

Contribution in modelling and control of Traffic flow system using Bond Graph

M. Uzunova, A. Grantcharov, K. Dimitrov and R. Velichkova

Abstract— Traffic modelling and control is one of the major problems nowadays. The main contribution of the presented paper is the modelling of the macroscopic traffic flow model, applied in an urban area, using Bond Graph approach, based on flow /effort relation. The idea is to obtain and validate a suitable model in order to control the traffic flow between segments, after segmentation of the road length and with obtained bond graph model of traffic lights. The challenge to the traffic flow modelling, using bond graphs is the complex nature of the Traffic Flow domain and the difficult translation and quantisation of the traffic variables into bond graph elements. Although the research gives valuable insight on the process of designing a traffic light controlled crossroad, using bond graph switching network, and also on the concept of segmentation of long roads for better in-depth analysis of the processes within the road.

I. INTRODUCTION

Based on the level of detail, we distinguish two types of traffic models: microscopic and macroscopic models.

Microscopic traffic models are models in which all vehicles or “particles” in the system are described individually. Macroscopic traffic models are models that use aggregate variables, which summarises information about multiple vehicles, in order to describe the traffic situation. Typically, a macroscopic model defines a relation between the traffic density, the average velocity and the traffic flow. The traffic density is defined as the number of vehicles per kilometre and per lane, while the traffic flow or the traffic intensity is defined as the number of vehicles passing a certain point per hour. Within the class of macroscopic models, a classification based on the order of the models can be made [5],[10] and [14]. Traffic model is from origin a continuous model which is discretised in space (with motorway stretches of typically 500 meter) and time (with time intervals of typically 15 seconds) for implementation and simulation on a computer [4], [5] and [9]. In the remainder of this paper, we will more extensively look at macroscopic traffic models, since these kind of models are better suited for model-based control design methods than microscopic traffic flow models. But first we will examine one of the basic concepts in traffic flow theory - the fundamental diagram [1], [3], [14] and [15].

II. FORMULATION OF DESIGNING OF TRAFFIC FLOW

A. Theoretical formulation of traffic flow model

Building traffic models for uninterrupted flow is relatively easy and quite a few researchers have proposed different models, depending on the goals pursued. But building a model for switching network, consisting of traffic lights has certain challenges that require some Boolean math.

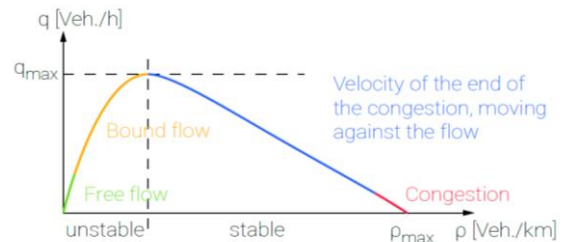
This section of the document is on digital logic. Karnough maps are a method for simplifying and graphically representing Boolean functions. A Boolean function $f(x_1, x_2, x_3, \dots, x_n)$ is a function of n individual statements $x_1, x_2, x_3, \dots, x_n$, combined by AND, OR, and NOT operations. The statements $x_1, x_2, x_3, \dots, x_n$ are known as Boolean variables that can either be true or false, corresponding to a 1 or 0 in Boolean algebra.

From other hand another approach of modelling of systems is using Bond graphs, originated by [1], [2] and [3] concern with the conservation of energy. Further details can easily be found upon search, including in [4], [6] and [10] Energy can be transported from one place to another, can be stored and can be converted into different forms, but cannot be dissipated.

