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REVIEW ARTICLE

Sustainable Urban Mobility: What Can Be Done to Achieve It?

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Abstract | The harmonious development of cities is a key problem of our times. Is it possible to have sustainable urban areas that enhance rather than diminish the standard of living of their inhabitants? To better understand the issues behind this question, we begin by defining sustainability and the factors that should be associated with a sustainable urban development. We then consider urban mobility, focusing on one of its major challenges: vehicle congestion. With a view to devising possible solutions to the congestion challenge, we characterize it using basic tools from the field of traffic management and engineering. This reveals that, as with many other problems, apparently common sense solutions do not work, and in particular that congestion cannot be solved by road infrastructure construction alone. In this context, we also discuss two paradoxes that reinforce the idea that "obvious" solutions do not work, and outline certain phenomena suggesting that the worst enemy of urban sustainability is the indiscriminate use of private cars in congested scenarios. We then argue that urban development and mobility are wicked problems in organized complexity and, as such, do not have completely satisfactory solutions. In this light we propose what we believe has become the most consensual solution among specialists: a stick and carrot approach. The stick is a policy such as road pricing that charges for using cars in urban areas during congested periods, while the carrot consists of a good public transport system. Finally, we caution that this approach is unlikely to be implemented unless there is a political champion who is prepared to lead longer-term strategies that can capture the enthusiasm of the citizenry.

1 Defining Sustainability[1]

The term sustainable development was first introduced by the International Union for Conservation of Nature and Natural Resources[16] in a study commissioned by the United Nations Environment Programme (UNEP) and the World Wide Fund for Nature (WWF). The document proposed a world conservation strategy that was later popularized by the widely publicized Brundtland Report[4], which appealed to the idea that the entire planet has a common future. Then, in 1992, the UN made public its Agenda 21, an action plan on sustainable development that was intended for adoption locally, nationally and globally. The main objective of the plan was to improve the social, economic and environmental quality of human settlements, and the living and working environments of all persons, but especially the urban and rural poor (see De Lisio, 1999[11]).

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[1] The discussion that follows is based on information treated in greater depth in the book *Sustentabilidad a Escala de Barrio. Re-visitando el programa "Quiero mi Barrio"*[9].

In broad terms, sustainability was understood in these reports as a strategy for promoting development that maintains a harmonious relationship between humanity and nature in three aspects: social inclusion, economic development and environmental balance. This gave rise to the three pillars concept of sustainability. Figure 1 shows one of the first diagrams used to illustrate sustainability in an urban setting[4].

More recently, however, it has been argued that these three pillars exclude aspects that are also important such as the cultural–aesthetic, the political–institutional and the religious–spiritual dimensions[19]. Other writers have incorporated governance as a fourth pillar[5], based on an understanding of institutions and their institutional, social, political, legal and normative mechanisms[29]. The integration of this political component, shown in the diagram in Fig. 2, implies that what is needed is the power to "do," not just "aspire to."

Diagrams used today are rather more complex (see Fig. 3) and include criteria for determining the degree of progress or compliance on each element, particularly in the context of diverse urban areas[32]. This is reflected in the definition of sustainability recently adopted in Chile, for example, by the Centre for Sustainable Urban Development as … "a process by which present and future communities flourish harmoniously"[8]. Three elements of this definition are particularly worthy of highlight: (i) by referring to communities, it includes urban realities in the collective rather than just the functional sense; (ii) the term flourish, points to advances or improvements above and beyond a linear notion of progress, embracing such concepts as welfare and beauty; and (iii) the description of the process as harmonious relates to connection and equity.

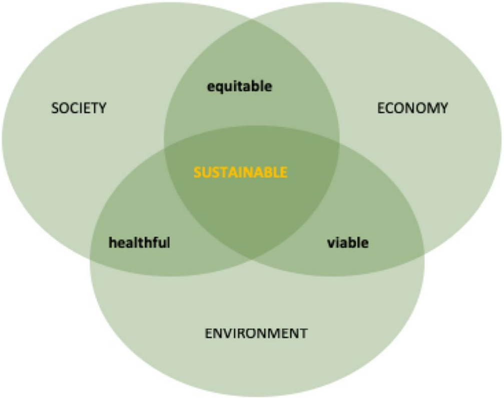

Figure 1: The three pillars of sustainability.

