Exploring Traffic and Congestion Policies
An entity-based SD Approach

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Abstract

Due to their wicked nature, transportation issues may be efficiently dealt with by means of models. Many approaches are available for policy making, among which system dynamics. Developed for planning purposes, existing models represent the system at a macroscopic level, wherein traffic dynamics are not properly accounted for. A possible solution to cope with it consists of using a cellular approach for the network. Furthermore, recent software developments enable to model smaller-scale phenomena within a macroscopic model and make model compression possible. This paper investigates the extent to which these new developments can be applied for traffic modeling and what its advantages are compared to more conventional ones such as four-step models. The elementary building blocks are introduced and combined in order to develop a small model of interest, which is the northern section of the Great Ring ('Grote Ring' or 'Grand Ring') of Brussels. This was chosen because level of congestion on it is the direst in Europe, just behind London. Its usefulness is finally assessed by discussing the different policies that may be tested thanks to the model. Finally, the value added of system dynamics is discussed.

1 Introduction

Transportation is one of the most important components of modern societies. The boom of private transportation and the soar of international trade have been generating a growing demand for several decades. In order to fulfill this need for transport, major pieces of infrastructure such as highways were built to enable high flows of vehicles. However, on the one hand, infrastructure was built when levels of transport demand were lower. On the other hand, its development requires time to be achieved whereas transport demand grows continuously. As a consequence, there exists an important mismatch between transport supply âĂŞ the infrastructure âĂŞ and transport demand. Congestion occurs and results in waste of time, extra air pollution and losses of money (FHWA, 2014). In France, transportation produces about a quarter of the total air pollution, the total cost of which was estimated to EUR 101 bn. per year in 2014 (Aïchi, 2015). In a developed country such as Belgium, congestion generates productivity losses of about EUR 600,000 per day (Le Soir, 2015). In developing countries, it starkly undermines economic growth: Ali et al. (2014) estimate this cost to USD 700 million per year for the city of Karachi.

In order to seek for solutions against this problem, transport-related research has been carried out since the 1950s (Lighthill and Whitham, 1955, Wardrop, 1952) so as to find out insights about traffic dynamics. Based on the findings, transport planning activities are undertaken for different time horizons to mitigate traffic congestion and find out sustainable solutions. The enhancement of computational power enabled the processing of an always growing amount of data Maerivoet

(2006) distinguishes two categories of models with respect to their purpose: planning models, and flow propagation/network loading models. These categories tend to be mutually exclusive: the dynamics of traffic propagation and congestion are of less interest for the former category. These models tend to be static models that aim at finding out an equilibrium for the transportation system of interest. However, congestion is a highly dynamic phenomenon, for which time-evolution is crucial.

System dynamics (SD) is a potential modeling approach for transportation planning problems. Indeed, such problems can be deemed "wicked" (Rittel and Webber, 1973) because of their complexity regarding the problem definition and the actors involved. Besides this, no unique solution exists for a problem, and the amount of resources required means that the decision maker has "no right to be wrong" (Rittel and Webber, 1973, p. 166). In such context, opposition to a solution may appear and decision-making become more hectic and inefficient. In Sterman (2000), SD is defined as a method that is promising to cope with dynamic complexity and policy resistance. Abbas (1990) was one of the first researchers to list numerous advantages of using it for transportation modeling and spatial planning issues in Egypt. More recently, Heimgartner (2001), Anh (2003), Wang, Lu, and Peng (2008) and Armah, Yawson, and Pappoe (2010) use system dynamics models to cope with issues related to transportation.

As explained before, these models are planning models and therefore do not feature the detailed traffic dynamics. Instead, the causality is either reduced to a blackbox (Anh, 2003, Armah et al., 2010, Wang et al., 2008) or merely ignored (Heimgartner, 2001). For the former case, the causal relationships—both effect and cause—matter more than the dynamics. The outcomes of these models tend to be "limited to being good enough to show policy impact, behavioral trends and levels of change across time in a highly aggregate way." (Abbas and Bell, 1994) On the other hand, no piece of work is available regarding the existence of SD models for traffic flow propagation. Unlike planning models, these models do not seek for a traffic equilibrium and may be hence of interest while managing daily traffic operations for instance.

There currently exist many different analytical models for flow propagation. As Hoogendoorn and Bovy (2001) and Maerivoet (2006) point out, there exist several ways of classifying them: modeling scale, continuous or discrete time base, deterministic or stochastic and so on. The usual classification is made with respect to the modeling scale. Models can be

- Macroscopic: vehicles flows are seen as a continuum from which individual vehicles cannot be distinguished. Models of this kind are based on fluid dynamics, more especially hydrodynamics.
- Mesoscopic: vehicles can be individually identified, but their behavior is ruled by probabilistic. Models are commonly based on gas-kinetics equations;
- Microscopic: vehicles can be individually mapped, as well as the driver, whose behavior follows predefined patterns randomly assigned during the run. A good example of such a model is the "follow-the-leader", wherein vehicles in a platoon seek for following the leading one by assuming a different behavior regarding the reaction time or perceived safety distance;
- Sub-microscopic: microscopic model for which the vehicles have their own behavior (maximal speed, mean time between failure and so on.)

Among these categories, macroscopic models seem to be the most appropriate models that can be modeled by means of a SD approach.

The objective of this paper is to find out the extent to which a flow propagation model can be created by means of SD, and the value added that it can bring in transportation research. In order to do so, a section of the R0 ring road around Brussels has been chosen to carry out this comparison.

This paper is organized as follows. The section 2 introduces the theoretical background and methodological considerations of this research. Section 3 presents the case chosen for this research and the different conditions. In section 4, the usefulness of the model for policy analysis is developed.

2 Methods

2.1 Macroscopic Flow Propagation Models

Macroscopic continuous models are among the most ancient models of flow propagation. Hoogendoorn and Bovy (2001) list three different families of models: Lighthill-Whitham-Roberts (LWR)-type, Payne-type, and Helbing-type. Payne-type models are actually LWR-type models for which the speed must fulfill another differential equation. Similarly, Helbing-type models are Payne-type models wherein the speed variance is ruled by a specific differential equation. It can then be seen that any of these models lies on the LWR model. As a consequence, it is deemed appropriate to use the LWR model as an analytical foundation for the research since the two other categories consist of extensions of this model.

The seminal model for LWR-type models was developed by Lighthill and Whitham (1955) and expanded by Roberts in 1956. This paradigm is based on an analogy between the propagation of a traffic flow and the runoff of a water stream. The key hypothesis of this approach is that, "at any point of the road the flow $q(x,t)$ (vehicles per hour) is a function of the concentration[1] $k(x,t)$ (vehicles per mile)" (Lighthill and Whitham, 1955, p. 319). In other words,

$$\forall x, t,\, q(x,t) \equiv q(k(x,t)) \tag{1}$$

This relation is also expressed as a relation between the density $k(x,t)$ and the average flow speed $v(x,t)$ (Costeseque and Lebacque, 2014, Hoogendoorn and Bovy, 2001). Indeed, the three aforementioned quantities are related by a equation called the 'fundamental relation' or equation of continuity (Hoogendoorn and Knoop, 2013):

$$q(x,t) = k(x,t) \cdot v(x,t) \tag{2}$$

However, this relation only holds true if the speed is the space-mean speed, that is average speed of the flow at a given time instant (Hoogendoorn and Knoop, 2013, Wardrop, 1952). As a result thereof, the relation 1 becomes:

$$\forall x, t,\, v(x,t) \equiv v(k(x,t)) \tag{3}$$

[1] Also called 'Flow density' in this paper

Costeseque and Lebacque (2014) present three different fundamental relations, two of which are common:

- The Greenshields model, developed in the 1930s, wherein is assumed a linear relation between the average speed and the traffic density (Kühne, 2011). This model is practical even though unrealistic.
- The triangular model, based on actual data analysis, wherein a two-fold continuous function is assumed. On every domain, the function is assumed to be linear. This model is more complex but presents a better fit with the observed behavior (de Jong, 2012, Qian, 2009).

