

REVIEW

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Why do we rely on cars? Car dependence assessment and dimensions from a systematic literature review

Jaime Sierra Muñoz^{1,2*} , Louison Duboz¹ , Paola Pucci²  and Biagio Ciuffo¹ 

Abstract

“Car dependence” emerges as an academic concept supported by decades of multidisciplinary research, which aims to understand the factors that drive car-based choices. The variety of approaches and indicators used to interpret this phenomenon underscores its multidimensionality and highlights the necessity for a comprehensive framework to define and operationalise it. This paper contributes to this goal by conducting a systematic literature review that examines the indicators, associations, and meanings used by research in defining and quantifying car dependence. Results show that car dependence has been mainly studied considering transport demand, despite criticisms pointing out to the need of including accessibility and subjective perceptions as well. As a consequence, the paper proposes a holistic approach to the term car dependence by proposing six dimensions covering the full spectrum of the concept as presented in the academic literature. The findings also suggest to move towards harmonising measures of the concept, which would facilitate the development of policies and the assessment of their effectiveness.

Keywords Car dependence, Transport, Territory, Accessibility, Systematic literature review

1 Introduction

The decision to drive generates individual benefits while creating costs and externalities that transcend personal boundaries and affect the society and the environment. Growing impact on the environment and public health emerged as cars increasingly populated roads and streets [30, 57]. It also involves higher energy consumption while occupying valuable urban space, preventing open and green spaces, kids’ play and independence or further social use of places [3, 85]. Still, reshaping transport choices presents a long-discussed challenge. A modal shift towards more sustainable transport options has to

deal with the so-called automobility system [88]: a complex interplay between lifestyle and economy around cars, involving various industries, upscaling of resources uses and mass culture together to expanded mobility aspirations. Automobility hinders policies and solutions transitioning towards fairer transport options [6, 15, 77], enclosing a pervasive, locked-in and resilient system [67]. In addition, it is expected that innovative transport solutions and services will outbreak (e.g., automated vehicles, shared mobility), raising uncertainty about the future shape of mobility [4, 58, 62] and its territorial effects [1, 76].

In this context, where tensions between transport externalities and new technological possibilities emerge, some challenges appear around the role of the automobile. First, the focus on technological fixes is not effective in reclaiming cities from the car. Coping with the deep-seated reliance of contemporary lifestyles and business models on automobiles needs more holistic approaches [45]. Second, ‘transition’ strategies are needed [36] to face

*Correspondence:

Jaime Sierra Muñoz
jaime.sierra@polimi.it

¹ Joint Research Centre, European Commission, Via E. Fermi 2749,
21027 Ispra, VA, Italy

² Department of Architecture and Urban Studies, Politecnico di Milano,
Via Bonardi 3, 20133 Milan, MI, Italy



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automobility resistance to change [10, 67], providing not only a shift to different cars, but also reducing the quantity of cars [16]. Third, urban mobility visions need to be not only sustainable but also fair and able to deal with different place-based mobility conditions and mobility needs.

Understanding the variety of motivations underpinning the societal reliance on cars is crucial for addressing those challenges. This issue is not new in the academic realm: car dependence, as a concept, has been raising those questions since Newman & Kenworthy's [74] first contribution on the topic. Their demonstration of how certain urban qualities were linked to car usage drew the attention of geographers and social scientists to the concept. Therefore, the subject started to be explored from a multidisciplinary point of view and potentially transcended academic limits [39, 43, 64]. Raising social awareness about car-induced problems makes the use of word *dependence* relevant in this context. It evokes a sense of being reliant on or driven by an object, but there is a broader complexity beyond the words car and dependence placed together.

While interest in the term grows, car dependence still remains a term open to diverse interpretations and approaches, even after more than three decades of publications. While the first articles pictured car dependence as a matter of high car use [51, 74], later other research enlarged the scope of the concept [38, 40, 42]. Some argued that those who use a car when alternatives do not exist may not be as car-dependent as those who have other choices [8, 20]. This distinction comes together to take into consideration how behaviour affects transport choices, so car dependence is classified as both subjective and objective, as conscious and structural [61, 66, 69, 98]. Other conceptualisations have also approached the term as a path-dependent process [38] following many different elements, such as societal, political, economic and energetic [67].

Thus, car dependence can be regarded as an intricate phenomenon with various facets. Framing the concept is even more challenging due to its complexity and pervasiveness, as the academic discussion has yet to agree on a definition. As a result operationalising car dependence is all but a clear subject, being a challenge for research which could spread the concept enabling larger practical application of it. A car dependence measurement would include the elements that influence car-based mobility, providing clear insights to create policies addressing it.

At the current point, the concept is also developed enough to assess its current position and consider future directions critically. With that intention, this article aims to explore systematically how car dependence has been quantitatively assessed in research and studies published

in peer-reviewed journals. To our knowledge, such a literature review perspective on car dependence assessment has never been included in research. Therefore, this article contributes to the literature and represents the first exercise of its kind, expecting to answer the following research questions:

1. How has car dependence been assessed in literature?
2. Which factors push car dependence?

This paper is structured as follows to address these research questions: the next section presents the methodology used to select the references used in the study. Results are then shown in the following two sections. In particular, first, the analysis explores each reference's conceptual approach to car dependence; then, the paper focuses on which indicators were related to it and their correlations. Finally, discussion and conclusion describe the main outcomes of the review study, placing issues for further research.

