Joint Traffic Management and Logistics optimization: a game theoretical approach

Marco Rinaldi, KU Leuven

Rodrigo Amaral, Universiteit Gent

El-Houssaine Aghezzaf, Universiteit Gent

Pieter Vansteenwegen, KU Leuven

Chris M.J. Tampère, KU Leuven

Introduction

Traffic Management and Logistics optimization, when considered separately, are well-known problems which have been studied for several years. There is in fact for each of these problems a very large literature rich with different methodologies, mathematical models and algorithmic solutions.

Traffic Management is a special case of the Network Design Problem (NDP), which is usually formulated in literature as a bi-level optimization problem. Logistics optimization, on the other hand, deals with the distribution of goods and materials between suppliers, manufacturers and retailers. Concerns such as fleet composition, product handling, inventory management and routing are taken into account to formulate the problems.

While the problems have been addressed separately, no attention has been devoted yet to exploring the interactions between the two players. We believe this to be of considerable importance, since partial or incomplete knowledge on one another's decisions might yield sub-optimality for either or both of them.

As a first step towards exploring these interactions in greater detail, we propose a framework integrating both the Traffic Management and the Logistics optimization problems in one, comprehensive model by means of a game theoretical approach. Once the model is specified, we perform numerical tests in order to assess the impact of the two players on each other.

Methodology

Traffic Manager modeling: the NDP bi-level formulation

As introduced earlier, the interaction between the traffic manager and the road users is usually modeled, in the NDP framework, through a bi-level formulation (Yang and H. Bell, 1998), which can be expressed as follows:

$$\min_{u} F(u, v(u)) \\ s.t. \begin{cases} G(u, v(u)) \leq 0 \\ v(u) : v = \begin{array}{c} \arg\min H(u, v) \\ s.t.\, g(u, v) \leq 0 \end{array} \end{cases} \tag{1}$$

The upper level is that of determining the set of control variables u such that an objective function F (usually, Total Cost) is minimized. The objective function doesn't only depend on the control input directly, but also indirectly through the link flow's response $v(u)$ to changes in the control variable u. This qualifies as anticipatory control, as introduced in (Allsop, 1974).

The lower level comprises of a different minimization problem, which can be seen in the constraint set of the NDP. The users seek a distribution of link flows over the network such that the following condition (User Equilibrium, (Wardrop, 1952)) is met:

$$v^* = \arg\min H(u, v) = \arg\min \sum_l v_l(c_l) \cdot c_l(v_l) \tag{2}$$

This is a Nash equilibrium and, in various circumstances, can lead to a subutilization of the network capacity. The Downs-Thomson Paradox (Downs, 1962) and the Braess Paradox (Braess, 1968) exemplify this fact. (Amaral and Aghezzaf, 2014) showed how these paradoxes could occur also in multi-modal networks. By setting the traffic controls wisely, the traffic manager can avoid the unwelcome consequences of the generally uncooperative network users' behavior.

Logistic management modeling

Logistics is one of the most important areas of study in Supply Chain Management. It addresses the planning, implementation and control of the flows and storage of goods, services, and information in a network consisting of providers and customers. In this study, we are mainly concerned with the aspects of Logistics which are related to Traffic Management. Research on City Logistics is possibly the most relevant for our current work, since it considers congestion and other traffic aspects more closely than other studies made on routing problems. An in-depth discussion of the challenges and perspectives in City logistics can be found in (Crainic et al., 2009), (Benjelloun and Crainic, 2008), (Dablanc, 2007), (Russo and Comi, 2010), and (Taniguchi and Thompson, 2011). Since the number, the requirements and the properties of the involved vehicles, products, customers and of the network itself strongly differ in each type of problem, the complexity of the models depends on the distribution system and the degree in which its dynamics must be captured.

Combined modeling:

When integrating the Traffic Manager (TM) and the Logistic Player (LP) dynamics into one connected framework, different models can be developed depending on the assumed game theoretical interaction that ensues between the three players participating in the game (TM, LP and the road users). These interactions depend entirely on if/how the TM and the LP obtain information over each other's intentions and/or the users'. The different alternatives are summarized in the following table.