Besides the relation, three different characteristics are defined:

- The road capacity q_∞, which is equal to the maximal flow that can be borne by the road of interest;
- The jam density k_j, the density from which the flow becomes still;
- The free flow speed v_∞, the speed at which the flow proceeds for light traffic conditions;

and two critical values, the critical density k_C and the critical average speed v_C. When the flow characteristics reach these quantities, the flow dynamics are optimal: the flow intensity is equal to the road capacity. However, as soon as the density has overshot its critical value, the flow dynamics are undermined: any increase of the density leads to a slower, less intense flow.

The relations 2 and 3 can be plotted in order to see the behavior of each variable with respect to another one. Three plots are usually presented: the plot (k, v), the plot (k, q), and the plot (q, v). The graph(s) thereby gotten are known as fundamental diagrams of traffic. The figure 1, taken from Gordon and Tighe (2005), presents the Macroscopic Fundamental Diagrams (MFD) for the Greenshields model. Since the relation between the density and the speed is linear, the critical values for the average speed and the density are respectively equal to half of the free flow speed and of the jam density. This does not hold true for other models though. The oversaturated curves—flow density greater than the critical density—are dash-dotted.

The second equation of the LWR-type models is the equation of conservation. It translates the conservation of the number of vehicles constituting the flow through a road section. Its expression is the following:

$$\frac{\partial q}{\partial x} + \frac{\partial k}{\partial t} = 0 \tag{4}$$

This equation means that any small variation of the vehicle density across time locally leads to a opposite variation of the flow intensity. The number of vehicles in a small section depends then on the balance between its inflow and outflow. Although this equation is important, it outlines the spatial character of congestion, the effects of which cannot be easily accounted for by a SD model (Abbas, 1990).

Besides these three equations, the LWR theory predicts the generation of waves when flow intensity changes (Lighthill and Whitham, 1955, p. 322). These waves, named kinematic, "are always transmitted backwards relative to the vehicles on the road." This change in speed can be either positive or negative and never exceeds the flow speed. This value is actually equal to the slope of the fundamental diagram of flow intensity with respect to flow density. If a triangular relation is assumed for the MFD, this difference in slope is neat. The figure 2 presents such diagram.

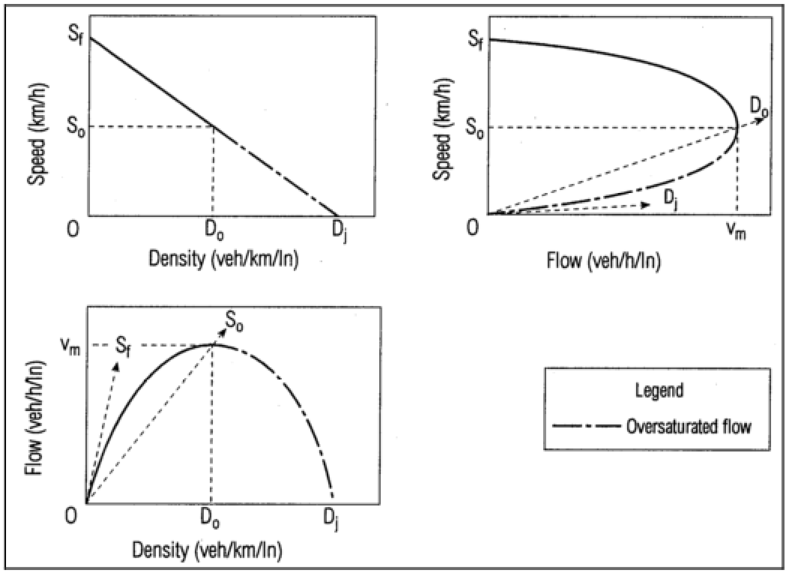

Figure 1: *Macroscopic fundamental diagrams for the Greenshields model (Gordon and Tighe, 2005)*

2.2 Cell-Transmission Model

As explained before, SD is not adapted for spatial effects induced by traffic. In order to discard this issue, a numerical model can be developed to estimate a solution given initial conditions. Many theoretical models (Gani et al., 2011, Kabir et al., 2010) and numerical algorithms (Mazaré et al., 2011) have been recently developed. Their key idea is to discretize both time and space, which yields then a recurring scheme for the the density (Gani et al., 2011), knowing both time and space increments. However, the resulting equations cannot be easily adapted into a stock-flow structure. Another possible scheme consists in considering a road section as a sequence of contiguous finite cells through which a flow of vehicles proceeds. The seminal example for such models in the Cell-Transmission Model (CTM), twofold developed by Daganzo (1993) and Daganzo (1995). In this approach, a road section is divided into cells the length of which is equal to the distance crossed by a vehicle driving at the highest speed allowed, or free flow speed, during one time step. This means that, for light traffic conditions all the vehicles located in a given cell i at time step **t** can be found in the next cell $i+1$ downstream at time step **t+1**:

$$n_i(\mathbf{t}) = n_{i+1}(\mathbf{t+1}) \tag{5}$$

The length of a cell is hence equal to the product of the free flow speed of the road section v_∞ times the time step of the simulation δt. In congested conditions, the number of vehicles flowing between two cells depends on the current occupancy of the upstream cell, the available space downstream of it and the maximal flow that the cells can simultaneously bear.

The flowing mechanism, adapted from Daganzo (1995), is quite straightforward: let be a road cell labeled i, the characteristics of which are:

- Its size [2] N_i^0, to say the maximal number of cars that a cell can contain. It is a function,

[2]In Daganzo (1995), both size and capacity are assumed to be time-dependent. For the sake of explanation, they are assumed to be constant here.

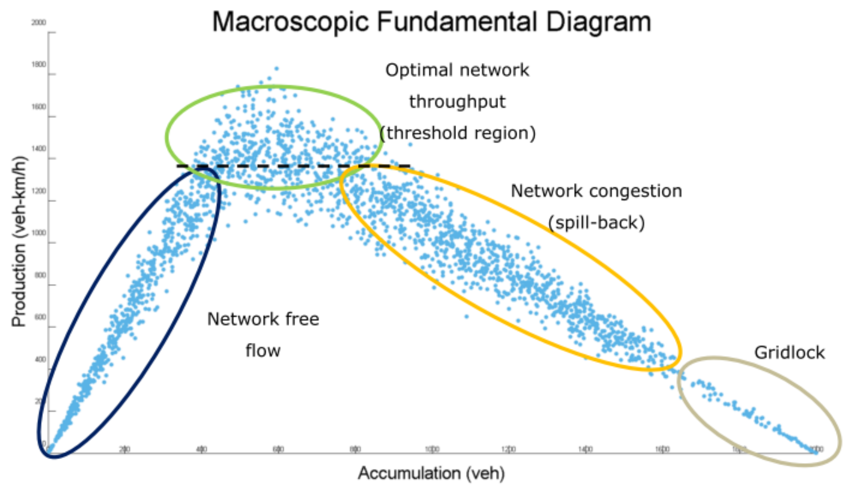

Figure 2: *Example of a triagular MFD (de Jong, 2012)*

among others, of the cell length, the cell free flow speed and number of lanes;

- Its capacity C_i, which is equal to the maximal number of vehicles that the cell can either send or receive per time unit;
- Its current occupancy $n_i(t)$, or the total number of vehicles the cell encompasses at time t.