2 Methodology

The systematic literature review conducted in this research focuses on articles assessing car dependence, both as their primary goal or connecting the concept to other subjects. Publications which did not have a quantitative approach to car dependence (planning and policy, social practices, theoretical frameworks, etc.) were then not considered. The literature review has been performed following van Wee & Banister [92] recommendations. The process is also outlined in Fig. 1:

- First is performed an extensive research using the Scopus database. This included peer-reviewed articles ranging from Newman & Kenworthy [74] seminal book to the first trimester of 2023. The search key was restricted to the terms "Car" or "Automobile" together with "Dependence" or "Dependency" in titles, abstracts and keywords. This allowed to cover fully the subject, considering multiple spellings present in literature and obtaining papers mostly written in English or, at least, including an English abstract. This search returned 651 results.
- A first scope check was performed on the abstracts. Papers not mentioning a quantitative assessment of car dependence were systematically excluded. After this selection, the papers shortlisted were 102.
- A second scope check followed, observing the full text and its outcomes. Several papers were excluded due to their focus on developing theoretical conceptualizations of car dependence without providing clear quantitative operationalization or conducting

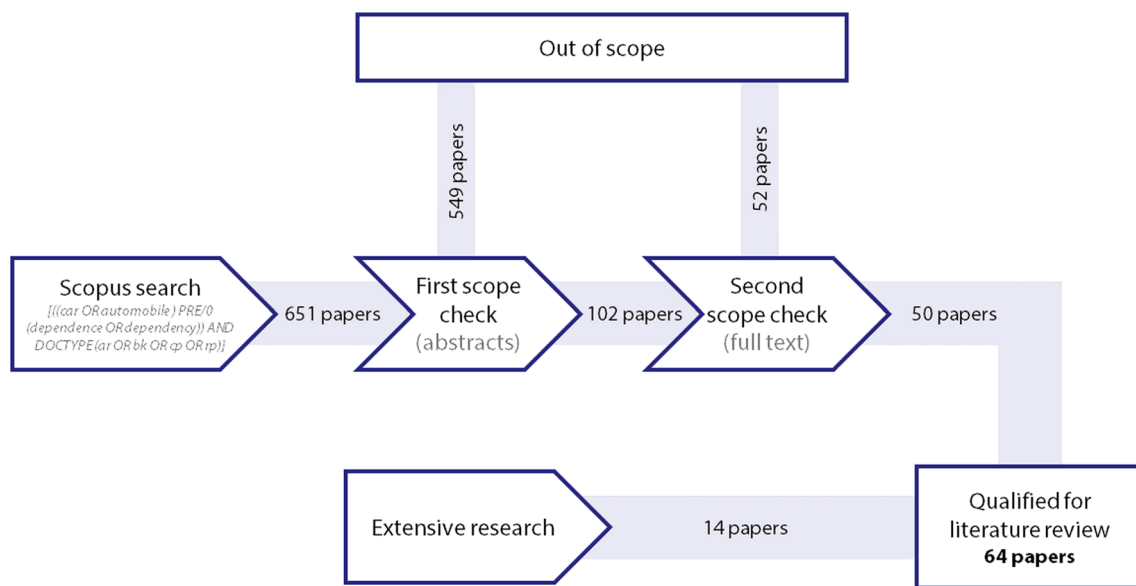


Fig. 1 Literature review methodological process

descriptive analysis. After this, 50 papers qualified for the full study.

- Finally, 14 additional publications were included, aiming to cover larger limits in the research and expand the literature review. These come primarily from snowballing, experts' advice and larger literature reviews on related concepts. Among them, several publications previously outlined were not considered by the Scopus search, such as the aforementioned book by Newman & Kenworthy [74]. On the other, some papers dealt with car dependence even if not explicitly mentioning it, developing extensive research that covers additional insights on land use or travel behaviour. Every additional publication has undergone a peer review process, except for Newman & Kenworthy [74], for which no such confirmation exists.

Therefore, 64 papers were selected.

3 Literature approaches to car dependence

The literature sample considered in the paper is specified in Table 1 and represents various approaches. Most of the papers emerge from transport-related journals, but environmental and urban studies, economics, regional planning and geography also apply to a lesser extent. Even though the concept emerged in 1989, the following academic contribution appeared in 1996. Still, two-thirds of the selected papers have been published from 2013 on, showing that the interest in car dependence has grown with time.

The articles' territorial origin primarily centres in Europe, North America and China. However, some parts of the world are noticeably absent from these studies. Some are Central and South America, where significant urbanisation processes are occurring, probably following car-centred models as global north countries did decades earlier. On the other hand, most papers frame car dependence in metropolitan contexts, considering country or worldwide less and paying fewer attention to wide regional settings. Specifically, rural contexts do not gather specific attention on car dependence assessment. Altogether, the concept focus on specific contexts also points out the necessity of expanding car dependence studies towards different settings and regions of the world.

Since car dependence is a concept open to various interpretations, it is worthwhile to begin by examining how the selected papers have conceptually approached this idea. This analysis is conducted in two different directions in this section: the meaning each paper gives to car dependence and, according to different agents (person, practices or territories), the level where dependence is studied.

3.1 Car dependence operationalisation trends

Car dependence is a latent construct, requiring a framework to define and operationalise it. Each paper analysed, explicitly or not, assumes its own meaning to car dependence, ultimately influencing quantitative approaches. From there, the concept of "operationalisation trends" emerges as the group of understandings used to depict

Table 1 Selected publications classification according to the level where car dependence is assessed (i.e., car-dependent agent)

