Policy options for sustainable urban development: a modeling approach

Options politiques pour un développement urbain durable: une approche par la modélisation

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ABSTRACT: An optimal control model is presented that characterizes the changing states of system capacity and allowable traffic volume as a result of transport planners' investment in mode-specific infrastructure, e.g. bus-lanes, or road maintenance as well as his financial sustainability constraint. A common throughput-based optimization criterion is compared with an accessibility based criterion. The feasibility is demonstrated for a case study, which is representative for a developing city.

RÉSUMÉ: Un modèle de contrôle optimum du réseau de transport urbain est présenté dans ce document. Il caractérise les changements apportés a un système en termes de capacité globale et de trafic autorisé en fonction des investissements en infrastructures telles que voies réservées aux bus ou maintenance des routes effectués par les planificateurs de transport avec comme principale contrainte un équilibre financier à long terme. L'approche habituelle d'optimisation du critère trafic est comparée avec celle d'optimisation du critère accessibilité. La faisabilité est démontrée pour un cas, représentatif des villes des pays en voie de développement.

1 INTRODUCTION

To be effective, transport policy must satisfy three main requirements (World Bank, 1996):

1. It must ensure that a continuing capacity exists to support an improved material standard of living. This corresponds to the concept of economic and financial sustainability;
2. It must generate the greatest possible improvement in the general quality of life. This relates to the concept of environmental and ecological sustainability;
3. The benefits that transport produces must be shared equitably by all sections of the community. This is termed social sustainability.

Economic, environmental and social sustainability in transport are often mutually reinforcing. This urges the need to develop sets of policy instruments that serve the different dimensions of sustainability in a synergetic way.

The principle idea of sustainable development takes this even further by relating this to present as well as long-term development, as becomes clear from the definition posed by (WCED, 1987):

"development that meets the needs of the present without compromising the ability of future generations to meet their own needs.".

The concept of sustainable development evokes fundamental questions, such as how to define intergenerational equity, how to indicate quality of human life, how to maintain global life-support systems, how to value multifunctional natural resources, how to bring an end to global inequity, and how to design institutional frameworks for change.

Related to transport these fundamental questions also hold, but can be more specifically stated as:

- how to use limited transportation related resources to guarantee intergenerational equity;
- how to sustain or enhance basic mobility and accessibility options to people.

In this research a multi-directional concept of sustainable development is adapted, after (Gudmundsson & Höjer, 1996), i.e. a conception where sustainability and development represent different dimensions. Sustainability refers to criteria for long-term stability of the social system, relevant for future generations, while development is the perceptible improvement of the quality of human life for the present generation.

From this view it is clear that sustainable development is unconditionally related to a long-term perspective. This urges the use of long-term, dynamic models. Current transportation models are mostly static and, therefore, often fail in incorporating dynamic feedbacks. The continuous-time optimal control models presented in a/o (Donaghy & Schintler, 1998) appear to be very suitable for modeling sustainable development in a transportation context.

The presented model in this paper will have its application in developing countries. Cities in these countries are often confronted with sustainable development requirements (e.g. in their search for loans). The modeling framework proposed in this research reckons with sustainability requirements as well as the development of the transportation system itself. A dynamic model reveals what steps ought to be taken, when and where, and by how much in order to achieve sustainability targets. The model is can be extended with for example, an elastic demand model as to reveal latent demand, that is the existing demand that cannot be satisfied, perhaps because of inadequacies in the infrastructure or prohibitive costs.

2 CONCEPTUAL FRAMEWORK

In recent years, the concept of sustainable development and its meaning in transportation have been given many interpretations. Some of the characteristics and problems of the common interpretations have been highlighted in (Akinyemi & Zuidgeest, 2000) as well as (Akinyemi & Zuidgeest, 2002). Undoubtedly, the current debate has been useful in generating ideas and suggestions. However, the current focus and most of the presentations have been generally limited to (*a*) the issues that need to be resolved for transportation to conform to the principles of sustainable development and (*b*) the required policy paths. The idea has not yet reached planning and operational practices and actions in transportation infrastructure. Consequently, two major needs can be defined. The first is to define specific requirements that can be used as guidelines in infrastructure design and management. The second is to find ways of operationalizing the concept of sustainable development in infrastructure performance planning and management. Table 1 shows some different levels of the requirements that have been defined on the basis of the basic definition of sustainable development.

