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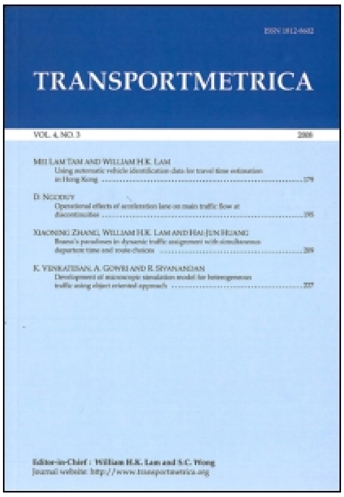

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Distributive impacts of demand-based modelling

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Transport demand models play a crucial role in the distribution of transport facilities, and hence accessibility, over population groups. The goal of this article is to assess the distributive impacts of the widely-used four-step, demand-based, transport model. This article starts from the hypothesis that the consecutive application of the four-step model over a number of years, and successive investments in transport infrastructure consistent with the model results, will widen existing gaps between high-mobile and low-mobile groups, in terms of transport facilities and accessibility available to each group. A simplified four-step model is then developed to test the hypothesis under different policy scenarios. The results are mixed. In each scenario, gaps between high-mobile and low-mobile groups are increasing and decreasing at the same time. Against expectations, the distributive implications of demand-based modelling seem to depend on the situation and the focus of analysis. Given the unpredictable distributive impacts, it is suggested that explicit justice indicators be incorporated in transport modelling if it is to contribute to a more just distribution of transport facilities and accessibility over population groups.

Keywords: transport modelling; four-step model; social justice; distributive justice; accessibility

1. Introduction

Transport is a key responsibility of modern governments. Governments not only set the regulatory framework for the transport sector, but also determine the size and scope of investments in transport facilities. Given the importance of transport in current high-mobile societies, the way in which governments distribute transport facilities over their citizens is of the utmost importance (e.g. Farrington and Farrington 2005, Blumenberg and Schweitzer 2006, Lucas 2006).

The goal of this article is to critically analyse the role that transport demand models play in the distribution of transport infrastructure and, through it, in the distribution of accessibility. Transport demand models, and most notably the four-step model, are used throughout the world and feed decision-makers with data on where to provide what kind of transport infrastructures (Bates 2000, Committee for Determination of the State of the Practice in Metropolitan Area Travel Forecasting 2007). By doing so, these models play a crucial role in the ultimate distribution of transport facilities over population groups.

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While the existing literature on transport modelling hardly addresses distributive issues, a closer look shows that two types of studies do link demand modelling and justice.[1] The first type is primarily methodological in nature and views equity as an optimisation problem of a particular kind. For instance, alternative transport investment schemes are assessed regarding the extent to which they fulfil a specific equity constraint, such as a pre-set ratio between travel costs after and before network improvement. Examples of this kind of studies include Meng and Yang (2002), Lee *et al.* (2006) and Pilko (2007). The second type of studies is more practical in nature and employs transport models to explore the equity impacts of particular transport policy packages. Examples of such studies include Deakin and Harvey (1996), Replogle (2000), USDOT-FHWA (2000), Slavin and Lam (2001) and Castiglione *et al.* (2006). These studies use models comparable to the traditional four-step model to explore how different transport policies work out for different population groups.

While both types of studies do provide insight into the distributive impacts of transport investments and policies, they do not explore whether demand-based modelling has a *systematic* impact on the distribution of infrastructure or accessibility over population groups. Given the dominance of the four-step model in actual practice and the increasing emphasis on transport equity in Western societies (see, e.g. USDOT-FHWA 2000, Social Exclusion Unit (UK) 2003), it is important to explore whether such a systematic, and inequitable, bias may actually occur. This is the goal of this article.

This article is structured as follows. First, a justice approach to transport is developed (Section 2). Then, we discuss the still-dominant four-step transport model and criticise it from the perspective of justice. This results in the formulation of the hypothesis that the consecutive application of the four-step model over a period of time, with consequent development of transport infrastructure based on the model results, will exacerbate existing accessibility gaps between population groups (Section 3). We then present a simplified four-step model that will assist us in testing this hypothesis. Section 5 discusses the application of the model for a number of scenarios and presents the results. We end this article with a discussion linking justice, transport and modelling.

The model presented in this article is the first result of a long-term research project into transport and justice. The project consists of theoretical explorations and modelling exercises. The first one includes, among others, investigations into the merits of the distributive approach for the transport field, and an inquiry into just criteria for the distribution of transport-related benefits (Martens 2006a, 2008). The modelling exercises will encompass more advanced versions of the model presented here, including a model incorporating financial constraints on transport investments and a simplified cost–benefit analysis. Ultimately, the project is to result in a transport model based on principles of social justice, as an equitable alternative for existing demand-based models. While not a sufficient condition for bringing about change in current policies, we assert that the availability of adequate tools is a *sine qua non* for a transformation towards more equitable transport policies.

2. Justice and transport

Most contemporary scholars define social justice as *the morally proper distribution of benefits and burdens among members of a society* (Boucher and Kelly 1998, Miller 1999a).

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The way these benefits and burdens are and should be distributed is the subject of study. Social justice scholars apply this distributive approach to fields like health, education or employment, and explore how a specific set of benefits and burdens is and should be distributed over men and women, rich and poor, white and black, and so on.

This article will apply the distributive justice approach to the field of transport. Scholars of social justice have largely overlooked this topic, apart from a few authors who have dealt with it only in the sidelines (e.g. Walzer 1983, Sadurski 1985, Braybrooke 1987, Elster 1992, Miller 1999a). A limited number of transport researchers have taken a distributive approach, most notably with regard to road taxes (Altshuler 1979), public transport subsidies (Cervero 1981, Pucher 1981, 1982), and public transport services (Murray and Davis 2001, Cha and Murray 2002). However, as discussed above, to the best of our knowledge no efforts have been made to systematically analyse transport demand modelling from the perspective of distributive justice.

