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Yibing Wang	Zhejiang University, China
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Keynote speaker

Managing Network Mobility with Tradable Travel Credits

Professor Hai Yang

The Hong Kong University of Science and Technology, Hong Kong

Hai Yang is currently a Chair Professor at The Hong Kong University of Science and Technology. He is internationally known as an active scholar in the field of transportation, with more than 200 papers published in SCI/SSCI indexed journals and an H-index citation rate of 41. Most of his publications appeared in leading international journals, such as Transportation Research, Transportation Science and Operations Research. Prof. Yang received a number of national and international awards, including National Natural Science Award bestowed by the State Council of PR China (2011). He was appointed as Chang Jiang Chair Professor of the Ministry of Education of PR China. Prof. Yang is now the Editor-in-Chief of Transportation Research Part B: Methodological, a top journal in the field of transportation.

Keynote speaker

Combined Lane Change and Variable Speed Control: Analysis and Simulations

Professor Petros Ioannou

University of Southern California, Los Angeles, California

Petros A. Ioannou received the B.Sc. degree with First Class Honors from University College, London, England, in 1978 and the M.S. and Ph.D. degrees from the University of Illinois, Urbana, Illinois, in 1980 and 1982, respectively. In 1982, Dr. Ioannou joined the Department of Electrical Engineering-Systems, University of Southern California, Los Angeles, California. He is currently a Professor in the same Department and holds the A.V. 'Bal' Balakrishnan Chair. He is the Director of the Center of Advanced Transportation Technologies and Associate Director for Research of METRANS, a University Transportation Center. He also holds a courtesy appointment with the Department of Aerospace and Mechanical Engineering and the Department of Industrial Engineering. His research interests are in the areas of adaptive control, neural networks, nonlinear systems, vehicle dynamics and control, intelligent transportation systems and marine transportation. Dr. Ioannou was the recipient of the Outstanding Transactions Paper Award by the IEEE Control System Society in 1984 and the recipient of a 1985 Presidential Young Investigator Award for his research in Adaptive Control. In 2009 he received the IEEE ITSS Outstanding ITS Application Award and the IET Heaviside Medal for Achievement in Control by the Institution of Engineering and Technology (former IEE). In 2012 he received the IEEE ITSS Outstanding ITS Research Award and in 2015 the 2016 IEEE Transportation Technologies Award. Dr. Ioannou is a Fellow of IEEE, Fellow of International Federation of Automatic Control (IFAC), Fellow of the Institution of Engineering and Technology (IET), and the author/co-author of 8 books and over 300 research papers in the area of controls, vehicle dynamics, neural networks, nonlinear dynamical systems and intelligent transportation systems.

Symposium Program

Day 1 - Thursday, June 2, 2016

9:00	Registration
9:30	South room - Keynote speech 1: Hai Yang
10:30	Coffee break
11:00	Parallel sessions South room - Motorway traffic management with connected/automated vehicles (1) North room - Urban traffic management with conventional vehicles
12:40	Lunch break
14:10	Parallel sessions South room - Motorway traffic management with connected/automated vehicles (2) North room - Urban traffic management with connected/automated vehicles
15:50	Coffee break
16:20	Parallel sessions South room - Network traffic management (1) North room - Motorway traffic management with conventional vehicles (1)
18:00	End of Day 1
20:30	Symposium dinner

Day 2 - Friday, June 3, 2016

9:00	Registration
9:30	South room - Keynote speech 2: Petros Ioannou
10:30	Coffee break
11:00	Parallel sessions South room - Network traffic management (2) North room - Urban and network traffic management with connected/automated vehicles
12:40	Lunch break
14:10	Parallel sessions South room - Public and sharing-based transportation systems North room - Motorway traffic management with conventional vehicles (2)
16:15	Coffee break
16:45	Parallel sessions South room - Modelling and management of future traffic systems North room - Motorway traffic management with conventional vehicles (3)
18:00	Final thanks
18:05	End of the Symposium

Day 1 Sessions

Keynote speech 1

Chairman: Markos Papageorgiou

Hai Yang *The Hong Kong University of Science and Technology, China*	Managing Network Mobility with Tradable Travel Credits

Motorway traffic management with connected/automated vehicles (1)

Chairman: Peter Wagner

Alexander Skabardonis *University of California Berkeley, USA*	Control strategies for corridor management
Jack Haddad *Israel Institute of Technology, Israel*	Vehicle platoon formation using interpolating control: A laboratory experimental analysis
Felix Rempe *BMW – UBM, Germany*	A comparison of traffic estimation algorithms based on floating car data
Claudio Roncoli *Technical University of Crete, Greece*	Optimal lane-changing control at motorway bottlenecks

Urban traffic management with conventional vehicles

Chairman: Anastasios Kouvelas

Andy Chow *University College London, UK*	Distributed control systems for urban traffic management
Giovanni De Nunzio *IFPEN, France*	Speed advisory and signal offsets control for arterial bandwidth maximization and energy consumption reduction
Baohua Mao *Beijing Jiaotong University, China*	The development of traffic control at signalized intersections in Beijing, China
Anastasios Kouvelas *EPFL, Switzerland*	High-level perimeter flow control for megacities in presence of uncertainties: three recent approaches

Motorway traffic management with connected/automated vehicles (2)

Chairman: Claudio Roncoli

Apostolos Kotsialos *Durham University, UK*	Hierarchical motorway traffic control: adding a new layer
Julien Monteil *Trinity College Dublin, Ireland*	Driver-assisted vehicles as actuators to increase traffic flow safety and efficiency
Peter Wagner *DLR, Germany*	Autonomous vehicles and capacity of freeways
Tomer Toledo *Israel Institute of Technology, Israel*	Modeling needs for micro-simulation of future driving

Urban traffic management with connected/automated vehicles

Chairman: Meng Wang

Rodrigo Castelan Carlson *Universidade Federal de Santa Catarina, Brazil*	Mixed-integer linear programming modeling for the control of automated vehicles through intersections
Konstantinos Ampountolas *University of Glasgow, UK*	Decentralised urban traffic signal control in a connected/autonomous vehicle environment
Felipe Augusto de Souza *University of California Irvine, USA*	Optimal urban traffic signal control and route guidance based on the store-and-forward model
Meng Wang *TU Delft, the Netherlands*	Velocity coordination for cooperative vehicles at junctions

Network traffic management (1)

Chairman: Carolina Osorio

Marios Polycarpou *University of Cyprus, Cyprus*	Congestion-free vehicle routing using road-link reservations
Mehmet Yildirimoglu *EPFL, Switzerland*	Aggregated traffic modeling and assignment in large-scale networks
Nadir Farhi *IFSTTAR, France*	Upper bounds for the travel time in road networks
Carolina Osorio *MIT, USA*	Efficient large-scale traffic management with inefficient traffic models

Motorway traffic management with conventional vehicles (1)

Chairman: Yibing Wang

Francesc Soriguera *Technical University of Catalunya, Spain*	Effects of low speed limits on motorway traffic: Some empirical findings
Hillel Bar-Gera *Ben-Gurion University, Israel*	High-Occupancy-Toll: potential benefits and modelling challenges
Dimitris Chryssagis *IBI Group, Greece*	Integrated Traffic and Facility Motorway Management – the Greek evolution
Yibing Wang *Zhejiang University, China*	Off-ramp blockage on freeways

Day 2 Sessions

Keynote speech 2

Chairman: Carlos Canudas de Wit

Petros Ioannou *University of Southern California, USA*	Combined Lane Change and Variable Speed Control: Analysis and Simulations

Network traffic management (2)

Chairman: Francesco Viti

Carlos Canudas-de-Wit *CNRS, France*	Using the averaged link transmission model for efficient control design of large-scale urban networks
Marco Rinaldi *University of Luxembourg, Luxembourg*	Decomposing the anticipatory network traffic control problem
Chris Manzie *University of Melbourne, Australia*	Decentralised extremum seeking in urban traffic network controllers
Biagio Ciuffo *European Commission JRC, Italy*	The quest for an optimized road transportation system through autonomous vehicles

Urban and network traffic management with connected/automated vehicles

Chairman: Eleni Christofa

Stefano Carrese *Universita degli Studi Roma Tre, Italy*	Dynamic demand estimation and prediction for traffic urban networks
Bernhard Friedrich *TU Braunschweig, Germany*	Traffic light assistance based on low frequency FCD
Ketan Savla *University of Southern California, USA*	Throughput analysis of a horizontal traffic queue
Eleni Christofa *University of Massachusetts Amherst, USA*	Reliability of transit vehicle arrival prediction using connected vehicle data

Public and sharing-based transportation systems

Chairman: Samitha Samaranayake

Yasuo Asakura *Tokyo Institute of Technology, Japan*	Sharing based transport systems for given activity pattern
Klaus Bogenberger *Universität der Bundeswehr München, Germany*	Shared autonomous electric vehicle systems: Relocation, charging and maintenance
Marcin Seredynski *Luxembourg Institute of Science and Technology, Luxembourg*	Towards efficient prioritisation of public transport vehicles through cooperative ITS technology
Neila Bhouri *IFSTTAR, France*	Bimodal traffic control: Public transport and private vehicles
Samitha Samaranayake *Cornell University, USA*	Ridesharing in a mobility-on-demand system