Based on these variables, two quantities can be defined. The first [3], noted S_i, is the number of vehicles currently within the cell that can be sent to the first cell downstream [4]. The second is noted R_i and stands for the number of vehicles contained in the cell upstream that can enter the cell i. Both quantities are bound by the product of the capacity times the time step. They can then be mathematically defined as follows:

$$S_i = \min\left(C_i \cdot \delta t, n_i\right) \tag{6}$$

$$R_i = \min\left(C_i \cdot \delta t, N_i^0 - n_i\right) \tag{7}$$

The number of vehicles flowing between two consecutive cells $i-1$ and i, noted Q_i, is therefore equal to:

$$Q_i = \min\left(S_{i-1}, R_i\right) \tag{8}$$

The associated MFD of the CTM is presented in the figure 3. Because of the flow conservation equation, the variation of the number of vehicles inside a cell depends on its inflow and outflow. This can be written as follows,

$$n_i(t+\delta t) = n_i(t) + Q_i - Q_{i+1} \tag{9}$$

[3]Uppercase variables are used for describing a number of vehicles. Rate of vehicles per unit of time—that are introduced in the subsection 2.3—are written with lowercase characters. The relation between the number of vehicles X and the instantaneous flow is the following: $X = x \cdot \delta t$

[4]Time dependency has been removed for the sake of clarity. If not explicitly indicated, a variable is always assumed to be at least time-dependent

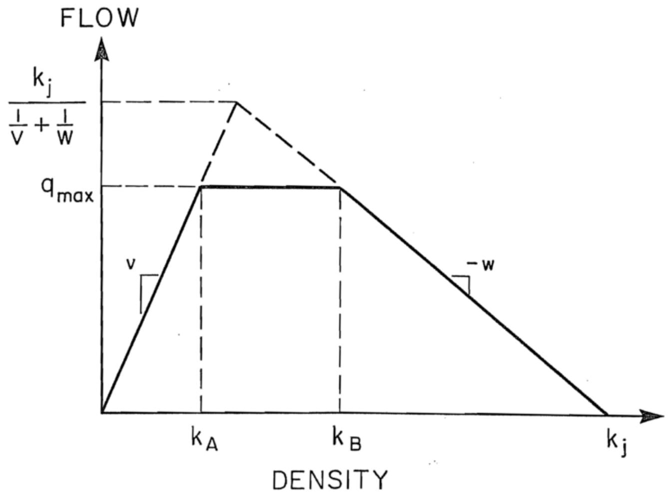

Figure 3: *MFD of the CTM (Daganzo, 1993)*

These equations do not hold true at the boundaries of the road section, where vehicles either enter or leave the system. In Daganzo (1993), two models are proposed for the source and the sink of vehicles:

- The sink actually consists of a cell the size of which is infinite, thus its received flow is assumed to be equal to its capacity
- The source is made of two cells: a first cell containing an infinite number of vehicles connected to a second cell that acts as a queue. Its size is infinite, which enables the holding of vehicles into the system. Its capacity determines the rate at which vehicles are released into the road section in free flow conditions.

However, a sole cell model is not enough to model complex networks, where different flows of vehicles can merge for instance. In order to make this possible, two other basic cells are introduced.

The first is known as a merge cell, where two flows are combined into a single one. The inflow of this cell depends on the total flow sent by both cells upstream of it and the flow that can be received. If the latter is greater than the sum of the two former, then the allocation is straightforward. Instead, the composition of the inflow in the case where the value of the total flow sent overshoots the flow that can be received becomes more complex. In that case, the notion of priority of a flow over the other one is introduced in order to determine the proportion of each flow that is merged at each time step. In Corthout (2012), this priority factor is determined as the ratio of the capacity of one link over the sum of both link capacities. The equations for this cell can be found in Daganzo (1995).

The last type of cell splits a flow into two complementary sub-flows and is therefore defined as a diverge cell. Like the merge, two cases are distinguished: the case where the percentage of diverging vehicles is known and the case where it is unknown and where FIFO rules must be respected. In the former case, the total flow emitted by the merging cell is equal the minimal value between the total flow that can be sent by it and the minimal flow that each branch stemming from the cell can receive versus the proportion of vehicles going on it. In the latter case, the flow of vehicles entering the cell must be tracked across time in order to allocate in priority to the outflow vehicles that have queued for the longest time. Carey et al. (2014) proposes different ways to implement FIFO discipline into a cell-based model. The figure below summarizes the layout of these three types of cells.

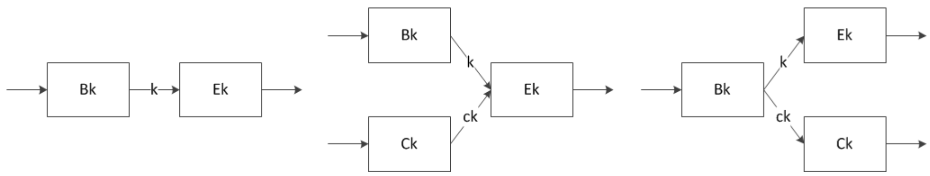

Figure 4: *Overview of the 3 cell categories described by Daganzo (1995). The notations are the one used in the paper.*

2.3 Network Elements

The different equations presented in subsection 2.2 must be slightly adapted. Indeed, the equations 6, 7 and 8 actually describes a number of vehicles. In order to build a SD model, they must be defined as flows of vehicles, that is a number of vehicles per unit of time. Since the time step δt is strictly greater than 0, these equations still hold true if divided by it. They become then:

$$s_i = \min\left(C_i, \frac{n_i}{\delta t}\right) \tag{10}$$

$$r_i = \min\left(C_i, \frac{N_i - n_i}{\delta t}\right) \tag{11}$$

$$q_i = \min\left(s_{i-1}, r_i\right) \tag{12}$$

Besides this, the term $\frac{N_i - n_i}{\delta t}$ from equation 11 must be corrected by a factor taking into account the fact that kinematic waves may propagate at a lower speed than the flow for free flow conditions. Let w be this speed. In the equation 11, it is assumed to be equal to the free flow speed. This equation can be generalized as follows:

$$r_i = \min\left(C_i, \frac{w}{v} \cdot \frac{N_i - n_i}{\delta t}\right) \tag{13}$$

Basic Elements

By defining flows instead of a number of vehicles flowing, it is possible to bring out stock-flow equations. Indeed, the equation 9 can be written as:

$$n_i(t + \delta t) - n_i(t) = Q_i(t) - Q_{i+1}(t)$$

Or

$$\frac{dn_i(t)}{dt} \cdot \delta t = Q_i(t) - Q_{i+1}(t)$$

And finally

$$\frac{dn_i(t)}{dt} = q_i(t) - q_{i+1}(t) \tag{14}$$

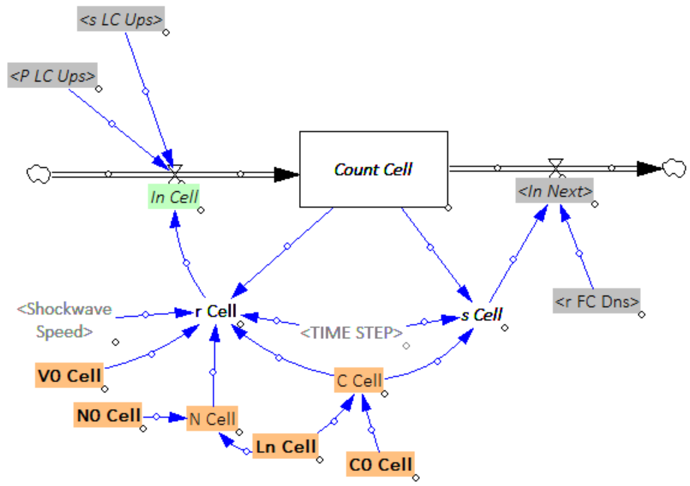

Figure 5: *Model for a road cell. Inputs are variable with an orange background; outputs are with a green one. Variables with a grey background are variables that are to be connected to other elements.*