The application of the distributive approach to the field of transport requires a clear demarcation of three key elements: (1) the *benefits and burdens* that are the subject of analysis; (2) the *members of society* between whom the benefits and burdens are distributed and (3) the *distributive principles* that determine what is a fair distribution of the benefits and burdens under discussion.

First, a decision has to be made with regard to the *benefits and burdens* that are the subject of analysis. Here, two possibilities can be distinguished. The first is to focus on *single* transport-related benefits and burdens, such as roads, public transport services, taxes or pollution. The second approach is to conceive transport as a *complex* benefit composed of various objects and services, which, taken together, enable members of society to fulfil a specific want or need – commonly defined as 'transport' or 'accessibility' (Portugali 1980). Transport demand modelling directs the attention, first and foremost, to the distribution of infrastructure. However, investments in new transport infrastructure also shape the distribution of accessibility over people, which is arguably of even more importance to citizens. In this article, we will analyse how transport demand modelling shapes the distribution of both benefits – infrastructure and accessibility. No attention will be paid to the related distribution of transport-generated burdens.

The second element that requires demarcation concerns the *members of society* between whom benefits are distributed. The challenge here is to divide the members of society into relevant groups so that potential injustices may be revealed. In case of transport demand modelling, two distinctions are relevant: by the availability of transport mode and income. Mode availability is especially important in the case of investments in road infrastructure, as car availability is either a prerequisite to benefit from a road, or substantially increases the gains that can be derived from such infrastructure. Income is also relevant, as accessibility is not only a function of the availability and quality of transport facilities but also of the financial ability of people to make use of these facilities. Note that mode availability and income are closely linked, implying that groups by mode and income will overlap.

The third element that requires demarcation concerns the *distributive principle* that will be used as the yardstick to judge whether a specific distribution of the benefits discussed above is fair or not. A wide variety of principles could be used, ranging from the need principle to Rawls' famous maximin principle (Rawls 1971; see Beatley 1988 for an application to infrastructure planning). Without an explicit and well-motivated decision

Table 1. Key components of a distributive approach to social justice and practical application to the analysis of transport demand modelling.

Key elements	Description	Application to transport modelling
Benefits and burdens	The 'things' that are distributed (shared, divided, exchanged, dispersed) in society	– Transport facilities – Accessibility
Members of society	Recipients of benefits or burdens divided into groups based on characteristics that are relevant for the distribution of the benefit or burden under discussion	– By car availability – By income
Distributive principles or criteria	Principles that determine which distribution is just	– Equality/equalisation

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which yardstick to use, any justice analysis is ultimately pointless. The principle often considered as the 'default' option is equality, which describes a distribution in which each recipient or group of recipients receive the same amount of a certain benefit, irrespective of their particular characteristics (see, e.g. Walzer 1983, Miller 1999a). Smith (1994) even argues that the challenge for scholars of social justice is to provide convincing arguments why to deviate from the criterion of equality. Lacking such arguments, equality remains as the only correct yardstick to assess specific distributions.

The question that needs to be answered, then, is whether good arguments can be given for providing the benefits discussed above – transport facilities and/or accessibility – in any other way than according to the principle of equality. Since a full exploration of possible distributive principles applicable to these benefits is beyond the scope of this article (for explorations, see Beatley 1988, Khisty 1996, Martens 2008), we will use the default option of equality as the yardstick to judge distributive patterns. More specifically, since current motorised societies display substantial gaps between population groups in terms of available transport facilities and levels of accessibility (e.g. Hine and Mitchell 2001, Blumenberg 2004), we will focus on equalisation (cf. Smith 1994, Martens 2006b). That is to say, we will assess to what extent transport improvements suggested by transport modelling lead to a *decrease* or an *increase* in the existing gaps between population groups, i.e. whether these investments result in a *progress towards*, or *move away* from, a distribution based on equality. If the former holds, we consider transport modelling to contribute to a fair distribution of transport. Table 1 summarises the three constitutive elements of a distributive approach to justice, and its application to the field of transport modelling as employed in this article.

3. The four-step model from the perspective justice

Transport demand modelling has gained widespread use in the industrialised world since the late 1950s and is now an integral part of transport planning in virtually all motorised countries. Most of these countries still apply variations of the four-step model, despite widespread criticism and the development of more advanced activity-based models (Bates 2000, McNally 2000a, Committee for Determination of the State of the Practice in Metropolitan Area Travel Forecasting 2007). The four-step model forecasts future

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transport demand in four steps (see e.g. de Dios Ortuzar and Willumsen 2001, McNally 2000b): trip generation, which estimates the number of trips at the level of transport activity zones; trip distribution, in which trips are spatially distributed over attraction zones; mode choice, which determines the transport mode of trips between each origin-destination pair and, finally, traffic assignment, which assigns the trips onto mode-specific transport networks. The four-step model ultimately results in a forecast of future travel demand, which in turn can be used to assess the future performance of the existing transport system, to identify transport links that lack sufficient capacity and to assess the impact of various infrastructure improvements on the performance of the system.

From a social justice perspective, the first step of the model is of key importance (Martens 2006a). In this step, total trip numbers are estimated per transport zone based on current trip patterns. For this purpose, households are distinguished according to a number of characteristics, most notably size, car ownership level and income. Then, for each household type, the average number of trips is derived from current travel patterns of comparable households. This approach typically results in large gaps in average trip rates per household, with higher trip rates linked to higher levels of income and car ownership. The different trip rates, in turn, are used to calculate the total number of trips per activity zone.