2 Urban Mobility and the Congestion Challenge

A recent report from the Texas A&M Transportation Institute[27] made the following observations regarding the 70 largest cities in the USA:

- In 20 years, the population increased 10% and urban street mileage grew 15%, but the value of lost time due to traffic congestion tripled to US$80 million per year.
- Drivers spent 60 h in traffic jams (twice as much as 10 years earlier).
- On average, congested periods grew 50% and trip times at rush hours increased by about 10%.

Since these findings relate to the country with the biggest urban motorway investment in the

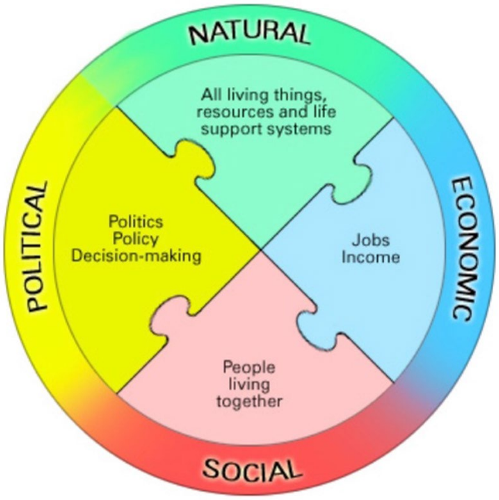

Figure 2: The four pillars of sustainability.

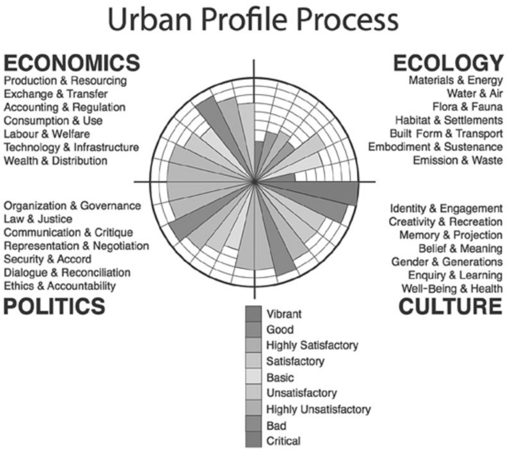

Figure 3: Circles of sustainability.

world, it would seem reasonable to conclude that investing in enlarging capacity is not the solution to the traffic congestion pandemic affecting most large urban areas today. Furthermore, the periods of congestion are growing in both length and intensity, giving rise to negative phenomena such as road rage (https://en.wikipedia.org/wiki/Road_rage) and reckless driving even in cities such as London, where the local population has traditionally been known for its restrained and civilized behaviour.

2.1 Some Basic Principles for Understanding the Congestion Problem

Ideas from the field of traffic engineering (TE) should help improve our understanding of the road congestion problem. Let us start by defining the degree of saturation (x) of a road as the ratio of vehicle flow (q) along it to its traffic capacity, the latter given by its saturation flow (s). The degree of congestion is evident to bystanders if x is over 0.7, and the problem is known to become chaotic (as in some American and Asian cities) once the figure reaches 0.9.

The most visible cost of congestion is the increase in trip times. But individuals only perceive the impact on their own trips (that is, their average or private cost); they do not recognize the total impact on all travellers, which is the social or marginal cost. In effect, each vehicle in a congested flow inflicts additional time (cost) on all the other vehicles in it[1]. Figure 4 depicts these costs, as well as the relative zones of congestion (when costs start increasing with flow) and evident congestion (a bit further down the line).

But trips in different types of vehicles have various operating and external costs associated with them in addition to the aforementioned costs in terms of time. For example, Rizzi and de la Maza[26], in a recent calculation of the marginal external costs of travelling in Santiago, Chile, by car or bus (including costs due to congestion, pollution and traffic accidents) arrived at the following values:

Cost	Cars (Gasoline)	Cars (Diesel)	Buses
US$/km at peak hours	0.51	0.53	1.80
US$/passenger-km at peak hours	0.41	0.42	0.04
US$/km at off-peak hours	0.15	0.16	0.78
US$/passenger-km at off-peak hours	0.12	0.13	0.05

These results suggest that during peak hours, the external cost of car travel is ten times higher per passenger-km than the cost of bus travel. In off-peak periods with less congestion and lower bus occupancy rates, the comparison

Private cost: refers to the cost that is incurred to and paid by a consumer for using a product. For example, private cost of travel in a car includes ownership cost, fuel cost, maintenance cost including wear and tear, and a monetary value of the time spent travelling.