Which is the differential equation of a simple stock-flow structure. This equation, as well as equations 10, 12 and 13, can be used for building a stock-flow model of the CTM. This structure is shown on the figure 5

Even though straightforward, this structure is not suitable for long networks. Indeed, as explained in section 2.2, the cell length depends on the free flow speed of the road section and on the time step. Given a speed of 120 km/h and a time step of 8 seconds, the length of a cell is about 250 m, or one quarter kilometer. In order to model a dual-carriageway road section of 10 km without interchange, 40 cells are required for each carriageway, that is to say 80 cells in total. Modeling of long networks quickly becomes tedious if this simple structure is solely used. The model presented in the figure 5 needs some adaptation and is shown in figure 6

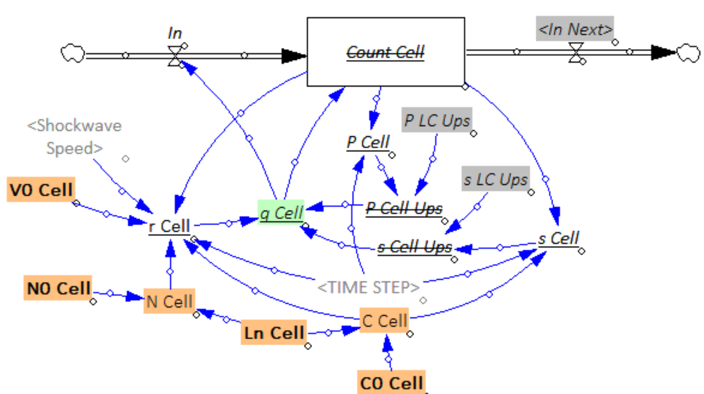

Figure 6: *Model for a road cell.*

In order to limit the number of cells to be modeled, a smaller-scale dynamics can be introduced within a road section. As Fallah-Fini et al. (2013) show out, using subscripts is a way of creating this smaller-scale dynamics into a stock. In the case of a road section, cells can be created inside a stock by means of subscripts. This turns the different variables into vectors, the number of components of which is equal to the number of cells created. Vector-based functions enable easy browsing through the different components of each variable. Besides this, sub-ranges of subscripts can be defined so that the number of equations to be written for each variable remains limited. In this case, three ranges were defined: one for the first cell, one for the last cell—because of the boundary conditions—and one for all the cells in-between if there are at least three cells inside the road section. If there are only two cells, the last sub-range is not defined.

The different elements presented so far are only suitable for a single flow of vehicles. However, in reality, a single flow going through a road section may consist of the sum of several flows the origin, the destination and the time-pattern of which may differ. In this case, the way of allocating the available flow to each of these sub-flows is not onefold. If the allocation of available capacity is proportional to the number of vehicles associated with one specific OD inside the cell, a slight FIFO discipline is guaranteed (Carey et al., 2014). Stricter rules can be defined, but are actually based on algorithms. At each time step, for every cell, inbound flows (and through this vehicles) are time-stamped whereas outbound flows are allocated to the available capacity downstream with respect to their time spent queuing: older vehicles get a higher priority.

Instead of this algorithm, a combination of built-in VENSIM functions can be a plain and suitable alternative for a first model. In order to map the different sub-flows, a second subscript range is added to the model so as to define different OD flows, that is flows between a given origin and destination. Thanks to this, it is possible to:

1. Determine, for each OD, the oldest age of material contained in a given cell. This is done by means of the QUEUE FIFO function while writing the stock equations;
2. Allocate, for each OD, the flow leaving a cell for the cell downstream, with respect to the age of oldest material and available capacity downstream. The process is done by the ALLOCATE BY PRIORITY function, which is implemented into the flow equations.

Complex Elements

The three elements that have been introduced are actually sufficient to model complex networks:

- Road sections and ramps, by means of single-cell or multiple-cell sections, with respect to the free flow speed of the link.
- Interchanges, by combining road sections, merges and diverges with respect to the current configuration of the interchange.

The latter point can be observed on an actual motorway intersection, as the one displayed by figure7. A flow arriving at the interchange from a given direction is divided twice: once to separate through traffic from leaving traffic, and a second time to separate flow leftwards to flow rightwards. Similarly, the flow leaving one of the crossing roads is twofold merged. Whatever the situation, a flow is either exactly split into two sub-flows, or exactly two flows are merged into a “super-flow”. Finally, an important rule defined by Daganzo (1995) must be followed while combining the elements into an interchange: no link should be simultaneously connected to a merge cell and a diverge cell. As a consequence, merge and diverge structure are always assumed to be made of a single cell. The figure 8 presents the plain stock-flow structure of the Machelen interchange on Brussels ring R0. For the sake of clarity, auxiliaries were not represented.

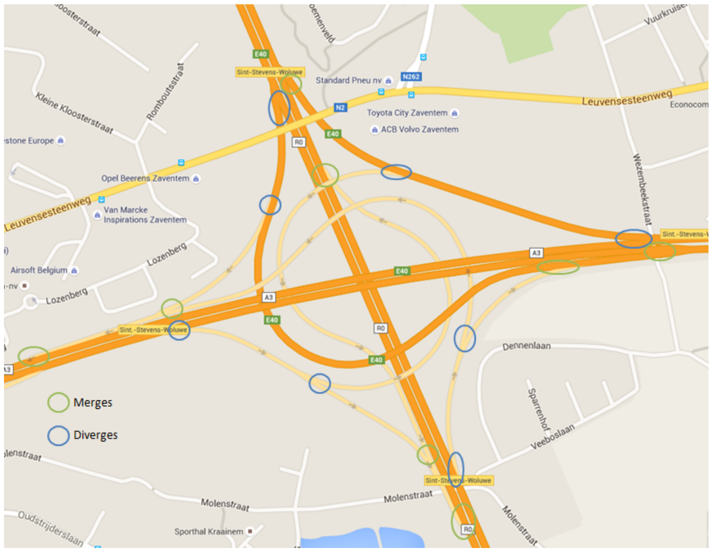

Figure 7: *Sint-Stevens Woluwe Interchange on Brussels Ring R0.*

Outputs

Some of the model parameters, such as the capacity, the size or the free flow speed, have already been introduced in the previous subsections. Regarding the different variables and auxiliaries included into the model, one can be considered as an output, the 'Inflow Cell', or 'q Cell'. Taken alone, this output is suitable for validation purposes. Since a cell is assumed to represent a small section of a one-way carriageway, then the flow must never take negative values, and cannot exceed the road capacity. By plotting in a same graph the inflows of consecutive cells, a propagation pattern can be outlined.