Motorway traffic management with conventional vehicles (2)

Chairman: Ioannis Papamichail

Alfréd Csikós *Chalmers University of Technology, Sweden*	Switching CTM for mode dependent travel delay minimisation
Silvia Siri *University of Genova, Italy*	Two-class freeway traffic control for reducing congestion and emissions: a computational analysis
Simona Sacone *University of Genova, Italy*	A two-class traffic control scheme for reducing congestion, decreasing emissions and improving safety in freeway systems
Maria Kontorinaki *Technical University of Crete, Greece*	Applications of nonlinear adaptive control to local and coordinated ramp metering

Modelling and management of future traffic systems

Chairman: Anargiros Delis

Anargiros Delis *Technical University of Crete, Greece*	On macroscopic modelling of ACC/CACC traffic flows
Gaetano Fusco *Università di Roma La Sapienza, Italy*	Big data oriented models for Intelligent Transport Systems
Ioannis Ntousakis *Technical University of Crete, Greece*	Using motion planning techniques as a means to improve traffic flow

Motorway traffic management with conventional vehicles (3)

Chairman: Silvia Siri

Azita Dabiri *Chalmers University of Technology, Sweden*	Coordinated risk-aware ramp metering
Ioannis Papamichail *Technical University of Crete, Greece*	Feedback-based integrated motorway traffic flow control
Marius Schmitt *ETH Zurich, Switzerland*	Stability results for a monotonic ramp metering controller

Control strategies for corridor management

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Iintegrated management of highway corridors comprising of freeways and adjacent arterial streets controlled by traffic signals is a promising approach for improving the transportation system. However, the implementation and effectiveness of corridor management strategies has been limited because of the lack of information on traffic conditions on the highway facilities. Recently the availability of High-resolution (HR) data from fixed and mobile sources provides significant opportunities for assessing the performance of existing control and developing new control strategies. In this presentation, we first describe the collection and analysis of fixed sensor HR data from several real-world test sites and the calculation of performance measures. Next, we present the development and testing of control strategies for freeway and arterial control coordinated operation. Under recurrent congestion, the proposed control adjusts the signal settings to prevent the on-ramp demand from obstructing traffic along surface streets and triggering the "queue override" feature which reduces the effectiveness of the freeway on-ramp metering. Under non recurrent congestion, strategies are proposed for efficient utilization of adjacent arterial(s) as reliever route(s) to the freeway travelers whenever there is a capacity reducing incident on the freeway.

The Connected Vehicle (CV) technology is a mobile platform that enables a new dimension of data exchange among vehicles and between vehicles and infrastructure and offers significant potential for developing improved signal control strategies. We present the development and testing of algorithms for queue spillback detection and control in congested signal controlled grid networks with *CV* data. First a methodology was developed and tested to determine the minimum CV market penetration rates to guarantee accurate estimates of performance, measures (e.g., delay, number of stops) as a function of traffic conditions, signal settings, and sampling duration.

Two queue spillback detection methods were developed based on CV data. The first method requires only the use of CV data and is based on the notion that nonequipped vehicles in queue that arrive after the last CV-equipped vehicle can be modeled by using a geometric distribution. The second spillback detection method combines CV data with information about the signal settings at the upstream intersection and is based on a kinematic wave theory of traffic. The findings fro the evaluation of the methods indicate that the shock-wave theory based methods produces better results under low CV penetration rates. Three control strategies were developed for congested networks: perimeter control, spillback-based phase changing control strategy, and reduction in the system-wide cycle time with additional green times to the links with the highest vehicle accumulation. The strategies were tested through simulation in a real-life network. The findings indicate that statistically significant improvements can be obtained from the implementation of these strategies in the network throughput expressed in total distance travelled and number of vehicles served, and the network average travel speed.

References

[1] A. Skabardonis, Z. Amini and P.P. Varaiya, "Control strategies for corridor management". *Research Report, University of California UC Connect Transportation Center*, April 2016.

[2] J. Argote, E. Christofa and A. Skabardonis, "Connected vehicle penetration rate for estimation of arterial measures of effectiveness". *Transportation Research C*, vol. 60, pp. 298-312, 2015.

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Vehicle Platoon Formation Using Interpolating Control: A Laboratory Experimental Analysis

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Platooning of vehicles, i.e. grouping cars, buses, or trucks into a road train, can improve the traffic flow performances of transportation systems. The main idea is that the throughput of vehicles on freeways may potentially increase by forming vehicle platoons with small inter-vehicle spacings, which might allow more vehicles to fit on a road segment. Vehicle platooning can also improve traffic emission and fuel consumption, as it can potentially reduce fuel consumptions by creating better group aerodynamics and reduced drag forces, especially if the vehicle leader is a truck or a bus.

Recent research works have shown that creating platoons with small inter-vehicle spacings is feasible with the use of cooperative multi-agent technology, such as Cooperative Adaptive Cruise Control (CACC). CACC requires vehicle to vehicle communication capability, e.g. VANET - vehicular ad-hoc network, which enables vehicles to transmit real-time data such as their individual accelerations, absolute positions, and speeds to other vehicles in the shared network. The acquisition of this data in real-time can improve the control performance of the platoon, and can enable vehicles to maintain small inter-vehicle spacings while keeping the vehicle-string stable. The string stability of a platoon of vehicles has several definitions in the literature. Simply put, a string is called stable if an interference that is created downstream is not amplified as it propagates upstream. CACC evaluation and experimental results can be found. These works also compare CACC with other methods that can be used for automatic platooning such as Adaptive Cruise Control (ACC), in which every vehicle behaves autonomously, relying on data acquired only from its onboard sensors.

In this research, the problem of platoon formation is defined using a consensus objective, i.e., tracking predefined velocity and inter-vehicle spacing, and is addressed with state space control methods for discrete-time systems. The problem is solved by utilizing a novel approach called Interpolating Control (also known as Improved Vertex Control), which has been recently presented in [1]. This approach aims at regulating to the origin uncertain and/or time-varying linear discrete-time systems, with state and control constraints. The vehicle platooning is maintained by explicitly enforcing constraints such as minimum and maximum spacings at all times. Other constraints arising from the dynamics and limitations of the vehicles are also handled. Simulation and laboratory experiment results are compared with other methods in the literature.

References

[1] H. N. Nguyen, P.O. Gutman, S. Olaru, M. Hovd, “Implicit improved vertex control for uncertain, time-varying linear discrete-time systems with state and control constraints”. *Automatica*, vol. 49, pp. 2754-477, 2013.

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A Comparison of Traffic Estimation Algorithms Based on Floating Car Data

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Estimating traffic variables from incomplete and noisy sensor information is fundamental for understanding traffic phenomena, developing traffic models and providing current and predictive traffic information for travelers and traffic managers. While past research is mostly based on detectors, which provide aggregated traffic flow, density and velocity at fixed time intervals Δt at positions x_i along a road, nowadays, the increasing availability of Floating Car Data (FCD) allows to deduce traffic information on a wider scale and a higher precision than detectors can usually do.

The main challenges of traffic estimation with FCD are that data provide only travel times or current velocities of single cars, but not aggregate traffic variables such as flow and density. Therefore, the traffic state is under-determined. Additionally, data density is not constant as the penetration rate of a vehicle fleet varies depending on place and time. Thus, an algorithm providing an accurate traffic speed estimation $V(x,t)$ needs work well with both, low and high data densities.

Many algorithms have been developed that are able to process FCD, though, most of them also require density or flow information. Therefore, the scalability of those approaches is limited by the access to fixed sensor data. Few approaches are published that work solely on FCD. Among others, one promising one is the Generalized Adaptive Smoothing Method (GASM) [2] that smooths traffic data in direction of wave propagation. Another is the adapted ASDA/FOTO (Automatic Tracking of Moving Jams/Forecasting of Traffic Objects) [1] which, based on Kerner's Three Phase Theory, analyzes trajectories for state transitions and reconstructs phase objects. Third, there is an ensemble Kalman filter approach called EnKF CTM-v that includes a Cell Transmission Modell deduced from the Lighthill-Whitham-Richards PDE [3].

All of these approaches have been applied to real probe data and show promising results when reconstructing traffic speed. However, each algorithm has different requirements regarding its input data, processes data in a different way and, consequently, results in a different traffic estimation $V(x,t)$. Thus, for researchers as well as practitioners an objective comparison of different approaches is valuable in order to identify further directions of research and apply the most suitable method to given data, respectively.

Therefore, we first review the current state of the art of traffic speed reconstruction based on FCD with special emphasis on the strengths and weaknesses of the mentioned algorithms. Then, we present a method how to assess the accuracy of an estimation with FCD only. Subsequently, we take the anonymized FCD of a huge vehicle fleet and select three different congestion patterns on the A99 motorway in Germany. We compare the accuracy of a naïve approach, the GASM and, if possible, also the adapted ASDA/FOTO and the EnKF CTM-v quantitatively. Finally, we point out future directions for the development of traffic estimation algorithms.