For the macroscopic flow model fundamental relation is given by (1) the fundamental diagram is presented on Fig. 1. The diagram shows the relation between the three variables of the fundamental equation of traffic flow and in Greenshield’s diagrams, the capacity speed V_c is half the maximum speed V_f . The capacity density ρ_c in this model is half the maximum density ρ_{max} , q is traffic flux, ρ is density, V_f is velocity at free flow, V_c is critical velocity at maximum flux.

$$\left\{ \begin{array}{l} q(x, t) = \rho(x, t)V(x, t) \\ V(x, t) = V_f \left(1 - \frac{\rho}{\rho_{max}}\right) \\ \frac{\partial \rho(x, t)}{\partial t} + \frac{\partial q(x, t)}{\partial t} = 0 \end{array} \right. \quad (1)$$

$$\left\{ \begin{array}{l} q = \rho_{max} V \left(1 - \frac{v}{V_f}\right) \\ V = \frac{V_f}{\rho} (\rho_{max} - \rho) \end{array} \right. \quad \text{Greenshi}$$



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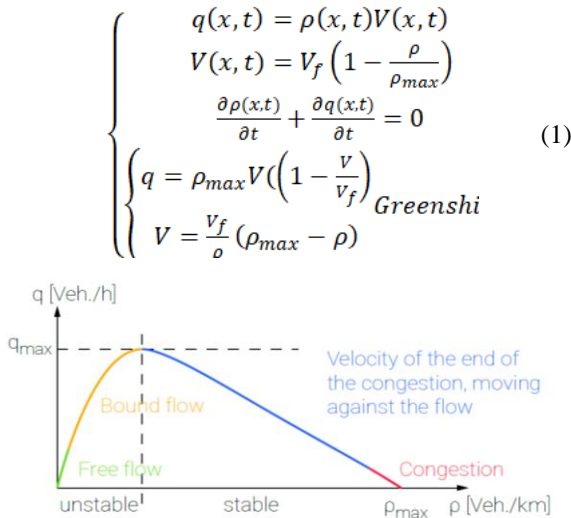


Figure 1. Generic fundamental diagrams of traffic flow based on the

B. Formulation of Bond Graph modelling approach

Bond graphs concern themselves with the conservation of energy. Energy can be transported from one place to another, can be stored and can be converted into different forms, but cannot be dissipated. Hence if the amount of energy is changing at a certain location, either additional energy is flowing in, or some of the initial energy is flowing out. In both cases, there exists a rate of change of energy in time; defined as power. Power flow can be expressed as the product of two variables: an extensive variable (proportional to the amount), and an intensive variable (independent of the amount). In Bond graphs, the energy flows are represented as directed harpoons between two pins. The two variables are the intensive effort variable, annotated above the harpoon with an "e" and the extensive flow variable, annotated below the harpoon with an "F". Voltage, temperature, force, torque, and pressure are examples of effort variables; while current, entropy flow, velocity, angular velocity, and fluid flow are

examples of flow variables. Table I shows these variables in their respective domains.

TABLE I. EFFORT AND FLOW IN VARIOUS DOMAINS

Domain	effort (e)	Notation & unit	flow: (f)	Notation & unit	Generalised momentum: (p)	Notation & unit	Generalised displacement: (q)	Notation & unit
Translation mechanics	force	F [N]	Velocity	v [m/s]	Momentum	p [kg]	Displacement	x [m]
Rotation mechanics	angular moment	M [Nm]	Angular velocity	ω [rad/s]	Angular momentum	p_ω [Nm.s]	Angle	θ [rad]
Electro-magnetics	voltage	u [V]	Current	i [A]	Linkage flux	λ [Vs]	Charge	q [As]
	magneto-motive force	V [A]	Magnetic Flux Rate	$\dot{\phi}$ [Wb/s]	N/A	N/A	Magnetic flux	ϕ [Wb]
Hydraulics	Total pressure	p [N/m ²]	Volume flow	Q [m ³ /s]	Pressure momentum	p_p [N/m ²]	volume	V_v [m ³]
Thermo-dynamics	Temperature	T [K]	Entropy flow	\dot{S} [J/K/s]	N/A	N/A	Entropy	S [J/K]
Chemistry	Chemical potential	μ [J/mole]	Molar flow	N [mole/s]	N/A	N/A	Molar mass	N [mole]

The system elements in Bond Graph are:

- source: Se (effort source) and Sf (flow source);
- passive elements : R (resistors), which dissipate energy irreversibly, C (capacitors) and I (inductance);
- reversible energy converters: TF (transformers) and GY (gyrators), both possessing an incoming and an outgoing bond;
- Sw (switches): passive elements with two states (open and close). When is close the flow through the switch is determined from the outside and the effort across the switch is zero. When is open the flow through the switch is zero and the two sides of the switch have independent effort values. Whereas resistors, inductors, capacitors, and sources are all modelled with a single equation, the switch element is described by two equations, one for each of the two possible switch positions.

$$0 = \text{Openswitch} * \text{flow} + (1 - \text{Openswitch}) * \text{effort} \quad (2)$$

Another important formulation in Bond Graphs is the causality: a vertical bar placed at one side of the bond indicates the side where the flow is being computed and is the way causality is notated.

Sources have fixed causality bars. The effort source computes the effort; therefore the flow is computed on the other side. The flow source computes the flow and consequently has the causality stroke at the source end of the bond.

Resistors, they have free causality - the causality stroke is placed depending on where the flow is being computed.

The causality of the storage elements is determined by the desire to use integrators instead of differentiators; however, this is a preference, not a requirement. In general the causality is preferable as: deferential relation for inductance and integral relation for capacitor.

As transformer compute one effort variable and one flow variable there is one causality stroke at the TF element. There are two possible causality allocations for the transformer element, depending on its location in a system.

As we must compute one equation at the left and the other at the right of the gyrator, the equations may either be solved for the two effort variables or for the two flow variables. Similar to the transformer, the causality for the gyrator can attain two different situations.

Junctions of type 0 have only one flow equation therefore exactly one causality bar must be at the junction. Junctions of type 1 have only one effort equation, resulting in exactly (n-1) causality bars at the junction.

The causality of the switch depends on the switch's state; an open switch necessitates a "flow = 0" for its relative junction and a closed switch inflicts an "effort = 0".

All the causality possibilities are presented on the Fig. 2.

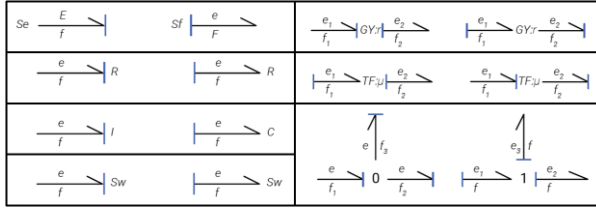


Figure 2. Causality in Bond Graph elements

III. TRANSLATION OF TRAFFIC INTO BOND GRAPH

Looking into deterministic model for the traffic dynamics, where the variability, which is probabilistic in nature, is separated and included as a potential field function. The deterministic traffic dynamic model that is based on bond graph approach is a good instrument for analysis of traffic conditions under standard potential fields [3], [4], [5], [18] and [19]. In general the macroscopic traffic assumption describes the traffic flow outside the cities, but in busy city traffic we consider that the vehicles move as a group [7], [10] and [17]. In order to model the macroscopic traffic flow model [8] and [9], we can make analogous with electrical system with the flow of electric charges in conductor and the vehicle is considered to be equivalent to an electric charge. Moreover the source element we need to discuss also the: storage and dissipative elements; kinetic and potential storage elements; modelling of road junction (0 and 1) as an analogue of the physical phenomenon of the traffic flow.

In the following we present a detailed analysis of traffic physical variables and notions and their analogous with bond graph elements.