It is this model that aims for operationalizing the concept of sustainable development in transportation engineering satisfaction of present needs is dealt with through a focus on enhancement of accessibility in the urban transportation system for all groups of people in the area. The ability to meet future needs is captured through the incorporation of strict resource use constraints. These can either be rate-limited, for example pollutant emissions, or stock-limited as the budget available for road construction and maintenance.

Table 1 Sustainable development criteria and implications for transportation.

Level 1 criteria	Level 2 criteria	Transportation-related requirements
Satisfaction of present needs	Improvement in (*a*) economic and social well-being (*b*) financial and economic efficiency and (*c*) equity	Improvement in (*a*) people and goods mobility, i.e. the ability of people and goods to move or be moved easily and comfortably around; (*b*) accessibility, i.e. the ability of people and goods to move or be moved easily to essential facilities and services; (*c*) distribution of mobility and accessibility among people and geographical areas
Ability to meet future needs	Sustainable use rate of rate-limited resources	Production rate of wastes is less than what the environment can accommodate
	Conservation of stock-limited resources	Resources consumed are, at any given time, less than the resources available during the time period

3 A DYNAMIC TRANSPORTATION MODEL

3.1 Introduction

A dynamic transportation model is presented and analyzed that seeks partial equilibria between infrastructure supply and travel demand, constrained by a financial resource constraint using an optimal control technique. It is the transportation planner who aims to reach a certain objective. This objective traditionally is to focus on revealing congestion. Confronted with sustainable development ideas the planner might wish to adapt his main objective to one that is aiming at optimizing accessibility more than having a primary focus on revealing congestion.

3.2 Infrastructure supply

Based on (Donaghy and Schintler, 1994) the following simple dynamic disequilibrium model can be used.

Let G(N,L) be a network with nodes $n \in$ set N and links $l \in$ set L. Let links that lack facilities to be dedicated for exclusive use be indexed by l=1,…,L-H. Links that are dedicated to exclusive use are indexed by lh=1,…,H. When it is not dedicated, but facilities are present, its capacity is added to that of the other lanes in the link, la=1,…,H.

The changing state of the capacity C_{lt} of the different link sections l at time t and capacity C_{lat} for link sections lat at time t is formulated with the use of differential Equations as:

$$\frac{dC_{lt}}{dt} = NC_{lt} - \delta C_{lt} \quad l = 1, \cdots, L-H \tag{1}$$

$$\frac{dC_{lat}}{dt} = NC_{lat} - \delta C_{lat} + \phi_1 C^*_{lh} \tag{2}$$
$$la = 1, \cdots, H, \; lh = la$$

with,

$$\phi_1 = [(1 - I_{lht})(1 - S_{lht}) - S_{lht} I_{lht}] \tag{3}$$

The control variable NC_{lt} is newly constructed capacity at linksection l at time t, δ is a road capacity deterioration factor that accounts for road condition.

The control variable S_{lht} is a switching variable that if unit valued denotes a link is to be dedicated for exclusive vehicle use (a fixed link capacity C_{lh}*. It is zero valued otherwise. I_{lht} is a switching variable that if zero valued denotes that a link is dedicated for the exclusive vehicle use. It is unit valued otherwise.

From Equation 3 decision table 2 results:

Table 2 Possible combinations of switching variables I_{lht} and S_{lht} and their implication for the value ϕ_1 in eqation 3.

I_{lht}	S_{lht}	ϕ	Description
1	0	0	No change
0	1	0	No change
1	1	-1	Changes to exclusive use
0	0	1	Changes from exclusive use

The third option is illustrated in Figure 1.