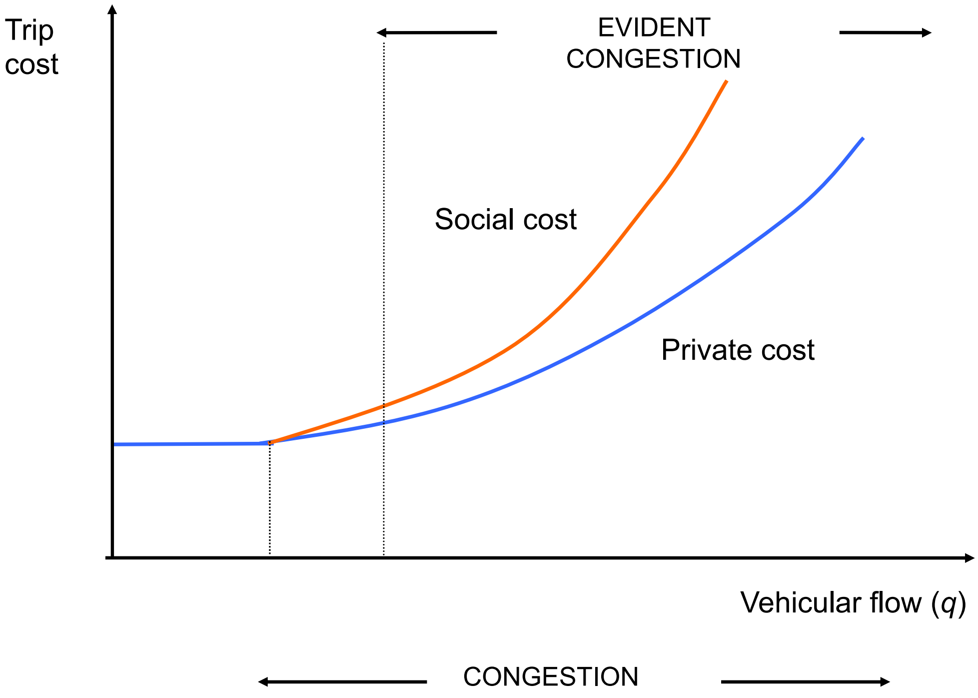

Figure 4: Private and social congestion costs.

Figure 5: Comparative efficiency of buses and cars in road space use.

is less dramatic, the car travel cost dropping to 2.5 times higher.

Since traffic flows are made up of cars, buses and lorries, TE analyses involving multiple vehicle types use the concept of passenger car units (pcu; see[18]). Thus:

- A car travelling in a single direction (no turns) is equivalent to 1 pcu, and in Santiago—for example—it carries approximately 1.25 passengers in peak hours[1].
- A city bus is the equivalent of 2.5 pcu, carrying in this same city approximately 40 passengers in peak hours.

From these values we may conclude that a bus is about 12 times more efficient than a car in terms of congestion (that is, as regards the use of scarce road space) in a city like Santiago. This is illustrated by the photo in Fig. 5.

Note also that the capacity of an urban street is determined by its signalized intersections. Along each intersection access link, the following equation is satisfied:

$$x = \frac{q}{\lambda_s},$$

where q and s have already been defined and λ is the link's effective green time proportion.

Effective green time: at a traffic signal is the time during which vehicles along an approach can travel through the intersection at the saturation flow rate (i.e. the rate of vehicular flow if the vehicles were only given green but no red or amber nor any interference from vehicles along other approaches). The proportion of effective green time with respect to the total cycle length is denoted λ. Cycle length is the duration of a traffic signal cycle, which includes green, red, and amber phases.

It follows from this relationship that to reduce congestion (which is increasing in x), there are only three possibilities:

- Increase the capacity of the access links and therefore the saturation flow s; this is the archetypal man-in-the-street solution and an example of the common sense fallacy[14]; unfortunately, it is no solution at all, since as mentioned in the introduction, it only works in the short run[13].
- Replace signalized intersections with grade separations[2], in which case $\lambda = 1$.
- Reduce vehicle flow q by inducing some car users to change the route, mode or time of day of their trip (known as demand management).

We will return to these ideas later when we analyze possible solutions to the urban mobility problem caused by road congestion.