A. Modelling of source

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Vehicle is considered as an electrical charge and the rate of flow of traffic is defined as the flow variable and the rate of flow is equivalent to the current in electrical domain. The effort is defined as the traffic-motive force, (TMF) or the motive force for the movement of vehicles on the road. Respectively (e_T , f_T) are defined to be the effort and the flow variables in the traffic energy domain (3).

$$\begin{cases} f_T = q[\text{Veh./s}] \\ e_T = \text{TMF}[\text{J/Veh.}] \\ \text{Power} = f_T \cdot e_T \rightarrow \left[\frac{\text{Veh.}}{\text{s}} \right] \cdot \left[\frac{\text{J}}{\text{Veh.}} \right] = \left[\frac{\text{J}}{\text{s}} \right] = \text{I} \end{cases} \quad (3)$$

B. Modelling dissipative and storage elements

Road resistance is a dissipative element that models the resistance to the flow of vehicles. The resistance is similar to that in the hydraulic domain impeding the flow of fluids. That resistance depends on the physical conditions as: speed breakers, numbers of roads ramps (in and out) etc. That phenomenon is similar to the resistance of a conductor. The road resistance is given by (4).

$$\begin{cases} R \approx \frac{1}{\delta n}, \begin{cases} \delta = 1 \text{ if ideal road} \\ \delta < 1, \text{ otherwise} \end{cases} \\ R = \frac{e_T}{f_T} \rightarrow \left[\frac{\text{J/Veh.}}{\text{Veh./s}} \right] = \left[\frac{\text{J.s}}{\text{Veh.}^2} \right] \end{cases} \quad (4)$$

The flow rate q [Veh./s] (5), can be acquired by monitoring the traffic during the entire period of the day and then averaged. The work done in moving a vehicle over a distance L is the traffic potential difference.

$$\begin{cases} \text{TMF} = m \frac{dv}{dt} L, [\text{J/Veh.}] \\ m - \text{masse of vehicle [kg]} \\ L - \text{distance travelled in [m]} \\ v - \text{velocity in } \left[\frac{\text{m}}{\text{s}} \right] \end{cases} \quad (5)$$

For the resistance element the effort and flow causal relation are presented in (6)

$$\begin{cases} f_T = \frac{e_T}{R} - \text{effort caus} \\ e_T = \frac{f_T}{R} - \text{flow caus} \end{cases} \quad (6)$$

C. Modelling kinetic storage elements

Kinetic storage element represents the energy, stored by the velocity of the aggregated traffic mass. When vehicles start to move from one point of the road, the flow rate will increase and when the road is occupied by constantly moved cars, we can observe a similar as in electrical domain behaviour when we observe saturation in inductor. When the road is entirely occupied by moving vehicles, it's like saturated inductor. The rate of flow rate of the aggregate traffic mass in such a situation is zero and under steady flow rate condition the effect of this element is absent. Red signal at crossroads is also considered as inertia element, reducing the flow rate to zero, but not instantaneously. When the signal goes green then the flow rate not rise instantaneously too. The road inductance depends on dimensions of the road (length, lanes, and curvatures) (7).

$$\begin{cases} I \text{ or } L, \frac{1}{\text{Road Width}} \\ I = e_T \frac{dt}{df_T} \rightarrow \left[\frac{\text{J}}{\text{Veh.} \cdot \frac{\text{Veh.}}{\text{s}}} \right] = \left[\frac{\text{J.s}}{\text{Veh.}} \right] \\ \begin{cases} f_T = \frac{1}{I} \int e_T dt - \text{effort caus} \\ e_T = I \frac{df_T}{dt} - \text{flow causal} \end{cases} \end{cases} \quad (7)$$

D. Modelling of road junctions

Figure When modelling a traffic network we have on/off ramp and then the conservation law of vehicles, or the sum of the flow from roads is equal to zero (9), that is a typically modelled by “03 junction as presented on Fig. 3. Effort is identical for each road.