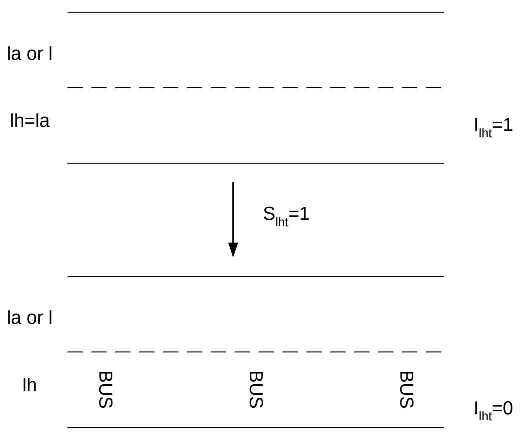

Figure 1. The switching variables I_{lht} and S_{lht} illustrated

3.3 *Travel demand*

The changing state of the volumes of traffic V_{lt} in linksections l, la and lh at time t is formulated as:

$$\frac{dV_{lt}}{dt} = \gamma_1(\hat{V}_{lt} - V_{lt}) \quad l = 1, \cdots, L-H \tag{4}$$

with hatted $\hat{V}_{lt}$ being the partial equilibrium that will initiate a time-lagged adjustment from the actual level to this partial equilibrium level (γ_1 denotes the disequilibrium adjustment parameter). For links of the type la or lh similar Equations for (hatted) $\hat{V}_{lat}$ and $\hat{V}_{lht}$ exist. (1)

This partial-equilibrium link-demand can be derived using a direct-demand model (see a/o (Donaghy & Schintler, 1998) or (Ortúzar & Willumsen, 1994)) that is simultaneous calculating route-choice, mode-choice and destination-choice on the basis of the utility experienced by the trip-maker of choosing a certain route, mode and destination. The direct demand model is not discussed in this text, but is available on request and can also be found in (Donaghy & Schintler, 1998).

The number of trips possibly generated in the several zones of the study area are exogenously determined with a trip generation (regression) model on the basis of production attractiveness and attraction attractiveness of the zones. For example land-use developments can be (exogenously) added to the model (see also paragraph 4).

The utility experienced by a trip-maker in its simplest form is a function of the travel-time tt as well as the out-of-pocket costs tc experienced by a trip-maker going from i to j with mode m, taking route r at time t, which can be depicted as:

$$gc_{ijmrt} = \beta_1 tt_{ijmrt} + \beta_2 tc_{ijmrt} \tag{5}$$

This utility denoted in this Equation is often called generalized costs gc of the trip. The parameters $\beta_{1,2}$ are negative. The utility function is easily extended with location specific choice variables as safety, comfort etc. The travel-time is formulated as a decreasing negative exponential function of the link-intensity versus the link-capacity and is commonly stated as:

$$tt_{ijmrt} = \sum_{l \in R_{ij}} tt^0{}_l [1.0 + \alpha (\frac{V_{lt}}{C_{lt}})^{\beta_3}] \tag{6}$$

here the set R_{ij} denotes the set of links that make the route ij, $tt^0{}_l$ is the free-flow travel time on link l. α and β are parameters. In Equation 6 the infrastructure supply side C_{lt} and travel demand V_{lt} side come together.

3.4 *Sustainability constraint*

Since this paper intends to show the feasibility of the dynamic approach only the financial sustainability constraint is discussed in this paper.

First a land-use limitation is imposed to put a limit to total new construction in a certain period t:

$$0 \le NC_{lt} \le NC^u_{lt} \tag{7}$$

Furthermore, it could be stated that the minimum new construction to a link in a period is equal to the physical deterioration, through which Equation 7 changes in:

$$\delta C_{lt} \le NC_{lt} \le NC^u_{lt} \tag{8}$$

Lastly the financial sustainability requirement puts a financial resource limitation as a budget constraint:

$$\sum_{l} CC_{lt} NC_{lt} \leq B_t \tag{9}$$

which simply states that the amount of new construction at time t times a unit cost of construction at time t, CC_t must be less or equal the available budget for construction B_t at time t.