References	Source origin		Car-dependent agent			Territorial application	
	Scopus	Extensive	Macro	Meso	Micro	Places	Context
<i>Car dependence as car use and access (37 papers)</i>							
[78]	X		X			55 metropolitan areas worldwide (5 from North America, 30 from Europe, 4 from Africa, 8 from Middle East, 6 from the rest of Asia, 2 from Australia)	Worldwide
[31]		X	X			Meta Analysis	Other
[51]	X		X			34 cities worldwide (11 cities from Europe, 14 from North America, 3 from Asia, 6 from Australia)	Worldwide
[22]		X	X			San Francisco, United States	United States
[15]	X		X			3 cities in Germany (Berlin, Hamburg, Munich), one in Austria (Vienna), one in Switzerland (Zurich)	Europe
[74]*		X	X			32 cities worldwide (5 from Australia, 11 from North America, 13 from Europe, 3 from Asia)	Worldwide
[44]		X			X	Guangzhou, China	China
[65]	X		X			United Kingdom	Europe
[63]		X	X	X		Montreal, Canada	United States
[59]	X		X			Brisbane, Australia; Hong Kong	Worldwide
[29]	X		X			Västra Götaland, Netherlands	Europe
[97]	X		X			Changghung, China	China
[102]	X				X	Changghung, China	China
[87]		X			X	Netherlands	Europe
[60]		X		X		Netherlands	Europe
[107]		X	X			Beijing, China	China
[47]		X			X	Germany (Augsburg, Bielefeld, Magdeburg)	Europe
[96]		X	X		X	Changghung, China	China
[106]	X				X	Austin, United States	United States
[33]		X			X	European Union	Europe
[86]		X		X	X	Copenhagen, Denmark	Europe
[101]	X		X		X	Nanjing, China	China
[2]	X		X			Toronto, Canada	Canada
[5]	X				X	United States	United States
[11]	X		X			France's mainland metropolitan areas	Europe
[12]	X		X			United States	United States
[14]	X		X			United States and Germany	Worldwide
[19]	X		X			London	Europe
[90]	X				X	Flanders, Belgium	Europe
[34]	X		X			United States	United States
[49]	X		X			Jinan, China	China
[50]	X		X			Germany	Europe
[52]	X		X			46 cities worldwide	Worldwide
[68]	X		X			26 cities worldwide	Worldwide
[69]	X				X	Sydney Greater Metropolitan Area	Australia
[73]	X		X			37 global cities	Worldwide
[80]	X				X	Shanghai	China
<i>Car dependence as an accessibility outcome (9 papers)</i>							
[98]	X		X	X		Netherlands	Europe
[72]	X		X			Paris, France	Europe
[95]	X		X			Xiamen, China	China
[71]		X	X		X	Paris, France	Europe
[9]	X		X			Tel Aviv, Israel	Middle East

Table 1 (continued)

References	Source origin		Car-dependent agent			Territorial application	
	Scopus	Extensive	Macro	Meso	Micro	Places	Context
[99]	X		X	X		South Limburg Region, Netherlands	Europe
[91]	X		X		X	Flanders, Belgium	Europe
[100]	X		X			Three European cities (Eindhoven, Southampton, Aachen)	Europe
[54]		X	X			Munich Transport Region, Germany	Europe
<i>Car dependence as subjective perceptions (6 papers)</i>							
[8]	X				X	Shanghai, China; Berlin, Germany; San Francisco, US	Worldwide
[109]	X				X	London, United Kingdom	Europe
[46]	X				X	United Kingdom	Europe
[82]	X				X	Seoul, South Korea	South Korea
[84]	X				X	Banda Aceh City, Indonesia	Indonesia
[93]	X				X	India	India
<i>Car Dependence as a modelling of choices (3 papers)</i>							
[105]	X		X		X	Boston, US	United States
[104]	X		X		X	Boston, Portland, Houston	United States
[103]	X		X		X	Boston, US	United States
<i>Car dependence as an explanatory variable for other issues (9 papers)</i>							
[23]	X		X		X	US Counties	United States
[24]	X			X		British Islands	Europe
[25]	X				X	Netherlands	Europe
[26]	X		X			United States and Germany	United States
[28]	X				X	Stockholm, Sweden	Europe
[56]	X				X	Maricopa County, United States	United States
[94]	X		X			Seven metropolitan areas in Canada	Canada
[108]	X		X			United States	United States
[35]	X				X	Germany and Canada	Worldwide
TOTAL: 64	50	14	40	6	28		

* Unknown if peer-reviewed

car dependence. Therefore, the selected publications are categorised according to how car dependence is inferred.

3.1.1 Car dependence as car use and ownership

Newman & Kenworthy [74] developed a first car dependence inference from car use and ownership results, a lead followed by many other papers. From analysed travel diaries, Merom et al. [69] defined car dependence as exclusive driver car use, with no walking trip at all. Cao & Hickman [19] stated car dependence levels based on motor vehicle ownership values, work-related car trip quantity, and average distance. Many other articles used more direct inferences, such as car choice and frequency use [5, 34, 90, 106], car mileage [14, 29, 68] or ownership [12, 49, 50, 80]. 60% of the qualified papers (37) used these straightforward points of view, being then the ones with strongest acceptance in literature.

Picturing car dependence as mere car use and ownership has been criticised because it does not explain “the

reality of a situation of dependence” [71, pp. 899–900], that is to say “an irrepressible surge with incoercible effects on human settlements” [27, 71, p. 900]. For example, owning a car does not necessarily represent its extended use (it could only be used for specific trips or as an added value for some mobility necessities), so neither means dependence by itself. These critiques show that a car-dependent situation is much more complex than some of its outcomes. For instance, people who do not have access to cars (and so don’t use them) can also experience car dependence [20, 65, 89] and still remain invisible according to this operationalisation approach. This only recalls that the causes, not only the massive and direct outcomes, form a core part of the phenomenon.

3.1.2 Car dependence as an accessibility outcome

Accessibility is observed as a basic need, being presented as “the capacity to reach a place, event, opportunity or social contact in a way that fulfils what people need” [32]

or “a way of characterising the available choices” [41]. A lack of accessibility on a local scale, as well as speed-centric transport planning, can shift accessibility to a regional scale [81], pushing to drive. However, while accessibility has a strong tradition in research, it is still not fully understood by practitioners [13]. Its definitions have come up throughout time without consensus on standardisation [37, 41, 70], even though some progress has been introduced recently [75].

Some authors understand that car dependence is fuelled by the lack of accessibility, especially in the proximity extent. Wiersma et al. [98, 99], and similarly Benenson et al. [9] inferred car dependence from a travel choice score comparing the ratio of jobs accessible by car and other modes (cycling and public transport).

The quantity and the qualities of amenities available are presented by Motte-Baumvol et al. [72] as a way to characterise car dependence. Wiersma et al. [100] defined car-dependent population as individuals living beyond 1 km to amenities and/or job commuting further than feasible cycling distance. Such a relationship between amenities and transport is also developed by Van Eenoo et al. [91], who use scores on both to determine “theoretically car-independent” areas while they look subsequently for car-reliance feelings in those places. Langer et al. [54] understood car dependence as a “transport development focused on the car as the main mode of transport to access basic opportunities” (p. 89). From there, they developed a “Car Dependence Factor” depending on the ratio of motorisation rate and average accessibility to points of interest and public transport stations.