References

[1] B. Kerner, H. Rehborn, R. Schäfer, S. Klenov, J. Palmer, S. Lorkowski, N. Witte, „Traffic dynamics in empirical probe vehicle data studied with the three-phase theory: Spatiotemporal reconstruction of traffic phases and generation of jam warning messages“. *Physica A: Statistical Mechanics and its Applications*, vol. 392, pp. 221-251, 2013

[2] M. Treiber, A. Kesting, R. Wilson, "Reconstructing the Traffic State by Fusion of Heterogeneous Data". *Computer-Aided Civil and Infrastructure Engineering*, vol. 26, pp. 408-419, 2010

[3] W. Work, O. Tossavainen, S. Blandin, A. Bayen, T. Uwuchukwu, K. Tracton, ": An ensemble Kalman filtering approach to highway traffic estimation using GPS enabled mobile devices". 47th *IEEE Conference on Decision and Control*, pp. 5062-5068, 2008.

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Optimal lane-changing control at motorway bottlenecks

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In the near future, Vehicle Automation and Communication Systems (VACS) are expected to revolutionise the features and capabilities of individual vehicles. Among the wide range of introduced VACS, some may be exploited to interfere with the driving behaviour via recommending, supporting, or even executing appropriately designed traffic control tasks. A promising feature that can be exploited for traffic management is lane-changing control. In fact, particularly at bottleneck locations (e.g., lane-drops, on-ramp merges), human drivers usually perform suboptimal lane-changes based on erroneous perceptions, which may trigger congestion, and, thus, deteriorate the overall travel time. In case a sufficient percentage of vehicles are equipped with VACS having vehicle-to-infrastructure (V2I) capabilities and appropriate lane-changing automatic controllers or advisory systems, the overall throughput at the bottleneck location may be improved by execution of specific lane-changing commands dictated by a central decision maker.

We propose an optimal feedback control strategy for lane-changing control at bottleneck locations, assuming that a percentage of vehicles, equipped with vehicle automation and communication systems, are capable of receiving and executing specific lane-changing orders or recommendations.

We propose an optimal feedback control strategy for lane-changing control at bottleneck locations assuming that a percentage of vehicles, equipped with vehicle automation and communication systems, are capable of receiving and executing specific lane-changing orders or recommendations. The problem is formulated as a linear quadratic regulator, where the solution is applied in the form of a linear state-feedback control law, which is highly efficient in real-time, even for large-scale networks. We show that, with appropriate modelling treatments, our control strategy can be applied to any network configuration. The control strategy aims at regulating the lane assignment of vehicles upstream of a bottleneck location so as to maximise the bottleneck throughput.

The feedback control decisions are based on appropriate choice of set-points for traffic densities and real-time measurements of the state of the system. Since the critical densities at bottleneck locations may not be available a priori, we also employ a non-model-based real-time optimisation technique, namely, extremum seeking, to identify them, with the aim of minimising a performance index, namely the total travel time over a finite time horizon.

We tested the proposed strategy on a nonlinear first-order macroscopic multi-lane traffic flow model, which accounts also for the capacity drop phenomenon.

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Distributed control systems for urban traffic management

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This paper investigates the design and use of distributed systems for urban traffic control with consideration of real time variations and uncertainties in traffic flow. Urban traffic networks are complicated systems that involve dynamics and interaction of a vast number of components including different types of junctions, vehicle classes, and road users. It is expected that efficiency and resilience of road networks can be significantly improved by coordinating all components under a centralised framework. Nevertheless, the complexity of urban networks makes it difficult to be managed by a single central system. This calls for a number of research effort on the more parsimonious and 'easy-to-run' distributed control systems in which the local components can derive their own control actions (see e.g. [1], [2], [3], [4]) It is understood that a centralised system will theoretically be able to derive a more effective policy than its distributed counterparts with better coordination. Nevertheless, the computational time for deriving such global optimal control plan increases exponentially with the size of the underlying transport networks and would eventually become intractable. One would argue that the computational efficiency gained by adopting distributed systems will have to come at the expense of the overall system-wide performance. However, a number of recent studies have suggested that the performance of a well-designed distributed system would not be significantly outperformed by a centralised one ([2], [3]).

This paper starts with presenting a comparative study looking at the performance differences between the centralised and distributed systems for urban network traffic control. Unlike the centralised control systems which make all control actions within the network of interest by itself, the distributed systems decompose the global problem into smaller 'sub-problems' and delegate the control decisions to local controllers. Consequently, the distributed systems are able to derive control plans with much shorter computational time and effort. In this paper, the centralised control plan is represented by the global brute force and genetic optimisation algorithms (GA). It is known that the brute force approach takes enormous time to compute the global optimal solution and it is rarely used in general applications. Nevertheless, the brute force solution can be taken as a useful benchmark for evaluating the performance of each controller. For the distributed counterparts, we consider the established 'semi-distributed' TUC controller and the fully distributed max-pressure controller. The control systems are applied to both one-dimensional corridor and two-dimensional grid network with different levels of demand. Considering its plausibility, the dynamics of network traffic is modelled by a cell transmission model (CTM). The performances of the controllers are evaluated through a Monte Carlo stochastic simulation framework which incorporates various sources of stochastic disturbances that mimic the traffic variability observed in the real world. The controllers are applied to a range of test networks including one-way and two-way corridors and a two-dimensional grid network with different levels of traffic demand. It is found that most benefit gained from centralised control indeed comes from its setting of signal offsets. The paper concludes with presenting a centralised hill climbing based offset refiner which is integrated with the distributed controllers. The integrated system is shown to be able to deliver a similar performance as the centralised optimiser but with significantly less computational effort.

References

[1] P. Varaiya, "Max pressure control of a network of signalised intersections". *Transportation Research Part C*, vol. 36, pp. 177-195, 2013.

[2] L. de Oliveira and E. Camponogara, "Multi-agent model predictive control of signalling split in urban traffic networks". *Transportation Research Part C*, vol. 18, pp. 120-139, 2010.

[3] A. Chow, "Optimisation of dynamic motorway traffic via a parsimonious and decentralised approach". *Transportation Research Part C*, vol. 55, pp. 69-84, 2015.

[4] T. Le, et al. "Decentralised signal control for urban road networks". *Transportation Research Part C*, vol. 58, pp. 431-450, 2015.

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Speed Advisory and Signal Offsets Control for Arterial Bandwidth Maximization and Energy Consumption Reduction

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Benefits of traffic light coordination on traffic relief are undeniable. Well-coordinated traffic lights can reduce travel time, delays, stops, and energy consumption. The size of the progression band enabled by a sequence of coordinated signalized intersections is known as bandwidth. Maximizing the bandwidth of a signalized arterial corresponds to maximizing the time during which vehicles can drive the entire length of the arterial without stopping. The first mathematical formulation of the bandwidth maximization problem was given by Morgan and Little in the 60s [1, 2], and many future extensions stemmed from these pioneering works. However, most of the current traffic-signals optimization algorithms for delay minimization or bandwidth maximization still act only on the green light durations and/or the signals offsets.

The two-way arterial bandwidth maximization problem is here addressed combining the signals offsets and the travel speed in each road segment as control actions, with a particular focus on the reduction of energy consumption. The proposed mathematical formulation is inspired by the idea in [3], where the one-way and the two-way bandwidth maximization problems were solved as an LP, using only the signal offsets as decision variables. The result was based on the observation that the integer unknowns are closely related to the inter-signal travel times, and can therefore be computed a priori if the travel times are known. However, in the current framework with the segment speeds being unknown, the two-way bandwidth maximization problem presents difficulties that make necessary the formulation of the problem as an MILP [4]. The first contribution of this work lies in the addition of terms representing traffic energy consumption and network travel time to the objective function of the two-way arterial bandwidth maximization problem. The segment speeds, as additional control action, allow to reach higher bandwidth but might induce driving discomfort and higher energy consumption if the variability of the recommended speeds is too high. Furthermore, optimal solutions with low speeds and high travel time are to be avoided, in trade-off with the energy consumption. The second contribution of this work is given by the extensive evaluation of the benefits of bandwidth maximization via a microscopic traffic simulator. Bandwidth is a theoretical quantity and a correlation with known traffic performance metrics needs to be established in order to justify its use. The combined control of offsets and speed advisory is shown to have a large impact on energy consumption without affecting the travel time. Lastly, an analysis of the traffic performance at different levels of traffic demand has been conducted, testing both under-saturated traffic conditions with the existence of a green wave, and saturated conditions. The goal of this analysis is to identify the best operation conditions of the presented approach, assess the performance degradation with traffic load, and, most importantly, propose a demand-dependent optimization.

References

[1] J. Morgan and J. Little, "Synchronizing Traffic Signals for Maximal Bandwidth," *Operations Research*, vol. 12, no. 6, pp. 896–912, 1964.

[2] J. Little, "The Synchronization of Traffic Signals by Mixed-Integer Linear Programming," *Operations Research*, vol. 14, no. 4, pp. 568–594, 1966.

[3] G. Gomes, "Bandwidth Maximization Using Vehicle Arrival Functions," *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, no. 4, pp. 1977–1988, 2015.

[4] G. De Nunzio, G. Gomes, C. Canudas de Wit, R. Horowitz, P. Moulin, "Arterial Bandwidth Maximization via Signal Offsets and Variable Speed Limits Control," *54th IEEE Conference on Decision and Control*, 2015.