The prime weakness of this approach lies in the use of current travel patterns for the forecasting exercise. Conventionally, these patterns are viewed as the result of free household choice, suggesting that they represent 'the best possible set of actions that individuals could have taken given their preferences and the spatial structure of the city' (Sheppard 1995). However, as Sheppard (1995) rightfully points out, current travel patterns are as much a result of constraint as they are of choice. These constraints not only include household budgets (time and money), but also the availability of transport services in its broadest sense (roads, parking facilities, public transport services, etc.). These constraints will be reflected in current travel patterns of households, with households experiencing larger constraints revealing lower levels of accessibility and mobility, *ceteris paribus*. Travel models that use existing travel patterns as the basis for forecasting will, implicitly, reproduce these differences in accessibility and mobility. More specifically, such models will strengthen the position of those who received transport facilities in the past and are thus more likely to travel (typically the car owner, given the extensive road building over the past decades in Western societies), and weaken the position of those who received few facilities and are thus limited in their possibilities to travel (typically the car-less, given the reduction in public transport services during the same period in Western societies).

The use of current trip patterns for the forecasting exercise is legitimised, implicitly, by the goal of transport models to forecast future travel *demand*. Within economics, demand is defined as a want backed by a willingness and ability to pay. Current travel patterns obviously live up to these conditions – they are a result of wants of households backed by a revealed willingness and ability to pay. The aim to forecast future travel demand thus makes it possible to use current, revealed, travel patterns as a basis for the estimations. It cancels out the need to take into account the existence of latent demand, as well as the possible interplay between transport infrastructure and travel patterns, including the possible impact of poor transport services on household trip rates. The focus on travel demand, in short, dismisses transport planners of the obligation to look critically into current travel patterns of households and the reasons for the disparities between them.

The second weakness of demand-based models lies in the use of the level-of-service criterion (see, e.g. de Dios Ortuzar and Willumsen 2001). This criterion is not only used as a performance indicator to rate the quality of transport links, but also as a tool to guide investment decisions: links that do not provide the aimed-for level-of-service will be 'shortlisted' for capacity extension or other ways of improvement. From a social justice perspective, the level-of-service criterion is of key importance because it establishes a link between current travel patterns and the provision of new infrastructure. This link runs as follows: first, current travel patterns are used to forecast future travel demand; then, this future travel demand is projected onto the existing transport network; subsequently, current capacity and future demand are compared with one another and, finally, the level-of-service criterion is employed to determine which transport links are in need of improvement.

This interrelationship between current travel patterns and the level-of-service criterion inserts a loop into transport demand modelling. These models start with the current high trip rates among certain population groups (mostly car owners and high-income groups), then predict high trip levels among comparable future population groups, and subsequently suggest ways to cater for this growth through improved services (road building or high-quality public transport services), which in turn results in higher trip rates among these population groups. From here on, the loop starts again (Martens 2006a).

Given the link between current travel patterns and future demand, we expect that the consecutive application of the four-step model over a period of time, with the consequent development of transport infrastructure based on the model results at each stage, will exacerbate the existing gaps between high-mobile and low-mobile groups, in terms of available transport facilities and accessibility.

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4. Toy model

The hypothesis outlined at the end of the previous section has been tested using a simplified version of the four-step model. This 'toy model' is tested in a simple environment consisting of three residential zones (R) and one attraction zone (A). Each R contains a fixed number of households that does not change over time. R's differ in socio-economic composition and subsequently in their initial level of car ownership. Each R is composed of four income groups, but the relative share of each group differs between the R's. Hence, the R's differ in their overall socio-economic level. $R_{\mathrm{p(oor)}}$ is the poorest residential area and has the largest share of low-income households (INC1), while $R_{\mathrm{r(ich)}}$ is the richest area with the largest share of high-income households (INC4). $R_{\mathrm{m(iddle)}}$ has a middle position. Land use patterns are assumed to be fixed, i.e. households cannot move from one R to another. As a result, the socio-economic composition of each R does not change over time, but car ownership levels can alter as a result of car purchases by households. Each R is connected to A by road and transit. In the initial situation, the road is faster but more costly than the transit mode. The initial quality of both road and transit, in terms of travel speed and time, is identical for each R, but can change over time as a result of changes in traffic volumes and/or investments in transport infrastructure. Each trip generated in any R has destination A, while A does not generate any trips (Figure 1).

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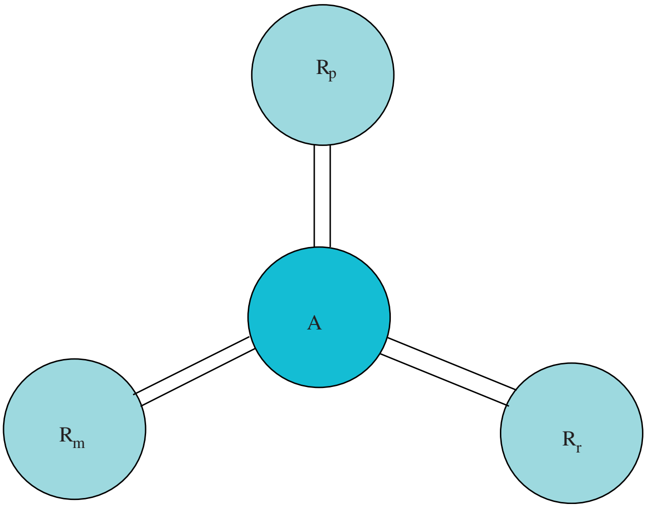

Figure 1. Model environment.

Since in this simple model environment there is only one destination and one link for each transport mode, the modelling steps of trip distribution and trip assignment become completely trivial. The toy model can thus be limited to the steps of trip generation and mode choice. In addition, in line with state-of-the-art models, a car-ownership feedback loop is added to the toy model.