Those examples mostly come from a European setting, being suitable for integrating transport poverty related issues, where citizens who are unable to drive could result in deprivation. Also, they specifically examine the proximity extent in different settlement types. Thus, these studies imply that car dependence is more related to longer-distance trips, where it is more difficult for other modes to compete with cars.

3.1.3 Car dependence as subjective perceptions

Behavioural and perceptual aspects also drive car mode choice [55]. How much individuals are favourable to complete certain activities, how experiences shape preferences or how difficult it is to perform a behaviour are reasons behind travel mode choice. Car use can be trend or fashion related, able to channel adrenaline or other feelings, as well as car ownership is used to communicate status [83]. All these are part of the car mass-culture side of automobility, which drives car dependence to some extent.

This perspective presents one of the most direct ways to check on car dependence. Indeed, Zhao [109] qualified

subjective car dependence from Likert scaled questions (e.g., “my lifestyle is dependent on having a car”, “I don’t have time to think about how I travel, I just get in my car and go”, among others). Other papers use a similar approach [46, 84, 93], as well as Sohn & Yun [82], who also built different profiles around the issue regarding perceptual elements: privacy, safety, weather comfort, driving pleasure, speed enjoyers and self-personality communication, among others.

This attitudinal way of approaching car dependence needs to be related to factual information, such as transport supply or surroundings characteristics. Otherwise, the concept would remain disconnected from the conditions creating such perceptions. This is done by most of the publications analysed, even though causal linkages are not demonstrated.

However, the subjective approach places a subtle difference on what is intended by car dependence. Lucas [61, p. 10] put it in the following terms:

“It is difficult to assess from the literature, however, at what point people’s car-use behaviors at the individual level can be described as merely a perceived reliance or when this reliance becomes an actual dependence or, indeed, when it may be considered to be an effective dependency on or addiction to the car.”

This distinction recalls that the complexity in car dependence might lead to broader operationalisation methodologies which consider different approaches together.

3.1.4 Car dependence as a modelling of choices

A different way of understanding car dependence was introduced by Zhang [103] from a modelling approach, defining mode choice possibilities and how feasible they could be.

It assumes that a person makes a trip modal decision based on the cost and time of the transport options available. A person is considered car-dependent if, given those conditions, the only choice set to the trip is using the automobile. This is modelled using a probabilistic approach from a maximum likelihood estimator. This approach, further developed in subsequent publications ([104, 105]), is more related to the car use and ownership one, as it is framed on characterising the final travel outcome.

However, this perspective only considers car dependence if a car trip is made. Then, other factors involving trip decisions are not considered, such as reasons preventing activity participation due to no access to cars. As a solution, the correlated results with further variables presented a methodology that could open possibilities to

link his approach with other perspectives. Still, no evidence of further developments has been found in this area.

3.1.5 *Car dependence as an explanatory variable*

An explanatory variable is used to explain or construct another concept, being also car dependence used this way, as a lateral term to other issues. Even if the meaning given to car dependence in this section is related to previous categories, exploring these cases apart remains interesting to have a broader insight.

Overall, car dependence term has been related to attitudes towards transport policies such as active transport improvements [23], congestion charge [28], tradable credit schemes [25] and openness to automotive innovations [35]. In those cases, the definition of car dependence follows car ownership, car choice on commuting and subjective reliance on cars for the last two. Mode choice is also used to frame car dependence when depicting mobility patterns of university students, housing recession and household debts [24, 26, 94]. Obesity is also a related topic to car dependence [56, 108], using a more developed conceptualisation in the former publication (vehicle ownership, share of commuters who drive more than 45 min and public transport users) than in the latter (modal choice).

When used as a lateral term, few indicators, if not only one, are applied to frame car dependence, mostly following its effects on car use and ownership. Building a clear operationalisation scheme for car dependence could help to connect the term more efficiently with other concepts and disciplines.

3.2 *Car-dependent agent: macro, meso and/or micro*

The complexity around car dependence also develops along the levels it can be studied. There are different contexts, from person to environment, where the need for a car appears to different extents. Following this reflection, Mattioli et al. [66] introduced three “typologies of understandings” that frame those levels or, in other words, outline which is the car-dependent agent: territories (macro approach), individuals (micro) and trips and activities (meso). They are introduced throughout this section, although the meso approach is developed last as it emerges from macro and micro interphases, as well as being far-less used.

3.2.1 *Macro: car-dependent territories*

The macro approach, as Mattioli et al. [66] depicts, mainly characterises what opportunities territories provide, how they are physically organised and their relation with transport. Most of them follow Newman and Kenworthy [74], which included dozens of metropolitan

areas around the world, comparing how car use change related to other variables, such as population density or transport supply [51, 52, 68, 73, 78]. Even if these comparisons clarified the relation of population density with car use, many authors have questioned limiting car dependence to that insight, as that would overshadow individual or socio-economic agents [18, 40, 66, 78]. This also questions whether increasing density is the only solution to pursue, pushing for diversifying studies and broader understandings.

Many other papers also put stress on the relation to the built environment [22, 31, 59, 97, 101]. Stronger zoning policy (i.e. mono-functional areas), as derived from modernist planning, will make people travel further to reach their needs, being more related to car dependence. Also, public space plays an important role in travel, not only on quantitative issues, but also on qualities that generate different feelings of comfort or nuisance that might enhance certain modes of transport [48]. Displacing through a building continuum in a tree-equipped street with facilities at each side of the way might produce less car-oriented behaviours than moving through a set of highway interchanges and empty places. This is a matter of perceptions, but physical settings of the context produce them.

Macro approaches also tend to analyse the territorial features considering different urban settlements (i.e., different cities worldwide considered separately, the study of a city into transport zones or a region within municipalities). Such a framework shows better the heterogeneities within the inner areas, even though it usually takes a more descriptive approach in literature. Data, however, is aggregated within those statistical units, so selecting the size and the limits represents a relevant decision.

