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On the ratios of urban mobility, Part 2:

Is street space a scarce resource for urban transportation? Physical model and a tale of five cities in France

Fabien LEURENT¹, Edwin RUALES & Rémy LE BOENNEC,
CIRED, Ecole des Ponts ParisTech, France

Abstract

Urban streets are laid out as longitudinal stretches of space and their width is split into sidewalks for pedestrians and lanes for vehicle running and parking. The specific width assigned to each function determines its flowing capacity. Considering the respective spatial footprints of modal vehicles, urban planners demonstrate that pedestrians and bikes use public space more efficiently than cars. Yet, traffic engineers and economists keep to modal trip flow rates as the key indicators of the streets' social utility. The article has a twofold objective first of unifying the respective measurements of planners and economists and, second, of investigating the urban conditions under which street capacity is a scarce resource. The first objective is achieved by relating vehicle spatial footprint to vehicular spatial concentration, and vehicle time-area footprint (TAF) to vehicular flow rate. At the link level the demand-supply ratios of TAF and trip flow rate are fairly equivalent. The second objective is addressed at the city level by modeling urban conditions both on the demand and supply sides of people mobility: on the demand side, population density, trip generation rate and average trip length per travel mode and per longitudinal axiality versus, on the supply side, the lateral, "way density" of longitudinal routes and their respective widths and lanes. The model is applied to five cities spanning the range of population density in urban France, considering their respective mobility parameters and street network geometry. It comes out that people density below 4,000 p/km² have some slack street space, hence no scarcity issue, whereas densities above 6,000 p/km² combined to typical street geometry require transit services on the ground and also underground beyond 10,000 p/km².

Keywords: Time-space consumption; Time-area footprint; Supply-demand ratio; Traffic variables; Way capacity; Urban planning

Highlights:

- Facing occupation concepts and measures of urban planners and traffic engineers
- multilevel model of street space occupation, from vehicle level to link level and up to city level
- time-area footprint of travel modes per functional unit of person.km or veh.km
- urban conditions depicted in terms of population density, mobility behavioral parameters and "way density" of link capacity and network geometry
- application instances to five French cities exhibiting population density sub-ranges of street space scarcity or not

¹ Corresponding author: fabien.leurent@enpc.fr

1/ Introduction

Background

From the 1950s onwards, the mass diffusion of cars in developed countries has entailed specific urban planning to accommodate car traffic and car parking on-street as well as off-street (Héran, 2013). It did not take long for urban planners and traffic engineers to recognize that car transportation requires more space per person than active modes and public transit (Smeed, 1961; Buchanan, 1963). In 1955, the Danish transit engineer Enjar Nielsen measured the elementary areas occupied by modal vehicles, then per occupant, and combined them with lane modal flows at capacity flow rate to predict the width of way (road or rail) required to accommodate a given number of passenger trips using either cars, buses or trains (UITP, 1959). The French engineer Louis Marchand (1977) provided an explicit model and encompassed traffic and parking requirements at the level of the activity tour of an individual, including the return trip and the sojourn in the destination place. Subsequent authors (Schmider, 1977; Vuchic, 1981; Beauvais, 1984; Bruun & Vuchic, 1995; Héran & Ravalet, 2008; Stransky, 2017; Drut, 2018; Will et al., 2020) applied the time-area concept at the level of (i) the vehicle footprint depending on its width, length and speed, (ii) the passenger tour, including travelled distance and vehicle occupancy. These works typically compare the car as a TA expensive mode to active modes and transit modes as TA economical modes, and devise recommendations for street sharing policies.

Yet, beyond the existence of mode-specific TA footprints, the key issue of street-sharing policies would be the relationship between the amounts of TA demand and TA supply. If the quantity of TA supply is much in excess of that of TA demand, then there is no scarcity issue (leaving the remaining economic issues of supply oversizing, of usage pricing etc). Apart from general statements, little evidence has been provided regarding the TA balance of demand and supply. Apel (2000) compared cities in Europe and the United States according to a set of indicators to apprehend mobility demand (city population, its spatial density, trip generation rates, modal split) and the supply of roadway space (the proportion of land space devoted to roadways). Nicolas et al. (2001) provided similar indicators for Lyons, the second French metropolis, distinguishing between the city central area, its inner and outer suburbs. Héran (2013) attempted similar calculations for the Paris metropolitan area and Cordier (2021) for 8 French cities. All of these calculations are incomplete since they lack, on the demand side, the average trip length, and, on the supply side, the width (hence the number of lanes) of the roads. Previous works therefore did not reach as far as demand-supply ratios, i.e., indicators of degree of usage that are the key performance indicators to apprehend the issue of resource scarcity. Shin et al. (2009) modeled the TA requirement of multimodal mobility at the city level and derived the corresponding minimum amount of roadway space – yet with no consideration of the actual capacity.

As noted by Bruun & Vuchic (1995), in parallel to the assessment of modal footprints at the trip level, the time-area concept has also been developed by spatial planners and traffic engineers to analyze pedestrian traffic and design pedestrian spatial elements. Fruin (1971) devised scales of Level-of-Service (LOS) for walkways and for waiting areas by relating traffic variables (pedestrian density in m² per person, walk speed, pedestrian flow rate in pedestrians per unit time and per unit of lateral length) to qualitative conditions of either moving or just standing. Fruin & Benz (1984) provided an evaluation methodology of time-

space both on the demand side and on the supply side, for applications to corners at street intersections and to crosswalks as two prominent instances where space may be scarce: their model outputs an average area per person at a given instant, which is tantamount to a TA per person (the method was stated more clearly by Benz, 1986, and Grigoriadou & Braaksma, 1986). The resulting value, depending on the application, determines the case LOS, which can then be compared to target values so as to inspire the allocation of space in designing pedestrian facilities. It is a systemic methodology (Romer & Sathisan, 1997) that has been embedded in the Highway Capacity Manual for pedestrian spaces on roadways (HCM, 2000) as well as in the Transit Capacity and Quality of Service Manual for pedestrian spaces in bus and railway stations (TCQSM, 1999). Many developments have made this stream a flourishing one, e.g. to develop Standard Pedestrian Equivalent (SPE) factors to depict pedestrian heterogeneity in a way mirroring the Passenger Car Equivalent (PCE) factors of various vehicle types in roadway traffic (Galiza & Ferreira, 2013); see Kadali & Vedagiri (2016) for a review of LOS in pedestrian research (traffic, safety). Overall, the pedestrian traffic stream of TA research is aimed to the local level and delivers demand-supply indicators as key outcome.

A third stream of TA research has recently emerged in environmental economics to assess the respective shares of transport modes in cities in two respects: first, the modal shares of people trips, second, the modal shares of street space. Arasan & Vedagiri (2010) applied a microsimulation model of heterogeneous traffic flow to assess the use of road space available in Indian cities: they found that, on the road considered and at a given level of service, bus users making 66% of all travelers were only allotted a 26% share of road space. Creutzig et al. (2020), aiming to assess the fairness of street space distribution, established 14 street space allocation mechanisms from 10 ethical principles and 3 normative perspectives on street space. In an application to 18 streets in Berlin, Germany, comparing the observed street space allocation and people usage with allocation mechanisms, they found that car users, on average, had 3.5 times more space available than non-car users (or 1.6 times without off-street parking). Lefebvre-Ropars et al. (2021) proposed a needs-gap methodology to assess the discrepancy between transportation supply and demand in Montreal's streets, Canada. Combining open and proprietary datasets, they found that the cyclists' share of passenger traffic, at 4.3% of observed p-km, was about four times the share of street space exclusively allocated to them. Similar considerations were contributed by De Gruyter et al. (2022) for the city of Melbourne, Australia, on the basis of street space measurements and multi-modal person counts at 57 different locations within 36 activity centers across the city. Comparing at the site level the modal shares among observed people to the respective modal spaces, they found that pedestrians with 56% share of multimodal trips could only avail themselves of the 33% of street space allocated to sidewalks. Their study also delivered some less expected results regarding specific street elements "oversupplied" in Melbourne: in particular, bike lanes (12% of space vs. 2% of trips), and shared general traffic bus lanes (42% of space vs. 29% of trips).

To sum up, the environmental economics stream takes a top-down approach to TA by going from space capacity at the upper, macro level to, at the lower level, micro TA available per individual user according to the travel mode. It goes opposite to the bottom-up approach of urban planners in the first stream, who first calculate individual, micro TAs before aggregating them as macro TAs. The second stream, that of pedestrian traffic engineering, integrates both approaches and delivers demand-supply indicators, yet at a local level,

whereas some works in the 1st and 3rd streams have addressed the city level.

In urban economic theory dealing with transportation, car transport is given much consideration as the major carrier of people and goods – alongside mass urban transit in the large cities (see e.g. Anas & Moses, 1979, Kilani et al., 2010). Space occupation is often considered in an indirect way only, through car flow rates and the related spatial densities of vehicles along roads: the spatial capacity of streets is basically measured as their flow rate capacities in number of passenger car equivalents (pce) per hour. Recent interest in the frame of the International Transport Forum has prompted a discussion paper by Yves Crozet (2020), who pointed out to the relationship between the micro TA and the speed-flow law of roadway traffic (similarly to Bruun & Vuchic, 1995), as well as a group report (ITF, 2022), stating that more space efficient modes should be given more street space compared to cars: related actions include the dedication of traffic lanes to buses or to bikes, as well as sidewalk enlargement to accommodate pedestrians better.

Article objective

This article addresses the following four research questions (RQs):

RQ1: Facing the two perspectives of urban planners and traffic engineers on street space occupation, what is the common basis, and how far does it extend? Is there some equivalency at a higher level or a fundamental difference?

RQ2: assuming some equivalency around a notion of time-area footprint (TAF), what are the TAFs of travel modes in the urban setting? What are the ratios of TAF magnitude between Walking, Cycling and Transit modes, on the one hand, and the car mode, on the other hand?

RQ3: taking street space as a supplied resource and considering urban mobility as a multimodal demand for space occupation, what are the fundamental features of supply and demand, and which parameters may be used to express them?

RQ4: Then, under which parametric conditions may the resource be a scarce one? More specifically, considering a range of conditions among French cities, under which sub-ranges is street space a resource either scarce or not?

To answer these questions, our study is based on elementary physics of vehicular traffic, first at the vehicle level, then at the level of a road link that can be parameterized to represent any instance of roadway from local streets to avenues, to arterial roads and up to motorways. On the supply side, the link width is a major factor since it determines the number and specialization level of lanes for the diverse modal kinds of traffic. On the demand side, along with the vehicle width and length, speed is an essential factor that determines TAF in two ways: first through the safety margin in front of the vehicle, second through the time spent by the vehicle on the link.

To address urban characteristic features at the city level, we model supply and demand in a simplified way, assuming spatial homogeneity of mobility demand in terms of population density, trip generation and spatial distribution, and also of transport supply represented as a grid network of homogenous links according to either axially (axial direction). The cumulated TAF according to the travel modes as used can then be faced to the amounts of spatial capacity as provided over time by the network links. We utilize the city-level model in two ways. The first way is an abstract, theoretical one: by casting the relation between supply

and demand into a mathematical inequality between two formulas involving their respective parameters, therefore enabling for theoretical interpretation and parametric analysis. The second way is an applied one, by making a numerical experiment to five cities spanning the range of urban population density in France.

Article structure

The main body of the article is structured in four sections. Section Two models spatial occupation from the vehicle to the link level: it brings together the considerations of urban planners and traffic engineers, before introducing the city-level model (the exogenous version of the Hoter model in Leurent, 2022). In Section Three, five instances of French cities exhibiting contrasted population densities are studied: after estimating the parameters of supply and demand, the reference situation is assessed, before simulating the effects on street space occupation of three scenarios of modal diversion. Section Four discusses the model assumptions and the numerical outcomes. Lastly, Section Five summarizes the study and indicates some directions of further research.

2/ Physical model and reference values

2.1/ Space occupation and the spatial density of vehicles

2.1.1 Vehicular static spatial footprint

A vehicle i with length and width sizes of ℓ_i and w_i , respectively, occupies an elementary area of surface $s_i = \ell_i \cdot w_i$. When the vehicle lies on this ground area, it occupies it in an exclusive way, making it its static spatial footprint.

2.1.2 Dynamic Vehicular spatial footprint: the first role of speed

To move at speed v along some trajectory, the vehicle requires (i) some additional width to avoid any contact with other vehicles or elements, turning width w_i in w'_i accrued by a small increment that increases with speed, say 20 cm at low speeds below 20 km/h, (ii) a safety margin in front of it, i.e., a front area that needs be void of any other occupation. The length of the safety area depends on the vehicle speed: assuming a reaction time of t_0 and an emergency deceleration rate of α , the safety length $\bar{\ell}_v$ stems from the following formula:

$$\bar{\ell}_v = vt_0 + \frac{v^2}{2\alpha}. \quad (1)$$

The reason is that during deceleration, instant speed $v_t = v - \alpha t$ decreases from v to zero depending on time t up to $t_1 = v/\alpha$: the travelled length amounts to $\int_0^{t_1} (v - \alpha t) dt = v^2/2\alpha$.