	LP anticipates road users	**LP does not anticipate road users**
TM anticipates LP & road users	→ Three level game with TM on top, LP in the middle and Road Users as pure followers	→ Pure Stackelberg with TM as a leader and LP and Road Users as pure followers
TM anticipates road users only	→ Nash-Cournot game between TM and LP, Road Users as pure followers	→ "Incomplete" Stackelberg, TM has wrong assumptions about LP's strategies (considers them as road users)

Table 1

In all of the aforementioned alternatives, the road users (i.e. private transportation) are considered as a pure follower, always subject to the decisions of the other two players, and always behaving accordingly to User Equilibrium principles.

For the sake of clarity, we schematize the interactions above in Figure 1 (following the same tabular configuration).

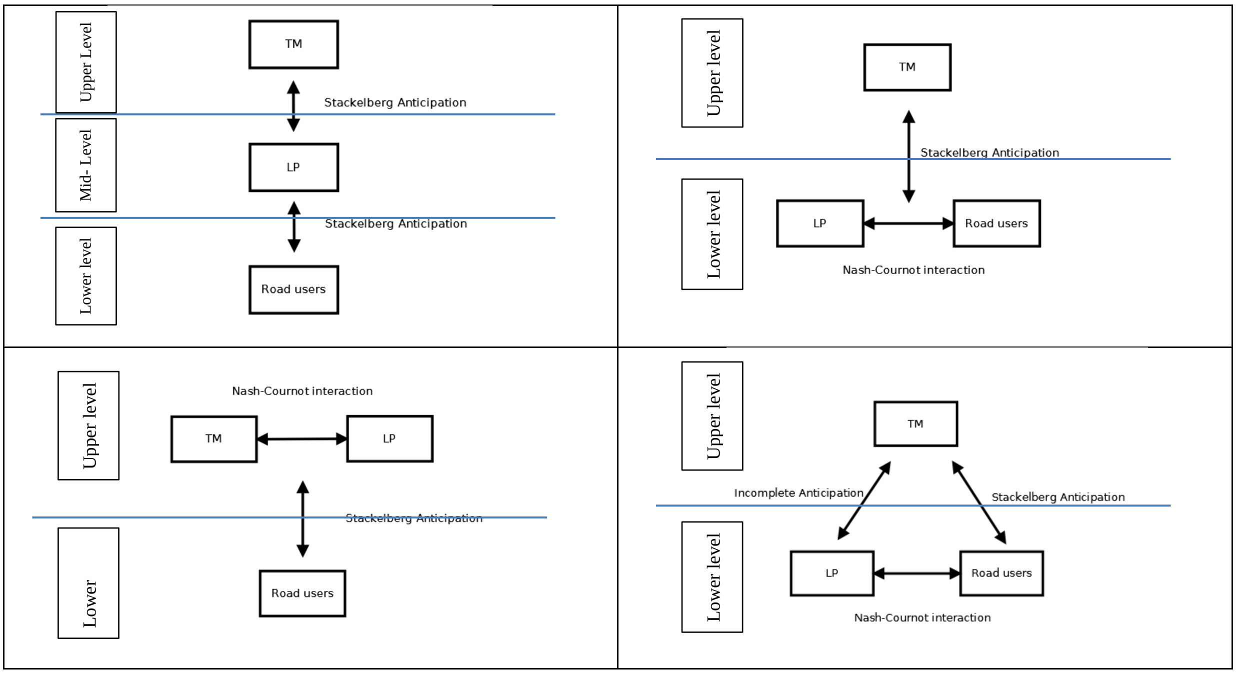

Figure 1

Experimental Results

We focus on the case in which the TM is in the pure leader position, and devise a simple test case to assess the impact of correctly anticipating the LP's moves (upper right corner in Table/Figure 1) with respect to having only partial knowledge (lower right corner). The test network is detailed in Figure 2a.