3.2.2 *Micro: car-dependent individuals*

Following Mattioli et al. [66], micro approaches model car dependence considering persons' conditions and perceptions, being further developed in two ways. On one side, conscious car dependence relates to persons still reliant on cars disregarding possible transport alternatives, developing attachments or preferences. On the other hand, structural car dependence involves persons who might not have those alternatives to car, being forced to use it.

Behind those perspectives, there are frequently personal and individual factors that probably affect mobility decisions and fuel car dependence. Many papers study households' structure, income and employment regarding car use and ownership [5, 69, 80, 87, 90, 96, 101, 102, 106]. Personal conditions vary not only on a spatial basis, but also in time, placing a further element in car dependence complexity.

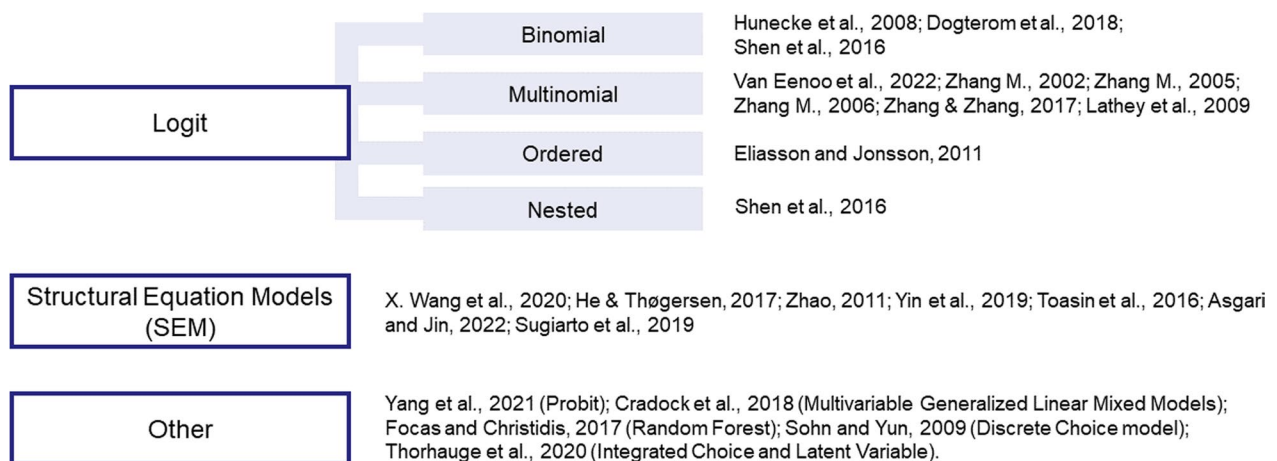


Fig. 2 Statistical models used in the micro approach

The micro approach also develops behavioural and perceptual issues, being closely related to the subjective car dependence operationalisation (see previous section). This makes individual or household analysis a usual choice for this point of view rather than territorial aggregations. In the latter case, emerging connections would not be so clear, as the person, being the respondent, is the primary source for micro approach data. Following that line, Behren et al. [8] took a completely disaggregated perspective: several car-dependent person clusters were obtained from their typical travel behaviour, involving patterns and possibilities, combined with perceptions on public transport autonomy or driving excitement. Other authors also explored the perception role of individuals' mobility necessities and externalities [33, 44, 86], as well as their attitudes towards different modes of transport [47].

Most of the micro publications correlate variables between them, usually modelling by different logit options or structural equation models, as Fig. 2 shows. This intrinsically assumes that the different car-dependent agents follow the same rationale to different inputs. This methodology could be arguable if the realities concerned within the models are different between them and variables that account for those differences are not present (for instance, correlating together a wide regional context, including metropolitan and isolated contexts). Such continuous basis has been tried to be overcome by some authors, who divided their analysis into different groups, such as car use frequency [90], car-dependent users [25] or health activity [23].

At the individual level, car dependence can appear from the preferences and attitudes of users, shaping their choices as their personal conditions do. The micro approach focus covers this phenomenon side using

disaggregated statistical units, requiring bigger efforts to gather information in broad extents, as the macro approach does.

3.2.3 Meso: car-dependent practices and activities

From Mattioli et al. [66] point of view, meso perspective accounts for the trip characteristic as the main subject of study. Certain activities are difficult to perform without a car, such as a vacation road trip, carrying voluminous bulks or escorting children to different activities. This insight relates those eventualities with the spatial and individual context, representing an intermediate position between the micro and macro approaches, usually mixed with both.

Most of the meso studies focus on the process of reaching the workplace [63, 98, 99], but also include the role of complexity and linked trips [86] or medium-long travel [60]. These studies include sharper detail in particular elements of the trips, such as the type of activity performed or the existence of errant detours.

In their typologies' organisation, [66] claimed that meso approaches were less conceptualised and researched. In fact, within the literature review, only six papers were considered to fit this approach. Although it could raise interesting insights, its specificity (to activity or practices) limits this research area.

4 Magnitudes related to car dependence

This section explores the quantitative assessment of car dependence in literature, building upon each paper's conceptual understanding of the phenomenon. Measuring car dependence, as a latent concept, relies on which magnitudes are associated with it. In physics, a magnitude refers to any measurable property of a system, and in this context, it expresses the different elements that

contribute to developing the phenomenon. This section examines how literature approaches this assessment from two perspectives: firstly, by examining the variables used to characterise car dependence; secondly, by exploring the correlations between these variables (i.e., which are the explanatory variables, through which dependent variables car dependence is modelled).

4.1 Car dependence dimensions from observed topics

From the analysis of the 64 selected publications, 583 entries are extracted for variables, which have been grouped into 39 different topics and six different dimensions for clarity purposes. Table 2 shows how they are organised within six car dependence dimensions, being the following: transport demand, transport supply, land use and form, accessibility, opinions and experiences, as well as socio-demographic factors. All together, they provide a conceptual framework for car dependence and represent its full complexity according to literature. The topics that form the dimensions are groups of similar indicators used in literature, encompassing magnitudes that academia has studied related to the topic in strict and broader terms.