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[2] Note, however, that in 1976, Caracas had the worst traffic jams in Latin America even though the city's mayor had replaced all signalized intersections with grade separations.

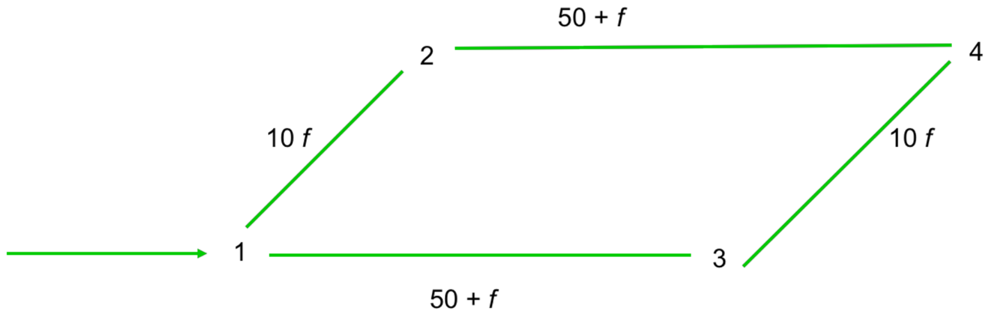

Figure 6: Simple example of Braess's paradox.

3 Some Paradoxes in Transportation Engineering

3.1 Braess's Paradox

Originally proposed in a German-language publication in 1968[3], this paradox has been extensively studied in the ensuing decades. Consider the example of a simple network in Fig. 6. In the initial state, there are only four links along which a vehicle can travel between origin node 1 and destination node 4. The horizontal links (1–3 and 2–4) have a cost of $50+f$ (where f is the vehicle flow) while the rising diagonal links (1–2 and 3–4) have a cost of $10f$.

If a total flow of six vehicles desire to travel between nodes 1 and 4, it is evident that the optimum for the initial state is attained when three of the vehicles use route 1–2–4 and the other three the alternative route 1–3–4. In this case, the cost experienced by each vehicle is the same at 83 (50 + 3 + 30).

Now imagine that the transport authority considers this cost to be too high and decides to build new road infrastructure to ameliorate the situation. Suppose, for instance, that a new link is added between nodes 2 and 3, the associated cost of which is significantly less than that of the previous links ($10+f$). There are now three routes; the two previous ones, 1–2–4 and 1–3–4, with a cost of 50 + 11f, and the new one, with a cost of $10+21f$.

As can easily be shown, in this new state the spontaneous equilibrium (individual optimum) occurs when exactly two vehicles choose each route. In any other case, the cost would be higher for some vehicles than for others. What is paradoxical, however, is that in this situation the cost incurred by each vehicle is equal to 92 (route 1: 40 + 50 + 2; route 2: 40 + 12 + 40 and route 3: 50 + 2 + 40), higher than the figure of 83 for the previous state.

The socially or collectively optimal solution can in fact be reached only if no one uses the new link—which is unlikely in practice given that the new link is cheaper than the previous ones.

Thus, in this example, adding a link, even one that is better than the existing ones, leads to a situation that worsens trip times if each vehicle chooses the route that is individually the most attractive.

3.2 The Downs–Thomson Mogridge Paradox

An example of this famous paradox[12, 22, 30] is shown in Fig. 7. It illustrates an imaginary situation in which two transport modes, cars and buses, compete to carry a set number of users Q between two points. The cost of car travel, plotted from right to left, follows the typical congestion curve presented here earlier in Fig. 4. Bus transport, however, is a mode that has economies of density, meaning that the (cost-based) fare charged each passenger carried for a given service (i.e. a fleet operated with given service frequencies) should decline as the number of users rises. This cost is shown in the figure from left to right.

The initial equilibrium occurs at an intermediate point when costs equalize at C_0. There, the number of car users is Q_A^0 and the number of bus riders is $Q_B^0 = Q - Q_A^0$:

Suppose once again that the transport authority considers C_0 to be too high and therefore decides to improve the road infrastructure. In this case, the roads are rebuilt to a higher standard (for example, with fewer curves and traffic signals) and widened to increase the number of lanes. This not only results in a lower initial car user costs, but also slows the rise toward more obvious levels of congestion.