Thus the dynamic spatial footprint of vehicle i at speed v amounts to

$$\bar{s}_{i,v} = w'_i \cdot (\ell_i + \bar{\ell}_v) = w'_i \cdot (\ell_i + vt_0 + \frac{v^2}{2\alpha}). \quad (2)$$

Wherein: ℓ_i and $\bar{\ell}_v$ are measured in meters, $\bar{s}_{i,v}$ in m^2 , t_0 in seconds, v in m/s and α in m/s^2 .

2.1.3 From micro to macro: vehicular spatial density

a/ Vehicular spatial density

Along a road stretch of length L km, the number N_m of vehicles of mode m circulating in line gives rise to a spatial density (concentration) of $\rho_m = N_m/L$ vehicles per km.

The respective densities of distinct traffic lines or traffic lanes on the same roadway add up in a natural way. So do the vehicular densities of different travel modes. Spatial densities may also be considered for people, be they walking or using vehicles.

b/ The macro spatial footprint of independent vehicles

Vehicles of a single kind that run independently on a single line of circulation at about homogenous speed v yield an overall spatial footprint of $N_m \bar{s}_{i,v}$. Per km, the macro spatial footprint is denoted

$$\bar{s}_{m,v} = \frac{N_m}{L} \bar{s}_{i,v} = \rho_m \bar{s}_{i,v}. \quad (3)$$

It is measured in m^2/km .

c/ Platooning

Vehicles of similar dynamical abilities that circulate in line at homogenous speed can follow one another at headways smaller than the full safety length, which is only required by the leading vehicles. Any follower can reduce its headway to the distance required for reaction, which is the product $v \cdot t_0$ of reaction time t_0 and the current speed, that is, $\underline{\ell}_v = vt_0$. Then, a follower vehicle has dynamic spatial footprint of

$$\underline{s}_{i,v} = w'_i \cdot (\ell_i + \underline{\ell}_v) = w'_i \cdot (\ell_i + vt_0). \quad (4)$$

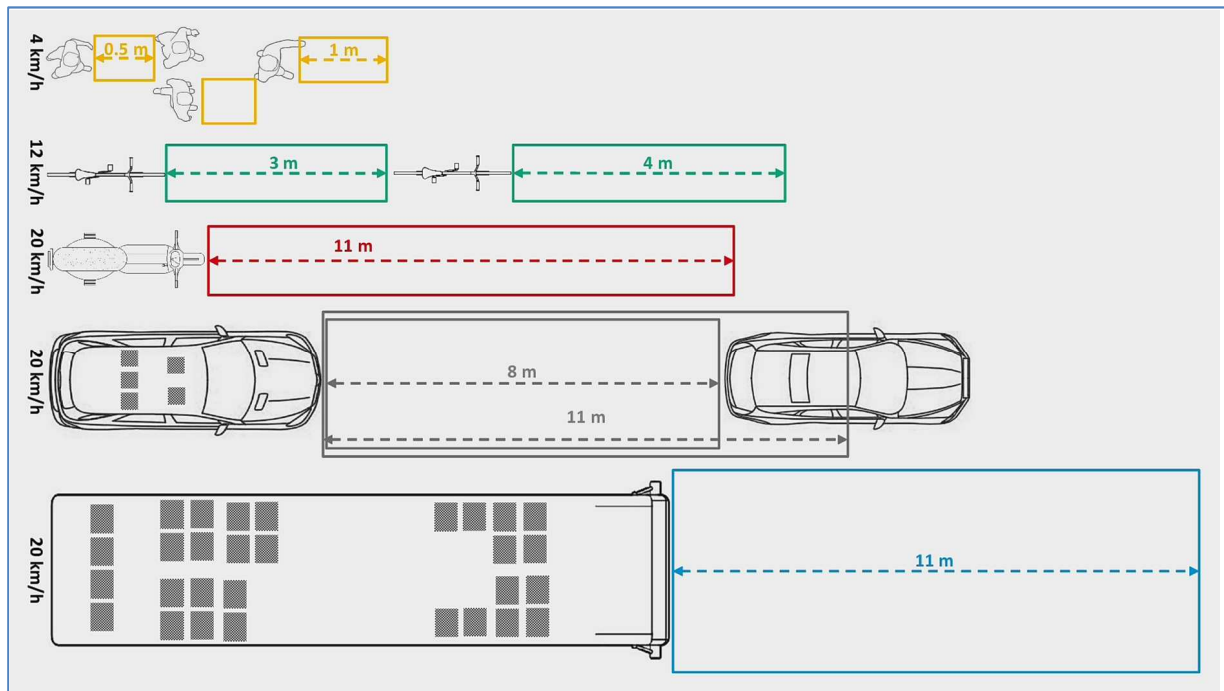


Fig. 1: Dynamic spatial footprints: vehicle types and front margins queued / independent.

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A follow-the-leader group of vehicles is called a platoon. It can also be seen as a moving queue.

Platooned vehicles give rise to a reduced spatial footprint: per km,

$$\underline{S}_{m,v} = \frac{N_m}{L} \underline{S}_{i,v} = \rho_m \underline{S}_{i,v}. \quad (5)$$

d/ Macro spatial footprint

Denoting as β the share of independent vehicles (including platoon leaders) and $1 - \beta$ that of follower vehicles in platoons, the average spatial footprint per vehicle amounts to

$$\hat{S}_{m,v}^{[\beta]} = \beta \bar{S}_{i,v} + (1 - \beta) \underline{S}_{i,v} = w'_m \ell_{i,v}^{[\beta]}. \quad (6)$$

Wherein: $\ell_{i,v}^{[\beta]} = \ell_i + vt_0 + \beta \frac{v^2}{2\alpha}$.

From this stems the macro spatial footprint per km of road stretch:

$$\hat{S}_{m,v}^{[\beta]} = \rho_m \hat{S}_{m,v}^{[\beta]} = \rho_m w'_m \ell_{i,v}^{[\beta]}. \quad (7)$$

As β belongs to $[0,1]$, the macro spatial footprint per km belongs to the interval $[\underline{S}_{m,v}, \bar{S}_{m,v}]$. Up to vehicle dynamic width w'_m and to a length factor that involves the share of independent vehicles, macro spatial footprint is proportional to vehicular density.

e/ Capacity values

At speed v , the maximum density of independent vehicles on a given lane would amount to $\rho_{m,v}^{\text{ind}} = 1000/(\ell_i + \bar{\ell}_v)$, with ℓ in m and ρ in veh/km. Yet the platooning effect allows for a maximum concentration of

$$\rho_{m,v}^* = 1000/(\ell_i + \underline{\ell}_v). \quad (8)$$

Vehicles circulating in line at speed v with density lower than $\rho_{m,v}^{\text{ind}}$ are mostly independent; but higher density indicates the occurrence of platooning.

The maximum spatial concentration is conditional to speed v . It induces a related maximal macro spatial footprint per km of

$$S_{m,v}^* = \rho_{m,v}^* w'_m (\ell_i + \underline{\ell}_v) = 1000 w'_m. \quad (9)$$

Wherein: S is in m^2 , ℓ and w in m, ρ in veh/km.

2.1.4 Modal values and multimodal comparison

At very low speeds, cars of average length between 4 and 5 meters can follow one another at say 2 m of headway, giving rise to $\ell_i + \underline{\ell}_v \approx 7$ m and $\rho_{m,v}^* \approx 150$ veh/km on a single lane. Under medium speed of 50 km/h (i.e. $v \approx 14$ m/s) and reaction time t_0 of 1.5 second, then $\underline{\ell}_v \approx 20$ m and $\rho_{m,v}^* \approx 40$ veh/km. At moderate speed of 20 km/h (i.e. $v \approx 5.5$ m/s), then $\underline{\ell}_v \approx 8$ m and $\rho_{m,v}^* \approx 75$ veh/km. Average car width of 1.6 m plus 10 cm margins on each side yield operational width of 1.8 m, hence spatial footprints from 9 m^2 (static) to 23 m^2 (dynamic, 20 km/h, queued).

Among pedestrians walking in line at 4 km/h (about 1.1 m/s), a reaction time of 0.5 s requires $\ell_v \approx 0.55$ m which adds up to say 0.35 m of “body depth”, taken as vehicle length, yielding a maximum concentration of 1,100 p/km. Average person width of 50 cm (Buchmueller & Weidmann, 2006) plus 10 cm margins on each side yield operational width of 0.7 m, hence spatial footprints from 0.2 m² (static) to 0.6 m² (dynamic, 4 km/h, queued).

Among cyclists riding in line at 12 km/h ($v \approx 3.3$ m/s), a reaction time of 1.0 s requires $\ell_v \approx 3.3$ m, which adds up to say 1.2 m of bike length to yield a maximum concentration of 220 veh/km. Average bike width of 60 cm plus 10 cm margins on each side yield operational width of 0.8 m, hence spatial footprints from 1 m² (static) to 3.7 m² (dynamic, 12 km/h, queued).

A traffic lane of say 2.5 m width can accommodate one car at most at any point along it, while 3 pedestrians or 3 cyclists can move abreast on it. The resulting maximum spatial concentrations would be, respectively:

- Of cars at 20 km/h: 75 veh/km, making 75 persons/km if people drive in solo mode or 300 p/km if 4 seats are occupied in each car.
- Of bikes at 12 km/h: 3 channels each at 220 veh/km make 660 p/km.
- Of pedestrians at 4 km/h: 3 channels each at 1,100 p/km make 3,300 p/km.

Thus, considering maximum spatial concentration of people, soft modes have a clear advantage over the car mode.

2.2/ Time-area footprint and flow rate

2.2.1 Static TAF

A vehicle occupies an elementary stretch of space at any instant during a certain time length. For a vehicle resting on a parking spot during time $T_{i,0}$, the time-area consumption amounts to $\omega_{i,0} = s_i \cdot T_{i,0}$: it is the time-area footprint of the vehicle on a space where it rests. We call it TAF for short. It is the product of an area and a time.

2.2.2 Dynamic TAF: the second role of speed

To run along a length of L_a km at average speed V in km/h, the required time is $T_{i,v} = L_a/V$ (in hours) and the dynamic time-area footprint of an independent vehicle is

$$\bar{\omega}_{i,v} = \bar{s}_{i,v} \cdot T_{i,v}. \quad (10)$$

It is measured in m².h. From its definition, it satisfies that

$$\bar{\omega}_{i,v} = w'_i L_a \frac{\ell_i + \bar{\ell}_v}{v} = w'_i L_a \frac{1}{3.6} \left(t_0 + \frac{\ell_i}{v} + \frac{v}{2\alpha} \right). \quad (11)$$

Wherein: ω is in m².h, w and ℓ in m, L in km, V in km/h, v in m/s and t in s.

The TAF of an independent vehicle is thus a U-shaped function of speed, first decreasing then increasing, with turn point at $\hat{v} = \sqrt{2\alpha\ell_i}$ and related deceleration time of $\hat{t} = \sqrt{2\ell_i/\alpha}$.

Yet for a queued vehicle, the time-area footprint reduces to a decreasing function of speed:

$$\underline{\omega}_{i,v} = \underline{s}_{i,v} \cdot T_{i,v} = w'_i L_a \frac{1}{3.6} \left(t_0 + \frac{\ell_i}{v} \right). \quad (12)$$

Thus, speed exerts a second role that diminishes the occupation of space over time of a vehicle.

2.2.3 From micro to macro: vehicular flow rate relative to time

a/ Vehicular flow rate

The vehicles of a given mode m going through a link a during a period of H hours, in number of N_m , give rise to a flow rate (relative to time) of

$$q_m = N_m/H. \quad (13)$$

b/ Traffic conservation

By the traffic law of vehicle conservation along time and through space, the flow rate in veh/h, q_m , and the vehicle concentration in veh/km, ρ_m , are related to the speed in km/h, V_m , in the following way: $q_m = \rho_m \cdot V_m$. The proportion β of independent vehicles is the same in the flow rate as in the vehicular spatial density, since the specific proportions both stem from that in vehicle number N_m .

c/ Macro TAF

From the previous statements, the average TAF of a vehicle is the product of average spatial footprint and link time, $\hat{\omega}_{m,v}^{[\beta]} = \hat{s}_{m,v}^{[\beta]} T_{i,v}$.

Assuming that the N_m vehicles flow in a unit time duration of $1_H = 1$ hour, then, per km of road and per hour of flowing duration, the macro TAF of N_m vehicles is

$$\hat{\Omega}_{m,v}^{[\beta]} = \frac{N_m}{1_H} \hat{s}_{m,v}^{[\beta]} \frac{1}{3.6v} = q_m w'_m \frac{1}{3.6} t_{i,v}^{[\beta]}. \quad (14)$$

Wherein: $t_{i,v}^{[\beta]} \equiv \frac{1}{v} \ell_{i,v}^{[\beta]} = t_0 + \frac{\ell_i}{v} + \beta \frac{v}{2\alpha}$ is in s, Ω in m²h per km-h, w and ℓ in m, v in m/s.