4.1.1 Transport demand

This dimension involves topics that cover the use of different transport modes. Indicators that look at distance, time, purpose, or –to a lesser extent– rate of trips are grouped under the trip characterisation topic. Many of them focus on commuting, even if there are other examples framing errand or leisure activities [8, 86, 105]. Only one paper included an indicator of accidents, looking for the part involving active mobility users [54]. Automobile ownership is expressed homogeneously through the quantity of vehicles at the statistical unit (vehicles per person, vehicle rate per 1000 inhabitants). On the other hand, automobile use topic is mainly related to mileage (expressed as vehicle kilometres travelled at an amount of time, usually a year) and car-use frequency. At the same time, modal choice is typically a percentage or a dummy on the use of a particular transport option.

4.1.2 Transport supply

Picturing the possibilities on transport, this dimension mainly focuses on public transport network deployment, which involves a heterogeneous range of indicators. Public transport network in literature is principally characterised by the distance to the nearest public transport stop and the availability of rail-based services. However, some entries for service kilometres per capita and bus stop density are also common. Among other topics were transport costs (including automobile operating costs, gas prices or public transport fares), parking (density and

Table 2 Topics, dimensions and appearances in selected papers

Dimension	Topic	Appearances
Transport demand	Trip characterisation	54
	Automobile ownership	42
	Automobile use	28
	Modal choice	26
	PuT use	12
	Active modes use	6
	Driving license	4
	Congestion and speed	3
	Gas use	2
	Sharing and hailing use	1
Transport supply	PuT network deployment	32
	Transport costs	11
	Parking	10
	Road network deployment	4
	PuT performance	4
	Road expenditure	2
Land use and form	Density	30
	Urban morphology	23
	Built environment use	11
	Land use mix	16
	Urban structure	11
Accessibility	Amenities accessibility	43
	Jobs accessibility	11
Opinions and experiences	Transport perception and insights	17
	Automobile affinity	10
	Public transport affinity	7
	Automobile self-reliance	7
	Socio-ethical attitude	4
	Ecological concern	3
	Cycling affinity	2
Socio-demographic	Household structure	41
	Employment situation	23
	Financial situation	23
	Gender	20
	Age	20
	Education	8
	Dwelling situation	3
	Register and location	5
	Country-ethnicity	3

PuT Public transport

availability), and road network deployment (length of road per capita, mainly).

4.1.3 Land use and form

The main topic within this dimension is density, mostly addressed as inhabitants per squared kilometre, following Newman and Kenworthy [74] findings. Urban

morphology is also used from a higher variance of indicators, mainly regarding intersection density (quantity per square kilometre) over street density (metres per square kilometre) and the percentage of 4-way intersections over the total account. Built environment use accounts for building density and purpose, land use mix is related to an entropy-based measure on different land uses (coming from Cervero [21], according to Kockelman [53]) while urban structure topic characterises the statistical unit (distance to CBD,¹ district/municipality category, total population...).

4.1.4 Accessibility

This dimension is related to access to amenities and job opportunities, as potential public transport issues related to accessibility belong to the transport supply dimension. Accessibility to amenities includes a wide range of services and measures. This may include stores (supermarkets, convenience stores, groceries, clothes, durable goods...) as well as primary schools, banks, pharmacies or restaurants in most of the accessibility-related papers. Methods for measuring accessibility in academic research are varied and involve different procedures and points of view [37], posing additional challenges to the most suitable approach to this extent. It is treated from distance-related measures, population within a range or ratio of jobs accessible comparing different modes of transport.

4.1.5 Opinions and experiences

This dimension encompasses attitudes and perceptions of users regarding transport, taking into account preferences, capabilities or feelings. The most used indicator within it is transport perception and insights, including statements on transport externalities, necessities and assets such as mode comfort, safety, quality or supply. Affinity to automobile (symbolic value, convenience, purchasing intention, driving feelings) and public transport (feelings about autonomy, control, excitement, privacy...) also gain attention. Some papers ask about perceived or subjective car dependence, while socio-ethical attitudes (community belonging, openness to change, competitive attitude), ecological concerns and cycling affinity have less attention.

4.1.6 Socio-demographic factors

This dimension characterises society, being mainly focused on household structure, which encompasses different indicators: presence of children or elderly in the household, quantity of persons belonging to it or if it hosts a married couple, among others. Also, employment

and financial situations are approached, looking for job-holders, quantity of working hours, and income. Age and education level are also used in literature, while dwelling situation (rent price, house ownership), location, and ethnicity are approached less.

4.2 Correlations

Many indicators in the literature are related, as they seek to provide explanations for car dependence. These connections are categorised as correlations, meaning numerically and statistically significant relationships derived from the literature. 595 correlations have been found, 195 if only unique connections between topics are considered. In these correlations, dependent variables are the ones from which car dependence is inferred, while explanatory or independent variables show secondary factors related to the phenomenon. Figure 3 shows topics including variables considered dependent on car dependence: mostly modal choice, automobile use, automobile ownership and trip characterisation, which together account for 437 correlations. Therefore, inferences to car dependence in literature are made mostly from a transport point of view, while perceptions or territorial characteristics follow far behind, and socio-demographic variables do not account for the appearance of any dependent variable. These results are coherent with the findings in the operationalisation trends subsection.

The fact that there is no dependent variable involving socio-demographic dimension may be due to its more probabilistic than deterministic relationship with car dependence. Even so, these are among the most used variables, as Table 2 and Fig. 3 show. The latter explicitly shows how much household structure, financial and employment situation are used to explain automobile ownership, probably due to data gathering easiness, both in aggregate and individual terms. Also, automobile use and modal choice are related to socio-demographic factors. In fact, findings show that men, graduated, larger families (especially those with children), higher incomes and full-time employees, mainly highly qualified, are more likely to use or own cars [5, 12, 14, 47, 49, 63, 69, 79, 80, 87, 97, 101, 102, 107, 109]. Buehler [14] found that retired and under-age persons use cars less, while Shen et al. [80] showed that women prefer walking, bus and rail more.

Many other correlations follow Newman and Kenworthy [74] finding density as a relevant explicative variable for car-dependent related issues: it is mainly associated with a positive relation to car ownership [12, 87, 96, 97, 101], car mode choice [52, 78, 80, 106, 109], distance travelled by car [14, 22, 51, 68] and negatively to the feeling of being dependent of a car [109].