The graph 9 represent the propagation of a vehicle flow through a road section in congested conditions. Network is loading during the first part of the run. During the second part, the inflow has been set to 0, in order to let the network unload. Two different regimes can be observed:

- A forward propagation pattern when condition upstream of the flow drives the propagation. In other words, changes in inflow intensity are driven by variations of the level of demand. The kinematic waves propagates forward from the first cell to the last cell of the section.
- A backwards propagation pattern when conditions downstream of the flow drives the propagation. In this situation, changes are generated by variations of transport supply, such as a bottleneck. The kinematic waves propagates backwards from the cell where the disruption is to the first cell of the section.

This figure explicitly represents these two propagation regimes. An extra point should be noted regarding the change in intensity. As long as the flow has not met the bottleneck yet, the propagation regime is forward. The network loading is stiff and is in line with the structure of the CTM. When congestion spills back once the bottleneck has been reached, the backwards regime

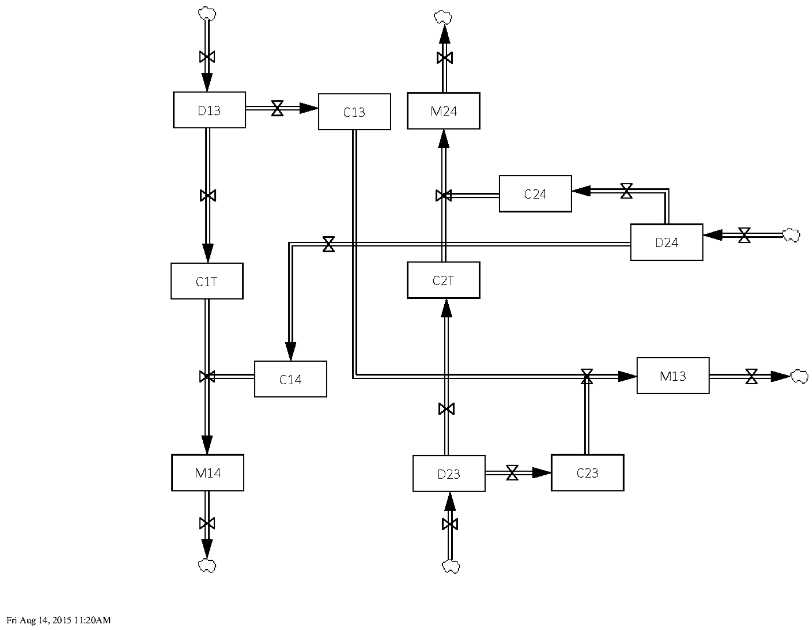

Figure 8: *Model of Machelen interchange nearby Brussels. Only the road elements have been represented.*

can be observed: changes propagate well from the last cell of the section to the first cell. Changes in flow intensity are slower and smoother than for network loading, but do make sense. Indeed, the shock wave generated at the bottleneck propagates backwards more slowly compared to flow in free flow conditions: changes in intensity are carried upstream slower. Because of that, the inflow intensity may be different than the outflow intensity. The stock structure tends to average this discrepancy, which smooths its variations.

The sole flow intensity is a practical output, but may not be clear enough to describe traffic conditions. Two variables are usually calculated to quantify the level of congestion: the section travel time and the congested length. Similar concepts were then embedded into the model as extra outputs. The first is cell travel time t_{tr}, which is equal to the ratio of the cell occupancy versus its outflow:

$$t_{tr,i} = \frac{n_i}{q_{i+1}} \tag{15}$$

The section travel time is easily gotten by summing the travel times of all the cells that compound it. The second variable is the total length congested and is defined as the total length on which traffic load exceeds 75 % of a reference capacity (Conseil Economique et Social, 2012).

The equation 15 is not usual to estimate the travel time. The Bureau of Public Road (BPR) formula is more frequently used. It estimates the cell travel time based on the current traffic load on the cell and a list of parameters α_i and β_i and the cell capacity C_i which depend on the kind of

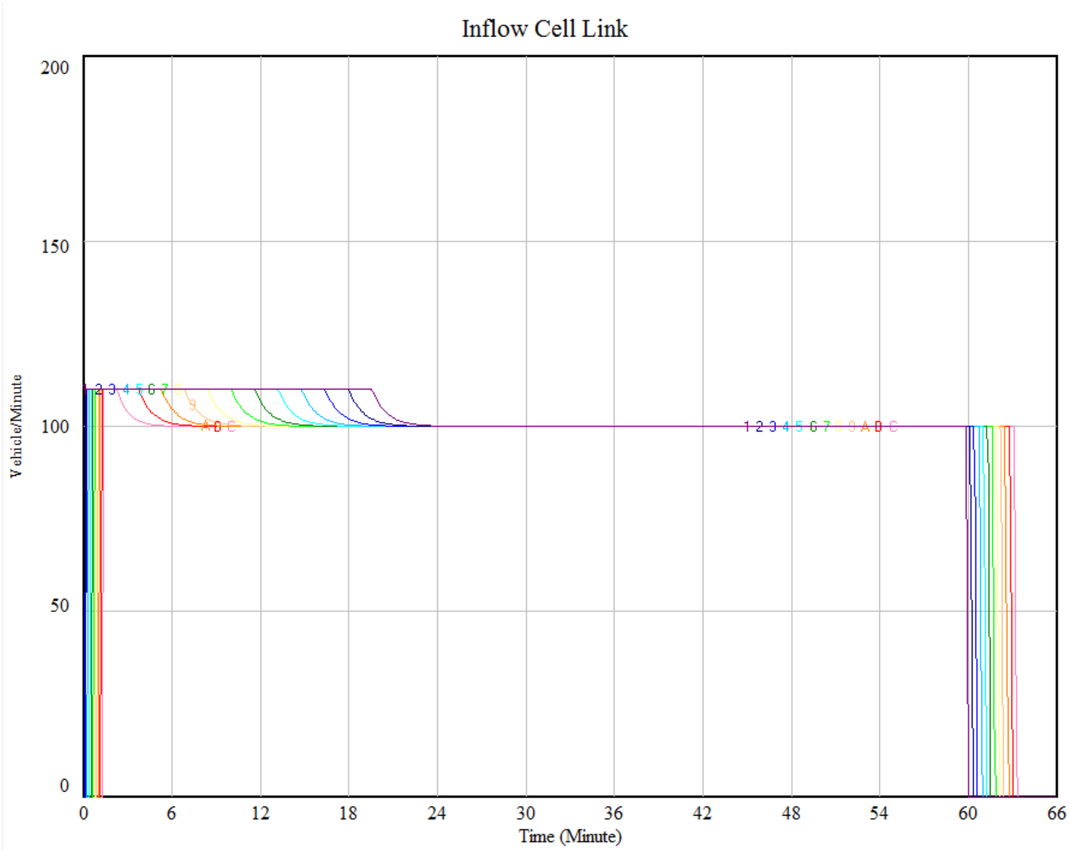

Figure 9: *Congested flow propagation through a road section.*

road considered in the model (Davis and Xiong, 2007, Transportation Research Board, 2000):

$$t_{tr,i}(q) = t^0_{tr,i} \cdot \left(1 + \alpha_i \cdot \left(\frac{q}{C_i}\right)^{\beta_i}\right) \tag{16}$$

In Manley et al. (2014), a extra term $\delta \cdot \max(0, q - C)$ can be added to the equation 16, where δ_i stands for the marginal cost in minutes of traffic when the current flow overshoots the road capacity. The main reasons for not implementing this formula are the need for external data to calibrate some of its parameters (Cascetta, 2009) and the possibility for the flow to exceed the capacity (Maerivoet, 2006). The use of model variables reduces the need for extra data.