The trip generation step requires input with regard to total number of households by category, and trip rates per household category. Households are classified according to income level and car ownership, as detailed above. For the initial situation, the size of each household category is derived from the model specifications and subsequently adjusted based on the results of the car-ownership model. The trip matrix is considered fixed throughout all iterations of the model, i.e. trip rates remain the same for each category of households. In line with actual practice, trip rates are positively correlated to household income and car-ownership level. For reasons of simplicity, all trips are executed during one time interval.

The mode choice step consists of a computation of the distribution of total trips over the two available modes (car and transit). The calculation is based on a simple utility function representing the generalised cost of each mode, which is a function of: (1) level-of-service provided by each mode (travel time and cost) and (2) socio-economic situation of the trip maker. Poor households are assumed to attach more weight to money and less to time, while the opposite holds for rich households. The probability of using a specific mode is inversely related to the mode's generalised cost, in a way that resembles common practice in discrete choice analysis (Ben-Akiva and Lerman 1985). Formally, the utility function of a transport mode can be presented as follows:

$$U_{\text{mode}} = a * 1/q * \text{COST}_{\text{mode}} + b * q * \text{TIME}_{\text{mode}} \tag{1}$$

where $\text{COST}_{\text{mode}}$ and $\text{TIME}_{\text{mode}}$ refer to travel cost and travel time, respectively, incurred when choosing the particular mode of transport; q is an income-group specific coefficient

($q = 1$ for poorest income group and $q = 4$ for richest income group); and a and b are constant parameters. This results, for each population segment, in generalised cost values for each mode, incorporating both monetary expenses and time spent on travelling. Subsequently, the probability of a household to use each transport mode for a specific trip can be formalised as follows:

$$P_{\mathrm{car}} = 1 - U_{\mathrm{car}}/(U_{\mathrm{car}} + U_{\mathrm{transit}}) = U_{\mathrm{transit}}/(U_{\mathrm{car}} + U_{\mathrm{transit}}) \tag{2}$$

$$P_{\mathrm{transit}} = 1 - U_{\mathrm{transit}}/(U_{\mathrm{car}} + U_{\mathrm{transit}}) = U_{\mathrm{car}}/(U_{\mathrm{car}} + U_{\mathrm{transit}}) \tag{3}$$

The inverse form of the probability function is the result of the fact that the utility function is in fact a generalised cost function. The probability of using a specific mode is thus inversely related to the utility derived from that mode. Finally, to get the modal split figures, the probability values are multiplied by the total number of trips.

The car-ownership feedback model is a crucial part of the toy model. The model relates a household's decision to purchase an additional car to two factors: (1) the advantage of car use over transit use ($U_{\mathrm{car}}/U_{\mathrm{transit}}$) and (2) household income (q). The first is calculated as the ratio of generalised costs of car and transit, and thus depends on travel speed and costs of each mode. Growth in car ownership is subsequently calculated per income group using a linear function of these two components. The function computes, for each model iteration, the probability for each population group that a household will buy an additional car

$$P_{\mathrm{car\_purchase}} = f(U_{\mathrm{car}}, U_{\mathrm{transit}}, q) \tag{4}$$

where q denotes household income, and c and d are constants. Growth in car ownership is limited by the model stipulation that households cannot purchase more than two cars. This limit has been set in order to avoid endless growth in car ownership and trip rates. The result is that growth in car ownership evens out in the later iterations of the model.

The toy model has been applied five times in a sequence in order to explore the implications of the consecutive application of the four-step model, as may happen in practice when versions of the model are used for several decades. Each iteration of the model can be considered to represent a fixed time interval of, for instance, 10 years. At the end of each iteration, data are generated on, e.g. number of trips, car ownership, modal split, road congestion, etc. These data – most notably the updated figures on car ownership per income group and data on increased transport capacity – are subsequently fed into the model as starting condition for next iteration. Figure 2 present the model flowchart.

The model has been applied to three scenarios. In the do-nothing scenario (S_0) no improvements are made in existing transport facilities (road and transit). Like in the other scenarios, in each model iteration households determine whether or not to purchase a car. Households that buy a car will 'move up' in the trip matrix and generate more trips than in the previous iteration. Most of these trips will be made by car, but some by public transport. The growth in trips results in increased congestion on road and transit, and subsequently in increased travel times.

The predict-and-provide scenario (S_1) represents the transport policy applied throughout much of the second half of the twentieth century, in the US and elsewhere. In S_1 road capacity is added whenever volume exceeds capacity by more than 20% and severe congestion occurs. In that case, road space is added in fixed portions till the

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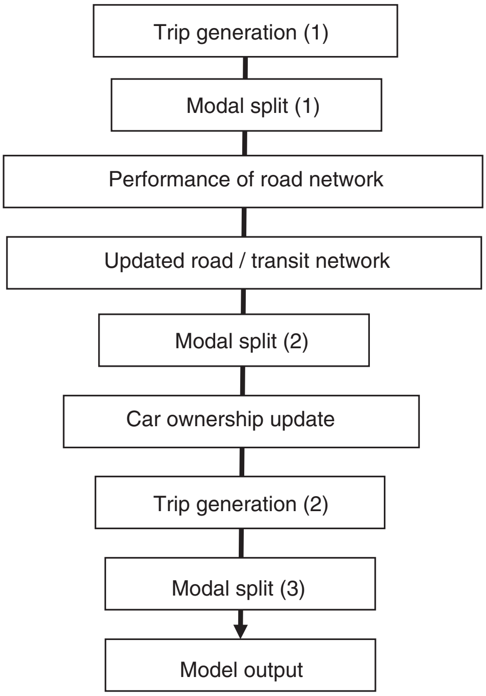

Figure 2. Model flow for one model iteration. The flowchart shows the car ownership feedback loop in a sequential way. First, the transport system is improved (step 'updated road/transit network'), resulting in a change in travel speed for car and transit, in part as a result of the increased capacity and in part because of a change in the modal split (step 'modal split (2)'). Based on the new travel speeds for each mode, households can then decide to purchase an (additional) car (step 'car ownership update'). The new data on car ownership level are then used to generate the model output, through the relevant steps of the regular four-step model (steps 'trip generation (2)' and 'modal split (3)'). For the results presented in this, the model flow has been applied for five consecutive times, each iteration building on the model output of the previous iteration.

volume/capacity ratio is less than 120%, without any financial constraint regarding the total capacity that can be added in each model iteration. No improvements are made in transit service in S_1.