As can be seen in Fig. 7, in this new situation with the expanded infrastructure, equilibrium occurs at a point with more car users ($Q_A^1 > Q_A^0$), fewer bus users ($Q_B^1 < Q_B^0$) and a higher cost ($C_1 > C_0$) than in the initial situation. This

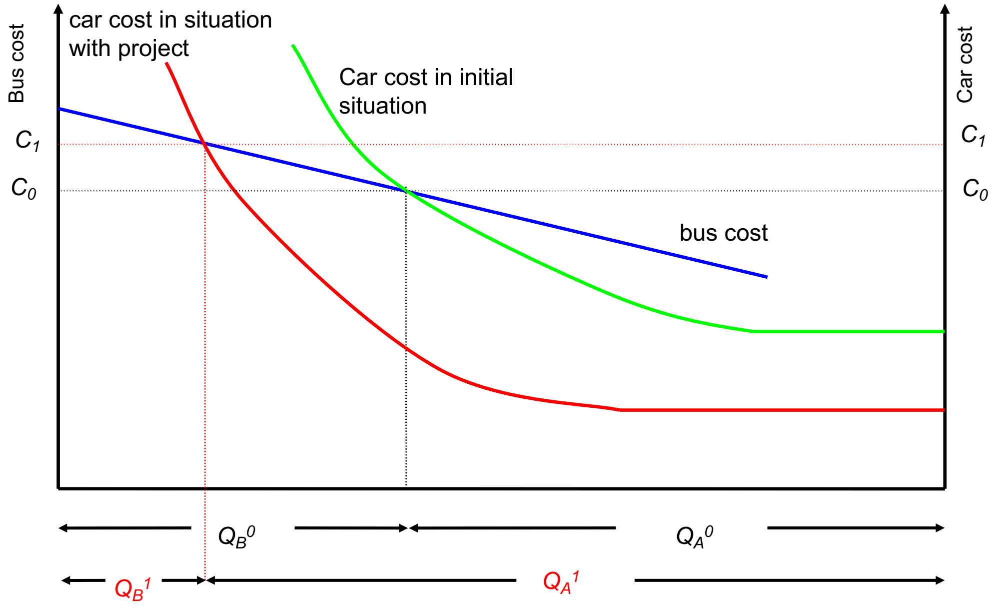

Figure 7: The Downs–Thomson Mogridge paradox.

paradox is frequently encountered in practice, although rarely in highly congested cities[2].

3.3 The Public Transport Vicious Circle

A well-known representation of this problem is set out in Fig. 8 and [24] p. 8). As can be seen, with a growing population and rising living standards a number of phenomena appear simultaneously: (i) property prices increase in city centres, prompting a trend among local residents to move to the outskirts; (ii) this migration is facilitated and thus reinforced by a natural growth in private car ownership due to the higher incomes; (iii) lower pollution levels provide an additional incentive for the demographic shift to more affluent areas.

The rising congestion in the city stemming from the greater use of cars negatively affects surface public transport modes, which is further impaired by the population increase in the more spatially disaggregated suburbs. Thus, the two processes combine to bring about a major reduction in the efficiency of public transport services. This makes car ownership comparatively more attractive, reducing the number of bus users and thereby pushing bus operators towards a deficit.

In response to this financial deterioration, the operators will tend to reduce frequencies, eliminate lesser-used services and/or raise fares, all of which prompts yet more bus users to consider switching to private transport modes, aggravating the vicious circle as bus services continue to decline.

To halt this downward spiral (as also shown in Fig. 8), the public transport authority could try to isolate buses from the growing congestion problem by defining dedicated bus lanes, or better still, building bus corridors as part of a bus rapid transit system (BRT). In addition, subsidies could be granted to protect sectors where frequencies would decline significantly or disappear completely in a strictly market context. Funding could also be provided to maintain reasonable fare levels in terms of disposable income for those in lower-income groups, who are typically captive users of public transport. The danger is that if not implemented carefully, the cost of such subsidies can balloon dramatically.

4 Facing the Urban Sustainability Challenge

There is a fair degree of consensus among specialists that as regards mobility, the challenge of urban sustainability has three main components:

- Excessive dependence on private cars;
- Overconsumption of land area (often good quality farmland);
- An unacceptably large ecological footprint.