3 Case Study

Capital of Belgium and headquarters of Belgian and European institutions, Brussels is the city of continental Europe[5] where congestion is the direst. As pointed out by INRIX (2014), a driver spend on average 76 hours per year in traffic jams. Compared to Paris, Rome or Amsterdam, which are bigger and more densely inhabited, this figure is outstanding. Several reasons can explain the starkness of congestion in Brussels, among which the fact that people tend to live in

[5]Western Europe without the British islands

areas where fast public transport may not be available. As a result thereof, these persons commute to Brussels by car (Vermeersch, 2014).

The road network around Brussels is structured around four different ringways, which are, from the innermost to the outermost:

- The ring R20, or 'Petite Ceinture'[6], a urban ring surrounding the city of Brussels. It consists of two dual carriageways with graded or signalized intersections.
- The ring R21, or 'Grande Ceinture'[7], a half-ringway located 3 km east of Brussels and of the R20. Similarly to the R20, it is made of two dual carriageways with both graded or signalized intersections. Three of the main Belgian motorways—A12 to Antwerp, A3/E40 to Leuven and Liège, A4/E411 to Namur and Arlon—stem from it.
- The ring R22, or 'Vallée de la Woluwe'[8], surrounding the R21 and connecting farther suburbs of Brussels to the different ring roads and other arterials of Brussels
- The ring R0, or 'Grand Ring'[9], a motorway ring—except on a small section where it is a highway— made of a dual carriageway with graded intersections. All the structural Belgian highways connecting Brussels to the main Belgian cities radiate from it. All interchanges are graded, signalized intersections can only be found on ramps.

The figure 10 presents the spatial layout of the rings.

Figure 10: *Spatial layout of Brussels ring roads. The R0 is the circular road around represented with a three-striped line.*

Stark congestion occurs on these ring roads every day. However, the focus was made on a small portion of the R0 in the first time: the section between the interchanges Strombeek-Bever and Zaventem. The choice of this section is motivated by several reasons. First of all, this section is part of the two direst corridors in Belgium. During the peak hours, most these sections are

[6]In French: Small Ring of Brussels.
[7]In French: Intermediate Ring of Brussels.
[8]In French: Woluwe dale.
[9]In French: Great Ring of Brussels

saturated—the total flow intensity is beyond 1,500 vehicles per hour—and the average flow speed is around 50 km/h (Conseil Economique et Social, 2012, INRIX, 2014). Even if the actual corridor actually includes other interchanges, their number remains limited, which limits the time that may be required for debugging. The second is related to technical considerations: this section features only graded interchanges. Such interchanges were designed in order to avoid crossing conflicts on main roads by pulling them away on another level. From a modeling point of view, these intersections make the modeling of traffic flow easier since discrete events such as a traffic signal need not be included in a model.

The final reason comes from the importance of the R0 in Belgium. As explained before, the main Belgian cities such as Antwerp, Ghent, Liège or Leuven are connected to Brussels ring R0. This means that drivers along the R0 are not only commuters from/to Brussels, but may also be in transit around Brussels. Moreover, the section chosen is actually part of the European route E40, which connects Calais to Aachen (Germany), and is a major corridor for freight between UK, Northern France and Germany. Due to the importance of this section, the Flemish community includes this portion of the R0 in its regional traffic model (Liebens and Vieren, 2014).

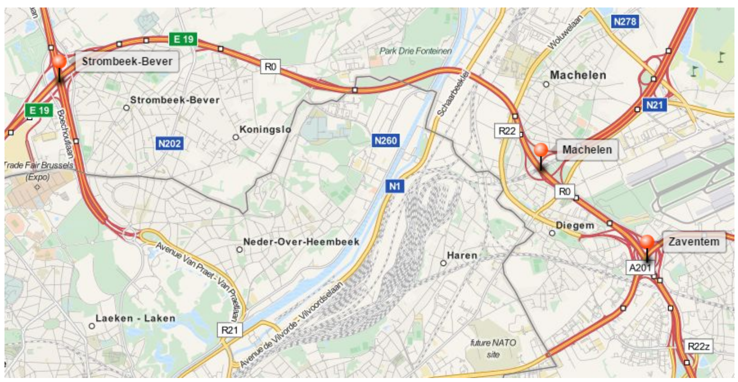

Figure 11: *Zoom on the section of interest. The different interchanges are indicated with pins.*

The network, or transportation supply, is made of three interchanges:

- Strombeek-Bever, between the R0 and the A12 Brussels-Antwerp;
- Machelen, between the R0 and the A1/E19 Machelen-Antwerp;
- Zaventem, between the R0 and the A201 Brussels-Brussels Airport.

Two road sections bind Strombeek-Bever to Machelen, and Machelen to Zaventem. The former can actually be divided into two distinct sections where the free flow speed is the same: a normal motorway section with a free flow speed equal to 120 km/h; and the Vilvoorde viaduct, where the speed is limited to 90 km/h. The characteristics of each link/ramp have been retrieved from open data— for the number of lanes or the free flow speed—and found in reference works (Transportation Research Board, 2000)—for the capacity.

Regarding the transport demand, six different pairs of origins and destinations have been designed with respect to the possible trips along this road section:

1. Brussels-Antwerp via A12
2. Brussels-Antwerp via A201 and E19

3. Mons-Antwerp via E19
4. Ghent-Leuven via E40
5. Ghent-Namur via R0
6. Brussels-Ghent via E40 and A12

Thanks to the twelve flows—one clockwise or leaving Brussels and one counter-clockwise or heading to Brussels—these pairs generate, most of the section of interest bears the traffic load. The ramps where no traffic goes are then removed from the model, which therefore results in simplified interchanges. Since the level of demands are not known, a test pattern has been chosen in order to ensure that the total demand can exceed at some moments the available capacity. As a consequence, congestion occurs on the network can be shown.

4 Policy Analysis

Traffic models are often tools aiming at assessing the efficiency or the impact of different policies. Among existing policies, the following ones can be cited. This list is however not exhaustive.

- Modification of the speed limitation. Three cases of this exist:
  - definitive, for instance on the Boulevard Périphérique in Paris, where the speed was lowered from 80 km/h to 70 km/h in 2014;
  - temporary, in the case of infrastructure upgrading;
  - dynamic, that is dependent on traffic conditions or on the time of day, such as on the ring of Antwerp.
- Modification of the road capacity. Three cases can be distinguished:
  - definitive, by building an extra lane or upgrading an existing road, such as the section the the A4 in the Netherlands between the Belgian border and the A29;
  - temporary if there are working sites or accidents on the road;
  - dynamic, by opening extra lanes in peak hours as along the A13 nearby Delft for instance.
- Imposing a specific route to drivers. Again, there exist three different cases:
  - static, for instance on the A16 in the Netherlands for traffic outbound to Amsterdam
  - temporary, in the case of works on the way;
  - dynamic, by giving real-time travel time for two routes heading to an interchange, or an alternative route in case of an extreme event.
- Incentivizing the use of specific modes—carpooling or public-transports—by subsidizing users.
- Setting up pricing schemes to deter drivers from using their car or moving with more sustainable modes. This pricing can be done on:
  - Specific roads or areas, such as in London or Beijing;

– Parking policies, such as in Amsterdam

Among these policies, only the ones based on speed limitation and road capacity can be tested with the model as is. Indeed, both capacity, number of lanes and free flow speed are model parameters that can be easily changed. In the case of an increase of road capacity—number of lanes L_n or nominal capacity C_0—the updating is very simple, whatever the kind of policy: only the expression of the variables needs to be changed. For the case of a change of the free flow speed, more modifications may be brought to the model. Indeed, increasing or decreasing the free flow speed impacts the length of a cell. If the free flow speed increases, the cell length must increases, otherwise vehicles cannot be held by the cell. Since the length increases, the number of cells as well as the sub-ranges must be redefined too. If the free flow speed decreases, the cell length need not be changed. Since the flow cannot clear a complete cell in one time step, a similar smoothing as the one introduced in the section 2.3: outputs yielded are less accurate. However, in system dynamics, this loss of numerical accuracy matters less than potential changes in behavior (Abbas, 1990).