It is a convex combination of the queued macro TAF $\underline{\Omega}_{m,v} = q_m \underline{\omega}_{m,v}$ and of its independent counterpart $\bar{\Omega}_{m,v} = q_m \bar{\omega}_{m,v}$ with respective coefficients $1 - \beta$ and β .

d/ Maximum flow rate and the effect of Right-of-way metering

At speed V , a maximum vehicle density of $\rho_{m,v}^*$ would induce a related, maximum flow rate of $q_{m,v}^* = V \rho_{m,v}^*$. Yet it is only feasible when the vehicles have right-of-way (RoW) at the head junction of their link. Denoting as γ the share of RoW during period time H , the maximum flow rate feasible on the link at speed V is $\kappa_{m,v,\gamma} = \gamma q_{m,v}^* = \gamma V \rho_{m,v}^*$. Under uninterrupted flow, i.e., $\gamma = 1$, function $\kappa_{m,v,1}$ is a bell-shaped function of speed, first increasing then decreasing, with peak value κ_m^* at some speed value V_m^* (typically around 70 km/h for cars on motorways). Under share γ of RoW, the overall maximum flow rate is $\gamma \kappa_m^*$.

e/ Maximum TAF values

The macro TAF formula (14) involves width w'_m times the product of flow rate q_m and of a term $t_{i,v}^{[\beta]}$ that is notionally an inter-vehicular time (IVT) – precisely, a lower bound on effective IVT. In fact, on average the effective IVT (in hours) is equal to $1/q_m$ if $\gamma = 1$ and more generally to γ/q_m hours, hence to $3600 \gamma/q_m$ seconds. Thus, under RoW share γ ,

effective values of macro TAF $\widehat{\Omega}_{m,v}^{[\beta]}$ in m².h per km-h will exhibit an upper bound of

$$\Omega_{m,\gamma}^* = 1000 \gamma w_m'. \quad (15)$$

f/ Demand-supply ratios and the feasibility issue

At speed V on a road stretch with RoW share of γ , a demanded flow rate of q_m may be compared to the corresponding flow capacity $\kappa_{m,v,\gamma}$, yielding demand-supply ratio $q_m/\kappa_{m,v,\gamma}$. Recalling that $\kappa_{m,v,\gamma} = \gamma V \rho_{m,v}^*$ and that $\rho_{m,v}^* = 1000/\ell$ which involves the inter-vehicular length $\ell \equiv \ell_i + t_0 v$, then $V \rho_{m,v}^* = 3600 v/\ell$ involves the inverse of the inter-vehicular time measured in seconds,

$$\frac{\ell}{v} = t_0 + \frac{\ell_i}{v}.$$

Thus, $\frac{1}{\kappa_{m,v,\gamma}} = \frac{1}{\gamma} \frac{1}{3600} (t_0 + \frac{\ell_i}{v})$, yielding that

$$\frac{q_m}{\kappa_{m,v,\gamma}} = \frac{1}{\gamma} \frac{q_m}{3600} (t_0 + \frac{\ell_i}{v}).$$

Dividing similarly the demanded macro TAF $\widehat{\Omega}_{m,v}^{[\beta]}$ by its upper bound $\Omega_{m,\gamma}^*$, we obtain a TAF demand-supply ratio of

$$\frac{\widehat{\Omega}_{m,v}^{[\beta]}}{\Omega_{m,\gamma}^*} = \frac{q_m}{3600 \gamma} (t_0 + \frac{\ell_i}{v} + \beta \frac{v}{2\alpha}) = \frac{q_m}{\kappa_{m,v,\gamma}} + \frac{\beta}{\gamma} \frac{q_m}{3600} \frac{v}{2\alpha}.$$

When the proportion of independent vehicles is negligible, then the demand-supply ratio of macro TAF is about equivalent to that of flow rate. Ratios in excess of 100%, though not feasible, still measure the quantitative relation between demand and supply. In numerical applications, we shall substitute maximum flow $\gamma \kappa_m^*$ for $\kappa_{m,v,\gamma}$ in the demand-supply ratio of flow rate, as a first approximation that gives a lower bound, and consider also the two TAF ratios $\underline{\Omega}_{m,v}/\Omega_{m,\gamma}^*$ and $\bar{\Omega}_{m,v}/\Omega_{m,\gamma}^*$ as lower and upper bounds respectively.

2.2.4 Modal values and multimodal comparison

Considering a link length of one unit, $L_a = 1$ km, then $\underline{\omega}_{i,v}$ and $\bar{\omega}_{i,v}$ refer to TAF on 1 km, hence during $1/V$ hours with V in km/h. At pedestrian speed of 4 km/h, people walking independently have safety headways of 1 m, yielding micro TAF of $1.3 \times .7 \times \frac{1}{4} = 0.22$ m².h.

The queued TAF is $0.9 \times .7 \times \frac{1}{4} = 0.16$ m².h per person-km.

Cyclists in number of one thousand riding at 12 km/h will be queued: the associated individual TAF is of $4.5 \times .7 \times \frac{1}{12} = 0.26$ m².h.

At car speed of 20 km/h, queued cars have an individual TAF of $13 \times 2.1 \times \frac{1}{20} = 1.3$ m².h – indeed five or six times that of soft modes. At speed of 50 km/h, the individual car TAF is of $26 \times 2.1 \times \frac{1}{50} = 1.2$ m².h at following,. Yet, with five persons occupying each car, the car TAF per person would be of 0.26 m².h at 20 km/h and of 0.24 m².h at 50 km/h. This would make fully occupied, queued cars roughly equivalent to walking and cycling with respect to time-area footprint per person-km, owing to the complex role of speed combined to the

platooning effect. But solo car users consume time-area about 5 times those of soft mode users, even considering the platooning effect. At speed of 20 km/h, assuming deceleration rate $\alpha = 5 \text{ m/s}^2$, emergency deceleration takes a time of 0.5 s and an additional length of 3 m, yielding independent vehicle length footprint of 16 m – 20% more than the queued one.

As for transit modes, let us consider a bus route with high frequency of 30 runs per hour to carry 1,000 passengers. Assuming that the buses are 12 m long and 2.3 m wide, neglecting the dwell times but accounting for full safety headways since the bus runs are independent, at speed of 20 km/h the modal footprint is of $(12 + 11) \times 2.3 \times \frac{1}{20} = 2.9 \text{ m}^2\cdot\text{h}$ per km, totaling to 87 $\text{m}^2\cdot\text{h}$ for the full flow of passengers and yielding TAF per p.km of 0.087 $\text{m}^2\cdot\text{h}$ – indeed the most economical mode in TAF per person-km. Adding the static TAF of bus stops does augment the bus TAF per km only marginally: assuming 2 stops per km, each of 20 s, the 30 m^2 of static space occupation during 1/90 h make 0.33 $\text{m}^2\cdot\text{h}$ per bus.km – about 12% of the dynamic footprint.

Conversely, under light passenger occupation e.g. of 5 passengers in the bus at evening hours, the modal footprint per passenger-km raises to $3.2 \text{ m}^2\cdot\text{h} / 5 = 0.6 \text{ m}^2\cdot\text{h}$, making it half that of queued solo cars and twice that of queued cars occupied by 4 persons each.

2.3/ At link level: street layout and specific indicators

2.3.1 Link layout

As a link is purported to cross space, it is basically a longitudinal object so that vehicles can go along it. The length of a link indexed by a , denoted L_a , is a factor both of vehicular TAFs and of time-area supplied by the link. In the lateral dimension, the link width is the basic resource of its layout in one or several longitudinal bands. Urban streets typically have sidewalks for pedestrians at both ends of their widths, way bands in one or two directions of flow in the middle part, and possibly parking bands between the way bands and the sidewalks. The notion of lane is associated to vehicles following one another, be they parked or moving: the lane width matches that of the targeted vehicles, up to some margin. In general, at least one generic flow lane is designed to accommodate large vehicles such as fire brigade trucks, garbage collection trucks, removal trucks etc. While a so-designed lane can accommodate at most one car in its width (²), it may be used abreast by 3 or 4 pedestrians or cyclists.

2.3.2 Performance indicators at the lane level

A general purpose way lane in one direction of flow has traffic capacity of two kinds: the maximum spatial density of vehicles along it, versus the maximum flow rate. The latter is relevant to the flowing function, while the former addresses the parking function. When estimated as an equivalent number of passenger car units (pcu), the maximum flow rate of an uninterrupted motorway lane is about 2,000 pcu/h (HCM, 2000). Yet in the urban setting most lanes have their flow interrupted by traffic signals at their head junction: the share of right-of-way per signal cycle applies multiplicatively to the uninterrupted flow capacity. Thus, a 40% share yields lane flow capacity of 800 pcu/h.

A primary indicator of flow performance at the lane level is thus the flow rate in pcu/h, and

² i.e. not 2 cars, yet possibly one car and one bike

the ratio between it and the nominal flow capacity. Large vehicles such as buses and trucks typically represent 2 or 3 pcu each. Two-wheel vehicles notably bikes are graded at 0.3 pcu. Then, average vehicle speed makes a second indicator of flow performance: it represents quality of service to users within the frame of local regulations.

2.3.3 Parking lanes

The parking space required by a vehicle roughly matches its spatial footprint – up to some spare room around the vehicle to enable maneuvers to move in and out of the spot. The parking times exhibit large variations between vehicles and depending on places. A local average time may be used to calculate an average parking TAF per type of vehicle.

The basic indicator of parking occupancy is the average share of busy time among parking slots making a parking lot. Yet parking productivity is better measured by the number of vehicles that use the parking lot during a period, and the related average number of vehicles per parking spot.

The parking capacity of a link is null in the absence of dedicated lanes. Otherwise, by parking lane the parking capacity involves the longitudinal stretch of space available for parking, divided by an average vehicular spatial footprint.

2.3.4 Sidewalks as pedestrian ways and lanes

Sidewalks are typically laid out as long bands of relatively homogenous width, bordered by buildings on one side and by park or way lanes on the other side. The sidewalk width is basically intended for the motion of pedestrians – other functions include the installation of urban furniture and sometimes of “convivial terraces”. Pedestrian motion may use a sidewalk in either direction of flow. The pedestrian width requires a specific channel that can be considered as a pedestrian lane, up to its alternate usage in either flow direction. A sidewalk width of at least 1.4 m allows for comfortable crossing of two pedestrians walking in opposite directions.

2.3.5 Mode-specific lanes

When the link width is sufficient, and where traffic flows are large, mode-specific lanes may be implemented. Bus lanes have broadly the same width as generic flow lanes, while cycling lanes are relatively narrow – typically between 0.7 and 1 m. Tram lanes are akin to bus lanes, though narrower on some routes owing to specific trains. The share of TA capacity is generally low for tram lanes, being constrained by railway signaling as well as by the operations of multimodal junctions, in addition to the dwelling requirements that also apply to buses.

For transit modes however, the primary indicator of productivity is the number of passengers, first per vehicle to be compared to its nominal capacity, then per link and time unit as a flow rate of persons.

2.3.6 Shadow TAF to attribute the time-area capacity to vehicles and persons

The TAF is a microscopic notion at the level of a vehicle or a person. At the link level, the calculation of a modal TAF on a given lane during a time period, by multiplying the vehicular TAF and the related flow volume, is a bottom-up approach to the occupation of the link time-

area resource.

A converse way of analysis may be devised that constitutes a top-down approach: considering a link time-area capacity, its attribution to its actual users will yield a quantity analogous to a TAF: let us call it a shadow TAF. By construct, a shadow TAF is larger than the vehicle-based TAF. The shadow TAF indicates the actual usage of the link over time – yet another look at its economic productivity.

2.4/ A supply-demand model at the city level

Physical models of space occupation and of TAF have been provided first at the micro level of one vehicle and one person depending on the transport mode, then at the macro level of vehicle and people flows along a link, in relation to macro traffic variables of average speed, spatial concentration and flow rate. We also emphasized the maximum values, i.e., capacities, of link lanes to contain and flow vehicles and people using the main modes of urban transportation. Now, coming to the city level, the objective is to model the quantitative relation between the TAF of people mobility and the flowing capacity of the roadway network, taking into account not only the assignment of links to multimodal functions but also the density of links in the urban space: the “way density”. In the following, we adapt the Hoter model of Leurent (2022) to our purpose.

2.4.1 Multimodal roadway network and its spatial, way densities

In the Hoter model, the roadway network is idealized as a bi-dimensional grid with two axial directions (axialities): x ' x and y ' y that may be thought of as East-West and North-South. Along each axiality $z \in \{x, y\}$ taken as longitudinal direction, there are parallel routes each at distance L_{-z} of its neighbors, yielding a lateral density of $1/L_{-z}$ routes per distance unit along the other axiality $-z$.

Each route has usable width W_z , out of which W_z^S for sidewalks, W_z^P for parking lanes and W_z^G for generic vehicle flow. Denoting the width of pedestrian channels, of parking lanes and of way lanes as λ_S , λ_P and λ_G respectively, the corresponding number of lanes per route are of $\varphi_z^{(i)} = W_z^{(i)}/\lambda_i$ by function $i \in \{G, P, S\}$. Taken together, the longitudinal routes supply functional widths of $W_z^{(i)}/L_{-z}$ and lane numbers of $\varphi_z^{(i)}/L_{-z}$ as spatial densities with respect to the lateral direction. These are collectively designated as “way densities”.

Owing to spatial homogeneity, any lateral cut of space with unit width $1_L = 1$ km is traversed by $R_z = 1_L/L_{-z}$ longitudinal routes indexed by r , with respective lane number $\varphi_{z,r}^{(i)}$ by function i . For that function across the cut, the total number of lanes is

$$\Phi_{m,z}^{(i)} = \sum_{r=1}^{R_z} \varphi_{z,r}^{(i)}.$$

It gives rise to a way density of $\Phi_{m,z}^{(i)}/1_L$ lanes per lateral km. Such way density is an intrinsic physical property of the urban space.