¹ CBD: Central Business District.

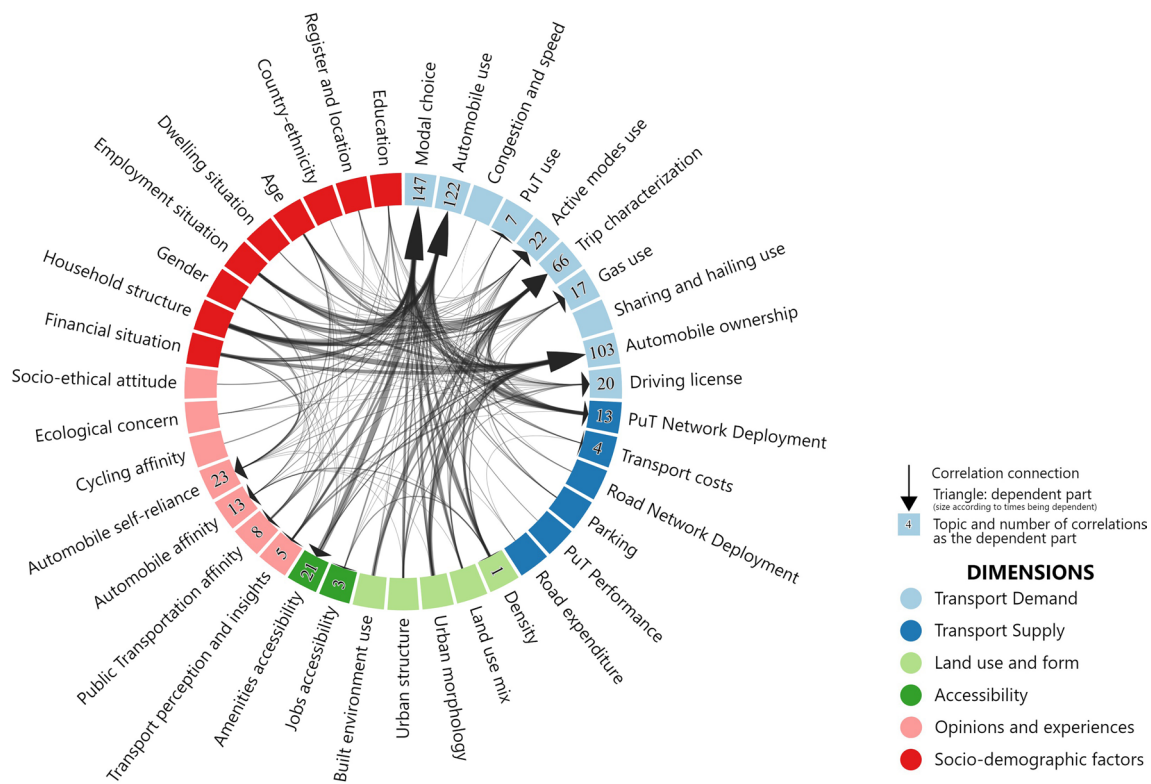


Fig. 3 Correlations found in literature. Source: own-created from literature review analysis through the Charticator app

Manauagh et al. [63] also explained higher commuting distance with certain land use kinds (higher in homes at waterfront, single family and train access areas and jobs in institutional and monofunctional places). Higher land use mix is also revealed as a way of fostering public transport and active modes use [80, 96, 106], while is negatively related to distance driven by car and automobile ownership [14, 31, 50, 102]. Also, urban morphology, from the density of street intersections, is related to less automobile ownership and less driving [31, 96, 97, 102, 107], while higher car ownership is explained by increased street widths [101] and lower percentage of 4-way intersection proportion [12].

Regarding accessibility, Elldér et al. [29] tested the relationship between many typologies of nearby amenities and lower car use, while Ewing and Cervero [31] show how distance to stores and higher walking choices are related. Zhang et al. [107] also found that retail and service facility density is one of the main automobile ownership predictors in Beijing. Langer et al. [54] found areas with lower employment, income and land value more likely to be car-dependent, understanding it as a factor depending on accessibility controlled by car ownership. Also, greater differences in outbound and inbound commuters, larger distances to the next town, and lower

shares of active mobility users involved in accidents were found to increase car dependence possibilities.

Better public transport supply is positively related to public transport use and walking choice [31], but also negatively to the choice of commuting by car [78, 101] or automobile ownership [50, 96, 101, 107]. Saeidizand et al. [78] found a positive correlation between congestion and car modal share, explained by car-oriented cities fostering traffic, even if unable to manage it. Meanwhile, less car-oriented cities, deploying less dedicated-infrastructure supply, induce less traffic.

Many of these correlations are well known and not only related to car dependence. However, accessibility correlations are widely concentrated in few papers and opinions and experiences factors are not so correlated, as Fig. 3 shows.

5 Discussion

Car dependence can be studied from the perspectives of different agents (territories, individuals, and practices), but it can also be framed considering different dimensions showing the causes and the effects of the phenomenon. Different understandings of car dependence have emerged during the analysis, proving that car dependence is a wide concept that raises interest in academia

from different fields. However, many publications pose car dependence as a baseline condition with no term conceptualisation, being this the reason for considering many papers out of scope. In other cases, the term is treated in a vague manner when used as an explanatory variable for different subjects. Those limited understandings can be overcome by the acceptance and diffusion of clearer theoretical frameworks, like car dependence agents or dimensions.

The different car-dependent agents show different realities within car dependence phenomenon. The meso approach still requires further research and remains a perspective linked to specific situations. It could give valuable insights regarding particular parts of trips, but hardly a wide picture of the phenomenon as macro and micro approaches do. Bridging the gap between those two is also crucial, as more individual perspectives (micro), mainly dealing with behavioural and perspectives, relate to a territory around pushing reliance on cars. To this extent, the macro approach, characterising territories and their relation with transport choices, roots widely with car dependence causes and allows broader territorial coverage.