3.5 *Transport planners' objective*

For this paper two system management approaches have been studied. First a common throughput-based approach, that is used by (Donaghy & Schinter, 1994) for a similar, but extended, network management problem. Here the quantity that the planner will seek to minimize can be stated as minimizing congestion, that is usually stated as the proportion V_{lt}/C_{lt}, (Level-of-Service) on a link. From a viewpoint of investment efficiency, the volume-capacity ratio is kept close to unity on a link, as to prevent the model from minimizing the ratio in the direction of zero. (Donaghy & Schintler, 1994)'s management problem over the time period t_0 to t_1 is formulated as:

$$\min \int_{t_0}^{t_1} \sum_{l} \left(\frac{V_{lt}}{C_{lt}} - 1 \right)^2 + \sum_{la} \left(\frac{V_{lat}}{C_{lat}} - 1 \right)^2 + \sum_{lh} \left(\frac{V_{lht}}{C^{*}_{lh}} - S_{lht} \right)^2 dt \tag{10}$$

Second, an accessibility-based approach is proposed, since accessibility-based approached are believed to be more suitable for sustainability studies than throughput-based approaches. Therefore, a throughput-based approach has been compared with an accessibility-based approach. In this research use is being made of the relative accessibility concept proposed by (Sales Filho, 1998). He proposes a model for relative accessibility using a geometric average of the origin and destination attractiveness:

$$A_{ijt} = \left(Q_{it} \cdot X_{jt} \right)^{1/2} f(gc_{ijt}) \tag{11}$$

In this formulation origin interaction potential Q_{it} and destination attraction potential X_{jt} are coupled as to be able to derive an accessibility matrix alike an origin-destination matrix, but with the cells filled with relative accessibility values. $f(gc_{ijt})$ is a monotonously decreasing function of the generalized costs depicted in Equation 5. For example an exponential function $\exp(gc_{ijt})$ where gc_{ijt} is negative. The exogenously determined values for Q'_{it} and X'_{jt} are corrected to obtain a more realistic level of interaction. For example for the extent to which a certain origin or destination contributes to the total origin or destination potential, or for the average number of possible interrelationships between origins and destinations. The correcting factors are not mentioned in this text, but are available on request or can be found in (Sales Filho, 1998).

Equation 11 is extended to obtain an objective function to the optimal control problem:

$$\max \int_{t_0}^{t_1} \sum_{m} \beta_m \sum_{i} \sum_{i \neq j} \sum_{r \in R_{ij}} \left(Q_{it} \cdot X_{jt} \right)^{1/2} \exp(gc_{ijt}) dt \tag{12}$$

Here, β_m is added as a weight for mode m, through which political or planner's preference can be expressed.

4 APPLICATION

The dynamic network management problem previously discussed with two objective function formulation has been applied to a small hypothetical transportation network, for example a corridor between two major zones with three routes and an intermediate zone.

A network with 3 nodes representing zones with production and attraction attractiveness and 4 two-way links G(3,4) is shown in Figure 2. Links 2 and 3 have facilities for an exclusive public transportation lane.

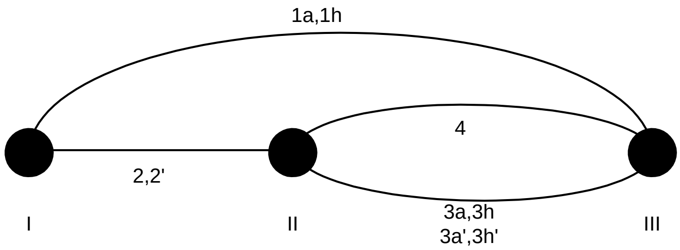

Figure 2. A hypothetical network

The three zones have a production attractiveness indicated through the number of households in the zones. The attraction attractiveness is indicated using an estimate of the total number of (formal and informal) job opportunities.

Table 3 has been constructed for a simulation horizon of 10 years, using a trip generation model and forecasts on developments in the three zones in the years ahead.