Considering now the flow rate of person trips using mode m on a z -link, denoted $q_{m,z}$, the R_z longitudinal routes traversing the lateral cut of space of unit distance width $1_L = 1$ km yield an aggregate flow rate in person trips of $R_z q_{m,z}$. The ratio $q_{m,z}/L_{-z}$ is the spatial density of person trip flow rate in the longitudinal dimension. It is thus another intrinsic physical

property of mobility in the urban space.

2.4.2 Mobility demand and the time-area density of generated traffic

In the Hoter model, the urban space is postulated homogenous with population density of δ_X . An area of surface A contains $\delta_X \cdot A$ residents. Individual mobility on a daily basis is represented by trip number μ_σ per person according to demand segment $\sigma = (p, m, h)$ in terms of activity purpose p , travel mode m and time period h of duration H . Furthermore, by segment σ the average distance travelled along axiality z is denoted $D_{\sigma,z}$. The trip generation rate per person and time unit is $\dot{\mu}_\sigma = \mu_\sigma/H$.

Thus, during period h , area A generates by mode m and axiality z a traffic quantity (travelled distance summed over people) of

$$Q_{m,z} = \delta_X \cdot A \cdot \dot{\mu}_m \cdot H \cdot D_{m,z}. \quad (16)$$

The demand indicator $Q_{m,z}/(AH) = \delta_X \dot{\mu}_m D_{m,z}$ is the area density and time rate of person traffic (in p-km) generated on mode m along axiality z . It is thus an intrinsic property of mobility in the urban space, hereafter denoted as

$$Y_{m,z} \equiv \delta_X D_{m,z} \dot{\mu}_m. \quad (17)$$

2.4.3 The usage relationship between supply and demand

Assuming finally that the city is sufficiently large to contain the major parts of its trips paths and that there is symmetry between urban areas of identical shape and surface, then, by area, its generated traffic and the traffic carried out by the local transport supply are equivalent. A block delimited by roadway links according to both axialities, with $A = L_z \cdot L_{-z}$, generates an amount of z -longitudinal traffic equivalent to that carried out by each of its z -edge links (since each link borders two blocks): as $q_{m,z}$ denotes the trip flow rate on a such link,

$$q_{m,z} H L_z = Q_{m,z} = L_z L_{-z} H Y_{m,z}.$$

Simplifying, we obtain the bidirectional trip flow rate on every longitudinal link:

$$q_{m,z} = L_{-z} Y_{m,z}. \quad (18)$$

Furthermore, at the more abstract level of a spatial cut of unit width 1_L in the lateral dimension, we obtain a balance relation of trip flow supply and demand:

$$\frac{q_{m,z}}{L_{-z}} = Y_{m,z}. \quad (19)$$

Thus, the supply-demand balance of longitudinal trip flows is stated as an intrinsic physical property of the mobility phenomenon in the urban space. This usage relationship matches the way density of trip flow rate, on the supply side, to, on the demand side, the product of people density δ_X , trip generation rate $\dot{\mu}_m$ and average longitudinal distance $D_{m,z}$.

2.4.4 By link and mode: usage quantity and traffic variables

Denoting as $\tau_{m,z}$ the average number of occupants per m -vehicle (occupancy rate), the vehicular flow rate of mode m on a z -link is

$$\tilde{q}_{m,z} = q_{m,z}/\tau_{m,z}. \quad (20)$$

Recalling the lane number $\varphi_{m,z}$ of mode m on a z -link, the vehicular flow rate per lane is simply

$$\tilde{q}_{m,z}^{(1)} = \tilde{q}_{m,z}/\varphi_{m,z}. \quad (21)$$

On generic way lanes utilized by multiple modes with passenger car equivalents of e_m per mode-specific vehicle, the equivalent flow rate in passenger car units amounts to

$$\tilde{q}_{G,z}^{(1)} = \sum_{m \in G} e_m \tilde{q}_{m,z}^{(1)}. \quad (22)$$

A modal flow $\tilde{q}_{m,z}^{(1)}$ is a demanded level of lane usage, which is faced to a nominal flow rate capacity of $\kappa_{m,z}$. The quotient $\tilde{q}_{m,z}^{(1)}/\kappa_{m,z}$ should be some share belonging to the 0-100% range, meaning that values below 100% are feasible whereas those above 100% are not – inducing local queues that would not vanish at the end of the traffic signal cycle during the period under study. Lastly, given an average modal speed of $V_{m,z}$, by the law of traffic conservation the vehicular concentration per lane of mode m on a z -link is

$$\tilde{\rho}_{m,z}^{(1)} = \tilde{q}_{m,z}^{(1)}/V_{m,z}.$$

2.4.5 Numerical values and parametric analysis

Let us apply the model in an idealized way, using both plausible values for most of the parameters and parametric analysis according to population density and way densities. Thinking of daily mobility in France, the average number of trips per person and per day is about $\mu = 4$. A two hour morning peak period encompasses 25% of trips, yielding $\dot{\mu} = 4 \times 25\% \times \frac{1}{2} = 0.5$ trips/(p-h). On assuming modal shares of 25-50% for Walking, of 25-65% for the Car, of 1-3% for the Bike, of 1-3% for the Moto, of 8-25% for public transit (including 8-10% on buses and 0-15% on trains), taking all modes from lower to upper values yields an interval of [60%,146%] which is not so wide around 100%. Furthermore, adding up the upper shares of all modes except the Car to the Car lower share, and conversely adding up the Car upper share and the non-car lower shares, yields “total shares” of 106% and 100% respectively.

Modal shares multiplied by $\dot{\mu}$ give the average number of modal trips per person and per hour during the period. As for axial trip lengths depending on the modes, halved modal trip lengths are considered with the plausible average values in km of $D_W = 0.5$, $D_B = 2$, $D_M = 3$, $D_C = 6$, $D_{SPT} = 5$ and $D_{uPT} = 7$ ³). Combining modal shares and modal axial lengths, on average per trip the Walk mode contributes 0.12-0.25, Bike 0.02-0.06, Moto 0.03-0.09, Car 1.5-3.9, Bus 0.4-0.5, Train 0-0.9. Then, the average axial length per trip has lower bound of 2.1 and upper bound of 5.9 km. The two alternative totals of “min car” and “max car” yield respective estimates of 3.4 and 4.5 km.

Taking a conservative estimate of 4 km as average axial length per person trip, the modal shares in travelled distances have lower and upper bounds of 3-6% for Walking, 0.5-1.5% for

³ sPT and uPT for Surface and Underground (rail) public transit respectively

the Bike, 0.8-2.3 for the Moto, 37-97% for the Car, 10-12% for the Bus and 0-26% for the Train.

On combining the modal axial distances with the vehicle occupancy rates of, respectively, 1.2 for cars, 17 for buses and 83 for trains, on average per person trip the axial vehicular distances amount to 1.25-3.25 of Car, 0.024-0.029 of Bus and 0-0.01 of Train (all in veh.km). Integrating further the passenger car equivalents of bikes (0.3), motorcycles (0.4) and buses (3.0), the respective pcu.km amount to 0.006-0.018 using the Bike, 0.01-0.04 using Motorcycles, 0.07-0.09 using the Bus. Thus, on average per person trip, the multimodal pcu.km has lower and upper bounds of 1.3 and 3.4. The alternative modal splits under “min car” and “max car” yield multimodal pcu.km of 1.4 and 3.3. All in all, the average axial pcu.km per person trip is bounded from above by $D_{pcu} = 3.5$ pcu.km.

Assuming lastly a flow rate capacity of 800 pcu/h per lane and an overall number of Φ longitudinal lanes per lateral km, the demand-supply ratio of flow rate is estimated as

$$\frac{\delta_X \dot{\mu} D_{pcu}}{800 \Phi} \approx \frac{1}{457} \frac{\delta_X}{\Phi}$$

It is less than 100% if $\delta_X \leq 457\Phi$. If $\Phi = 10$ then population density up to 4500 h/km² can flow below saturation. Taking a 25% margin, a density of population below 3300 p/km² can flow fluently.

An “all car” modal assignment would involve $D_{car} = D_C/1.2 = 5.0$ pcu.km. At $\Phi = 10$ then $\delta_X \leq 3200$ p/km² could flow below saturation.

3/ Application to five cities in France

To figure out some numerical values of street time-area allocation and occupation at the city level, the model was applied to five cities spanning the range of urban density in France. After introducing the cities and their respective parameters (subsection 3.1), a reference situation of morning peak is simulated for each of them, showing the influence of urban densities onto the demand-supply ratios of flow rate and time-area (subsection 3.2). Then, simple scenarios of modal diversion are designed and assessed in terms of street space occupation and also of shadow TAF (subsection 3.3).

3.1/ Five cities as contrasted instances of population density

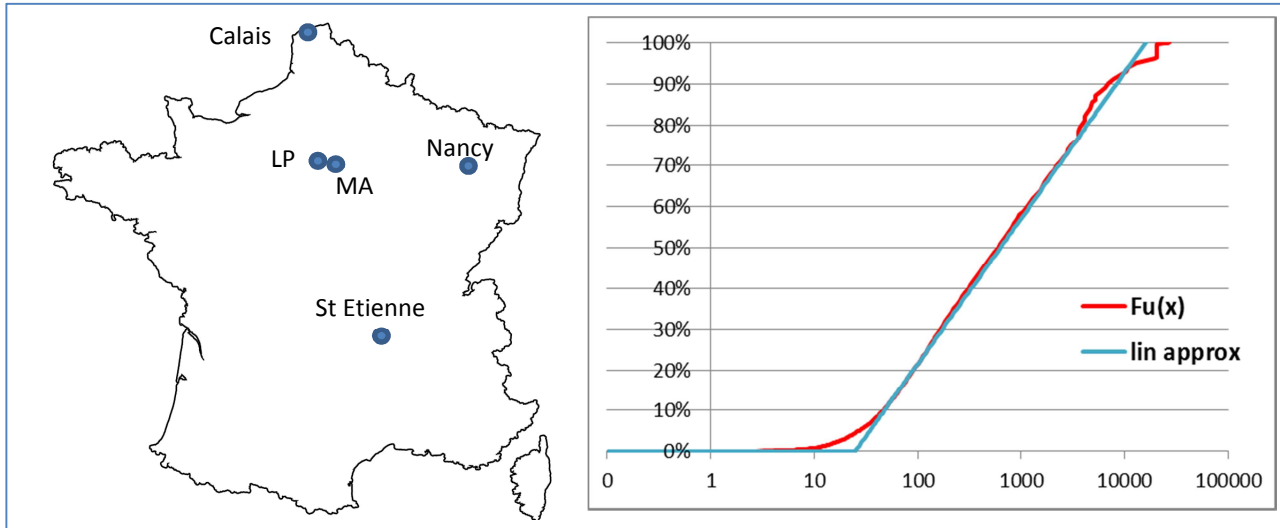
3.1.1 Selecting five cases of French cities

Metropolitan France stretches out over 550,000 km², divided into about 35,000 communes (or municipalities), yielding 15.6 km² as average commune area. France’s population of 67 M inhabitants as of 2021 would yield an average communal population of about 1,900 individuals and population density of 122 persons per km². Yet a majority of communes are rural ones, many of them with few inhabitants and very low density below 20 p/km². It turns out that 60% of French people live in communes of density below 1,200 p/km², 10% more people at density between 1,200 and 2,200 p/km², another 10% between 2,200 and 3,900 p/km², yet another 10% between 3,900 and 7,000 p/km², and the last 10% at communal density above 7,000 p/km² – most of them in Greater Paris (figure 2b).

Focusing on cities where street space may be scarce, we selected the five communes of

Calais, St Etienne, Nancy, Maisons-Alfort and Levallois-Perret – the latter two located within Greater Paris (figure 2a), so as to span the range from 2,000 to 28,000 p/km² (Table 1). City selection was also based on a second criterion of street network exhibiting regular geometry over a sampled square km. A third and last criterion was that of homogenous urbanization over a land stretch sufficiently large to contain most of people trips: to that end we dismissed about 60% of the St Etienne communal land that is only used as a green area.

Fig. 2: (a) Selected cities in France, (b) CDF of French population w.r.t. communal density.



Sources: (a) <https://www.pinterest.fr/pin/568298046711429455/> (b) Leurent (2022b).

Tab. 1: Cities, population and trip generation.

| City | Area (km ²) | Population (p) | Density (p/km ²) | Trips per person & day | Trips per km ² .h |
|------------------|-------------------------|----------------|------------------------------|------------------------|------------------------------|
| Calais | 33.5 | 67,544 | 2,016 | 3.88 | 978 |
| St Etienne | 31.2 ⁽⁴⁾ | 174,082 | 5,581 | 3.5 | 2,442 |
| Nancy | 15 | 104,403 | 6,960 | 3.7 | 3,219 |
| Maisons-Alfort | 5.4 | 57,639 | 10,674 | 3.5 | 4,710 |
| Levallois-Perret | 2.4 | 67,258 | 27,908 | 3.7 | 13,012 |

Sources: Insee, 2022; EMD 2014; EMC², 2021.