The analysis has placed different dimensions explaining the complexity of assessing car dependence. From there, some challenges appear, as the need for stronger conceptualisation of some variables or easing their acquisition. In the case of transport supply, little attention is paid to speed, frequency, operation time, or range within public transport metrics. This might be due to the lack of available data, measurement difficulties and lack of homogenisation, showing a gap for improving its assessment, especially for different context comparisons. This recalls the complexity of the public transport system, made from several services on the operator side and different actions in the user one.

Accessibility and land use and form data present different challenges regarding defining its indicators. Land use and form indicators depend on how well sorted and the scale where built environment properties are available, which is not common in many contexts. Efforts on that side have been made by different studies on urban form [7, 22], proving that well-defined and sorted metrics result in identifiable magnitudes from data. Additionally, accessibility assessment can also be influenced by each context's socio-cultural background: not all the same services are organised equally in different contexts, and not every context necessarily relies on the same amenities. Such evidence has been raised recently from an EIT Urban Mobility report on 15-min cities [17], which shows different prioritisation of amenities according to citizens in five European cities.

Opinions and experiences also suffer the difficulty of getting the related variables in broader contexts as a standard method to collect that information does not exist. In addition, as the indicators are gathered through surveys, they are heterogeneous because questions vary in wording and intention from one survey to another. Even if they are more common in specific case studies, it is necessary to establish a common ground and harmonise them to overcome these issues. On the other hand, sociodemographic variables usually come from statistical data, mostly census related. While this allows its wide implementation and use, these factors have little impact on car dependence if considered separately from other dimensions. Socio-demographic factors then are relevant for explaining car dependence if correlated with other dimensions, so emerging potential car-dependent patterns can appear.

Indicators behind dimensions show reasons and rationales underlying the reliance on cars, but could be further developed. Socio-demographic ones or automobile ownership indicators, usually obtained from statistical sources, are compared to accessibility or certain land use variables. If car dependence quantitative assessment depends on the more easily reachable data, the risk exists for a partial explanation of the phenomenon. This requires advancements in homogenising criteria and simplifying data acquisition so a standard assessment can be reached, making it easier to spread the concept and its policy implications.

The six dimensions describing car dependence illustrate its multifaceted nature. However, while socio-demographic factors include more explanatory-like variables, other dimensions are treated in the literature from a more proxy-like point of view, as happens with transport demand. Comparing it with other dimensions, not every dimension relates equally to car dependence. For instance, large families with young kids are a factor that generates chances for car dependence [11, 105, 109], like low proximity accessibility contexts [29, 54, 98] or poor public transport service do [59, 68, 78]. Such circumstances often produce high car use or a strong personal attachment to automobiles, which, by themselves, are a likely manifestation of car dependence. Those examples, together with the correlation section results (see Fig. 3), allow conceptualising car dependence dimensions into two groups: causes (sociodemographic factors, land use and form, accessibility, transport supply) and effects (transport demand, car-ownership, opinions and experiences) of car dependence. This conceptualisation makes it clearer that partial perspectives can show different facts around car dependence, but they would fail to capture the whole picture of the phenomenon.

Literature also shows that an agreement does not exist when developing car dependence. However, some authors have proposed indexes for car dependence, which only partially cover the concept. Behren et al. [8] proposed a score on objective car dependence according to users' conditions and activities, weighing different criteria. H. Wang [95] introduced a score based on walkability and public transport accessibility. Akbari and Nurul Habib [2] created a car dependence index from car ownership and share of trips by car, similar to Cao and Hickman [19], who added commuting distance variable to the previous two. Asgari and Jin [5] also crafted a car-dependent latent variable from car use frequency, vehicle ownership and mileage, while van Eeno et al. [91] defined car dependence from public transport and amenities accessibility, creating a score for each hectare cell in the studied region. Langer et al. [54] also made a Car Dependence Factor from a ratio of car ownership and accessibility to opportunities, including both local points of interest (e.g. food, health, education) and public transport stations.

Most of the previous intents condense different variables but follow a partial understanding of car dependence, which is a usual outcome in reviewed literature. In order to bridge the different understandings, contribute to further research and conceptualisation, a car dependence definition can be introduced as follows: the combination of personal and contextual factors that prioritise car-based mobility over alternative transport and access options. This statement can provide an orientation towards operationalisation, avoiding prior preferences for a particular dimension or understanding.

6 Conclusion

The systematic literature review process, from the quantity and diversity of publications analysed, demonstrates car dependence as a spread concept, not exempt of underlying complexities. The application of car dependence in different academic disciplines, together with different understandings, also proves the term's popularity. Still, the work in this paper shows the need for a more robust conceptual framework to understand car dependence fully. As a contribution, this paper provides guidance for new research in this domain: on the one hand, from the outline of different operationalisation perspectives, and on the other, by the setting up of different dimensions for car dependence.

Standardising car dependence assessment and homogenising its indicators represent a challenge for enlarging its application. Within this discussion, selecting the car dependence agent represents a relevant decision. While each perspective (macro, meso, micro) provides valuable information, fully harnessing their potential requires

collectively considering all dimensions of the phenomenon. By doing so, the full complexity of the phenomenon becomes clearer and more practically useful, as its implications would lead to different fields. On the other hand, if looking for wider territorial application, the macro perspective remains the more direct way to use. Therefore, a strategy for future research is developing this perspective while addressing any gaps from individual dimensions, as well as overcoming information loss during the aggregation process.

In an era of substantial transformations in urban transport, it becomes highly relevant to promote a clearer conceptualisation and assessment of car dependence, helping to spread the concept. Recognising the far-reaching impact of car-based mobility, there is an increasing need to highlight these effects to achieve more sustainable and human-scaled settlements. This recalls how car dependence could also contribute to effectively addressing planning and mobility policy to reduce car-based mobility in a more context-sensitive approach.

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Jaime Sierra Muñoz worked on conceptualization, methodology, analysis, writing original draft and final writing. Louison Duboz worked on literature advice, supervision, review and final writing. Paola Pucci contributed with conceptualization, literature advice and supervision. Biagio Ciuffo contributed with supervision and review.

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