The predict-and-prevent scenario (S_2) follows more recent policy lines that seek to limit the environmental impacts related to increasing car use (e.g. Vigar 2002). In S_2, transit services are improved in order to divert predicted increase in car use towards transit and avoid a volume/capacity ratio higher than 120%. It is important to stress that, for reasons of comparability between the scenarios, transit service is improved in the same way as the road system, i.e. through the addition of fixed portions of capacity, without taking into account real-life financial constraints. Also, like in the case of road infrastructure, increased capacity raises travel speeds of the transit service. This methodology reflects the real-life link between transit capacity (as measured in, e.g. seat-kilometres), transit frequency and travel times by transit. No improvements are made in road infrastructure in S_2.

The impacts of the scenarios on the distribution of the selected transport benefits (facilities and accessibility) will be explored through: (1) a before–after analysis and

(2) a with–without analysis. In the first method, for each scenario the final situation will be compared with the initial situation, in order to assess whether gaps between population groups in terms of infrastructure facilities or accessibility have increased or decreased. In the second method, S_0 will serve as the 'without' case and the final situation in S_1 and S_2 will be compared with the final situation in S_0. The latter approach is in line with assessment methodologies applied in, for instance, cost-benefit analysis.

5. Model results

The model and scenarios have been used to test the hypothesis formulated above – i.e. the hypothesis that a consecutive and consistent application of the four-step model will widen existing gaps between high-mobile and low-mobile groups in terms of transport facilities and accessibility. While in actual practice policies will often be based on other considerations than modelling results alone, these results do play a key role in shaping transport policies. Therefore, detailed understanding of possible distributive trends underlying demand-based modelling is relevant from a policy perspective.

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5.1. *General*

The results presented in this article refer to a case in which the toy model has been applied five times in a sequence. As specified above, number of households, trip rates by household type and socio-economic composition of each R does not change during the model iterations. However, in each model iteration, households can purchase a car (till a maximum of two per household). Since trip rates are positively correlated with the number of cars in a household, increasing car ownership also results in an increase in total trip numbers per R. This dynamics results in increasing congestion on road links in the do-nothing scenario (S_0). In the other scenarios, the capacity of the transport network is expanded to avoid increasing road congestion; in the predict-and-provide scenario (S_1) road capacity is increased; in the predict-and-prevent scenario (S_2) transit capacity is increased. In this section, we briefly describe the dynamics taking place in each scenario.

Like in the other two scenario's, in S_0 car ownership increases with each model iteration. As a result total trip numbers also increase, which result in substantial congestion on each of the road links. Car speed drops with more than 20 index points – how do you calculate this index? It is necessary to understand all your charts; transit also suffers delays due to congestion, but no more than a few index points (Figure 3). However, since travel by car remains substantially faster than by transit, car ownership continues to rise in each model iteration and car share in modal split increases by about 10%.

In S_1, road congestion resulting from higher car ownership and resulting trips numbers is countered with investments in road capacity. As a result, car speed drops by only five index points, the maximum drop following modelling specifications (Figure 3). This limited decrease in level-of-service is achieved by increasing road capacity in virtually every model iteration (Figure 4). Depending on the R, capacity is increased with 37% till 57% over five model iterations, with the highest increase in R_p. Due to these investments, car ownership is more attractive in S_1 than in S_0 and therefore increases more rapidly. In this way, capacity enhancement creates the need for further capacity increases in the

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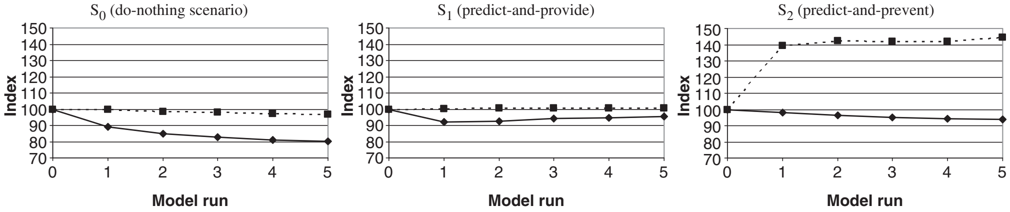

Figure 3. Change in travel speed by car (—◆—) and transit (-■-) over five model iterations, for each scenario (T_0 (initial situation) = 100). The presented data relate to the travel speeds on the road and transit links between R_m and A; the travel speeds on the links between R_p and A and between R_r and A show comparable trends.

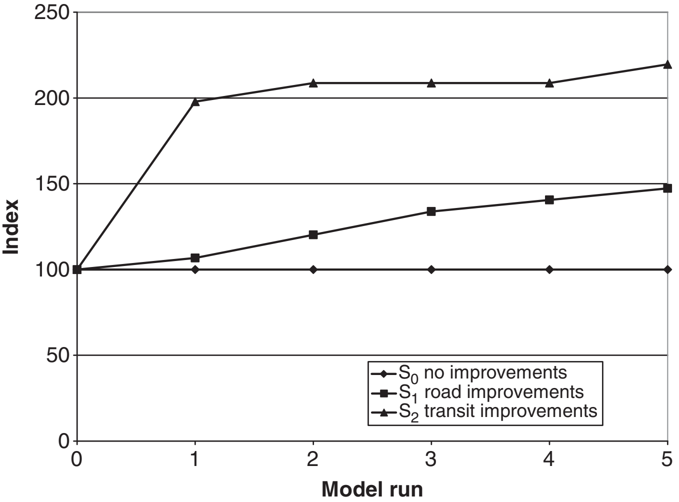

Figure 4. Increase in transport capacity over five model iterations, for each scenario (T_0 (initial situation) = 100). The presented data relate to capacity improvements on the road and transit links between R_m and A; the improvements on the links between R_p and A and between R_r and A show comparable trends.

next model iteration. Obviously, this is the result of model specifications, but can also be viewed as a representation of current real-world dynamics of increasing car ownership and road capacity improvement (Mogridge 1997).