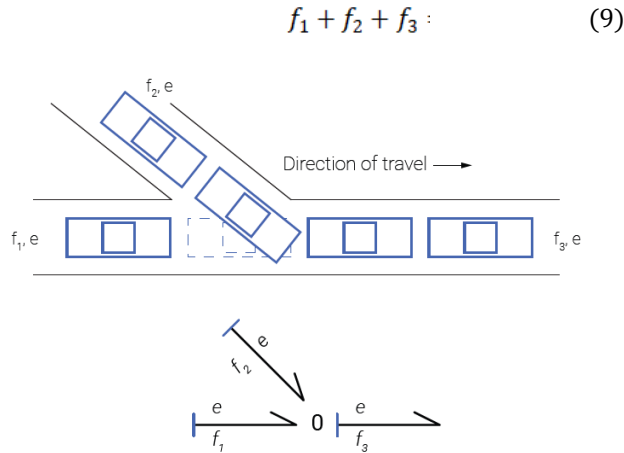


Figure 3. On-ramp road network and the bond graph model representation, using a 0-junction Causality in Bond Graph elements

When modelling a traffic network road having curved path and this kind of road can be modelled as kinetic storage element and road resistor. We build a “1” junction model having the same flow and from the principal of conservation of vehicles (10), the flow rate is the same and the TMF across the road is the sum of the TMF of all elements (the inductance storage element L and the road resistances R1 and R2). Obtained bond graph model is presented on Fig. 4.

$$e + e_1 + e_2 + e_3 = 0 \quad (10)$$

A conclusion section is not required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

IV. ROAD NETWORK MODELLING CONCEPT

In this section we will discuss the concept of modelling and segmentation of complex infrastructure. In order to get a better idea of how the traffic flows through a long road, it is worth it, when modelling that road, to divide it into short segments. This paper already discuss each element and how is translated from traffic theory to bond graph model. We need to decide on the length of the segment. Later, each segment has to be quantified, or translated from real-life flow variables into bond graph elements. The next step would be to build each segment as a separate bond graph model and use the output of the preceding segment to feed the data into the next one. We have two part of the modelling procedure when segmentation is required. In one hand we have the road characteristic (flow rate, resistance elements, storage elements etc.) and from other hand we have the traffic lights as a switching elements situated between two adjacent road segments and having important role in the traffic control strategy. This is why when designing such segmented model we have to make sure the traffic flow information propagates

both ways, so that the conditions of the road downstream affect the source (previous segments).

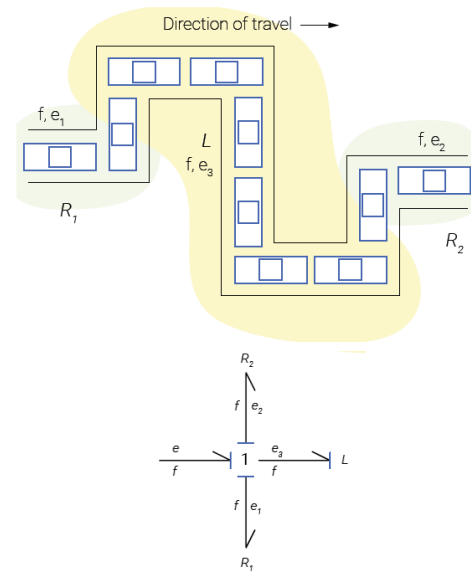


Figure 4. Road segment and the respective bond graph model representation, using a 1-junction

A. Traffic model elements

One example of the general concept is presented on Fig. 5. The model elements (Fig. 5) are:

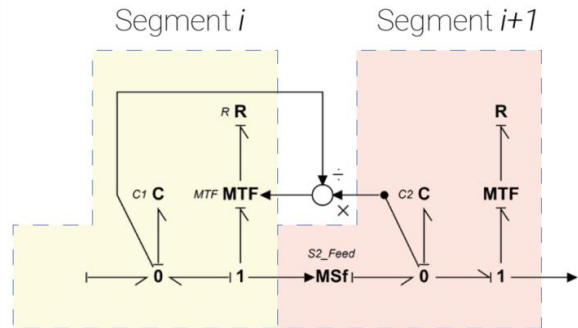


Figure 5. Segmented bond graph model of a long road

- C – the capacity – value of the C element, corresponds to amount of vehicles the road can hold, but this time it is strictly representing the limited capacity of the i_{th} segment [Veh.] ;
- the 0-junction ensures the conservation of the number of vehicles ;
- f_T – the flow variable – of the BG represents the average flow rate q [Veh./s], which represents the instantaneous number of vehicles per time unit ;
- q_T – the displacement variable – which defined by integrating the flow variable over time, represents the number of vehicles present in the segment i at time t ;
- e_T – the effort variable which related to the C-element, represents the vehicle density of the road segment ;