Almost 60 years ago, Jacobs[17] wrote that cities were problems of organized complexity. A decade later, Rittel and Webber[25] upped the ante, arguing that the challenges facing urban planning specialists were wicked problems,

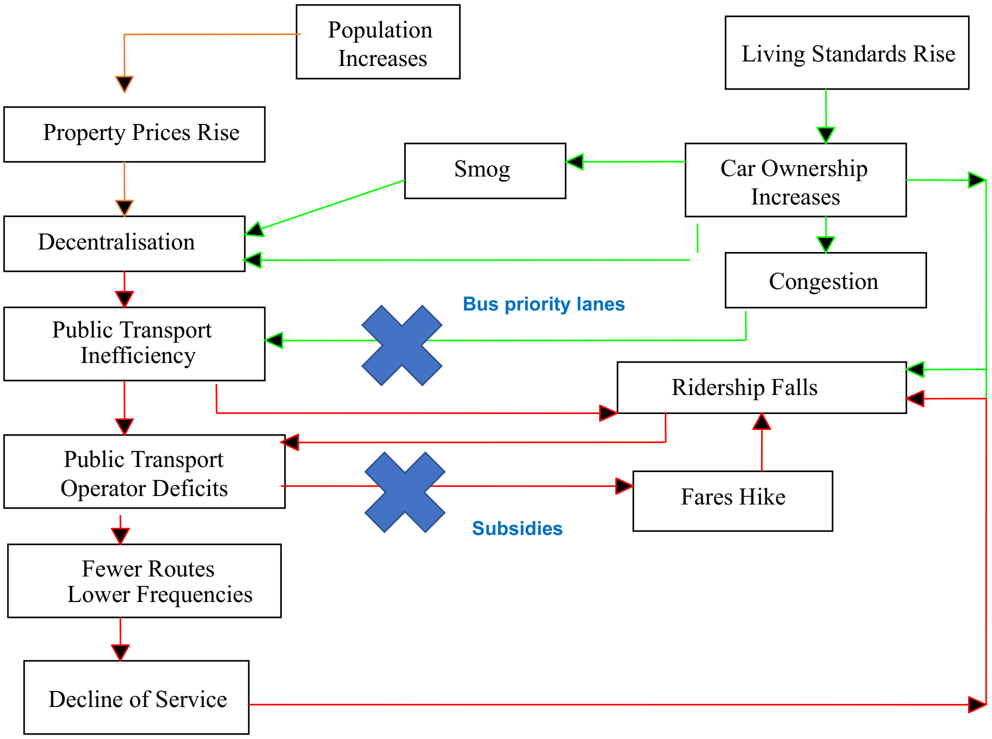

Figure 8: The vicious circle in public transport.

unlike the tame problems studied, for example, in physics. Wicked problems may be described as follows:

- Hard to solve, with no clear or absolute solution and a long history of failure to find one;
- Socially complex, interdependent and with multiple causes;
- Require solutions that may have unintended consequences;
- Involve changes in behaviour and straddle organizational divisions.

Cities today continue to be wicked problems of organized complexity. But even though there are no optimal solutions, advances in mathematical and analytical capabilities coupled with ever increasing computational power has made it possible to model the functioning of cities with considerable accuracy, opening up new possibilities for significant improvements. Even though all models virtually by definition are simplifications, incomplete and therefore in some sense inaccurate, many of them are in fact highly useful and can be applied to great advantage[24].

Miller[20] maintains that academics specializing in this area should do the following:

- Get out into the world, work on real problems, debate the issues and get their hands dirty;
- Popularize the field and engage with the general public about what we know;
- Frame our message in terms of the risks involved in not doing anything.

The task may not be a simple one, but it is extremely important. Unfortunately, our message often entails proposals that mean people will have to choose modes of transport that they, as individuals, may find undesirable. This has opened the door to self-appointed commentators with large audiences but relatively little knowledge, who spout simplistic visions that sometimes gain wide acceptance[3].

4.1 Technical Problems, Approaches and Solutions

A serious problem that has attracted little attention in the literature is how to properly evaluate transport and mobility projects. This is true in

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[3] See, for example, the notable column by Chilean sociologist Domingo Moreno, in which he analyses an article that appeared in a Santiago daily attacking those of us who propose the use of bicycles as a sustainable transport mode worthy of government support (https://medium.com/@domingomoreno/las-falacias-de-poduje-8f8d7d60ecca).

most countries, but particularly so in less developed nations. Social project evaluation, a key tool in determining which transport projects should be carried out, conditions approval upon the generation of a sufficient social return on the investment required. But the typical processes count as benefits only savings in time (90% or more of the total) and operating costs. Thus, a project that improves or adds to existing road infrastructure will be judged to have a high social return because it generates savings in both categories. Yet this approach has at least two weaknesses. The first and very important one is that such savings tend not to last, given that induced demand is likely to consume much of the additional road capacity in short order (3–5 years).