In S_2, transit capacity is extended in order to avoid an increase in congestion beyond a volume/capacity ratio of 120%. This policy goal requires enormous investments in transit capacity in the first model iteration: transit capacity is increased with 88–102%, with the highest increase in R_r. Investments in subsequent iterations are substantially lower, certainly when compared to road investments in S_1. While the absolute figures for capacity increases are difficult to compare, these differences in the sequence of investments are striking (Figure 4). The investments in transit capacity result in substantially lower increases in car ownership than in either S_0 or S_1. However, car ownership still increases slowly in S_2 as car travel times remain lower than transit travel times. The low increase in car ownership directly translates into a low growth in total number of trips – the growth rate in S_2 is only half the rate of growth registered in S_1. Further, the distributive implications of these dynamics are explored.

5.2. *Facilities*

The first distributive analysis explores the distribution of transport facilities over income groups. For this comparison, capacity per household has been calculated in a way that links capacity to trips, i.e. the higher the number of trips a household makes, the higher its share in total capacity. The obvious consequence of this measure is that in the initial situation, higher income groups will receive more capacity than lower income groups, simply because the former makes more trips. Furthermore, most additional capacity will flow to the income groups with the strongest overall increase in total trips. Recall that the latter increase is a direct result of car purchases.

The with–without analysis shows that in both S_1 and S_2 gaps between income groups are growing. In both cases, the richer income groups (INC3 and 4) benefit substantially more from the additional capacity, whether it is road capacity in S_1 or transit capacity in S_2. Interestingly, the before–after comparison shows somewhat different results. In the case of S_1, INC2 profits most from the additional road capacity. INC3 and 4 benefit less, mostly because of the maximum number of two cars per household specified in the model. This specification impacts richer households first, as they start off with higher car ownership levels and have the strongest tendency to purchase cars. They will therefore reach the maximum number of cars per household first, *de facto* blocking further growth in trip numbers. The result is that in S_1, gaps are shrinking between INC2 and the higher income groups, while gaps are growing for the poorest income group (INC1). The results thus neither confirm nor refute the hypothesis (Table 2).

Table 2. Increase in transport capacity per household, before–after comparison.

		S_1: car capacity			S_2: transit capacity		
Residential area	Income group	Initial capacity	Additional capacity	Final capacity	Initial capacity	Additional capacity	Final capacity
R_p	INC1	0.62	0.54	1.15	1.07	1.07	2.14
	INC2	2.69	2.51	5.20	2.42	2.58	5.00
	INC3	4.43	1.97	6.40	2.59	3.18	5.77
	INC4	6.86	1.37	8.23	3.30	4.10	7.41
R_m	INC1	0.62	0.62	1.24	1.06	1.09	2.15
	INC2	2.99	2.43	5.42	2.35	2.64	5.00
	INC3	4.51	2.10	6.60	2.56	3.21	5.77
	INC4	6.86	1.60	8.46	3.29	4.12	7.40
R_r	INC1	0.66	0.57	1.23	1.06	1.17	2.22
	INC2	2.68	2.57	5.24	2.40	2.77	5.17
	INC3	4.48	1.95	6.43	2.56	3.43	5.98
	INC4	6.82	1.42	8.24	3.28	4.39	7.66

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The situation is different in S_2. Here, transit improvements reduce travel time differences between car and transit. This reduces the incentive to purchase cars, especially among poorer households, and thus limits growth in trip rates for these groups. The result is that INC3 and 4 profit most from increases in transit capacity, while INC1 hardly benefits. Thus, while initially gaps in transit capacity are small, gaps grow at a high rate over time.

In contrast, in S_0 the gaps between income groups are decreasing, most notably for car capacity. This is due to the fact that poorer income groups increase their share in total number of trips, which is explained by low initial share in trip numbers and relatively strong growth in car ownership. Taken together, this increases the poorer income group's share in the existing, fixed, capacity.

5.3. *Travel time*

The second set of analyses explores the changes in travel time, as a first indicator of accessibility. From the wide range of accessibility measures discussed in the literature to assess the impact of transport investments (for an overview, see Handy and Niemeier 1997, Geurs and Ritsema van Eck 2001), travel time is a suitable and easy-to-interpret indicator, given the simple spatial environment used in the toy model. Because the spatial environment includes only one destination, some of the widely-used accessibility measures, such as contour-based and gravity-based measures, are either not applicable in the current case or unnecessarily complicated. Note that below, we also explore the distributive impacts of the four-step model using expected utility as the accessibility indicator.

A number of analyses have been carried out using travel time as the accessibility indicator. First, a with–without assessment of changes in travel times has been carried out. Naturally, travel times are shorter in the policy scenarios than in S_0. But there are substantial differences in travel time savings between the two scenarios. In case of S_1, car-drivers (owners and buyers) reap substantially more travel time savings than car-less households, enlarging the time gaps between both groups in comparison to S_0. Car drivers residing in R_p are better off than those residing in richer areas. This is a combined result of low initial road capacity and a large pool of potential car-buyers generating a relatively large increase in total trip numbers. In S_2, car-less households reap substantially more time savings than car-driving households. The result is that gaps in travel times are sharply reduced, although car drivers remain in a better position than transit users after five model iterations. Car-less households in R_r benefit slightly more than those in poorer areas. This is caused by the large share of high-income groups, which are more inclined to choose road rather than transit. Transit service thus has to improve more in the richer areas, in order to prevent additional car use. Note furthermore that car-driving households are somewhat better off in S_1, while car-less households are much better off in S_2. In terms of distribution of travel times, the results show that gaps in travel times are increasing in S_1 and decreasing in S_2.

