 as typically ranging between 0.08–0.12)

4. *Car use demand*

The *car use demand (U_{car})* is based on the number of residents and visitors (all people entering but not residing within area including commuters, business travellers, tourists, personal visitors, etc.) that need or would like to drive within typical day.

$$U_{car} = R * m_{rc} + V * m_{vc}$$

U_{car} = daily car travel demand [people]
R = number of mobile residents
V = number of visitors
m_{rc} = share of residents using cars/taxis [%]
m_{vc} = share of visitors using cars/taxis [%]

5. *Car use budget*

The *car use budget (CUB)* is then calculated for a given *core mobility time (t)* by dividing the urban grid capacity by the car travel demand. The urban grid capacity is adjusted for the *network utilisation (u)* (i.e. the unequal distribution of it use) and a *capacity reduction factor (g)* due to freight and other non-car and non-taxi traffic. The average occupancy rate (o) adjusts for people sharing the same car or taxi.

The resulting car use budget expressed in the number of kilometres for a core mobility time of 1h can then be adjusted to 3h or 12h considering that not all car travel demand will occur within the same hour but over a longer time period of a day.

$$CUB\,(t) = \frac{C_{urban} * u * g}{U_{car}/o} * t$$

u = network utilisation factor (0.5 for inner city areas)
g = capacity reduction factor due to freight (0.7 for inner city areas assuming that about 30% is typically non-car and non-taxi traffic, e.g. UK average share of non-car/taxi traffic is about 25% (DfT 2024))
o = occupancy rate
t = core mobility time (1h, 3h or 12h)

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