The other shortcoming of such analyses in the majority of countries is that they ignore other benefits that are also very valuable. Among these are a reduction in accidents (including the savings due to fewer non-fatal accidents), less pollution and lower noise levels. Meanwhile, a number of increasingly serious issues that should be considered tend not to be: overcrowding, unreliable service and the quality of the urban environment.

Yet another topic that should be incorporated when it comes to consider urban sustainability in all its complexity is the growth of cities. For decades, Robert Cervero and his colleagues have been insisting on the importance of what are now the five D's:[6, 10]

- Density: increases in this factor are positive in that they tend to reduce the indiscriminate use of cars (it has been argued that a level of 37.5 residential units per hectare is needed to sustain a good public transport system).
- Diversity: not only residential use, but also economic activities (commercial, light industry, services, etc.).
- Design: perhaps the most complex factor given that is has numerous meanings and levels relating to well conceived and varied public spaces: detailed design (streets for pedestrians, off-street parking), friendly design (for example, short blocks with more intersections facilitate walkability).
- Destination accessibility: the range of places that can be reached in 10–15 min by different transport modes; on this criterion, there can be no doubt that the bicycle is currently the best mode for trips of up to 7 km.
- Demand management: measures such as limited and more expensive parking or road pricing.

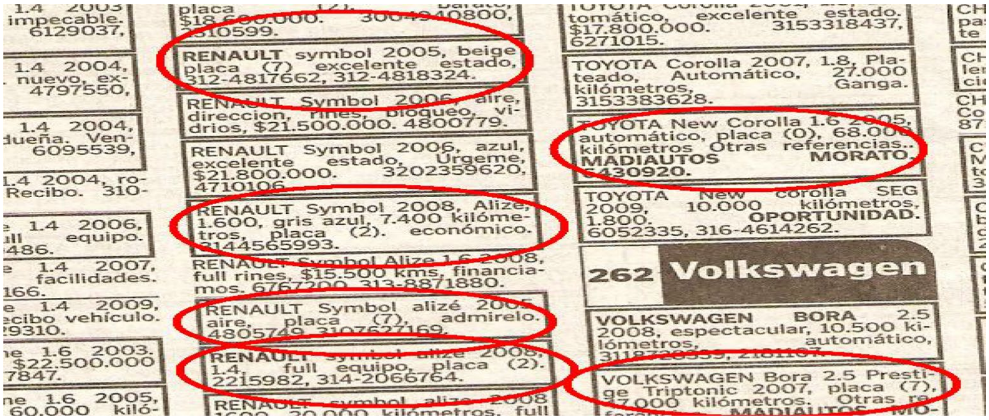
Finally, account must be taken of the indissoluble relationship between mobility and land use. There is considerable consensus among specialists that uncontrolled urban sprawl should be avoided, urban centres should be created that are accessible by public transport or active transport (bicycle and walking), services such as local train networks should be contemplated, urban motorways should be avoided, land should be acquired to facilitate public transport-oriented development (http://www.tod.org/) and approaches such as complete streets[28] should increasingly be adopted. Another major challenge is the generation of urban centralities that favour the use of active transport, reducing the need for long trips to access services such as shopping, medical centres, educational facilities, government offices and so on. Promoting strategies for telecommuting and flexible working hours are also important, though these initiatives have their own problems and challenges.

It must nevertheless be recognized that traffic congestion (due mainly to private car use) cannot be totally eliminated. What we can attempt to do is manage it in such a way that it stays within reasonable levels. As we saw earlier in our look at basic principles, the only efficient solution for the urban congestion problem is to manage demand, that is, reduce the flow of vehicles on city streets. It has long been known that increasing road capacity is not a long-term solution, as was masterfully demonstrated in the classic Buchanan Report, entitled Traffic in Towns[21].

Various measures have been proposed to reduce congestion (i.e. reduce traffic flows), some of which we have already mentioned. In what follows, we will look at just two fairly direct approaches: vehicle restrictions and road pricing.