Again, the results are somewhat different in case a before–after evaluation is carried out. In that case, gaps between car-owners and car-less households are decreasing in all scenarios (Table 3). In S_0, both car-owning and car-less households face an increase in travel time, but the latter substantially less than the former. This is due to the preference for the car over transit, which results in a stronger increase in road congestion and thus in travel time. In S_1, car-less households experience a small reduction in travel time, due

Table 3. Changes in travel time per user group as a result of transport investments, before–after comparison.

	Initial travel times		S_0 do-nothing			S_1 provide			S_2 prevent		
	Car	Transit	CO	CB	CL	CO	CB	CL	CO	CB	CL
R_P	20.78	33.14	+5.87	−6.49	+0.96	+1.22	−11.13	−0.17	+1.34	−11.02	−10.16
R_m	20.78	33.18	+5.14	−7.31	+1.06	+0.96	−11.49	−0.20	+1.33	−11.12	−10.24
R_r	20.84	33.02	+4.61	−7.84	+0.83	+1.15	−11.30	−0.29	+1.28	−11.17	−10.61

Note: CO = car owners, CB = car buyers, CL = car-less households.

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to a decrease in transit ridership and related increase in transit speed. Car-owning households, in turn, are faced with a light increase in travel time, despite investments in road infrastructure. This is largely a result of model specifications, which define no congestion in the initial situation but increasing congestion till a fixed maximum during the model iterations. This specification also plays a role in S_2, in which case car-owning households face a small increase in travel time too. Car-less households, as well as car-buyers, face a large reduction in travel time, substantially reducing the travel time gaps in comparison to the initial situation. The difference between both groups disappears completely after more model iterations, in which case transit becomes as attractive as the car, reducing car purchases till the minimum.

5.4. *Expected utility*

The second indicator of accessibility is expected utility. Utility associated with trips, and more specifically expected utility, is a widely used measure of accessibility (see, e.g. Miller 1999b, Garb and Levine 2002), particularly in use as part of advanced activity-based transport modelling approaches (Dong *et al.* 2006). It takes into account both the benefit, i.e. the desirability of a destination and the cost of reaching it. In our model, the benefit derived from each trip is identical, so only variations in costs play a role. Car-owners may choose between car or transit, so that their expected utility is a weighted average of the utilities of both modes, while the car-less are bound to use transit. Following Equation (1), expected utility for each group can be formalised as follows:

$$E(U_{\text{car-owner}}) = P_{\text{car}} * U_{\text{car}} + P_{\text{transit}} * U_{\text{transit}} \tag{5}$$

$$E(U_{\text{car-less}}) = U_{\text{transit}} \tag{6}$$

Note that since higher income groups ascribe higher value to time and since time is more dominant in the utility function than cost, higher income groups will always have the lowest utility (or: largest disutility) in the initial situation. This complicates the equity analysis, as the equalisation criterion now suggests that the utility of high-income groups should be brought on par with that of lower income groups. *De facto* this would mean investing in transport facilities that primarily serve rich and already high-mobile groups. While perhaps logical from an economic perspective, this seems counter-intuitive from a justice perspective. So rather than focusing on the equalisation of expected utility (henceforth U_{exp}) for all income groups, the focus of analysis has shifted to the *additional* expected utility received by each income group, using equality as the equity yardstick. Note that this implicitly assumes that the existing distribution of U_{exp} is proper.

The results of the with–without analysis show that higher income groups receive most additional U_{exp}, in both S_1 and S_2, and in all *R*'s. This is the combined result of the transport investments in the policy scenarios, which reduce travel times in comparison to S_0, and the fact that higher income groups attach higher value to the time savings generated by these investments. Note that gaps between income groups in additional U_{exp} are substantially larger in S_2 than S_1. This is a result of the fact that upgraded transit facilities decrease travel time for both car and transit. Higher income groups thus also profit from the large decrease in transit time in S_2, despite the fact that the car remains the fastest mode (at least after five model iterations). Furthermore, each income group reaps more additional U_{exp} in S_2 than in S_1. Once again, this is the result of a large decrease in transit time and a small decrease in car time in S_2. In sum, while S_2 makes everybody substantially better off than S_1, S_2 is also the scenario with the largest gaps in the distribution of additional U_{exp}. The before–after comparison shows comparable results.

The problems related to the utility measure disappear when expected utility is compared *within* income groups. In that case, the income effect on time and cost valuation disappears and the attention can be redirected towards total rather than additional U_{exp}. Because of this, the measure is well-suited to assess the distribution of accessibility over groups distinguished by mode availability. The results of the with–without comparison show that in the case of S_1, car-owning households always reap more additional U_{exp} than car-less households. This is obviously the result of investments in road infrastructure, which substantially improve car speed but only slightly reduce congestion on transit services and thus transit travel time. The result is that gaps between car-owning and car-less households in total U_{exp} increase for all income groups and in all *R*'s. In contrast, in $S_{2,}$ car-less households experience a stronger increase in additional U_{exp} than car-owning households. The result is that the gaps between both groups decrease substantially in comparison to S_0, even to such an extent that car-less households are better off after five model iterations than car-owning households in terms of total U_{exp}.

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5.5. Some remarks

Table 4 provides a qualitative overview of the impacts of each scenario on the distribution of the selected transport benefits over population groups. The most striking result is that the hypothesis formulated above cannot be confirmed throughout. In each scenario, gaps between high-mobile and low-mobile groups are increasing and decreasing at the same time. This result is most clear for S_2, but it also occurs for S_1. While some distributional trends will be the result of model specifications, the simple hypothetical case presented here makes clear that the four-step model has less clear-cut distributive implications than expected at the outset.