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The Development of Traffic Control at Signalized Intersections in Beijing, China

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The economic development and urbanization have speeded up the traffic congestion during the past two decades. The number of vehicles in Beijing has increased from 1.89 millions in 2002 to 5.59 millions in 2014 [1]. The utilization of urban main road increased from 0.81 in 2002 to about 1.10 in 2014 though urban network has also got rapid expansion at the same time, which leads to a very popular traffic jams in the urban areas. In 2014, the percentage of public transport is about 48% with urban rail traffic inclusive, mainly benefiting from the rapid decrease of bicycle traffic during past decade under very low price of public transport. The number of public transport vehicles in Beijing reaches 46,171 bus units, one of the biggest in the world [2]. However, the private cars share 31.5% of trips in urban areas, which greatly intensifies the contradiction between road capacity and traffic demand.

Based on the authors' experiences on relaxing road traffic congestion in Beijing from 2006 [3] to 2012, the paper analyzes the behaviour characteristics of traffic flow on road network under mixed traffic environment. With the practical investigation to hundreds of congestion points within Ring Road 5 of Beijing, the paper analyzes in detail their traffic operational process, and summarizes four causations, including poor pedestrian facilities, undesirable public facilities, poor signal timing scheme, and improper road traffic organization. Further to their analyses to different kinds of congestion points, the paper demonstrates some improvement plans to easy the existing traffic jams.

This paper highlights on the improvement of signal timing schemes at the intersections with signal based on the behaviours of mixed traffic flow data in Beijing. It firstly reviews the development of traffic control systems and facilities during the past two decades, and the problems existed in their operations in Beijing. Secondly, it introduces the signal timing policies applied in different kinds of intersections. Several typical policies have been studied with practical traffic flow data and simulation techniques. Thirdly, it studies the advantages and disadvantages of different signal timing policies under the high saturation traffic intersections, where traffic jams happens. Capacity coordination among pedestrians, bicycles and motor vehicles, including cars and public vehicles, has also been studied at the intersections with different efficiency indexes related to different kinds of transport entities. The results may be applied in searching some improvement plans. The paper gives an example to improve signal timing scheme at a typical intersection in Beijing.

The paper finally advances some suggestions to improve road traffic operations, organization and management in Beijing based on above achievement. The suggestions cover optimal signal timing schemes, additional traffic signs, re-channelization intersections and remodel traffic facilities related to pedestrians and bicycles. About one hundred and fifty improvement plans have been applied by related Beijing Transport Administration Departments, which have saw obvious effects to easy traffic jams in urban areas.

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References

[1] Gencheng Wang et al, 2015 Beijing Transport Annual Report, Beijing Transportation Research Center, 2015.
[2] DoT of P.R.China, National Report on Urban Passenger Transport Development, China Communication Press Co.Ltd., 2015
[3] Baohua Mao et al, Traffic organization with optimization in urban areas, China Communication Press, 2007

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High-level perimeter flow control for megacities in presence of uncertainties: three recent approaches

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As most cities around the world become persistently denser and wider the problem of urban traffic management is steadily gaining momentum over the last decades. Many efforts have been carried out on optimizing the signal settings during the peak hours where networks face serious congestion problems and the performance of the infrastructure degrades significantly. The state-of-practice strategies fail to deal efficiently with oversaturated conditions (i.e. queue spillbacks and partial gridlocks) as they are either designed by use of simplified models that derive convex optimization formulations (but do not accurately replicate the propagation of congestion) or they are based on application-specific heuristics. An alternative approach for real-time network-wide control that has recently gained a lot of interest is the perimeter flow control (or gating). The basic concept of such an approach is to partition heterogeneous megacities into a small number of homogeneous regions (zones) and apply perimeter control to the inter-regional flows along the boundaries between regions. The inter-transferring flows are controlled at the intersections located at the borders between regions, so as to distribute the congestion in an optimal way (master-slave concept) and minimize the total delay of the system. This can be viewed as a high-level control scheme and be combined with other strategies (e.g. local or coordinated controllers) in a hierarchical control framework (this topic has gained a lot of attraction in the research community lately). For a recent review on this research direction the reader is referred to [1]-[4].

In the current work we focus on the same problem described above and we study three different approaches. The first methodology is described in [4] and integrates model-based optimal control design with an online data-driven learning/adaptive technique that deals with model parameters uncertainties and variations of the dynamics; results from extensive microsimulation tests are reported here. The second methodology is a convex formulation of an optimal control problem that also includes the inference of model parameters from real data. The problem is solved in a rolling optimization horizon, model predictive control (MPC) framework and applied to a nonlinear macrosimulation model (plant). Finally, we study the application of max-pressure control (see e.g. [5]) to the perimeter control concept. An analogy to the link-based max-pressure is defined for regions (i.e. links are replaced by regions and queues by accumulations) that can derive pressures for neighbouring regions and computes feedback control actions, such that congested regions are protected and total throughput is maximized. One main difference with the equations in [5] is that queues have a monotonic relationship to pressure while in our case accumulations have a nonlinear relationship that is derived by utilizing the macroscopic fundamental diagram. The regional max-pressure is compared in simulation experiments with the convex MPC approach.

References

[1] M. Keyvan-Ekbatani, A. Kouvelas, I. Papamichail, M. Papageorgiou, "Exploiting the fundamental diagram of urban networks for feedback-based gating". *Transportation Research Part B*, vol. 46, pp. 1393-1403, 2012.

[2] K. Aboudolas and N. Geroliminis, "Perimeter and boundary flow control in multi-reservoir heterogeneous networks". *Transportation Research Part B*, vol. 55, pp. 265-281, 2013.

[3] M. Ramezani, J. Haddad, N. Geroliminis, "Dynamics of heterogeneity in urban networks: aggregated traffic modeling and hierarchical control". *Transportation Research Part B*, vol. 74, pp. 1-19, 2015.

[4] A. Kouvelas, M. Saeedmanesh, N. Geroliminis, "Feedback perimeter control for heterogeneous urban networks using adaptive optimization". *18th IEEE International Conference on Intelligent Transportation Systems*, pp. 882-887, 2015.

[5] P. Varaiya, "Max pressure control of a network of signalized intersections ". *Transportation Research Part C*, vol. 36, pp. 177-195, 2013.

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Hierarchical motorway traffic control: adding a new layer

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This paper is concerned with the problem of vehicle traffic control in highly communication networks enriched environments. The advent of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technologies create a parallel virtual information highway next to the existing real ones that is bound to change the way traffic operations are conducted. The support and complementary potential of this spatially distributed virtual environment needs to be studied and utilised in the best possible way for traffic control purposes. In effect, this new communications infrastructure technology offers a higher granularity on the control measures that can be applied in the traffic flow process. The ability to collect data and interfere at the vehicle level creates a wealth of opportunities for exploitation.

The approach proposed here is an extension of the hierarchical architecture described in [1] where decisions at a strategic level are taken by a model predictive controller that is informed about future disturbances and in anticipation determines optimal profiles of the macroscopic variables describing the desired future traffic conditions. These optimal density, speed and queue trajectories are given as time varying set-points to local regulators which are static and infrastructure based, e.g. traffic lights. V2V and V2I allow for the addition of another control layer in this architecture at the level of the instrumented and equipped vehicle. This extra control layer reflects a change of scale for the resulting modelling and control problems. Furthermore, the control actors at this level are mobile and therefore when viewed as control devices they have to consider their own dynamics.

Although the addition of an extra layer is conceptually straightforward, the interface between the static macroscopic traffic variable control device regulators and mobile vehicle control require the development of a suitable interface. This interface is explored here. At the higher strategic level of the hierarchy, a model predictive controller based on a macroscopic traffic flow model is used. Simple regulators for ramp control and route guidance are used at the tactical level. The third layer of control is simulated by modifying the car following dynamics as modelled by the Intelligent Driver Model (IDM) [2] in view of information provided by the information highway.

The IDM is used as the microscopic component of the study with certain assumptions on driver and vehicle characteristics. Two possible implementations of the hierarchical traffic control structure of [1] are considered. The first one is a fully centralised scenario, where all the information is available to all equipped vehicles through the mediation of a traffic control centre (TCC). The second is a scenario where the information passes through limited range local *ad-hoc* wireless networks facilitating V2V and V2I interactions. The operational constraints of both scenarios are considered and their impact on traffic control is examined. The impact of technology penetration and level of instrumentation is considered as well.

Despite the fact that future motorway systems are going to be more equipped with sensors, communication and computing systems, we believe the availability of increased volumes of data, although very much desirable and welcome, cannot resolve on its own the challenge of the traffic control problem. The driver behaviour makes the control at the vehicle level a source of uncertainty and risk. It is the envisaged *modus operandi* that will affect the trajectory, impact and acceptance of V2V and V2I technologies for traffic control purposes by society.

[1] A. Kotsialos, Papageorgiou, M. and Middelham, F. “Local and optimal coordinated ramp metering for freeway networks,” *Journal of Intelligent Transportation Systems*, vol. 9, nr. 4, pp. 187–203, 2005.

[2] M. Treiber, Hennecke, A. and Helbing, D. “Congested traffic states in empirical observations and microscopic simulations,” *Physical Review E*, vol. 62, nr. 2, pp. 1805–1824, 2000.