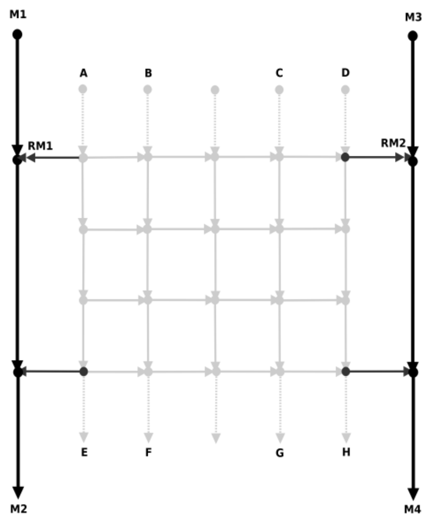

Figure 2a

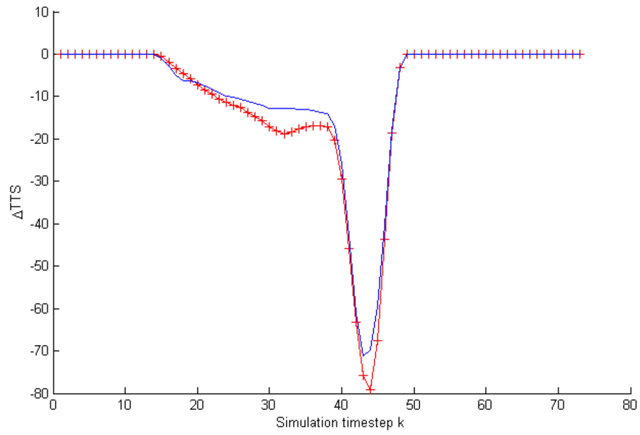

Figure 3b

This network is composed of two parallel motorways running, respectively, from M1 to M2 and from M3 to M4, amidst whose lays a lower-capacitated urban area with four Origin/Destination pairs: AE, BF, CH and DH. A logistic player is also delivering packages within the urban area, creating therefore extra congestion and externalities. The objective of this experimental setup is that of determining how the two Ramp Metering controllers RM1 and RM2 are impacted by the presence of the Logistic Player. The results from our initial tests, in which we optimize the TM's objective function following the approach we introduced in (Rinaldi and Tampère, 2015), are presented in Figure 2b. Indeed, the difference between anticipating (red line) or not (blue line) the presence of extra flow due to a logistic player in terms of optimal control and resulting Total Time Spent value is considerable.

Conclusions

In this paper, we develop a joint modeling framework to the combined problem of Network Traffic Management and Logistic optimization. We explore the joint model by means of a game theoretical approach, which allows us to define four different categories of problems, and we develop an experimental setup to compare the performances achieved by the Traffic Manager under the different conditions. Further research in these interactions and their effects depending on the magnitude of the logistic player's demand, together with applications to bigger size networks, will be presented during the symposium.

References

Amaral, R. R., Aghezzaf, E-H., 2014. Proceedings of the Second International Conference on Traffic and Transport Engineering (ICTTE). 76-85

Allsop, R.E., 1974. SOME POSSIBILITIES FOR USING TRAFFIC CONTROL TO INFLUENCE TRIP DISTRIBUTION AND ROUTE CHOICE. Presented at the Transportation and Traffic Theory, Proceedings.

Benjelloun, A., Crainic, T.G., 2008. Trends, challenges, and perspectives in city logistics. Transp. Land Use Interact. Proc. TRANSLU 8, 269–284.

Braess, D. , 1968. Uber ein paradoxen der verkehrsplaning. Unternehmensforschung 12, 258-268.Crainic, T.G., Ricciardi, N., Storchi, G., 2009. Models for Evaluating and Planning City Logistics Systems. Transp. Sci. 43, 432–454. doi:10.1287/trsc.1090.0279

Dablanc, L., 2007. Goods transport in large European cities: Difficult to organize, difficult to modernize. Transp. Res. Part Policy Pract. 41, 280–285. doi:10.1016/j.tra.2006.05.005

Downs, A., 1962. The Law of Peak-hour Expressway Congestion, Traffic Quarterly, 16, 393-409

Rinaldi, M., Tampère, C., 2015. Dynamic Traffic Control Clustering. Presented at the Annual meeting of the Transportation Board, Washington, DC.

Russo, F., Comi, A., 2010. A modelling system to link end-consumers and distribution logistics.

Taniguchi, E., Thompson, R.G., 2011. City Logistics Network Modelling and Intelligent Transport Systems.

Wardrop, J.G., 1952. ROAD PAPER. SOME THEORETICAL ASPECTS OF ROAD TRAFFIC RESEARCH. ICE Proc. Eng. Div. 1, 325–362. doi:10.1680/ipeds.1952.11259

Yang, H., H. Bell, M.G., 1998. Models and algorithms for road network design: a review and some new developments. Transp. Rev. 18, 257–278. doi:10.1080/01441649808717016