- the separation point – between the adjacent segments i and $(i+1)$ is modelled by an R-element, placed on a 1-junction (to ensure conservation of the mass) and controlled by a MTF (modulated transformer) with transformation coefficient μ_i ;
- R-element – involved when linking the effort to the flow, corresponds to the minimum time that a vehicle takes to pass through the segment i ;
- the modulated transformer MTF – is introduced to take into account the effect of downstream traffic conditions ;
- the coefficient μ_i – enables to represent the change in the driver behaviour, resulting from downstream traffic state. It is identified so that the ;
- output flow of a segment i – is estimated based on the number of the vehicles in the current segment i and the available capacity in the downstream segment $(i+1)$;
- MSf – the circulation of vehicles flow from one segment to the other is assured by the introduction of a modulated flow source MSf. The latter preserves the anisotropic character of the traffic flow in the developed bond graph model and guarantees that the vehicles can only move in the forward direction.

The generic bond graph model of the road section, shown in Fig. 6 can be obtained by modelling every segment of the section using a series of the elementary bond graph segments of Fig. 5.

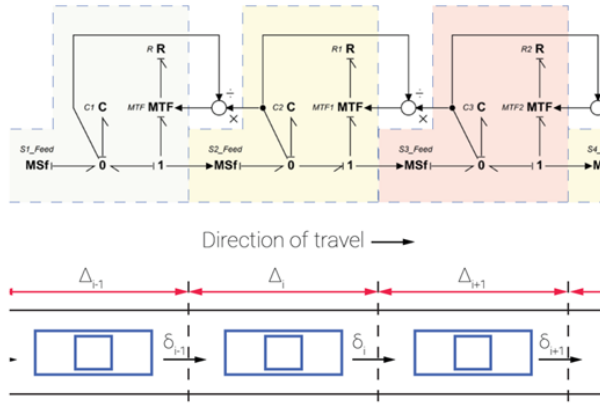


Figure 6. Generic bond graph model of multiple road network

B. Traffic lights bond graph model

As mentioned previously the switching elements in bond graph are used when we want to introduce some control of traffic in city area, using traffic lights. The changes in state in traffic lights is similar to the switching element with stop and go signal when the switch take open or close state (0 or 1). In this meaning we use bond graphs and digital logic to develop a structured algorithm for deriving switching networks in Bond graphs [11], [12], [13] and [16]. An example of a simple hypothetical 4-way traffic light controlled crossroad is present. Some simplifications are proposed: will take a look on one branch of the 4-way, the

flow is going to any of the 3 ranches (no U-turns are allowed), only one section is allowed to go at any given time, such as switching network with mutual exclusivity. The figure below (Fig. 7) represents that branch of the crossroad, where the theoretical traffic light model with 3 sections, would have the following logical representation.

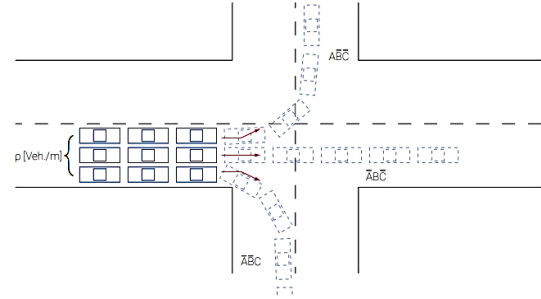


Figure 7. Simple 4-way crossroad with separate traffic light section for every direction

$$f(A, B, C) = \overline{A}BC + A\overline{B}C + A\overline{B}\overline{C} \quad (11)$$

We need to translate the expression (11), explaining the control traffic lights scenario into an electrical switching network using the Karnough map (Fig. 8).