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Driver-assisted vehicles as actuators to increase traffic flow safety and efficiency

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Vehicles with increasing levels of connection and automation will coexist with conventional vehicles on the roads. Our research investigates to what extent driver-assisted vehicles can help reduce traffic flow congestion and collision-prone situations in mixed traffic situations. Here we summarise our recent progress on modelling heterogeneous vehicles behaviours at a microscopic level, performing stability analyses of heterogeneous traffic, and designing adaptive controllers for embedded partially-automated and connected vehicles in the fleet to achieve more stable and safer traffic. We have evaluated, within our validated simulation framework Roundasim, how the proposed microscopic control strategy affects the macroscopic indicators of traffic flow.

First, we have investigated off-line parameter identification of car-following models, which enable the simulation of accurate heterogeneous traffic, the testing of control algorithms for mixed and heterogeneous traffic situations, and improved real-time estimation of driving behaviour. Offline parameter identification consists of the following: we need to fit the observed trajectory of a follower (the output) that reacts to its leader's trajectory (the input) with the modelled follower's trajectory. However, it is not a trivial problem, as depending on the input, not all the parameters can be estimated, and only the estimated parameters with objective functions that are steep enough around the minimum are valid. Inspired by recent published work on the topic [1], we have proposed a methodology to systematically address these issues: starting with any noisy dataset, we give identifiable parameters with their confidence values as outputs.

Secondly, having gained knowledge on how to reproduce realistic heterogeneous vehicles behaviour, we perform stability analyses of this heterogeneous traffic. Two transfer functions are of fundamental importance: the relation between an acceleration input -a driver's action on the throttle pedal- and the observed speeds and positions, and the relation between speeds or positions for consecutive vehicles. Stability analyses give insights on the ability of a system of vehicles to recover an equilibrium -asymptotic stability- and to attenuate the propagation of perturbations -string stability- as we move downstream, see [2]. Conditions for asymptotic and string stability are obtained for heterogeneous traffic, and controllers for driver-assisted vehicles are designed so that the derived stability criteria are verified when possible, and the instabilities are being reduced when not.

Finally, simulations are carried out to verify that the designed algorithms produce more efficient traffic while not deteriorating traffic safety. Contrary to some studies relying on the assumption of a homogeneous traffic and therefore presenting algorithms that might lead to unsafe behaviours if tested in more realistic settings, we have secured that the designed control strategies increasingly augment traffic flow stability while verifying the safety requirements of traffic flow. Future work will focus on increasing the robustness of the controllers to model uncertainty, sensors measurements and potentially communication latency time for control strategies relying on communication. It will also investigate how the proposed microscopic control of vehicles could be combined with macroscopic traffic management strategies [3].

References

[1] V. Punzo, M. Montanino, B. Ciuffo, "Do We Really Need to Calibrate All the Parameters? Variance-Based Sensitivity Analysis to Simplify Microscopic Traffic Flow Models," *in Intelligent Transportation Systems, IEEE Transactions on*, vol.16, no.1, pp.184-193, Feb. 2015

[2] Monteil, J.; Billot, R.; Sau, J.; El Faouzi, N.-E., "Linear and Weakly Nonlinear Stability Analyses of Cooperative Car-Following Models," *in Intelligent Transportation Systems, IEEE Transactions on*, vol.15, no.5, pp.2001-2013, Oct. 2014

[3] C. Roncoli, I. Papamichail, M. Papageorgiou, "Hierarchical model predictive control for multi-lane motorways in presence of Vehicle Automation and Communication Systems," *in Transportation Research Part C*, 2016, vol. 62, pp. 117-132.

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Autonomous Vehicles and Capacity of Freeways

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It is a controversially discussed question whether the introduction of autonomous our highly automated vehicles will change the capacity of the freeways in any sensible manner. Some claim that autonomous traffic will reduce the capacity of freeways [1], while others have argued in favour of a moderate [2] or even a dramatic increase of capacity [3]. To answer this important question in a reliable manner the preferred time headway T that will be built into the autonomous vehicles is needed: if it is the value that is the law in most countries, then capacity will suffer, however if autonomous cars are allowed to have at least the same preferred time headway as humans or even shorter ones, then considerable increases in capacity are possible.

Here, we will highlight another issue. Human drivers have a large variability especially in the time headway variable, the standard-deviation being of the order of the mean-value itself. This is not what is to be expected from autonomous vehicles. Therefore, one may ask the question whether this change alone, leaving anything else constant, make any difference on capacity.

We tried to answer this question by a simple microscopic simulation. Vehicles were run on a one-lane road in a circle. There were two types of them, vehicles that drive autonomously and other that do not. To keep things simple, we use a combination of two models. Most adaptive driver assistance systems (ADAS) that are able to follow another vehicle are designed as linear controllers:

$$\dot{v} = \alpha(g - VT) + \gamma\Delta v \tag{1}$$

In this Eq. (1), v is the speed of the following vehicle, g the net headway to the lead vehicle, $\Delta v = V - v$ the speed difference to the lead vehicle with speed V, $\dot{v}$ the acceleration, and $\alpha = 0.05\ 1/s^2$, $\gamma = 0.667\ 1/s$, $T = 1.4$ s are three constants. The numbers of α, γ are from [4]. The accelerations computed by Eq. (1) are restricted to an interval [-2,2] m/s^2 . To make this model crash-free, the model implemented in SUMO [5] is in addition wrapped around this linear ADAS model. It takes over whenever the speed computed from Eq. (1) becomes larger than the safe speed computed from SUMO's car-following model.

The human driver differs from the ADAS driver in two respects: (1) there is an acceleration noise of size $\sigma_a = 0.4$ m/s^2 added to Eq. (1), and (2), the driver changes the acceleration only if the newly computed acceleration differs by more than σ_a from the one currently in use. This makes the human behaviour noisy.

The fundamental diagram is computed for the two models. It results from $n = 200$ vehicles simulated for 25,000 s for each density, the first 5,000 s have been discarded to let transients die out. Any 10 s, all the microscopic values g, T, v, a, have been sampled from the simulation, from which the flow can be computed. It turns out, that there is practically no difference in the fundamental diagram of the two models, although there is a strong difference in the acceleration and time headway distributions belonging to the two models.

References

[1] M. Papageorgiou, presentation given at the IEEE-ITSC in Gran Canaria, 2015
[2] A. Kesting, M Treiber, D. Helbing, "Enhanced Intelligent Driver Model to Access the Impact of Driving Strategies on Traffic Capacity". *Philosophical Transactions Royal Society A* 368, pp. 4585-4605, 2010.
[3] P. Wagner, "Traffic Control and Traffic Management in a Transportation System with Autonomous Vehicles", in M. Maurer, J.C. Gerdes, B. Lenz, H. Winner (Eds), *Autonomous Driving – Technical, Legal and Social Aspects*, Springer.
[4] H. Winner, S. Hakuli, F. Lotz, C. Singer (Eds.), *Handbook of Driver Assistance Systems*, Springer, 2016.
[5] D. Krajzewicz, J. Erdmann, M. Behrisch, and L. Bieker. "Recent Development and Applications of SUMO - Simulation of Urban MObility". *International Journal on Advances in Systems and Measurements*, 5, pp. 128-138, 2012.

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Modeling needs for micro-simulation of future driving

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Autonomous and connected vehicles are likely to become an integral part of the traffic stream within the next few years. Their presence is expected to greatly modify travel demands and habits, traffic flow characteristics, traffic safety and related external influences, such as energy consumption, emissions and pollution.

Already a significant body of research exists on the technical requirements, sensing and communications systems and the algorithms that could control a single autonomous and connected vehicle or coordinate movement of these vehicles when they are interacting with each other.

It is important to evaluate the implications of the presence of these vehicles in the traffic stream on traffic flow as a whole and on externalities. This suggests a need to enhance current traffic simulation models, in particular microscopic ones, to represent autonomous and connected vehicles, the algorithms that control and coordinate between them, their interactions with non-autonomous vehicles and the behaviors of human drivers in the presence of these vehicles.

This talk focuses on an effort to create an overall framework for the microscopic simulation of traffic systems that include autonomous and connected vehicles. Within this framework, the possible future specific types of physical attributes of the vehicles and overall traffic control system that may materialize, their modes of operation and characteristics of scenarios in which they will operate will be identified. Modelling requirements that stem from this characterization of the system will address both algorithms for autonomous driving features and human driving behaviors. Within autonomous driving components, needs in terms of the representation of sensing systems, communications capabilities and protocols and driving algorithms for autonomous and connected vehicles will be listed. With human-controlled vehicles, potential differences in driving behaviour when interacting with different types of vehicles and decisions on releasing or taking control to and from the automated driving need to be identified.

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Mixed-integer linear programming modeling for the control of automated vehicles through intersections

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Traffic intersections are critical points in transportation networks both in terms of traffic efficiency and safety. The advances in vehicle automation and communication systems are giving a new direction to intersection management research [1]. These technologies enable the use of sophisticated strategies for intersection control and the possibility of designing systems that are safer and more efficient.

