# Analyzing the performance of distributed conflict resolution among autonomous vehicles

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## ABSTRACT

This paper presents a study on how cooperation versus non-cooperation, and centralization versus distribution impact the performance of a traffic game of autonomous vehicles. A model using a particle-based, Lagrange representation, is developed, instead of an Eulerian, flow-based one, usual in routing problems of the game-theoretical approach. This choice allows representation of phenomena such as fuel exhaustion, vehicle collision, and wave propagation. The elements necessary to represent interactions in a multi-agent transportation system are defined, including a distributed, priority-based resource allocation protocol, where resources are nodes and links in a spatial network and individual routing strategies are performed. A fuel consumption dynamics is developed in order to account for energy cost and vehicles having limited range. The analysis shows that only the scenarios with co-operative resource allocation can achieve optimal values of either collective cost or equity coefficient, corresponding respectively to the centralized and to the distributed cases.

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## 1. Introduction

A transportation system operated by different entities can be understood as a multi-agent system with a variety of concerns and goals. There are different degrees of centralization in the organization of these systems, varying from highly centralized and hierarchical ones such as railroads, to very anarchical and decentralized ones such as country road traffic. The concept of "anarchical" is understood here as each agent maximizing its utility without sharing decision making with other agents and with little or no consideration of systemic information, besides being selfish. Air traffic can be considered a middle case because, on the one hand, it is strongly managed by Air Traffic Control Centers; but, on the other hand, it has to accommodate a lot of non-determinism in the flight times, due to environmental and operational factors, and allows certain degrees of freedom for the pilot to choose its trajectory, as long as under proper coordination. Systems with loose coupling (i.e., with variable delay and hit rate caused by the human in the loop) limit the effectiveness that central coordination can achieve, making distributed control and self-organization a popular topic since many years (Bakule, 2008; Dimarogonas and Kyriakopoulos, 2003). Currently, with the expected increase in vehicle autonomy in various transportation modes, this becomes even more important. In the case of air traffic, approaches to decentralized or distributed control vary from the most radical ones (Hoekstra et al., 2001; RTC, 26-October-1995), passing through some moderate concepts (Blom and Bakker, 2015; Moniz et al., 2009; Vilaplana Ruiz, 2002) and including more conservative ones, such as market-based mechanisms (Castelli et al., 2011; Cruciol et al., 2015; Schummer and Vohra, 2013; Waslander et al., 2008) which take place

at the planning stages of the operations. The so-called Collaborative Decision Making (Zellweger and Donohue, 2001) in Air Traffic Management uses principles of negotiations but, as it is today, still needs hierarchy and a central authority.

The benefits of distributed control are more flexibility to the pursuit of individual goals and more reliability in conflict solving, which emanates from the shorter communication paths and avoiding processing overload to the central entity (Blom and Bakker, 2014), even though, it is less open to optimization than centralized solutions. Game theoretical studies show that huge performance improvements can be achieved in network traffic systems when coordinated solutions are implemented instead of anarchical ones (Correa et al., 2005; Roughgarden and Tardos, 2002), but most of these studies take an Eulerian approach, whereby the successive vehicles' positions are not taken into account and the traffic flows steadily during a given period of time. The abstraction of vehicle positions makes it difficult modeling the temporal propagation of the traffic, localized traffic surges and phenomena such as vehicle collision and fuel exhaustion. These aspects need some way to model the vehicle displacement in the network, and a seminal reference on such type of modeling is Daganzo (1994), which introduced the so-called Cell Transmission Model (CTM). In this model, a traffic way is divided into cells for which the counts of vehicles entering and leaving per unit of time are taken into account. Late evolutions of this model have been applied in combination with game theory (Schadschneider et al., 2010; Tanimoto, 2015), where the traffic is modeled by means of Cellular Automata (CA); however these CA case studies concern linear traffic and lane changes, not routing problems. Besides, the dominant approach of these works is related to statistical physics, which has a very different concept of equilibrium than that of game theory, despite these works making analogies with such theory.