3.1.2 Demand side: mobility generation

Individual daily trip generation rates of about 3.5 on weekdays were obtained from Household Travel Surveys at the urban, regional or national level. Focusing on a 2 hour period of “morning peak”, most of the trips depart from homes under purposes of Work or Study. Thus, the local numbers of dwellers make the statistical basis of trip generation. The period was assigned a 25% share of all trips in the day – encompassing the home-to-work and home-to-study purposes. The resulting numbers of trips emitted per land and time unit are thus proportional to the city density, with factor of about one half.

⁴ After subtracting a large green area from the nominal communal area of 80 km²

3.1.3 Modal shares and trip lengths

The modal shares of trips made by city dwellers were taken on a city basis from publicly available Household travel surveys (Table 2). The car mode holds a prominent share that decreases with population density from 65% in Calais, to 50% in Nancy, down to 24% in Levallois-Perret. The Walk mode is important, too, and its share of trips increases with density from 24% to 46%. Bikes and Motorcycles have respective shares between 0.6% and 3%: both their shares are maximal in Levallois-Perret, likely so in connection with lower parking requirements than private cars. The overall share of transit modes is also increasing with density, up to 23% in both MA and LP, among which 2/3 and 4/5 respectively using underground rail modes.

Trip lengths are mode-specific: assigning one half of average trip length by axial direction in each city, the half lengths are about one half km at Walking, or 2 to 3 km using Bikes, versus 4 to 8 km on using motorized modes (Table 2). Conditionally to the travel modes, the average trip lengths are relatively homogenous between the cities.

A last indicator of modal usage is the average number of occupants per vehicle, depending on the mode. It enables to convert person trips and travelled lengths into their respective vehicular counterparts, and conversely.

Tab. 2: Mobility behavioral parameters.

| City | Modal shares in trips (%) | | | | | | Average trip length per axiality (km) | | | | | |
|------------|---------------------------|------|------|-------|------|-------|---------------------------------------|------|------|------|------|-------|
| | Walk | Bike | Moto | Car | Bus | Train | Walk | Bike | Moto | Car | Bus | Train |
| Calais | 24.1% | 1.8% | 1.2% | 65.5% | 7.4% | 0.0% | 0.5 | 2.7 | 2.0 | 5.8 | 2.3 | - |
| St Etienne | 28% | 0.9% | 1.6% | 62% | 5.4% | 2.1% | 0.51 | 1.9 | 5.1 | 5.03 | 3.75 | 4.09 |
| Nancy | 36% | 1.3% | 0.4% | 50% | 8.7% | 3.7% | 0.51 | 1.9 | 5.1 | 5.03 | 3.75 | 4.09 |
| MA | 40% | 2.0% | 1.0% | 32% | 8.2% | 16.8% | 0.4 | 2.7 | 5.8 | 6.25 | 5.48 | 7.9 |
| LP | 46% | 3.0% | 3.0% | 24% | 4.8% | 19.2% | 0.4 | 2.7 | 5.8 | 6.25 | 5.48 | 7.9 |

Sources: Insee, 2019; EMD 2014; EMC², 2021.

3.1.4 Supply side: street networks and way densities

The model postulate of homogenous roadway links along each axial direction is only satisfied on restricted parts of the cities: corresponding subareas of about 1 km² were taken as samples to represent the situation of their cities (figure 3). From careful examination of city maps using Google Earth, longitudinal axes were identified and measured out in terms of length and above all width, paying attention to the local assignment of link width to sidewalks, parking lanes, generic flow lanes and mode-specific lanes if any (Table 3).

In the cities under study, rail transit when available is either an underground mode that does not interfere with roadway space (up to pedestrian traffic for station access, which is neglected here) or a tramway mode using routes outside the sampled roadway sub-networks. We also neglected the role of motorways in carrying out car traffic, because of their limited extent in the respective urbanized areas: as the typical link length between interchanges is about 5 km, their way density is about 1/5 per km, making them carriers of minor interest with respect to the rest of urban roads.

Specific outcomes were obtained by city and axiality, yet with a couple of regularities. Per

Is street space a scarce resource for urban transportation?

lateral km, there are from 6 to 12 longitudinal routes (axes) – giving way density of 9 routes per km plus or minus 30%. Overall width varies from 65 to 129 m per lateral km, yielding way densities between 6.5 and 13%. Sidewalks, totaling 28 to 60 m of width per lateral km, represent almost 40% of way density. Generic flow lanes hold a similar share of width, with own way density of 4% on average. Parking lanes, each about 2 m wide, amount to 24 m of width per lateral km – about one fourth of the overall way width.

Although these figures vary significantly between axialities at the city level, the added width of both axialities does not vary much between cities. Thus, there is no obvious linkage between way density and population density at the city level.

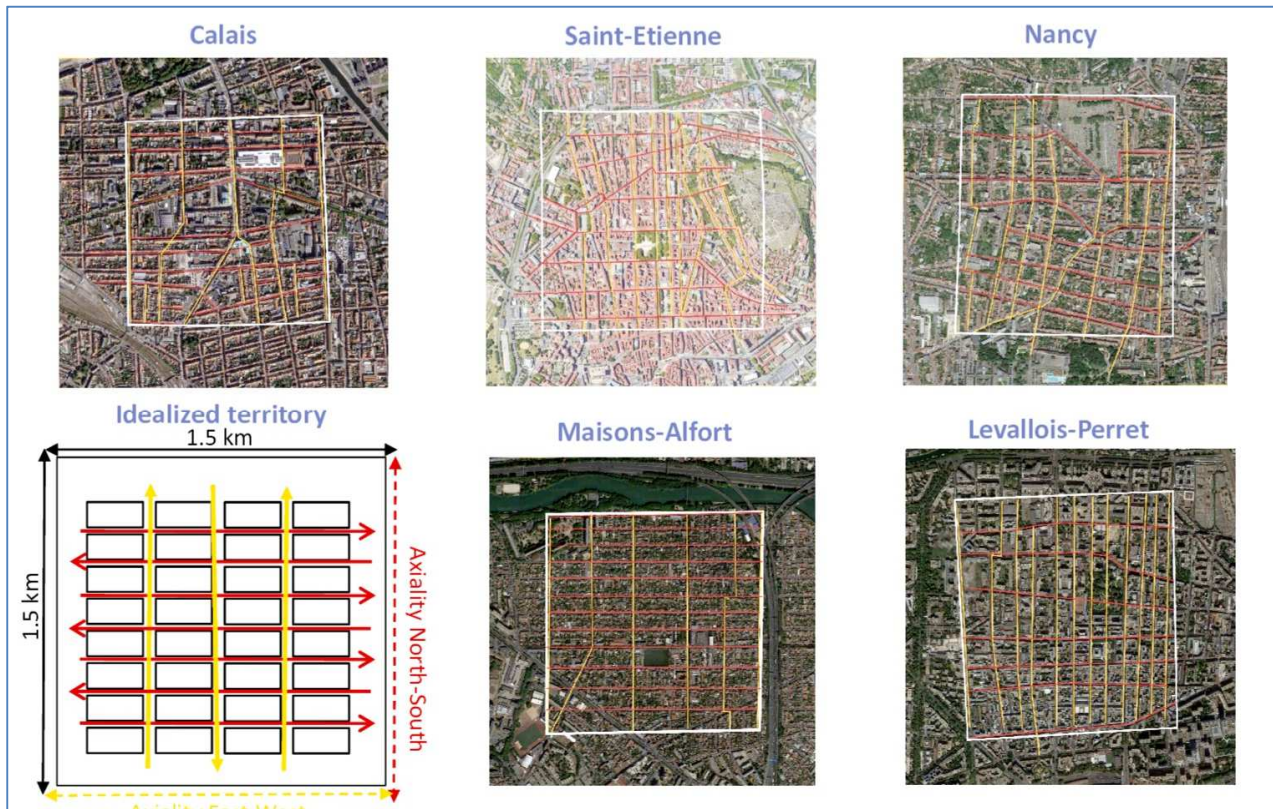


Fig. 3: Sample street sub-networks in the selected cities.

Tab. 3: Way densities in the sampled street networks (per lateral km).

| City & axiality | Longitudinal axes (#) | Total width (m) | Sidewalk width (m) | Parking lanes | Generic flow way width (m) | Generic flow lanes (#) |
|----------------------|-----------------------|-----------------|--------------------|---------------|----------------------------|------------------------|
| Calais, North-South | 8 | 84 | 34 | 10 | 34 | 11 |
| Calais, East-West | 12 | 119 | 48 | 13 | 48 | 14 |
| St Etienne, NS | 9 | 83 | 29 | 8 | 38 | 11 |
| St Etienne, EW | 8 | 74 | 28 | 15 | 24 | 8 |
| Nancy, NS | 8 | 99 | 36 | 16 | 31 | 9 |
| Nancy, EW | 8 | 97 | 34 | 11 | 41 | 11 |
| Maisons-Alfort, NS | 6 | 65 | 24 | 7 | 27 | 9 |
| Maisons-Alfort, EW | 12 | 128 | 47 | 14 | 53 | 18 |
| Levallois-Perret, NS | 12 | 145 | 60 | 19 | 47 | 15 |
| Levallois-Perret, EW | 7 | 74 | 28 | 9 | 28 | 8 |

Source: Authors' calculations using Google Earth as of mid-2023

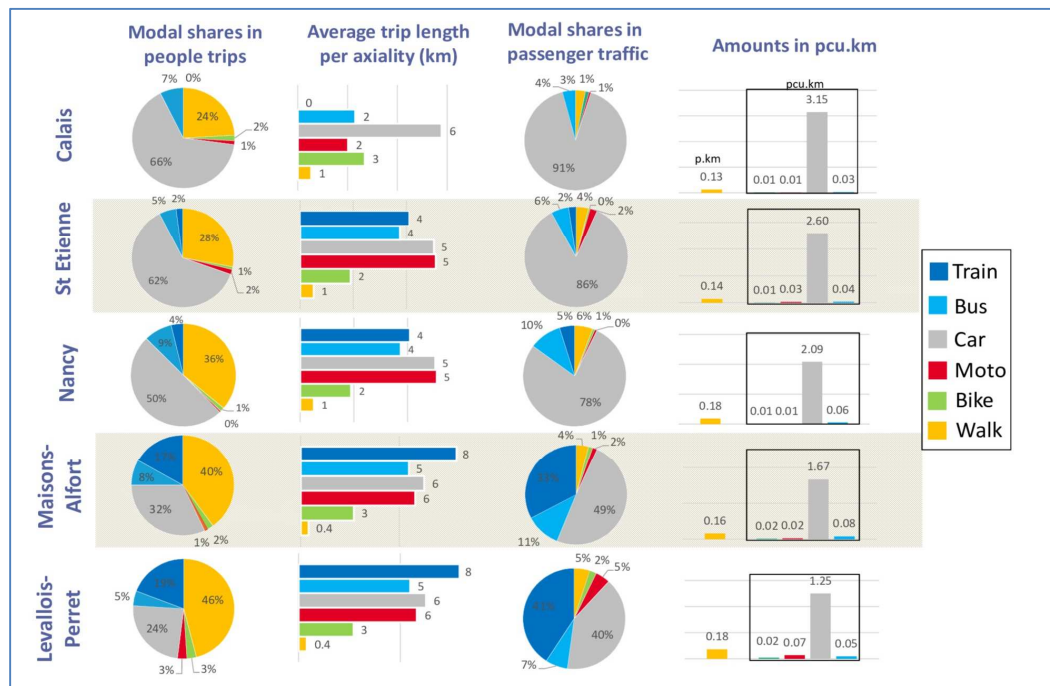
3.2/ Street time-area demand-supply relation: base case

Our study relies upon modeling assumptions as much as on parameter values summarizing the city conditions. The “base case” is a hypothetical situation of morning peak on an average weekday, facing a notional demand combining population densities as of 2021 with mobility behaviors taken from several household travel surveys made between 2010 and 2020, to a state of street network observed in 2023. Thus the “base case” has 2022 average year. Dealing with 5 cities and 2 axialities in each, there are 10 data points for each street-related indicator.

3.2.1 Traffic flows and average lane flow variables

Urban conditions of population density and mobility behavior generate traffic by mode and axiality. From the interplay of modal shares in people trips and of mode-specific trip lengths stem the modal shares of passenger traffic in p.km, proportionally to the modal lane flows. In less dense cities the car mode prevails very strongly, carrying up to 90% of traffic (Figure 4 & Table 4). Its share decreases with density, down to 40% in LP, owing essentially to the rise of transit modes from 1% to 50% of traffic. Walking has a minor share of traffic, varying between 3% and 6%. Mode-specific trip lengths make the cycling modes comparable to Walking regarding passenger traffic in Greater Paris, but not so in the other cities.

Fig. 4: Modal axial lengths and shares in (i) trips, (ii) passenger traffic.