4.2 Vehicle Restrictions

Systems of vehicle restrictions such as Colombia's *pico y placa*, based on car registration plate numbers have been implemented by various cities in Latin America and elsewhere, but they tend to work only in the short term[7]. To get around the restrictions, many drivers will eventually acquire a second car, often an older, cheaper one that is likely to be more polluting. Worse still, this vehicle will then be used by other family members on days when the first car is not restricted, in the end actually increasing congestion (as well as pollution). In cities that have maintained this system over a long period such as Bogota, it is not unusual to see used car advertisements in newspaper classifieds that specify the plate number as one of the vehicle's key features (Fig. 9).



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262 Volkswagen

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Figure 9: Classified advertisements for cars in a Colombian newspaper.

4.3 Road Pricing

In economic theory, optimal use of a congested public good is achieved by pricing it at its marginal cost. This principle is the regulatory norm applied to most utilities in the majority of countries such as drinking water, electricity and landline telephones (as well as certain transport services, our concern here, such as air fares). The rates charged for these services are higher during periods of greater consumption.

Based on this concept, transport specialists have for some years been proposing the application of a carrot and stick approach. The stick in this case, involves charging car owners the marginal (social) cost of using the roads so that their travel decisions (mode, time of day, route) will be based on the real costs of the system. This policy, known as road pricing, has been implemented with great success in Singapore, certain Nordic countries and, more recently, London (https://en.wikipedia.org/wiki/Road_pricing). As for the carrot, it consists in providing a decent, efficient and safe public transport system that can be continually improved thanks precisely to the road pricing revenues, plus any subsidies that might be granted. Both elements—carrot and stick—are key to a sustainable strategy.

4.4 How to Implement a Practical Road Pricing Policy

The first question that arises in the implementation of a road pricing policy is how to translate the optimal value into an actual charge or toll (for example, the charge that is "most appropriate"). The answer depends on whether the idea is to price only for congestion or to consider additional externalities such as pollution. Extending the pricing system to include other externality mitigation objectives is in fact highly recommended from the viewpoint of gaining the support of public opinion[15].

There are also problems of approximations given that the optimal charge is by its very nature (because of the distinction between private and social cost) different for each road and time of day. If the zone of application of the pricing system is marked off by imaginary boundaries, which is typically the case, and the charge can vary only over discrete periods, the toll will have to be an approximation to the optimal value. How that is done must be determined on a case-by-case basis.

Social cost: is the sum of private costs and external costs caused by the usage of a product. In the case of travelling by car, social cost includes the private costs as well as the costs of externalities such as traffic congestion, accidents, noise and air pollution which are suffered by other travellers and society. Social cost is also referred to as marginal cost, for it is the cost per additional traveller on the transportation network.

Note also that identifying the most appropriate charge also depends on the definition of the zone of application[23], since both issues are obviously interdependent. In practice, designers of road pricing systems have opted for simple solutions to ensure public acceptance at the risk of losing some economic benefits.

Another fundamental issue is how to ensure the fiscal neutrality of a road pricing system, given that the concept is commonly derided as "yet another tax". Some years ago, the UK Commission for Integrated Transport, which brings together the Royal Automobile Club, the Confederation of British Industry and the Road Haulage Association, agreed to support and promote road pricing in Britain on the condition it would be implemented within a legal framework in which the expected revenue collected by the system would be compensated by a reduction in the road licence fee.

This seems to be a practical way of securing the consensus necessary to implement a project of this nature. Reducing road licence fees (which do not consider consumption, time of day or location) and/or gasoline or diesel fuel taxes (which do take consumption into account, but not time of day or location) to offset the expected revenue collections from marginal cost road pricing is an intelligent approach that should help in getting closer to the optimal charge.

4.5 A Final Thought: The Role of the People

We strongly believe that none of the foregoing ideas would serve much purpose if no-one is prepared to take up the cudgels for them. Our cities need better political champions, people like former mayors Jaime Lerner of Curitiba, Ken Livingstone of London and Enrique Peñalosa of Bogota, all positive leaders who listened, learned and then took decisive action for their communities using all the available information.

But the citizenry must also play its part by demanding more of their politicians. We must be prepared to think about the future generations. Unfortunately, politicians are almost always focussed on the short term. The only way forward, then, appears to be the creation of permanent institutions that can act independently of political agendas set by the government of the day.

Publisher's Note

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