Table 3 Exogenously forecasted attractiveness data and balanced trip generation data

t	Q	X	Trip Prod	Trip Attr
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

The transportation routes are depicted in table 4.

Table 4 The transportation network routes

Route	Origin	Destination	Links
1	1	2	2
2	1	2	1a, 3a'
3	1	2	1a, 3h'
4	1	2	1h, 3a'
5	1	2	1h, 3h'
6	1	3	1a
7	1	3	1h
8	1	3	2, 4
9	1	3	2, 3a
10	1	3	2, 3h
11	2	1	2'
12	2	3	4
13	2	3	3a
14	2	3	3h
15	3	2	3a'
16	3	2	3h'
17	3	1	3a', 2'
18	3	1	3h', 2'

5 RELEVANCE TO DEVELOPING CITIES

5.1 *Critiques to forecasting models*

Many critiques are known to the use of traffic forecasting models in developed countries, let alone in developing countries. Therefore, long-term forecasts in developing countries can be irresponsible if not carefully studied upon on beforehand. (Vasconcellos, 2001) gives an impressive write-up on shortcomings and threats to using traditional forecasting techniques in developing cities from a technical, strategic, political, ideological as well as appraisal point of view. Some of them are:

Technical:

- the lack of procedures to model non-motorized and public transport demand;
- the disregard of non-conventional factors that lie behind travelling decisions, and the existence of latent demand;
- the inadequate treatment of typical traffic mix.

Strategic:

- due to unstable social and political environments permanent changes occur to user-groups, proposal appear to be unsustainable and unrealistic afterwards;
- the ongoing struggle between the long-term perspective of planners and the short-term perspective of politicians.

Political:

- the political reality in many developing countries, where the state and not the sectors make the final decisions.

Ideological:

- models lack possibility for adequately modeling modal choice processes as those exist in developing cities;
- neglect of walking, cycling and public transport.

(Langen & Tembele, 2001) state that traditional travel demand forecast models as the basis for infrastructure construction requirements have shortcoming, since:

- the road network and the road design strongly influence the demand for travel;
- the road design choices strongly influence the modal split development;
- the combination of income level, vehicle ownership and latent demand is not well understood.
- the availability and type of infrastructure influences vehicle ownership.

These reasons plead for an approach in which the focus is on the (dynamic) equilibration of travel demand and infrastructure supply, since then there is a direct interrelationship between provided infrastructure and the type and extent of travel demand.

5.2 *Developing a dynamic model for developing cities*

The dynamic transport model developed in this research builds on the wish to derive an optimal mix of engineering as well as price measures as to optimize accessibility for different user-groups in an urban transport system. The engineering measures are typically supply related and may influence mode-specific capacity through new construction, maintenance and prioritization. Here, the modes considered represent the typical mix seen in developing cities, including non-motorized, public transport as well as motorized transport. Through an accessibility-based criterion, that uses a productive capacity (trip-based) of the system instead of physical capacity (vehicle-based) the model is multi-modal and considers user-groups explicitly, as to account for the social sustainability issue.

Further research is planned to replace the partial equilibrium flow V_{lt} with an elastic-demand model as to reveal suppressed, or latent demand.

The dynamic character makes it possible to see the implications of decisions made by the transport planner and the lagged reaction of the trip-maker. This reaction of course differs in intensity per measure, and is also delayed due to implementation and adaptation time considered.

The logit-type models intended to use will account for other decision making factors than merely time and costs encountered, like traffic unsafety, vehicle availability etc.

Some of the strategic and political critiques to forecasting cannot be rebutted, but it is believed that dynamic transportation models will bring more insight into the time-path of impacts due to combinations of system interventions in terms of traffic, but also in terms of trips made than standard static approaches.

Furthermore, will such a model give more openness in what sustainable development actually means to transportation for people in urban areas, and will give meaning to terms as sustainably developing transportation systems and sustainably developed transportation systems. What is the maximum achievable productive capacity (in terms of trips made) if sustainability targets are strictly taken into consideration? What latent demand is expected to be revealed and what is the impact in traffic terms of the newly generated trips?