Tab. 4: Modal shares in passenger traffic (p-km) and in equivalent car traffic (pcu-km).

| City | Modal shares in passenger traffic | | | | | | Shares in pcu.km | | | | Axial pcu.km |
|------------|-----------------------------------|------|------|-------|-------|-------|------------------|------|-------|------|--------------|
| | Walk | Bike | Moto | Car | Bus | Train | Bike | Moto | Car | Bus | |
| Calais | 3.1% | 1.2% | 0.6% | 91.0% | 4.1% | 0.0% | 0.5% | 0.3% | 98.3% | 0.9% | 3.20 |
| St Etienne | 3.9% | 0.5% | 2.2% | 85.5% | 5.6% | 2.4% | 0.2% | 1.2% | 97.3% | 1.3% | 2.67 |
| Nancy | 5.7% | 0.8% | 0.6% | 78.0% | 10.1% | 4.7% | 0.3% | 0.4% | 96.6% | 2.7% | 2.16 |
| MA | 4.0% | 1.3% | 1.4% | 49.4% | 11.1% | 32.8% | 0.9% | 1.3% | 93.4% | 4.4% | 1.79 |
| LP | 4.9% | 2.2% | 4.7% | 40.3% | 7.1% | 40.8% | 1.7% | 5.0% | 89.9% | 3.3% | 1.39 |

Source: authors' calculations.

3.2.2 Average lane flow variables

The area-time densities of generated traffic in person.km (per km² and per hour) are then assigned to street lanes as available to the mode, more precisely to lane length aggregated over the axial routes in the longitudinal dimension, itself in km per km² of land, yielding lane flow rate in p/h (Table 5). The spatial concentrations of modal passengers at any instant in the period follow by dividing the people flow rates by the respective modal speeds. Assuming Walk speed of 4 km/h, Bike speed of 12 km/h, Bus speed and Car speed around 20 km/h, the spatial concentrations vary from 3 to 75 p/km for pedestrians, from 0.3 to 11 bikes/km, 16 to 122 p/km in cars.

From dividing the lane person flow rates and spatial densities by the local average vehicle occupancy rate, stem their vehicular counterparts in veh/h and veh/km respectively (see Appendix). The car densities vary from 13 to 102 cars/km. Thus, cars are much more visible in the city streets than other modes – all the more so as their main competitor in traffic shares, namely rail transit when available, runs mostly underground in the Parisian instances.

Tab. 5: Lane bidirectional person flows: trip rates (p/h) and spatial concentration (p/km).

| City & axiality | Lane flow rates (p/h) | | | | | | Spatial density (p/km) | | | | | |
|----------------------|-----------------------|------|------|------|-----|-------|------------------------|------|------|-----|-----|-------|
| | Walk | Bike | Moto | Car | Bus | Train | Walk | Bike | Moto | Car | Bus | Train |
| Calais, NS | 8 | 4 | 2 | 328 | 15 | 0 | 2 | 0.3 | 0.1 | 16 | 1 | 0 |
| Calais, EW | 5 | 3 | 2 | 259 | 12 | 0 | 1 | 0.3 | 0.1 | 13 | 1 | 0 |
| St Etienne, NS | 19 | 4 | 18 | 692 | 45 | 19 | 5 | 0.3 | 0.9 | 35 | 2 | 1 |
| St Etienne, EW | 22 | 5 | 25 | 952 | 62 | 26 | 5 | 0.4 | 1.2 | 48 | 3 | 1 |
| Nancy, NS | 37 | 9 | 7 | 896 | 116 | 54 | 9 | 0.7 | 0.4 | 45 | 6 | 2 |
| Nancy, EW | 37 | 7 | 6 | 733 | 95 | 45 | 9 | 0.6 | 0.3 | 37 | 5 | 1 |
| Maisons-Alfort, NS | 63 | 29 | 31 | 1056 | 237 | 701 | 16 | 2.4 | 1.5 | 53 | 12 | 23 |
| Maisons-Alfort, EW | 32 | 14 | 15 | 528 | 119 | 351 | 8 | 1.2 | 0.8 | 26 | 6 | 12 |
| Levallois-Perret, NS | 100 | 70 | 151 | 1301 | 228 | 1316 | 25 | 5.9 | 7.5 | 65 | 11 | 44 |
| Levallois-Perret, EW | 171 | 132 | 283 | 2440 | 427 | 2467 | 43 | 11 | 14 | 122 | 21 | 82 |

Note: pedestrian flow per sidewalk. Source: authors' calculations.

3.2.3 TAF demand

From Section 2, at the assumed car speed the independent car TAF is only 20% more than the queued one, i.e., 1.6 m².h vs. 1.3 m².h on one km. Assuming independent walking but queued cycling and motorcycling (because of car traffic), the respective vehicular TAFs in m².h per person on one km are 0.48 for pedestrians, 0.35 for bikes, 1.1 – 1.3 by car occupant and 0.19 by bus rider under French average vehicle occupancy rate.

By km-h on generic flow lanes the overall TAF varies from 304 to 3036 m².h depending on city and axiality, among which 90+% come from cars. By km-h on sidewalks the pedestrian macro TAFs vary from 2 to 80 m².h.

Tab. 6: Lane bidirectional person flows: macro TAFs (per km.h) and demand-supply ratios.

| City & axially | Sidewalks | | Generic flow lanes: modal TAFs (m ² h) | | | | | | Flow rate | |
|----------------------|-----------|------|---|-----|------|-----|------|------|-----------|------|
| | TAF | D/S | Bike | M | C | Bus | All | D/S | Pcu/h | D/S |
| Calais, North-South | 4 | 0.4% | 2 | 1 | 383 | 2 | 386 | 39% | 278 | 35% |
| Calais, East-West | 2 | 0.3% | 1 | 1 | 302 | 2 | 304 | 30% | 219 | 27% |
| St Etienne, NS | 9 | 1.4% | 1 | 9 | 808 | 6 | 818 | 82% | 593 | 74% |
| St Etienne, EW | 10 | 1.4% | 2 | 12 | 1111 | 9 | 1125 | 112% | 816 | 102% |
| Nancy, NS | 17 | 1.9% | 3 | 4 | 1045 | 16 | 1052 | 105% | 773 | 97% |
| Nancy, EW | 17 | 2.0% | 3 | 3 | 855 | 13 | 861 | 86% | 632 | 79% |
| Maisons-Alfort, NS | 29 | 3.6% | 10 | 15 | 1232 | 33 | 1258 | 126% | 943 | 118% |
| Maisons-Alfort, EW | 14 | 1.8% | 5 | 8 | 616 | 16 | 629 | 63% | 472 | 59% |
| Levallois-Perret, NS | 45 | 4.5% | 25 | 75 | 1518 | 31 | 1619 | 162% | 1,206 | 151% |
| Levallois-Perret, EW | 77 | 9.6% | 48 | 142 | 2846 | 59 | 3036 | 304% | 2,261 | 283% |

Note: pedestrian flow per sidewalk. Source: authors' calculations.

3.2.4 Demand-supply ratios

The vehicular flow rates of the different modes using the generic flow way are aggregated using passenger car equivalents, in passenger car units per hour. The associated capacity amounts to 800 pcu/h per street lane with 40% of RoW at its head node. The ratio between the pcu flow and its capacity varies from 27% to 274%, mostly with increasing population density. Thus, in lower density cities cars can easily flow, street space is sufficient and still abundantly available. At middle values about 5000 – 7000 p/km², generic flow lanes are filled up at least along one axially, whereas at LP maximal density the demand-supply ratios reach 160% and 300%, i.e., considerably excessive loads. Put in other words, street space is scarce from densities beyond 7000 p/km², but not so below 5000 h/km².

Coming to TAFs, the maximum value per lane on one km during one hour is the product of the maximum vehicle dynamic width, that of buses at 2.5 m, and the RoW share of 40%, times 1 km, yielding 1000 m².h (see (15)). The time-area demand-supply ratios vary between 30% and 304%: they are quite similar to their flow rate counterparts.

On sidewalks the macro TAF demanded by pedestrians is faced to the product of sidewalk width by RoW share, times 1 km-hour. Among cities and axialities the product goes from 640 to 1000 m².h per sidewalk. The demand-supply ratios vary from 3‰ to 7%, meaning that pedestrians enjoy much free space for walking in all of the cities under study, at least in the morning peak period.

3.2.5 On shadow TAFs and lane flow productivity

Putting things in the other way round, the shadow TAF of pedestrians on sidewalks is calculated by aggregating the sidewalk widths of the longitudinal routes across the lateral cut, $\sum_{r=1}^R W_r^S$, by multiplying it by 1000 γ to obtain the maximum macro TAF in m².h (per km².h), and dividing the result by the generated pedestrian traffic that varies between 127 and 2400 p.km (also per km².h). The outcomes vary from 5 to 150 m².h per pedestrian-km: large to very large quantities indeed, indicating that the flowing productivity of sidewalks is low or very low in all five cities (Table 7).

On generic flow lanes, the width capacity of $\sum_{r=1}^R W_r^G$ in m per lateral km, times 1000 γ in longitudinal m-h per km-h, give rise to time-area capacity of 9 to 21 thousand m²h (per km².h). Dividing it by the people traffic in vehicles that goes from 4 to 26 thousand p-km (also per km².h), we obtain shadow TAFs of 0.4 to 5 m²h/p.km. Thus, the street space of generic lanes is used much more intensively than that of sidewalks: by one order of magnitude in the cities of higher density and by two orders of magnitude in those of lower density.

Tab. 7: Shadow TAF by city and axially: sidewalks vs. vehicle flow lanes.

| City & axially | Sidewalks | | | Vehicle flow lanes | | |
|----------------------|---------------------------------|---------------------------|------------------------------------|---------------------------------|-----------------------|------------------------------------|
| | TAF capacity (m ² h) | Pedestrian traffic (p-km) | Shadow TAF (m ² h/p.km) | TAF capacity (m ² h) | People traffic (p-km) | Shadow TAF (m ² h/p.km) |
| Calais, North-South | 13,500 | 127 | 106 | 13,500 | 3,932 | 3.4 |
| Calais, East-West | 19,048 | 127 | 150 | 19,048 | 3,932 | 4.8 |
| St Etienne, NS | 11,600 | 349 | 33 | 15,200 | 8,350 | 1.8 |
| St Etienne, EW | 11,200 | 349 | 32 | 9,600 | 8,350 | 1.1 |
| Nancy, NS | 14,400 | 593 | 24 | 12,400 | 9,257 | 1.3 |
| Nancy, EW | 13,600 | 593 | 23 | 16,400 | 9,257 | 1.8 |
| Maisons-Alfort, NS | 9,600 | 761 | 13 | 10,800 | 12,174 | 0.9 |
| Maisons-Alfort, EW | 18,800 | 761 | 25 | 21,200 | 12,174 | 1.7 |
| Levallois-Perret, NS | 24,000 | 2,394 | 10 | 18,800 | 26,256 | 0.7 |
| Levallois-Perret, EW | 11,200 | 2,394 | 5 | 11,200 | 26,256 | 0.4 |

Source: Authors' calculations

3.3/ Modal shift scenarios and their effects on street time-area occupation

3.3.1 Multimodal strategies and related scenarios

The allocation of street space to sidewalk, parking lanes, flow lanes either generic or mode-specific is a well-known action lever to manage urban mobility and orientate its modal split. Some evidence may be drawn from comparing the five cities under study: it appears that congested car lanes come along with increased modal shares of the Walk and Transit modes, and also of Cycling modes (bikes as well as motorcycles) in LP where car lanes are overloaded. Transit modes offer public transport to move people and achieve, through vehicle filling, scale economies in the utilization of production means including space occupation, therefore relieving street time-area occupation on car lanes – a positive externality to car users. Our objective here is to study, at the city level, the influence of alternative modal split on street time-area occupation. Alternative scenarios were designed as follows:

- 1) diverting all transit trips to the car mode, so as to measure the indirect usefulness of transit modes to car users,
- 2) conversely, diverting a significant share of car trips to transit modes in order to assess the consequence on lane occupation: a share of one fourth was considered,
- 3) diverting one fourth of car trips to the Bike mode,
- 4) diverting one fourth of car trips to Electric bikes.

Scenarios 1 to 4 keep to the allocation of street space in the Base case. Variants 3' and 4' of scenarios 3 and 4 additionally involve the reallocation of some generic flow lanes to bike lanes that can only be used by bikes, electric or not, but not by motorcycles.

3.3.2 A traffic conservation principle for modal diversion

A salient issue of modal split is the statistical population to which it applies: is it the set of people trips, or the traffic quantities in person-km? Modal shares in the latter case integrate the effect of mode-specific trip lengths, contrarily to their counterparts in the former case. At the city level, there are large discrepancies between the two alternative modal splits, as evidenced in the Base case simulation.

To make scenario assessment, if not fully traffic-behavioral, at least traffic-relevant, we designed a principle of length conservation through modal diversion as follows. Among trips using initially mode 1, with average length of \bar{D}_1 , a share p that would be transferred to mode 2 with average length of \bar{D}_2 would involve trips of suitable lengths on the alternative mode. Within the population of trips using initially the first mode, the rest of trips in proportion $1 - p$ have their own average length \bar{D}'_1 that makes up for the overall average:

$$p\bar{D}_2 + (1 - p)\bar{D}'_1 = \bar{D}_1. \quad (23)$$

Given \bar{D}_1 and \bar{D}_2 , the principle enables to infer the effect of modal diversion from the first mode at share p to the second mode onto the average length of trips keeping to the first mode, namely \bar{D}'_1 :

$$\bar{D}'_1 = \frac{1}{1-p}(\bar{D}_1 - p\bar{D}_2) = \bar{D}_1 + \frac{p}{1-p}(\bar{D}_1 - \bar{D}_2). \quad (24)$$

This rule is applied in Scenarios 1 and 3. In Scenario 2 there is an additional split between surface and underground public transit. As for Scenario 4, the diversion from Cars to e-Bikes is simulated on assuming that the average axial length of e-bike trips would be at the midpoint between the bike and car ones, 4 km say.