In this work, we present a Mixed Integer Linear Programming (MILP)-based strategy for intersection control in an urban environment of highly automated vehicles. The problem considered consists in enabling automated vehicles to cross an intersection while guaranteeing that no collisions occur. A Control Region (CR) is defined as an area in which vehicles follow trajectories decided by a cooperative intersection control algorithm. This region is composed by the intersection itself and a suitable stretch of the intersection approaches. The overall problem is decomposed into three subproblems. The first subproblem (SP1) consists in the computation of the feasible arrival interval for each vehicle inside the CR within which the intersection can be reached. This is achieved by solving linear motion equations for every vehicle in the CR, given the vehicle's current speed and position. The second subproblem (SP2) is a MILP for scheduling vehicle arrivals at the intersection, taking into account the intervals obtained in SP1 and suitable restrictions to avoid collisions. Finally, SP3 is a motion planning problem (see, e.g., [2]), in which suitable vehicle trajectories are obtained so that the schedules obtained in SP2 are effectively followed. A simple heuristic is used in this work.

In contrast to our previous work [3], turning movements are taken into account and conflicts are managed by explicitly modeling the possible collision regions inside the intersection (as in, e.g., [4]). Currently, the developed model is valid for an intersection of arbitrary geometry with one-lane approaches (overtaking is not considered). Moreover, we assume vehicles reach and cross the intersection with constant speed. These assumptions and the problem decomposition allow dealing with most of the problem non-linearities outside the optimization problem (SP2). The proposed strategy minimizes vehicle delay at the intersection approaches and is shown in microscopic simulation to adequately manage traffic at the intersection.

Future research should focus on relaxing some assumptions to account for more general cases; incorporating more sophisticated solutions for SP3, for example, taking into consideration aspects such as passenger comfort [5] or fuel consumption [6]; and studying coordination between multiple intersections.

References

[1] L. Chen and C. Englund, "Cooperative intersection management: a survey". *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, n. 2, pp. 570-586, 2015.
[2] C. Katrakazas *et. al.*, "Real-time motion planning methods for autonomous on-road driving: State-of-the-art and future research directions", *Transportation Research Part C: Emerging Technologies*, vol. 60, pp. 413-442, 2015.
[3] E.R. Müller, R.C. Carlson and W. Kraus Jr., "Intersection control for automated vehicles with MILP", *14th IFAC Symposium on Control in Transportation Systems*, accepted.
[4] F. Zhu and S.V. Ukkusuri, "A linear programming formulation for autonomous intersection control within a dynamic traffic assignment and connected vehicle environment", *Transportation Research Part C: Emerging Technologies*, vol. 55, pp. 363-378, 2015.
[5] S. Le Vine, A. Zolfaghari, and J. Polak, "Autonomous cars: The tension between occupant experience and intersection capacity." *Transportation Research Part C: Emerging Technologies*, vol. 52, pp. 1-14, 2015.
[6] C.F., Minett *et. al.* "Eco-routing: comparing the fuel consumption of different routes between an origin and destination using field test speed profiles and synthetic speed profiles." *2011 IEEE Forum on Integrated and Sustainable Transportation System (FISTS)*, pp. 32-39, 2011.

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Decentralised urban traffic signal control in a connected/autonomous vehicle environment

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Networks in near future would consist of mobile (cars, pedestrians, cyclists, etc.) and infrastructure-based static sensors (e.g. traffic signals, smart buildings, etc.). In particular, the recent advances in vehicle automation and communication technologies allows now for the deployment of Connected/Autonomous Vehicles (CAV) in a connected environment. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) cooperation (V2X in short) is a promising vehicle automation and communication technology for improving traffic management systems in real-time. In a V2X cooperative system, CAV will continuously broadcast location, speed, and other data (e.g. weather, pollution), while the infrastructure will play a coordination role by collecting global or local information on traffic and then imposing certain actions on individual or group of vehicles (forming a subsystem) through information provision. In this framework, the urban network is divided into subsystems and traffic probe-data from CAV can provide real-time measures of effectiveness that allow objective signal control (local level) and measurable improvements in the efficiency of the traffic network (global level). Thus a major challenge in the coming decade is the development and deployment of decentralised traffic signal control strategies in the presence of V2X systems, with particular focus on exploiting emerging technologies.

Decentralised control has been the subject of research in different communities especially in the seventies; see e.g. [1] and in recent years [2] due to the rapid development of communication networks, and the emergence of powerful computational tool for solving control problems in polynomial time. Nowadays the interest for decentralised control in urban networks is increased due to the presence of V2X cooperative systems. In the light of these developments, an extension of the traffic signal control strategy TUC [3] is proposed in this work that allows decentralised traffic signal control in CAV environment. The TUC strategy employs a very convenient linear control law to control the entire network in a centralised fashion using a global state vector. However, such centralised controller cannot easily integrate V2X systems into the traffic signal control problem. An alternative avenue is to view the urban network as a system consisting of a number of interconnected subsystems where each subsystem controls a single junction or a set of neighbourhood junctions forming an entity or connected system (with local V2V and V2I capabilities). Then the decentralised traffic signal control problem is to design a controller for each subsystem, where each individual controller uses its local state vector to generate the local control for the interconnected system. If the local state is available for feedback in each subsystem, a state-feedback control could be derived for each subsystem.

The primary limitation of this approach is that the individual controllers do not (a-priori) coordinate their actions and behaviour, except if appropriate stability criteria are fulfilled. Consequently, local controllers may select individual actions that are locally optimal but that together result in global inefficiencies or instabilities. Thus a coordination mechanism is necessary to guarantee stability of the overall system. In other words, the control of interconnected systems (within the V2X framework) under information and communication constraints introduces a number of theoretical and computational challenges; on the other hand network improvements can be achieved in terms of equity and fairness. This work presents a new framework for the traffic signal control strategy TUC that allows for the decentralised traffic signal control in the presence of V2X systems. The findings of this work would shed some light on the implication of V2X systems to traffic signal control and trigger further developments in traffic flow modelling and control research of urban networks.

References

[1] D. D. Siljak, *Large-Scale Dynamic Systems: Stability and Structure*. New York: North-Holland, 1978.

[2] A. Zecevic and D. D. Siljak, *Control of Complex Systems: Structural Constraints and Uncertainty*. New York: Springer, 2010.

[3] C. Diakaki, M. Papageorgiou, and K. Aboudolas, "A multivariable regulator approach to traffic-responsive network-wide signal control," *Control Engineering Practice*, vol. 10, pp. 183-195, 2002.

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Optimal urban traffic signal control and route guidance based on the store-and-forward model

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The increasing penetration rate of connected vehicles brings along a wide array of information that may become available to traffic management systems. Route-guidance and adaptive traffic signal control, for example, could take advantage of connected vehicles to operate simultaneously toward a common objective [1]. In this study, TUC-MPC [2], an adaptive traffic signal control method based on the store-and-forward model, is extended to provide both optimal signal timing (greens splits) and route guidance.

The proposed method takes advantage of a scenario in which all vehicles are connected and exchange information with the infrastructure. More specifically, vehicles provide current position and destination to a centralized controller and receive back an advised optimal route to be followed, whereas associated optimal signal plans are transmitted to the traffic controllers at the intersections.

The extension of TUC-MPC consists in expanding the usual link-based state and decision variables to variables based on link-destination pairs. Following this approach, it is possible to keep track of the vehicles through the network in an aggregated manner and guide them to their intended destinations while providing optimal signal timing along the route. Decisions are taken every cycle based on a rolling horizon approach, allowing the possibility of re-routing vehicles in response to disturbances. Despite the resulting increased number of decision variables, solutions to the optimization problem (with quadratic objective function and linear constraints) should be obtained in reasonable time even for problems with hundreds of decision variables [3].

Simulations were conducted for a square grid network with sixteen signalized intersections using the Cell Transmission Model [4]. Each intersection has two approaching links and two stages. Scenarios with constant and varying demands for a set of origin-destination pairs were simulated. Simulation results show that the extended method outperforms route guidance or TUC-MPC individually, as well as a fixed-time plan/fixed-route base case.

Future work should test the proposed approach for a larger realistic simulated network. The effects of the penetration rate of connected vehicles on the systems performance could be investigated for scenarios in which not all vehicles are connected.

References

[1] P. Li, P. Mirchandani, and X. Zhou, “Solving simultaneous route guidance and traffic signal optimization problem using space-phase-time hypernetwork.” *Transportation Research Part B: Methodological*, vol. 81, pp. 103-130, 2015.
[2] K. Aboudolas, M. Papageorgiou, A. Kouvelas, and E. Kosmatopoulos, "A rolling-horizon quadratic-programming approach to the signal control problem in large-scale congested urban road networks." *Transportation Research Part C: Emerging Technologies*, vol. 18, pp. 680-694, 2010.
[3] S. Boyd and L. Vandenberghe, *Convex Optimization*, Cambrigde University Press, 2004.
[4] C.F. Daganzo “The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory.” *Transportation Research Part B: Methodological*, vol. 28, pp. 269-287, 1994.

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Velocity coordination of cooperative vehicles at junctions

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The increasing issue of congestion causes many hour-losses in road networks. To address such issues, different approaches have been proposed, including spatial and transport planning, promoting public transport, dynamic traffic management and using transformational technologies such as automated vehicles and vehicular communications. In particular, automated driving attracts considerable attention due to the relief of large investment in infrastructure and the potential of significant change of driving behaviour.