6 CONCLUSIONS AND RECOMMENDATIONS

In this paper the conceptual background and the fundaments of a dynamic disequilibrium transportation model to be used for modeling sustainable development in transportation is discussed. The basic idea behind the approach is that transportation planners are constrained by sustainability requirements in their long-term planning activities. These constraints are often formulated as financial sustainability constraints (road budgets), environmental sustainability (emissions versus local environmental capacity) as well as social sustainability (equity). Within the boundaries of their constraints transportation planners aim at reaching a certain objective. A common objective is throughput-based in which volume-over-capacity ratios are kept close to unity to get good and efficient flow conditions. It has been shown in literature on sustainable transportation that a paradigm shift from the conventional focus on vehicle travel into access is necessary. Therefore, the transportation planners objective should change to one that aims at reaching optimal accessibility to the people in the area.

In the discussed model the transportation planner has the option of controlling mode-specific capacity through new construction and maintenance. Accordingly, two objective functions, a traditional objective versus a sustainable accessibility objective, are compared for a hypothetical transportation system. Optimal control simulation thus reveals that ….

The travel demand is kept fixed in this research. However making this demand elastic is one of the big challenges for future research.

Finally, the relevance for this type of research in the situation of developing cities, with their typical technical requirements is discussed. The transport system is seen as determinative in the generation of travel demand, thus there is a clear dynamic interrelation between infrastructure supply and travel demand. This will greatly improve with allowing the travel demand to be elastic, thus revealing latent demand. Furthermore, the typical choice behavior of all users has to be taken into account.

In spite of some political and strategic reasons opposed to transportation modeling in general and in developing cities in particular, this type of modeling and reasoning is believed to be an important contribution to get a better grip on quantifying the feasibility and time and location dependent package of interventions necessary to design a sustainably developed transport system in developing cities.

7 ACKNOWLEDGEMENTS

The authors wish to acknowledge dr. Kieran Donaghy of the University of Illinois as well as dr. Laurie Schintler for the interesting discussions on applying continuous-time models to transport. Futhermore, the great help with implementing this model in the Apredic model by dr. Clifford Wymer is acknowledged.

REFERENCES

Akinyemi, E.O. & Zuidgeest, M.H.P. 2000. Sustainable development & transportation: past experiences and future challenges. *World Transport Policy and Practice* 6(1): 31 – 39.

Akinyemi, E.O. & Zuidgeest, M.H.P. 2002. Managing transportation infrastructure for sustainable development. *Computer-Aided Civil and Infrastructure Engineering* 17(3): 148 – 161.

Donaghy, K.P. & Schintler, L.A. 1994. Optimal policies for reducing congestion of major commuting arteries in a growing urbanized area. *Journal of Planning and Research* 13: 189-198.

Donaghy, K.P. & Schintler, L.A. 1998. Managing congestion, pollution, and pavement conditions in a dynamic transportation network model. *Transportation Research – D* 3(2): 59-80.

Gudmundsson, H & Höjer, M. 1996. Sustainable development principles and their implications for transport. *Ecological Economics* 19: 269-282.

Langen, M. de & Tembele R. 2001. *Productive and liveable cities: guidelines for pedestrian and bicycle traffic in African cities*, Rotterdam: Balkema

Ortúzar, J. & Willumsen, L.G. 1994. *Modelling transport*. Chicester: John Wiley & Sons.

Sales Filho, L.H. 1998. The accessibility matrix: a new appraoch for evaluating urban transportation networks. In Meersman, Van de Voorde & Winkelmans (Ed.), *World Transport Research; Proc. intern. symp., Antwerp, 12-17 July1998*

Casconcellos, E. A. 2001. *Urban transport, environment and equity: the case for developing countries*. London: Earthscan

World Commission on Environment and Development 1987. *Our common future* England: Oxford

Wymer, C.R. 2001. *Wysea: systems estimation and analysis programs*