3.3.3 Sketch assessment of scenarios: modal shares

All scenarios have straightforward effects on the Car mode shares in passenger trips. Scenarios 2 to 4 divert one fourth of Car trips either to Transit or to Bike: the resulting shares in trips vary between cities depending on the respective initial share of trips using the Car mode (Table 8). Conversely, by diverting all transit trips to the Car mode, Scenario 1 gives it an overwhelming majority of p.km (around 90%), along with mode share in all trips comprised between one half and three fourths.

Scenarios 2 to 4 yield the same Car modal shares in trips but different Car modal shares in p.km, depending on the specific average lengths of the diverted trips. Scenario 2 augments the shares of transit modes both in trips and p.km consistently: very much so in Calais, much so in St Etienne and Nancy especially regarding the Bus share of p-km, not so much so in the Parisian instances where the respective initial shares are relatively low for the Car mode and relatively high for the Transit modes. Yet, taken together in MA and LP, the transit modes would reach 60% of the travelled distances.

Scenarios 3 and 4 augment the Bike share of trips to 9-10% in the Parisian instances and up to 14-18% in the other cities. Regarding Bike share in p.km, both scenarios have an increasing

effect: S3 yields share values between 7 and 12%, while S4 yields higher shares from 12 to 22%. These figures also apply in the variant scenarios S3' and S4' respectively.

Tab. 8: Modal shares in trips vs. in passenger traffic (p-km).

| City | S1: car issues | | S2-4 | S2: | Bus mode | | Train mode | | S3-4 | S3: p.km | | S4: p.km | |
|------------|----------------|-----------|------------|-----------|----------|--------|------------|-----------|---------------|-----------|------------|-----------|------------|
| | C in trips | C in p.km | C in trips | C in p.km | % trips | % p.km | % in trips | % in p.km | Bike in trips | Car share | Bike share | Car share | Bike share |
| Calais | 73% | 95% | 49% | 82% | 24% | 13% | 0% | 0% | 18% | 80% | 12% | 75% | 17% |
| St Etienne | 70% | 93% | 47% | 69% | 17% | 17% | 6% | 7% | 16% | 77% | 9% | 68% | 22% |
| Nancy | 62% | 93% | 37% | 63% | 17% | 20% | 7% | 9% | 14% | 71% | 8% | 62% | 20% |
| M-Alfort | 57% | 93% | 24% | 35% | 11% | 15% | 22% | 43% | 10% | 44% | 7% | 42% | 14% |
| L-Perret | 48% | 88% | 18% | 28% | 6% | 9% | 24% | 51% | 9% | 36% | 7% | 34% | 12% |

3.3.4 On lane flows

Leaving aside both the Rail mode that runs mostly underground and the Walk mode that is unaffected, the respective effects of the scenarios on lane flows depend not only on the modal shares in p.km but also on the number of longitudinal lanes per lateral km.

Scenario 1 increases the occupation of street time-area to a degree that depends on the city: modest in Calais (+2%) where the transit mode share is small in the Base situation, consistent around +10% in St Etienne and Nancy, leading to further overloading in one axially, and very important in the Parisian instances, in line with their important transit shares (Table 9).

Scenarios 2 to 4, on the contrary, relieve street occupation by substituting low TAF alternatives to a significant share of Car trips (25%). The magnitude of the effect involves the initial Car modal share as well as the mode specific axial length and the passenger occupancy and the passenger car equivalents per vehicle. Diversion to public transit in S2 or to e-Bikes in S4 is effective, all the more so as population density is higher; at the lowest density S4 is more efficient than S2, but the converse occurs above 10,000 p/km².

Between Scenarios 3 and 4 diverting one fourth of car trips to Bikes and e-Bikes respectively, S4 relieves street space occupation more than S3. In the related scenarios S3' and S4' that involve lane reallocation, relieves in car traffic (in veh.km per km²h) are often more than offset that the downsizing of generic flow lanes, then leading to higher lane occupation than in the Base Case.

The dedication of lanes to bikes in the primed scenarios was based on the following principle: from among about 10 longitudinal routes per lateral km in each city, four of them would be selected to design bidirectional bike paths on them, leading to about 8 one-way bike lanes, each available to 40% of the longitudinal bike traffic in its flow direction (figure 5). Such design of bike lane pairs may or not require reducing the number of generic flow lanes on some routes. Additionally, there are some large generic flow lanes that can each be split in two parts, namely less wide generic lane and a one-way bike lane. The route-specific outcomes, aggregated by axially and city, are reported in Table 10.

Bike lanes with 40% RoW may flow up to 1,000 bikes/hour each. The assigned bike flows would occupy that capacity at levels varying from 3 to 22% under S3' and from 4 to 30% under S4' owing to the farther outreach of e-Bikes. The related shadow TAFs vary from 1.4 to 15 m²h/p-km: they lie halfway between those of generic lanes and the sidewalk ones.

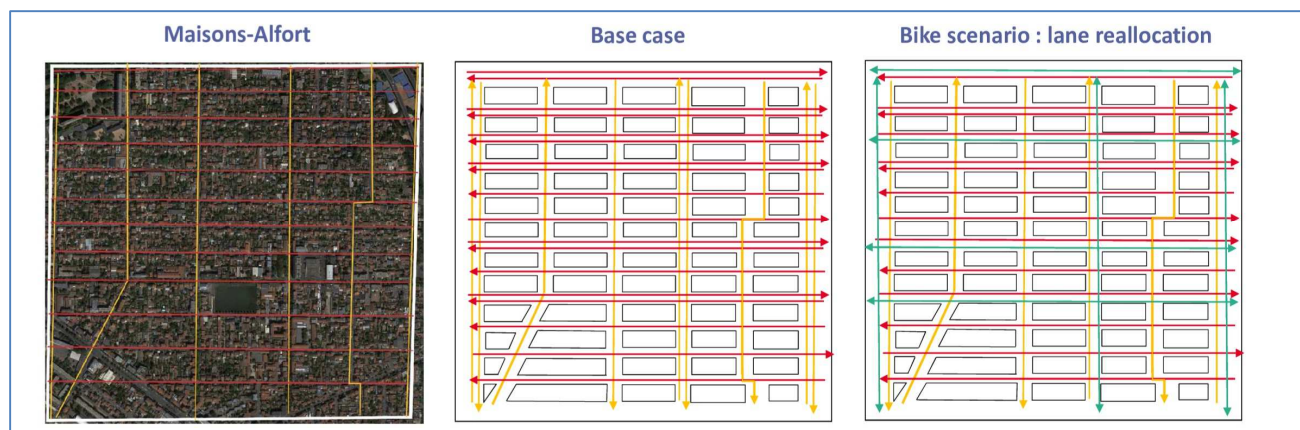


Fig. 5: Illustration of lane reallocation: the case of Maisons-Alfort.

Tab. 9: Scenario effects on lane demand-supply ratio of flow in pcu/h, with respect to Base Case.

| City & axiality | S1: PT 2 C | | S2: C 2 PT | | S3: C 2 B | | S3': C 2 B | | S4: C 2 e-B | | S4': C 2 e-B | |
|-----------------|------------|-------------|------------|-------------|-----------|-------------|------------|-------------|-------------|-------------|--------------|-------------|
| | D/S | ΔBC | D/S | ΔBC | D/S | ΔBC | D/S | ΔBC | D/S | ΔBC | D/S | ΔBC |
| Calais, NS | 37% | 2% | 33% | -2% | 33% | -2% | 52% | 17% | 30% | -5% | 46% | 12% |
| Calais, EW | 29% | 2% | 26% | -2% | 26% | -1% | 36% | 9% | 23% | -4% | 33% | 5% |
| St Etienne, NS | 80% | 6% | 62% | -12% | 70% | -4% | 85% | 11% | 60% | -14% | 73% | -1% |
| St Etienne, EW | 110% | 8% | 86% | -16% | 96% | -6% | 96% | -6% | 82% | -20% | 82% | -20% |
| Nancy, NS | 112% | 15% | 81% | -15% | 91% | -6% | 102% | 6% | 78% | -19% | 88% | -9% |
| Nancy, EW | 91% | 12% | 67% | -13% | 74% | -5% | 102% | 23% | 64% | -15% | 88% | 9% |
| MA, NS | 210% | 92% | 88% | -30% | 110% | -8% | 165% | 48% | 100% | -17% | 151% | 33% |
| MA, EW | 105% | 46% | 44% | -15% | 55% | -4% | 71% | 12% | 50% | -9% | 65% | 6% |
| LP, NS | 307% | 156% | 112% | -39% | 141% | -9% | 177% | 26% | 130% | -21% | 163% | 12% |
| LP, EW | 575% | 292% | 210% | -73% | 265% | -18% | 303% | 20% | 244% | -39% | 279% | -4% |

Tab. 10: Lane reallocation and the time-area productivity of bike lanes.

| City & axiality | Axiality layout | | | S3' | | | S4' | | |
|-----------------|---------------------|----------------------|-----------------------|------------------|-------------------|----------------------------------|------------------|-------------------|----------------------------------|
| | ex-post # gen lanes | Dedicated bike lanes | # lanes used by bikes | Bikes/h per lane | D/S on bike lanes | Shadow TAF m ² h/p-km | Bikes/h per lane | D/S on bike lanes | Shadow TAF m ² h/p-km |
| Calais, NS | 7 | 8 | 15 | 32 | 3% | 12.6 | 46 | 5% | 8.7 |
| Calais, EW | 10 | 8 | 18 | 27 | 3% | 15.1 | 38 | 4% | 10.5 |
| St Etienne, NS | 9 | 8 | 17 | 45 | 5% | 8.9 | 92 | 10% | 4.4 |
| St Etienne, EW | 8 | 8 | 16 | 48 | 5% | 8.4 | 97 | 10% | 4.1 |
| Nancy, NS | 8 | 8 | 16 | 53 | 6% | 7.6 | 105 | 11% | 3.8 |
| Nancy, EW | 8 | 12 | 20 | 42 | 4% | 9.5 | 84 | 9% | 4.8 |
| MA, NS | 6 | 12 | 18 | 71 | 8% | 5.6 | 99 | 11% | 4.0 |
| MA, EW | 14 | 16 | 30 | 43 | 5% | 9.3 | 59 | 6% | 6.7 |
| LP, NS | 12 | 12 | 24 | 132 | 14% | 3.0 | 174 | 19% | 2.3 |
| LP, EW | 7 | 8 | 15 | 211 | 22% | 1.9 | 278 | 30% | 1.4 |

4/ Discussion

4.1/ Concepts: the quantity & productivity of space as a resource

4.1.1 Footprint concepts and fruitful distinctions

A stretch of space accessible to people and their vehicles makes an obvious resource for occupation along time. We have considered the static footprint of a vehicle, depending on its length and width, and also its dynamic footprint that also involves its speed. The static footprint is relevant for vehicle parking, hence for the parking function of space, whereas the dynamic footprint is relevant for vehicle running along a trajectory, hence for the flowing function of space.

In either function the time length of space occupation by the vehicle is a basic factor of time-area occupation, which we have called the time-area footprint, in short the TAF. Vehicle speed is a complex factor of the dynamic TAF as it exerts a twofold influence: first, an increasing influence on the safety headway, second, a decreasing influence on the occupation time. Thus, vehicle speed is a major productivity factor of space as a resource.

We have refined the TAF concept in two ways: first, by devising the TAF per person-km as a basis to compare travel modes, second, by distinguishing between the “running regimes” either independent or queued. The queued TAF is smaller, having a reduced safety headway that just involves the user reaction time, not the emergency deceleration time.

4.1.2 Relationship to traffic variables

The independent vs. queued distinction is essential to relate the notions of spatial footprint and TAF, which belong to the field of urban planning, to the traffic variables that are familiar to transportation engineers. In the queued case, and up to the widths of vehicle and lane, spatial footprint corresponds to vehicle headway, while the TAF corresponds to inter-vehicle time. These correspondences at the micro level of the vehicle extend to the macro level of vehicle flows and the related macroscopic traffic variables: aggregated spatial footprint corresponds to the spatial concentration of vehicles, while aggregated TAF corresponds to the flow rate (relative to time).

4.1.3 On pictures comparing multiple modes according to space efficiency

It is thus easy to dismiss as fake images some pictures aimed to “demonstrate” the aggregate occupation of space by vehicles of different transport modes by exhibiting a given number of people, the number of the related vehicles depending on the mode and the vehicle spatial footprints on a stretch of road (e.g. a municipal campaign in 1989 for tramway development in the city of Strasbourg, as quoted by Héran, 2013). As those pictures emphasize the number of people using the roadway element by either mode, the relevant variable to compare the transport modes would be the people flow rate, not the spatial concentration at any instant. Yet it is the spatial concentration that would lend itself to a quasi-photograph of the traffic at any instant. A mode-comparing picture may only be true between modes of identical speeds – thus clearly excluding the walk modes. Furthermore, safety headways should be depicted between vehicles moving in line, be they cars or bikes.