Much research has been conducted to study the impacts of vehicle automation on highway traffic flow, particularly Adaptive Cruise Control (ACC) systems. It is widely concluded that autonomous ACC systems relying solely on on-board sensors may not significantly improve highway capacity, while Cooperative ACC (CACC) systems under Vehicle-to-Vehicle (V2V) communication can greatly enhance highway throughput and traffic flow stability [1].

Different from highway traffic, urban traffic flow is interrupted by junctions, where substantial amount of delay, fuel consumption and exhaust emissions are generated. From the driving task perspective, driving at urban junctions involves steering, accelerating, cruising, braking, while avoiding conflicts with other vehicles. The integrated longitudinal and lateral control of vehicles makes it challenging for automation.

Cooperative driving strategies to improve the utility of urban road networks have been proposed. The majority of current work assumes simple vehicle dynamics to the second order of position, i.e. the desired vehicle accelerations from vehicle controllers can be achieved instantaneously. Ignoring delay may lead to over-optimistic results in vehicle and platoon dynamics. More importantly, the simplified model assumptions may violates vehicle dynamic constraints and hence leads to discomfort and risk of collisions when applied in reality.

This contribution proposes a centralised velocity coordination method for cooperative vehicles under V2V communications. The coordination takes into account vehicle physical limits on acceleration and the delay in vehicle dynamics, while guaranteeing a safe envelop for all vehicles.

The coordination scheme works in the following way. A centralised (traffic) controller is assumed to reside at the junction in conjunction with a roadside communication unit. The centralised controller communicates with cooperative vehicles within the capacity of vehicle-to-infrastructure (V2I) communication, typically around 200 metres. All vehicles are assumed to have V2I communication units, sending their destination, position, speed and acceleration information to the centralised controller when entering the vicinity of the junction. The centralised controller predicts the arrival time of vehicles at the conflict zone of the intersection and plans the velocity profiles of all vehicles that maximises the throughput of the whole junction and minimises the overall control efforts. The planning guarantees that the (time) gap between consecutive vehicles crossing the conflict area is larger than a minimum value, i.e. the *safe envelop*, and obeys vehicle physical limits. Desired acceleration profiles are generated by the centralised controller for all vehicles and the profiles are sent to each cooperative vehicle via V2I communication. The desired acceleration will be used as command by vehicle's lower-level longitudinal control system to generate longitudinal torque by the vehicle engine or brake system. We model this lower-level closed loop system as a first-order time lag. The planning is recalculated regularly.

The optimal acceleration trajectories of cooperative vehicles are derived based on a Non-Linear Programming (NLP) approach. The proposed algorithm is tested in a microscopic traffic simulator and its performance is compared with a traditional priority traffic rule at a T junction.

References

[1] M. Wang, W. Daamen, S. P. Hoogendoorn, B. van Arem, "Cooperative car-following control: distributed algorithm and impact on moving jam features. ". *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 5, pp. 1459-1471, 2016.

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Congestion-free vehicle routing using road-link reservations

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Big cities have to deal with the movement of thousands of vehicles that traverse through the streets every day. As traffic demand increases traffic congestion aggravates causing incrementally higher delays, pollution emissions, fuel waste and non-predictable traveling times.

Advanced vehicle communication and automation technologies have made it possible to implement new traffic control strategy that allow road capacity reservations in order to avoid congestion. This work introduces a novel road reservation management system (RMS) that aims to control and manage the utilization of road transport networks aiming to prevent congestion. The RMS receives routing requests from connected or autonomous vehicles so as to compute appropriate paths through congestion-free routes, and reserves road links on the allocated path only for the time period of occupancy. To achieve congestion-free routing in an urban area, the occupancy of each road link is computed, based on the associated reservations, and maintained for future time periods so that following vehicles are allowed to use specific links only if the accumulated reserved traffic for the anticipated occupancy period is below the critical capacity. The concept of the Macroscopic Fundamental Diagram (MFD) [1] is employed to characterize the capacity of homogeneous regions of the network, so that all road segments in a region are assumed to have the same ratio between critical and maximum capacity.

The routing of vehicles in the RMS system requires the formulation and solution of an optimization problem involving the origin-destination of a vehicle, the traversal start time, as well as the cumulative reservation states of the network and aims to find the earliest-arrival-time path when waiting is allowed only at the origin node. Due to the presence/absence of road links at different time periods, the considered problem is shown to be *NP-hard*. For its solution, two heuristic algorithms suitable for real-time execution are proposed. The first, partitions time into discrete slots and appropriately constructs copies of the network graph at each time-slot using the links with available capacity; this construction results in a shortest path problem on a time-expanded graph that is efficiently solved using a customized dynamic programming algorithm. The second algorithm iterates between two stages. The first stage employs a modification of Dijkstra algorithm to return the earliest-arrival-time path when vehicle waiting is allowed at all road links. The second stage checks if the solution returned at the first stage requires waiting at any link other than the origin: if no waiting is required then the algorithm terminates as a valid path has been found, otherwise the minimum waiting time of all intermediate nodes is added to the source node and the procedure is repeated until convergence. In addition to the two heuristic algorithms, a mixed integer linear programming formulation is constructed that allows the optimal solution of the problem using suitable combinatorial optimization solvers.

To evaluate the performance of the developed algorithms, a realistic topology has been considered involving a large part of the road network of Nicosia, the capital city of Cyprus, consisting of 610 road segments and 253 road junctions. The SUMO mobility simulator was employed to create realistic mobility patterns according to the Krauss car following model. Monte-Carlo simulations for different flow rates demonstrate that the proposed reservation system achieves significant improvements in vehicle mobility compared to the current state of operation. Comparison between the developed heuristic algorithms indicates a trade-off between execution speed and mobility performance as the algorithm based on time-expanded graphs provides better results but is more computationally demanding compared to the iterative Dijkstra-based algorithm.

References

[1] N. Geroliminis and J. Sun, “Properties of a well-defined macroscopic fundamental diagram for urban traffic,” *Transportation Research Part B: Methodological*, vol. 45, no. 3, pp. 605–617, 2011.

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Aggregated traffic modeling and assignment in large-scale networks

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Large-scale traffic management strategies remain a big challenge due to complexity and unpredictability of transportation networks. This study tackles this problem through modeling and assignment techniques along with a novel holistic approach that enables an aggregated realistic representation of traffic dynamics. This approach provides a unimodal, low-scatter, and demand-insensitive relationship between average network flow and density, which is named macroscopic fundamental diagram (MFD) [1]. Building on the concept of MFD, this study elaborates new aspects of large-scale traffic modeling, and integrate route choice effects into that. This talk will mainly consist of three parts; establishment of equilibrium conditions in the large-scale urban networks, coordination and optimization of urban transportation systems and understanding of aggregated mobility patterns through big data.

The first part proposes a dynamic traffic assignment (DTA) model to establish equilibrium conditions in multi-region urban networks where the modeling is done through MFD dynamics. The method handles uncertain components of the aggregated model through a stochastic loading approach, and reaches equilibrium conditions via an iterative heuristic solution technique. This model enables us to consider the response of drivers to changing traffic conditions in an aggregated modeling framework. The second part extends the DTA model to a route guidance system, where drivers are given a sequence of subregions to follow. Two aggregated models, region- and subregion-based models, are introduced to develop the guidance scheme and to test its effect, respectively. Notably, these two models define state variables and route choice behavior at relatively different granularity levels. Therefore, the challenge here is to translate certain variables across the traffic models without a loss of significance and assure certain degree of consistency. This part presents novel techniques of coordination between travelers, and investigate what type of real-time active traffic management schemes (e.g. route guidance, large scale traffic signal control) can improve mobility measures in urban networks of different structures. The third part will describe how we can exploit "big mobility data" to discover aggregated mobility patterns and identify models that can lead to efficient traffic management strategies. It extracts and reconstructs aggregated route choice patterns through an extensive GPS data set from taxis in a mega city. Observed GPS trajectories are first grouped together to provide a physical evidence for consistent route patterns. Second, in order to investigate the consistency of equilibrium assumptions, observed trajectories are replaced with shortest path trajectories, and aggregated route choice patterns are reconstructed. Proposed approaches are validated through complex city structures using empirical data from large-scale networks and detailed traffic simulations.

References

[1] Geroliminis, Nikolas, and Carlos F. Daganzo. "Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings.", *Transportation Research Part B: Methodological*, 42(9), pp. 759-770, 2008.

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Upper bounds for the travel time in road networks

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We present an algebraic approach for the calculus of upper bounds for travel times in road networks. We focus here on the two dimensional (2D) traffic case, where traffic streams merge to, and diverge from road junctions. The approach is based on the min-plus algebra [3] and network calculus [4-7] theories. The 1D traffic model [1, 2] is a cell-transmission-like model, written in the min-plus algebra of functions. It is shown that a road section can be modeled as a linear system in this algebra. The impulse response of that system is derived, and is interpreted, in the network calculus theory, as a service guarantee (or service curve) through the section. Then by upper-bounding the arrival inflow to the road section, and by using the basic results of the network calculus, it is shown that an upper bound for the travel time through the section can be derived. Moreover, a result is given on the concatenation of 1D traffic systems (road sections), where it is shown that the obtained system is still linear, and where the impulse response (service curve) of the resulted system is derived analytically.