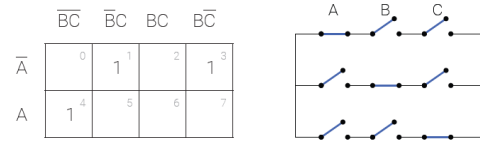


Figure 8. map and electrical switching network for simple 4-way crossroad with separate traffic light

Each row containing the three switches from Fig. 8 has been replaced with a type 1 junction, surrounded by five bonds, three of which are connected to switch elements. The effort source represents the traffic flux, building up the density at the traffic light queue, powering into a type 0 junction which is the entering node for the switching network. The three departing lines from this node correspond to the three sections of the traffic light, each one passing through its relevant series of switches and eventually arriving at a transformer, which is responsible for the distribution of the flux accordingly. The model in Fig. 9 is only a partial model, mainly to demonstrate the Bond graphic arrangement of the switching network.

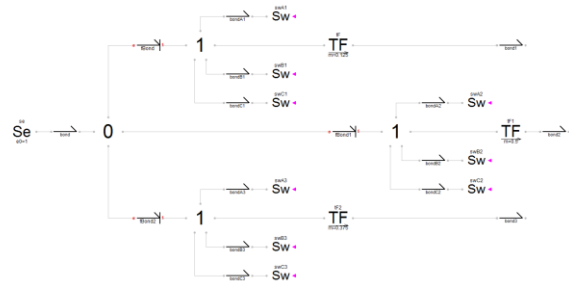


Figure 9. Three-section traffic light switching bond graph model with solved indeterminateness

On Fig. 10 we develop more the model, introducing passive elements and the logical control signals for the traffic lights. The C-element connected to the first 0-junction represents the traffic light queue and the C-elements at the ends of the 3 branches are to be considered as sinks to capture the traffic pouring in the different directions of the crossroad. Also the coefficients of transformation of the 3 TF-elements sums up to 1 and is effectively being used to account for the different amount of vehicles choosing to go in that direction of the crossroad. The control signals for the three sections of the traffic light. The applied control consist to introduce a Boolean pulses set to 60 seconds periods, being “true” for 20 seconds and “false” for 40 seconds, de-phased 20 seconds from each other. The logical “not” converts the “true” signal into “false” in order to open (disconnect) the respective switches.

V. CONCLUSION

This paper presents a detailed methodological study of the application of Bond Graph modelling approach to traffic flow model systems. Moreover, in order to implement in a real case study, we look on the importance to attempt modelling and simulation of complex traffic flow in an urban area. The study give an overview of the Bond Graph method as well as an examination of the available assumptions and transitions from the complexity of the traffic flow theory to the simplicity of the Bond Graph representation. Our first contribution is the translation of each physical phenomenon of traffic flow, traffic lights, roads structure to a bond presentation under assumption and some simplification, caused by computational constraints. Of course for a large urban area, this modelling approach has limits related of computational analysis and the decision making in real time. Although the research gives valuable insight on the process of designing a traffic light controlled crossroad, using bond graph switching network, and also on the concept of segmentation of long roads for better in-depth analysis of the processes within the road. As perspectives and a future consideration, we need to mention that all optimisation and prediction can be developed in order to face the main problem in traffic: the bottlenecks, especially in urban area.

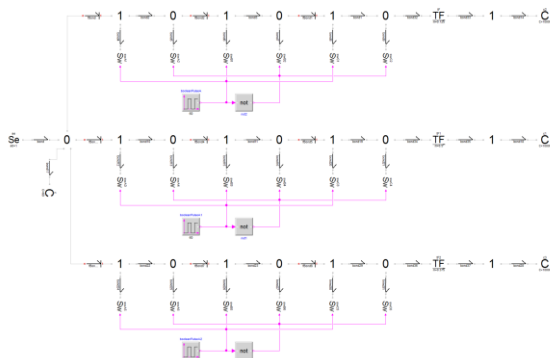


Figure 10. Three section traffic light switching bond graph model with solved indeterminateness and added switching control and passive elements.

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