On the other hand, the three other categories of policies cannot be directly tested in the model. Indeed, the notion of choice either regarding the mode or regarding the route has not been modeled so far. A possible way of modeling it consists of implementing discrete choice models (DCMs), that are very common in conventional transportation models. A complete description of them and the underlying theory can be found in Bonnel (2004) and Ortúzar and Willumsen (2011). Given a set of alternatives assumed as independent and the travel costs of which are known, a DCM aims at estimating the likelihood or share of each alternative. Such models are very straightforward to model into a SD model. However, these models have limitations. First, the different parameters required are dependent on the dataset used for computing it. The use of already existing DCMs is possible, but would not yield correct results. Second, these models are not easy to handle in the case where some alternatives are partially correlated. Indeed, the proportion gotten are inaccurate since links that are shared by several alternatives tend to be more utilized by users. Nested models exist to cope with this, but the resulting models are less intuitive. Finally, discrete choice models are based on full rationality: the most preferred alternative is the one with the lowest travel cost. However, as Sterman (2000) points out, human rationality is bounded, which may result in non-optimal choices. Moreover, rational behavior may be undermined by routine: a driver will prefer his or her usual route even if there exist a faster one. Unlike DCM, SD models are suitable to embed the complexity of human behavior. This may be valuable for the testing of policies where habits or policy resistance are bound to play a key role.

5 Discussion

Initially suitable for planning models only, this study has just shown that SD is also a potential method for building road networks through which flows of vehicles propagate. This is actually possible thanks to a cell-based model, which enables the internalization of spatial dependency of traffic propagation. The basic elements gotten actually reproduce properly flow propagation described in Daganzo's papers. Moreover, recent software features provide more advanced functions which helps to build quite compact models: a long sequence of cells can be compacted into a very compact structure.

Even though promising, the work presented in this paper seems to have no value added compared to existing methods. On the one hand, building complex networks quickly becomes tedious. Blank models can be built for components such as interchanges. Thanks to software features, it is possible to replicate the structure and simply create new variables by adding prefixes or suffixes to the old ones. However, this not work for subscripts: they have to be manually modified. For small networks such as the one chosen, this remains manageable. In the case of large network with numerous interchanges, this task quickly become long to modify all the elements and ensure that the model properly works. A potential way of dealing with this issue is to use an entity-based SD approach. Thanks to such approach, road cells, road sections and interchanges can be defined as a class of entity with specific parameters. The replication of elements is easier than with a classical SD software, which would make model building less hectic.

On the other hand, in spite of a skyrocketed computational power available compared to 1995, the complexity of the CTM is higher than other existing approaches for flow propagation or dynamic network loading. The link-transmission model (LTM), developed by the Katholieke Universiteit Leuven and Transport & Mobility Leuven by Yperman (2007) and expanded by Corthout (2012) and Frederix (2012), is based on the same theoretical approach as Daganzo (1993, 1995). Yperman (2007) showed that the LTM is actually a more efficient and more accurate scheme for modeling flow propagation through a network. In this context, the true value added of SD comes from its holistic and cross-disciplinary framework (Abbas, 1990, Sterman, 2000). SD models enable the inclusion of behavioral and psychological considerations into the model and therefore make the modeling of human behavior more realistic than a discrete choice model. By including habits, learning process or resistance to information, routing policies may be improved and lead to a decrease in travel times (Papageorgiou et al., 2007).

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References

Khaled A. Abbas. The Use of System Dynamics in Modelling Transportation Systems With Respect to New Cities in Egypt, 1990. URL `http://www.systemdynamics.org/conferences/1990/proceed/`.

Khaled A. Abbas and Michael G.H. Bell. System dynamics applicability to transportation modeling. *Transportation Research Part A: Policy and Practice*, 28A(5):373–400, 1994. ISSN 09658564. doi: 10.1016/0965-8564(94)90022-1.

Leila Aïchi. Sur le coût économique et financier de la pollution de l'air [In French: Over the Economic and Financial Cost of Air Pollution]. Technical Report 1, Sénat, Paris, 2015. URL `http://www.senat.fr/rap/r14-610-1/r14-610-11.pdf`.

Mir Shabbar Ali, Muhammad Adnan, Syed Muhammad Noman, and Syed Fazal Abbas Baqueri. Estimation of Traffic Congestion Cost-A Case Study of a Major Arterial in Karachi. In *Fourth International Symposium on Infrastructure Engineering in Developing Countries*, volume 77, pages 37–44. Elsevier B.V., 2014. doi: 10.1016/j.proeng.2014.07.030. URL `http://linkinghub.elsevier.com/retrieve/pii/S1877705814010078`.

Trinh Thuy Anh. System Dynamics Applied to Study the Urban Traffic Congestion of Hanoi. In *Eastern Asia Society for Transportation Studies*, pages 1693–1697, 2003.

Frederick A. Armah, David O. Yawson, and Alex A N M Pappoe. A systems dynamics approach to explore traffic congestion and air pollution link in the city of Accra, Ghana. *Sustainability*, 2 (1):252–265, 2010. ISSN 20711050. doi: 10.3390/su2010252.

Patrick Bonnel. *Prévoir la Demande de Transport [In French: Forecasting Transport Demand]*. Presses de l'école nationale des Ponts et Chaussées, Paris, 2004. ISBN 2859783954.

Malachy Carey, Hillel Bar-Gera, David Watling, and Chandra Balijepalli. Implementing first-in-first-out in the cell transmission model for networks. *Transportation Research Part B: Methodological*, 65:105–118, 2014. ISSN 01912615. doi: 10.1016/j.trb.2014.04.001. URL `http://dx.doi.org/10.1016/j.trb.2014.04.001`.

Ennio Cascetta. *TRANSPORTATION SYSTEMS Optimization and Its Applications*, volume 10. 2009. ISBN 9780387758565. doi: 10.1016/0041-1647(76)90008-3. URL `http://www.springer.com/mathematics/applications/book/978-0-387-75856-5`.

Conseil Economique et Social. Cahier du Conseil économique et social de la Région de Bruxelles-Capitale: La Mobilité en Région de Bruxelles-Capitale. 2012.

Ruben Corthout. *Intersection modelling and marginal simulation in macroscopic dynamic network loading*. Phd dissertation, Katholieke Universiteit Leuven, 2012. URL `http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:INTERSECTION+MODELLING+AND+MARGINAL+SIMULATION+IN+MACROSCOPIC+DYNAMIC+NETWORK+LOADING#0$\delimiter"026E30F$nhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:?Intersection+modelling+and+marginal+simul`.

Guillaume Costeseque and Jean-Patrick Lebacque. A variational formulation for higher order macroscopic traffic flow models: Numerical investigation. *Transportation Research Part B: Methodological*, 70:112–133, 2014. ISSN 01912615. doi: 10.1016/j.trb.2014.08.012. URL `http://dx.doi.org/10.1016/j.trb.2014.08.012http://linkinghub.elsevier.com/retrieve/pii/S0191261514001477`.

Carlos F. Daganzo. The Cell Transmission Model. Part I: A Simple Dynamic Representation of Highway Traffic. 1993.