4.2/ Quantitative modeling: indicators, relationships and performances

4.2.1 Indicators at micro and macro levels

The spatial footprint of a vehicle is a simple matter of physical analysis. It is easy to quantify both in the static and dynamic cases as the surface of an elementary ground area. Of course the shape of that area is important, too: it is addressed implicitly on considering that the vehicle length is aligned with the longitudinal dimension of the link where it lies and runs. The time-area footprint is a more elaborate concept that involves the speed and the micro-local traffic conditions – queued or independent. It is also easy to quantify by simple physical arguments.

The consideration of vehicle types is a preliminary step towards aggregation. So is the distinction of either queued or independent micro-local regimes. We utilized the classical aggregation rules of traffic science, including the aggregate indicators of vehicular spatial concentration and flow rate.

The distinction of queued vs. independent TAF, first introduced in this article, stems from the theory of car-following behaviors and the microscopic foundations of the Fundamental Traffic Diagram.

4.2.2 Theoretical formulas and physical analysis

Both the spatial footprint and the time-area footprint are expressed as mathematical functions of elementary physical variables – in other words, as engineering formulas. Such theoretical expression allows for addressing different vehicle types and different speed conditions on a common basis, making the model a fundamentally multimodal one. It also allows for comparing different footprints just by formula examination and the discussion of parameters, before turning to numerical application. The theoretical outreach of micro footprint formulas extends to macro footprint formulas that also involve vehicle concentration, in the static case, or flow rate, in the dynamic case.

4.2.3 Traffic capacities and the amounts of time-area resources

We utilized the reference values of roadway flow analysis, as capitalized in the Highway Capacity Manual, to quantify traffic capacities according to average vehicle speed. Focusing primarily on urban conditions, the relation between speed and flow rate belongs to the increasing part of the Fundamental traffic diagram, where higher speed enables for higher flow rate, yielding a speed-dependent notion of flow rate capacity.

The resulting flow rate capacities transfer to macro TAF capacities, with suitable adaptation to account for the respective widths of vehicles and link lanes. As the adaptation applies both to a particular state and a related reference state at same speed and maximum flow rate, considering the ratios of variables between particular and reference, the ratio of macro TAFs is identical to the ratio of flow rates.

These methodological lines elaborate on previous studies of time-area capacity, which lacked both the share of right-of-way (green time divided by signal cycle time) and the queuing behavior of vehicles. The double omission has some compensating effect, since capacity is increased by the latter but decreased by the former. But our model is more explicit and more comprehensive, making it more physically-grounded and more accurate.

4.2.4 On supply, demand and their relationships

Roadway links and their lanes, by their mere existence and their very nature as flat physical objects, constitute obvious resources for spatial occupation. Calling them the “supply side” refers to an underlying supplier – the roadway operator, acting on behalf of the city government in most city instances. Link layout is a basic issue of space supply as it includes the allocation of lanes to functions, and possibly the dedication of some lanes to specific modes of transportation.

On the demand side, at the micro level the demand for a parking spot is an obvious requirement of space occupation during a certain time. The demand of time-area is less straightforward for making one’s way along a network link: such time-area demand derives from the demand for link passage, which itself derives from that for activity-making at the user’s destination place. At the macro level, trip volumes and flow rates are basically indicators of usage: they make useful measures of demand. Yet the link flows per se do not reveal much about the demand, apart from its intensity. The consideration of multiple modes indicates the modal split at the level of the link: it is not equivalent to the modal split at the level of trips made by people from their origin places. The city-level model has much more expressive power in this respect, since it describes traffic formation on the basis of structural mobility parameters.

The signification of demand at the macro level induces that of the supply-demand relationship. At the link level, it is only the joint consideration of a demanded usage and the related supplied capacity, linked by a fundamental inequality. This makes the ratio of usage level and capacity an especially revealing indicator. At the city level, the relationship between supply and demand is much deeper, owing to the more expressive demand model and also to the geometric model of the roadway network.

4.2.5 What kinds of performances? ⁽⁵⁾

Flow rate is an indicator of link frequentation and productivity. Both features constitute positive performances for a traffic operator. To network users, flow rate is an indicator of usefulness (ITF). Yet the flow rate of 4+ wheels vehicles is also the generator of noise and pollutant emissions that are negative externalities to the city residents.

By type of vehicles, given the average speed, macro-TAF is fairly equivalent to flow rate. Occupation level at a high share of its capacity indicates good frequentation and productivity to the roadway operator, usefulness to the users, but potentially large negative externalities to the residents.

As for shadow TAFs, at the vehicle or person level, large values indicate a low level of usage of the time-area capacity. This can be interpreted as more quietness to the residents, but also of low usefulness to users and low productivity of the resource.

⁵ A quantitative indicator is purported to describe and measure some particular feature of an object or a system. It is thus a “state indicator”. As it is of general outreach, the mention of “state” is usually omitted and kept implicit. The very name of “statistical indicators” exhibits the notion of state and signifies a complex nature of the object under consideration – typically a complexity of abundance for a macro-object including many constituents, constituting individuals in a statistical population specific to the macro-object. In this sense, macro-level indicators of average speed, vehicle concentration and flow rate are statistical indicators.

4.3/ City-level model

4.3.1 Synthetic representation

The city-level model goes beyond spatial detail to address aggregate variables at the level of the whole city, or at least a large part of it. Most of the model variables constitute spatial averages, so that the model has a statistical outreach. While averaging local details over city space, the model captures spatial properties such as population density with respect to 2D space and way densities with respect to 1D spatial dimension. The latter notion stems from the physical theory of currents in space, as do network cuts in the theory of network flows (e.g. Ahuja et al., 1993) and some spatially-simplified models of dynamic traffic assignment (Beckmann, 1952; Wong, 1998; Sossoe et al. 2015).

4.3.2 On transport supply from link to city level

A link is fundamentally a 1D, longitudinal object, even on considering its width and layout in its lateral dimension. The city model covers the 2 dimensions of geographical space, owing to the 2 axialities and the grid postulate: this is akin to Daganzo's model of transit services and their frequentation in a city with a grid network such as Barcelona (Daganzo, 2010). The way densities capture the lateral density of longitudinal routes and constitute intrinsic spatial properties at a higher level.

4.3.3 Demand variables that sum up the four step TDM

On the demand side, the demand parameters and traffic outcomes in the city-level model do correspond to the classical four step model of travel demand (e.g. Ortuzar & Willumsen, 2011):

- city block as a traffic analysis zone,
- the generation rate parameters sum up a statistical model of trip generation,
- the average trip length per axiality sums up the spatial distribution of trips,
- demand segmentation in generation rates and axial lengths corresponds to a modal choice model,
- link traffic parameters and outcomes match those in a model of traffic assignment to a modal network.

4.3.4 Traffic equilibrium as an analytical formula

The 1-1 correspondence between a generic city block and its axial generated traffic, on one hand, and an axial link and its carried traffic, on the other hand, gives rise to the link flow formula (18). It is an analytical expression of the supply-demand relationship. This analytical statement has theoretical outreach to understand the interplay of the different variables involved in it, be they supply- or demand-related.

The traffic equilibrium considered here is an exogenous one since its basic features are all exogenous: axial link speeds on the supply side, modal split and modal axial average length on the demand side. In the general version of the Hoter model (Leurent, 2022), these features are endogenous, making the traffic equilibrium an endogenous one of much deeper outreach. Yet, the link formula remains the cornerstone of the supply-demand relationship.

4.3.5 On the postulates of spatial homogeneity

The spatial homogeneity postulates are essential to obtain analytical properties and easy theoretical interpretation. High level results of space-intrinsic properties may well have a further outreach than just for grid networks: other network shapes would yield similar properties by axial direction.

The homogeneity postulates on population density and the land use of city blocks are more restrictive: notably, a monocentric pattern of urban development would induce much spatial heterogeneity according to radius from city center, regarding local densities of population and of transport supply, and yielding large deviations in network flows and modal shares among roadway links.

4.4/ Application instances

4.4.1 City instances and model postulates

The city instances were selected to span the range of urban population densities in France and to match the model postulates. The postulate of “indefinite extension” is better suited to the communes of Maisons-Alfort and Levallois-Perret, both located in the Paris urban area, of which the axial dimensions exceed average trip lengths by far.

While the studied roadway networks exhibit satisfying grid shapes, there are some local variations between parallel routes in terms of number of lanes and the flow directions assigned to them: such discrepancies fade away when considering way densities. More troublesome is the spatial heterogeneity of population density, especially in the Saint-Etienne case, where about 60% of the communal area is devoted to a green area: both the urbanized area and its density need be defined in a suitable way to avoid systematic bias of demand underestimation that would propagate to demand flows, demand-supply ratios and other model outcomes.

4.4.2 On parameter values in the city instances

The five instances span the range of urban population density in France: the highest value is about maximal and arises only in the heart of the Paris urban area. The 2nd highest is typical of Paris inner suburbs and matches the central densities of other French metropolises. The lowest is typical of many medium-size cities. From among the instances, the two lowest densities correspond to a majority of the French population and a large majority of its medium and large cities.

On the supply side the five instances exhibit parameter values consistent in two respects. First, the way density of street width varies from 8% to 15% - about 12%, say. Second, the way density of overall width splits between the 3 functions of generic flow way, parking lanes and sidewalks in a relatively balanced way: about 40% for way lanes, 40% for sidewalks and 20% for parking lanes.

4.4.3 On model outcomes in the reference situations

The synthetic descriptions of urban conditions constitute liminary outcomes of the model. Beyond them, the most salient results pertain to link flow rates in pcu/h per lane and to TAF shares of their respective capacities by transport mode and axiality.

We simulated morning peak conditions in a crude way by setting up suitable trip generation rates and modal trip lengths corresponding essentially to the home-work commuting purpose. The outcomes are that generic flow lanes are densely occupied and even over-occupied. Such high levels were expected as the morning peak is the busiest period of working days regarding network flows in large cities. From the relative homogeneity of way densities across city instances, the respective levels of street space occupation exhibit the same ranking as the population densities. At densities above 7000 p/km² it was found that car lanes are over-occupied. This can be interpreted as (1) full occupation of car lanes, (2) the omission of motorways from the description of the roadway network, (3) local underestimation of the modal shares of transit modes, (4) local overestimation of population density, at least in the highest instance. Indeed the Levallois-Perret commune and its peak density extend on 2.4 km² only, that is, much less than the product of axial average trip lengths, meaning that much of the generated traffic takes place in neighboring areas that are less dense, while the communal streets carry out traffic generated from less dense areas, yielding lesser flows in real-world conditions than simulated in model application. The second cause of street lane overfilling, i.e., the omission of motorway capacity, may also have had more effect in the Levallois-Perret case than in the other cases, since the motorway meshes are denser in the vicinity of La Défense – the major business center in Paris and France. Based on map observation and rules-of-thumb calculation, we estimated motorway capacity to represent about one fifth to one third of the flowing capacity of other roadways.

Complementarily, dense levels of street lane occupation at morning peak in the two instances of relatively low density are still below the maximum values, meaning that street space is not a scarce resource in these places. At the two higher densities, the excess occupation of car lanes reveals the key contribution of urban mass transit to spare the time-area resource.

5/ Conclusion

We brought together the respective traffic models of transportation engineers and economists, on the one hand, and of urban planners, on the other hand. At the vehicle level, urban planners emphasize vehicular width together with the inter-vehicular length that is familiar to traffic engineers. By using passenger car equivalent factors, the latter ones can take into account the respective widths of two-wheelers and cars. At the macro level of link flows, the models are compatible and complement each other. The demand-supply ratio between a vehicular flow rate and its nominal traffic capacity is fairly equivalent to the demand-supply time-area ratio at the street level between demanded time-area footprint and the supplied quantity of time-area as a resource.

We then developed such ratios at the city level in order to indicate the relation of mobility demand and transport capacity as supplied by the street network. Postulating spatial homogeneity both on the demand and supply sides, the mobility demand for each travel mode is summarized by a *trip flow rate on a notional link lane*, while the network capacity is featured out using the “way density”. Thus, the demand-supply relation is basically the interplay of human density and way density, respectively modulated by mobility generation behaviors and traffic laws.

Next, we applied the synthetic indicators to four cities spanning the range of human density in urban France. Way density was found homogenous enough between the cities. So are the

mobility generation parameters, save for the modal splits. At lower population densities (2000 p/km²) street space was found sufficient to accommodate car traffic under high share of the private car among travel modes, whereas at higher population densities (above 7000 p/km²) the road and rail modes of public transport are key carriers of people mobility in the city.

Our model allows for quick assessment of mobility scenarios in terms of alternative modal split and alternative sharing of street width. We found that modal diversion from the car to public transport would have more effect to relieve street space than that to the bike mode, mainly because of the travel lengths of the trips susceptible to the respective diversions.

Further research may be targeted to: (1) the modeling of junctions as specific places of key importance in the allocation of way capacity to branches and modes, (2) the modeling of a hierarchical roadway network combining high capacity roadways with streets of local flow function, (3) parking issues both on- and off-street. Indeed, parking space is likely to be the most stringent constraint on car mobility in high density cities.

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