A remarkable study on congestion prediction in air traffic (Bayen et al., 2005) uses a fully Lagrangian model, where each vehicle is represented as a separate object, a hybrid automaton, for which a univocal trajectory is maintained. The present study is affine with such type of modeling but does not aim at predicting real traffic and, accordingly, uses a much simpler vehicle and traffic model. Another interesting aspect of Bayen et al. (2005) is that it demonstrates the relations of its Lagrangian model with previous Eulerian models. And, because both these types of model should represent the same phenomena, it is possible as well to mix their features as it was done in Sun and Bayen (2008), where an Eulerian–Lagrangian model, named Large Capacity Cell Transmission Model or CTM(L), becomes the basis for applying mixed integer linear programming to minimize the total travel time, in a fully centralized manner. The results presented in this work show the great potential of CTM(L) for traffic optimization, however, these models need some complementation for dealing with non-determinism and prioritization of individual vehicles.

The present work is devoted to efficiency and equity aspects of distributed control, the relevance of these topics coming from the following facts: first, one can observe the increasing importance of autonomous vehicles in several transportation modes, notably in ground transportation, with autonomous cars being developed by several vendors, and in aviation (Balin, 2016), with the ever growing importance of drones; and, second, the concept of autonomous vehicle is usually associated with distributed control. As written in the same reference Balin, 2016, "*Autonomy is the ability to achieve goals while operating independently from external control.*" Distributed control, however, can occur cooperatively or non-cooperatively, and this impacts the systemic traffic efficiency. When multiple autonomous vehicles use a protocol to resolve conflicts, there is some degree of cooperation, which can be as low as notifying the intent, and can be as high as agreeing to a conflict resolution algorithm and electing a leader to execute the algorithm and to direct the conflict resolution process. In the latter case, this cooperation becomes similar to centralized control, however, the uncertainties which this scenario retains on team formation and who will be elected as the leader still can be understood as a form of distributiveness. In this paper, however, the terms "non-cooperation" and "cooperation" refer to cases of cooperation in different degrees of cooperativeness among vehicles, as it will be explained in Section 5.

Recognizing the merits of the previous works on traffic modeling and optimization, cited above or else, the present paper aims at filling the existing void in applying game theory to study particle-based vehicle traffic models, contributing to developing a method for measuring the impact of cooperation *versus* non-cooperation on the performance of vehicle traffic systems, when micro-level interactions are taken into account. In order to achieve this aim, the paper is structured as follows: Section 2 introduces the basic model elements of the vehicle traffic game defined in this work, and presents the main features of a resource allocation protocol used to solve route conflicts among the vehicles in a decentralized manner; in Section 3 it is described how the vehicle traffic game was validated according to several aspects, such as overlappings, starvation, and entropy; further, in Section 4, a fuel consumption dynamics is introduced in order to represent this important aspect of real vehicles; then, in Section 5, the main goal of this paper is accomplished, which is to analyze the impact that cooperation and non-cooperation have in the performance of the system; and, finally, Section 6 discusses the results and how they can be used in further developments.

## 2. The traffic network game

Let $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ be a graph representing a traffic network. In the graph theory jargon, a network node is called a *vertex* and a network link called an *edge*, so these terms are used hereafter. Vehicle agents occupy the vertices in $\mathcal{V}$ and move through the edges in $\mathcal{E}$, in discrete time. Each vehicle $a_i$ starts at a source vertex $s_j$ and has a destination vertex $d_j$. At each time $t_n, n = 1, 2 \ldots$, a vehicle chooses the next vertex among the neighbors of the current vertex and moves to it between the times $t_n$ and $t_{n+1}$. This assumption of unitary travel time for all edges is used for simplicity, however, this can be generalized to arbitrary times. The choice of a vertex is instantaneous and respects certain restrictions. This assumption