6. Discussion

Based on an initial analysis of the still-dominant four-step model, we have formulated the hypothesis in this article that the consecutive application of the model will widen the

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Table 4. Overview of distributional impacts of all scenarios.[a]

			Distinction of population groups by	
Benefit	Comparison	Scenario	Income (INC)	Mode
Capacity per household	Before–after	S_0	−	Not analysed
		S_1	0	
		S_2	++	
	With–without	S_1	+	Not analysed
		S_2	++	
Travel time	Before–after	S_0	Not relevant	+
		S_1		−
		S_2		−−
	With–without	S_1	Not relevant	+
		S_2		−−
Total expected utility	Before–after	S_0	Not relevant	0
		S_1		+
		S_2		−−
	With–without	S_1	Not relevant	+
		S_2		−−
Additional expected utility[b]	Before–after	S_0	+	Not analysed
		S_1	++	
		S_2	+++	
	With–without	S_1	++	Not analysed
		S_2	+++	

Notes: [a]The table should be interpreted as follows: +(+) = gaps increase (strongly); −(−) = gaps decrease (strongly) and 0 = no clear tendency.
[b]For additional expected utility, the number of '+' signs indicates the size of the deviation from an equal distribution of the benefit in favour of richer income groups.

existing gaps between high-mobile and low-mobile groups, in terms of available transport facilities and accessibility. Subsequently, we have developed a simple model to test the hypothesis. The results of this article provide food for thought on two levels.

The first level concerns the distributive implications of the application of transport demand modelling, and more specifically the four-step model. Despite its limitations, we feel that the simple model and the 'longitudinal' modelling approach applied in this article have helped to shed light on these distributive implications. The results of our simple model show that the hypothesis formulated above cannot be confirmed. Against our expectations, the distributive implications of demand-based modelling seem to depend on the situation. They depend on the initial circumstances in which modelling is employed (e.g. level of population segregation, existing transport network and motorisation levels), on the policy responses derived from the modelling results (provide or prevent approach), on the transport benefit that is analysed (facilities or accessibility), on the groups that are compared (income or mode groups) and on the benchmark that is used (before–after or with-without).

Thus, while transport demand modelling has built-in tendencies to strengthen high-mobile groups at the expense of low-mobile groups, the actual translation of the model results into transport investment priorities may neutralise these tendencies. While this

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effect may not have occurred throughout much of the period in which the predict-and-provide approach was prevalent, it is a real possibility now that predict-and-prevent policies are gaining in importance. Since in real-life it will be difficult to assess whether the built-in tendencies will be neutralised or not, the danger remains that transport modelling will exacerbate existing gaps in mobility and accessibility. These observations suggest that, if transport modelling is to contribute to a more just distribution of transport facilities and accessibility, it will be necessary to incorporate explicit indicators concerning the distribution of transport improvements over population groups into transport modelling, as well as in transport project appraisal.

This brings us to the second level: the integration of social justice considerations into mainstream transport modelling and planning. Recent developments suggest that this issue can no longer be ignored. First, there is increasing evidence on the far-reaching implications of inadequate transport services on the everyday life of the most vulnerable groups in society (e.g. Hine and Mitchell 2001, Blumenberg 2004, Cebollada 2008). Second, the increasing political importance of the concepts of sustainable development and, in its wake, sustainable transport, requires elaboration of the social or equity dimension of sustainability (Boschmann and Kwan 2008). While a distributive approach is well-developed in fields like education and health (see, e.g. Elster 1992), the equity dimension of sustainable transport has remained largely implicit in research and practice. As a result, there has been hardly any systematic reflection on distributive issues in the field of transport (see also Martens 2008). This includes the three basic questions outlined at the beginning of this article: Which benefits are we actually distributing? What are the relevant population groups to distinguish? And how do we judge whether a certain distribution is just or not? The limited research in the transport field does not address these questions in any systematic way. Much of the work focuses on specific transport benefits, like transit subsidies or congestion pricing, while it could be argued that accessibility as such is of key importance to citizens (e.g. Garb and Levine 2002, Boschmann and Kwan 2008). Likewise, much of the literature implicitly or explicitly uses equality as the yardstick to assess the distribution of transport-related benefits, without providing convincing arguments that this is the proper criterion to apply in the field of transport. It may be clear that these questions need to be answered first, before distributive criteria can be fully integrated into transport modelling and planning.

7. Conclusion

In this article, we have linked two fields of research that traditionally do not meet: transport modelling and distributive justice. We have argued that explicit attention for the equity implications of transport models is called for, given the crucial, albeit often implicit, role of transport models in the distribution of transport facilities and accessibility. The exploration into the relationship between modelling and justice started from the hypothesis that the consecutive application of the four-step model over a number of years, and successive investments in transport infrastructure consistent with the model results, will widen existing gaps between high-mobile and low-mobile groups, in terms of transport facilities and accessibility available to each group. A simplified four-step model was developed to test this hypothesis under different policy scenarios. The results of the simulations are mixed. In each scenario, gaps between high-mobile and low-mobile groups are increasing and decreasing at the same time. Against expectations, the distributive implications of demand-based modelling seem to depend on the situation and the focus of analysis. Given the unpredictable distributive impacts, it is suggested that explicit justice indicators be incorporated in transport modelling if it is to contribute to a more just distribution of transport facilities and accessibility over population groups.

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Note

1. Throughout this article the terms ‘justice’ and ‘just’ are employed, rather than the terms ‘equity’, ‘fairness’ and ‘fair’. While each of these terms may refer to different concepts in certain contexts, in common usage the terms strongly overlap and are used interchangeably (see also Hay 1995).

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