Carlos F. Daganzo. The Cell Transmission Model. Part II: Network Traffic. *Transportation Research Part B: Methodological*, 29(2):79–93, 1995. ISSN 01912615. doi: 10.1016/0191-2615(94)00022-R. URL `http://www.path.berkeley.edu/`.

Gary A. Davis and Hui Xiong. Access to Destinations : Travel Time Estimation on Arterials. Technical report, University of Minnesota, Minneapolis, 2007. URL `http://www.lrrb.org/PDF/200735.pdf`.

David de Jong. *The Effect of Network Structure and Signal Settings on the Macroscopic Fundamental Diagram*. Master thesis, Delft University of Technology, 2012. URL `http://repository.tudelft.nl/`.

Saeideh Fallah-Fini, Hazhir Rahmandad, Hsin Jen Chen, Hong Xue, and Youfa Wang. Connecting micro dynamics and population distributions in system dynamics models. *System Dynamics Review*, 29(4):197–215, 2013. ISSN 10991727. doi: 10.1002/sdr.1508.

FHWA. FHWA Operations - Operations Story, 2014. URL `http://www.ops.fhwa.dot.gov/aboutus/opstory.htm`.

Rodric Frederix. *Dynamic origin-destination matrix estimation in large-scale*. PhD thesis, Katholieke Universiteit Leuven, 2012. URL `https://lirias.kuleuven.be/`.

M. O. Gani, M. M. Hossain, and L. S. Andallah. A finite difference scheme for a fluid dynamic traffic flow model appended with two-point boundary condition. *GANIT: Journal of Bangladesh Mathematical Society*, 31:43–52, 2011. ISSN 1606-3694. doi: 10.3329/ganit.v31i0.10307.

Robert Gordon and Warren Tighe. Traffic Control Systems Handbook. Technical Report October, Federal Highway Administration, 2005.

Christian Heimgartner. System Dynamic Modelling of Transport and Land use - A First Model Draft. In *1st Swiss Transport Research Conference*, Monte Verità / Ascona (CH), 2001.

Serge P. Hoogendoorn and Piet H. L. Bovy. State-of-the-art of Vehicular Traffic Flow Modelling. *Special Issue on Road Traffic Modelling and Control of the Journal of Systems and Control Engineering*, 215 (4):283–303, 2001. ISSN 00000000. doi: 10.1243/0959651011541120. URL `http://www.catchword.com/rpsv/cgi-bin/cgi?ini=xref&body=linker&reqdoi=10.1243/0959651011541120`.

Serge P. Hoogendoorn and Victor Knoop. Traffic flow theory and modelling. In *The Transport System and Transport Policy: An Introduction*, chapter 7, pages 125–159. 2013. ISBN 9780857936905. URL `http://books.google.com/books?hl=en&lr=&id=_UwJWfgo0eEC&oi=fnd&pg=PA125&dq=Traffic+flow+theory+and+modelling&ots=4dq-GBQZ2I&sig=aobOGIRBMgKjhyafk6qlMhIGfCQhttp://www.victorknoop.eu/research/`.

INRIX. Economic & Environmental Impact of Traffic Congestion in Europe & the US [Online], 2014. URL `http://www.inrix.com/scorecard/`.

M. H. Kabir, M. O. Gani, and L. S. Andallah. Numerical Simulation of a Mathematical Traffic Flow Model Based on a Non-Linear Velocity-Density Function. *Journal of Bangladesh Academy of Sciences*, 34(1):15–22, 2010.

Reinhart D. Kühne. Greenshields' Legacy: Highway Traffic. In *Greenshields 75 Symposium*, pages 3–10, Woods Hole (MA), 2011.

Le Soir. Les embouteillages coûtent 600.928 euros par jour [ONLINE, in French: Traffic Jam daily cost is equal to EUR 600,928], 2015. URL `http://www.lesoir.be/856216/article/actualite/belgique/2015-04-21/embouteillages-coutent-600928-euros-par-jour`.

Joris Liebens and Peter Vieren. Validatierapport basisresultaten provinciale verkeersmodellen versie 3.6.1 [In Dutch: Validation Report of Basic Results from the Provincial Traffic Models Version 3.6.1]. 2014.

M.J. Lighthill and G.B. Whitham. A Theory of Traffic Flow on Long Crowded Routes. In *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, pages 317–345, 1955.

Sven Maerivoet. *Modelling Traffic on Motorways: State-of-the-Art, Numerical Data Analysis, and Dynamic Traffic Assignment*. PhD thesis, Katholieke Universiteit Leuven, 2006. URL `http://www.maerivoet.org/index.php?page=traffic-dissertation`.

Ed Manley, Tao Cheng, Alan Penn, and Andy Emmonds. A framework for simulating large-scale complex urban traffic dynamics through hybrid agent-based modelling. *Computers, Environment and Urban Systems*, 44:27–36, 2014. ISSN 01989715. doi: 10.1016/j.compenvurbsys.2013.11.003. URL `http://dx.doi.org/10.1016/j.compenvurbsys.2013.11.003`.

Pierre-Emmanuel Mazaré, Ahmad H. Dehwah, Christian G. Claudel, and Alexandre M. Bayen. Analytical and grid-free solutions to the Lighthill-Whitham-Richards traffic flow model. *Transportation Research Part B: Methodological*, 45(10):1727–1748, 2011. ISSN 01912615. doi: 10.1016/j.trb.2011.07.004.

Juan de Dios Ortúzar and Luis G. Willumsen. *Modelling Transport*. John Wiley & Sons Ltd, 4 edition, 2011. ISBN 9780470760390. doi: 10.1002/9781119993308.

M. Papageorgiou, M. Ben-Akiva, J Bottom, Piet H. L. Bovy, Serge P. Hoogendoorn, N.B. Hounsell, A. Kotsialos, and M. McDonald. ITS and Traffic Management. In C. Barnhart and G. Laporte, editors, *Handbooks in Operations Research and Management Science*, volume 14, chapter 11, pages 715–774. Elsevier B.V., Amsterdam, 2007. ISBN 9780444513465. doi: 10.1016/S0927-0507(06) 14011-6. URL `http://www.sciencedirect.com/science/article/pii/S0927050706140116`.

Xiaoyu Qian. *Application of Macroscopic Fundamental Diagrams to Dynamic Traffic Management*. Master thesis, Delft University of Technology, 2009. URL `http://repository.tudelft.nl/`.

H.W.J. Rittel and M.M. Webber. Dilemnas in a general theory of planning. *Policy Sciences*, 4: 155–169, 1973.

John D. Sterman. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. Boston, MA, 1 edition, 2000. ISBN 9780072311358.

Transportation Research Board. Highway Capacity Manual. Technical report, National Research Council, 2000.

Laurent Vermeersch. Five reasons Belgium has the worst traffic in Europe [Online], 2014. URL `http://www.theguardian.com/cities/2014/aug/28/belgium-worst-traffic-europe-brussels-antwerp-congestion`.

Jifeng Wang, Huapu Lu, and Hu Peng. System Dynamics Model of Urban Transportation System and Its Application, 2008. ISSN 15706672.

John Glen Wardrop. Some Theoretical Aspects of Road Traffic Research. In *Road Engineering Division Meeting*, number 36, pages 325–362, 1952. doi: http://dx.doi.org/10.1680/ipeds.1952.11362.

Isaak Yperman. *The Link Transmission Model for dynamic network loading*. Phd dissertation, Katholieke Universiteit Leuven, 2007. URL `http://ideas.repec.org/p/ner/leuven/urnhdl1979-946.html`.