We investigate here the 2D traffic case. More precisely, we derive service curves for the flows of all the streams passing through a given road junction, and under given traffic controls. By that, upper bounds for the travel time through every stream are derived. Moreover, a road junction is seen as a traffic system, where the service of every stream passing through it, is lower-bounded by an impulse response of a min-plus linear traffic system. Those linear traffic systems are then concatenated with the ones associated to links of the network (by the 1D traffic model), in order to calculate a service curve for a given itinerary on the network. We base on the network calculus theory, and derive residual service curves for different input-output flows of a road junction, given its maximum capacity, and given the traffic control set on the junction. We consider traffic controls such as priority rules, fixed cycle controls, etc. We then show how to calculate an upper bound for the travel time through a whole itinerary of a road network, by combining service curves on links, with service curves on road junctions of the network. We illustrate our results with examples of such calculus.

References

[1] Nadir Farhi, Habib Haj-Salem, Jean-Patrick Lebacque, *Upper bounds for the travel time on traffic systems,* in Transportation Research Procedia 3, 349-358, 2014.
[2] Nadir Farhi, Habib Haj-Salem, Jean-Patrick Lebacque , *Algebraic Approach for Performance Bound Calculus on Transportation Networks (Road Network Calculus),* Transportation Research Record, Volume 2334, 2014.
[3] François Baccelli, Guy Cohen, Geert Jan Olsder, and Jean-Pierre Quadrat, *Synchronization and Linearity*. Wiley, 1992.
[4] Jean-Yves Le Boudec and Patrick Thiran, *Network calculus - A theory for deterministic queuing systems for the internet.* Springer-Verlag ,2001.
[5] R. Cruz, *A calculus of network delay.* Parts I and II, vol. 1, no. 137 pp. 114-141, 1991.
[6] C.-S. Chang, *Performance guarantees in communication networks.* Springer, 2000.
[7] Pravin Varaiya, *The Max-Pressure controller for arbitrary networks for signalised intersections.* Advances in Dynamic Network Modeling in Complex Transportation Systems, Springer. 2013.

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Efficient large-scale traffic management with inefficient traffic models

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This paper focuses on traffic signal control problems for large-scale congested urban areas. This paper discusses how efficient traffic models (e.g., macroscopic analytical differentiable models) can be used to enable inefficient traffic models (e.g., stochastic simulation-based mesoscopic or microscopic models) for large-scale traffic optimization. We discuss the design of simulation-based optimization (SO) algorithms, where: (i) the objective function is simulation-based, is not available in closed form, and can only be estimated via stochastic simulation, and (ii) the constraints are analytical, differentiable and have general-form (e.g., non-convex). We present algorithms for large-scale congested networks, and discuss their use for both offline and traffic-responsive signal control.

The algorithms are applied to several case studies within New York City (NYC). First, we discuss analysis for a Manhattan network that includes access to the Queensboro Bridge (QBB), which is the busiest bridge managed by the NYC Department of Transportation (NYCDOT). We discuss the use of the SO algorithms to mitigate the spatial propagation of congestion, the occurrence and the impact of link spillbacks. We show that the key to developing efficient SO algorithms for highly-congested networks is to provide the algorithm with an analytical description of between-link interactions. These results emphasize the need and importance of formulating analytical and differentiable macroscopic traffic models that both quantify these interactions and can be used for large-scale optimization. These results also highlight the need to develop methodologies that can improve our understanding of the relationship between spatial network dependencies and traffic operations.

Second, we use the methodological insights gained from the QBB case study to design an efficient and scalable algorithm, particularly suited for the control of large-scale networks. We apply the algorithm to the control of an area in Midtown Manhattan with 924 roads. We control all 96 signalized intersections in this area. Within few iterations, the proposed algorithm identifies signal plans that lead to network-wide improvements of the main performance metrics.

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Effects of Low Speed Limits on Motorway Traffic: Some Empirical Findings

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Variable Speed Limits (VSL) strategies are gaining popularity these days as an active traffic management strategy. Proposed strategies aim to use VSL as a homogenization scheme to reduce speed differences and lane changing maneuvers or as a mainline metering mechanism. This research examines both the macroscopic and microscopic effects of different speed limits on a traffic stream, especially when adopting sub-critical speed limits (i.e. lower than the speeds at which maximum flows take place). This is relevant, as the effects of VSL strategies especially on traffic operations are not fully understood yet. To the best of the authors' knowledge, this is the first empirical study evaluating the effects of a clear sub-critical speed limit (e.g. 40 km/h) in a wide range of occupancy levels. To that end, data from a VSL experiment carried out on a motorway in Spain is used [1]. The data includes vehicle counts, speeds and occupancy per lane, as well as lane changing rates for three days, each with a different fixed speed limit (80 km/h, 60 km/h, and 40km/h).

Results reveal some of the mechanisms through which VSL affects traffic performance, specifically the flow and speed distribution across lanes, as well as the ensuing lane changing maneuvers. Lowering the speed limit extends the range of critical occupancies beyond the typical values (e.g. up to 0.33 for the 40 km/h speed limit case) without reducing much the freeway capacity. In other words, drivers are able to travel at low speeds with small spacings, keeping a relatively high and stable throughput. As a consequence, even with very low speed limits (e.g. 40 km/h) flows around 1950 veh/h/lane can be stably sustained. To what extent this represents a significant capacity reduction or not, depends on the prevailing capacities without the sub-critical speed limits. This means that VSL strategies aiming to restrict the mainline flow on a freeway by creating severe artificial bottlenecks in otherwise free flowing sections could have, in some contexts, limited success. Metering capabilities based on even lower speed limits (e.g. 20 km/h) remain unexplored, and could be addressed in future research if they are considered feasible in practice. Besides, other VSL strategies trying to get the most from the increased vehicle storage capacity of freeways under sub-critical speed limits seem promising and should also be investigated.

At a "microscopic" level, results from this study confirm the importance of an Inversion Point, at which the flow distribution is homogeneous between the central and the median lanes. This point is achieved earlier (in terms of total flow) for lower speed limits. Therefore, low speed limits widen the range of flows under homogeneous lane flow distribution. Note that for total flows below those corresponding to the inversion point, the flow distribution per lane is not homogeneous. Neither is the speed. Moreover, relative speed differences across lanes increase for lower speed limits. This, in turn, increases the lane changing probability. Such increase in the lane changing rate with lower speed limits is not intuitive, and means that VSL strategies aiming to homogenize traffic and reduce lane changing activity might not be successful when adopting sub-critical speed limits.

These findings are useful not only for the implementation and assessment of VSL strategies, but also for the development of better traffic models that are able to emulate these effects.

References

[1] F. Soriguera and M. Sala, Freeway lab: testing dynamic speed limits. *Procedia - Social and Behavioral Sciences*, vol. 160, pp. 35–44, 2014.

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High-Occupancy-Toll: potential benefits and modelling challenges

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A high-occupancy/toll (HOT) lane is an increasingly popular form of traffic management strategy which reserves a set of freeway lanes for HOVs and transit users, while allowing low-occupancy vehicles (LOVs) to enter for a fee. HOT lanes can maintain a desired level of service by regulating the volume of entering LOVs. From a practical and economical point of view, HOTs have many potential benefits, including the possibility of combined projects that can offer Pareto improvement.

Furthermore, the introduction of driverless autonomous vehicles is likely to generate additional challenges for demand management. Vehicle occupancy levels today are slightly above one, and could possibly plummet substantially below one due to empty vehicles traveling to low cost parking, hovering in the street in order to avoid downtown parking costs, or delivering packages and other goods. Road pricing is a critical strategy for demand management in a world with driverless autonomous vehicles. Yet so far, most road pricing schemes (excluding HOT lanes) faced substantial difficulties in gaining public acceptance. Promoting HOT lanes can therefore be viewed as a tool for addressing current congestion needs, as well as a preparation step for the road pricing scheme that will be needed in the future.

The preliminary in HOT lane research is how to model the entrance choice process of individual drivers. Most previous studies used either all-or-nothing assignment or an additive logit model. We show the advantages of an alternative formulation based on the population value of time (VOT) distribution [1].

A key decision in HOT lane operation is how to set the tolls. In particular, agencies need to decide whether tolls should be pre-determined or actively change in real-time. Under simplistic conditions it is easy to show that the toll is optimal if full utilization (FU) of capacity in the HOT lane is achieved. Our research examined alternative toll schemes (both pre-determined and real-time), all aiming at full utilization of capacity, under various scenarios including: deterministic conditions [1], stochastic arrivals [2], and when departure time choice is considered [3].

References

[1] L. Gardner, H. Bar-Gera, and S. D. Boyles, "Development and comparison of choice models and tolling schemes for high-occupancy/toll (HOT) facilities." *Transportation Research Part B* vol. 55, pp. 142-153, 2013.

[2] L. Gardner, S. D. Boyles, H. Bar-Gera, and K. Tang "Robust tolling schemes for high-occupancy/toll (HOT) facilities under variable demand." *Transportation Research Record* vol. 2450, pp. 152-162, 2015.

[3] S. D. Boyles, L. Gardner, and H. Bar-Gera, "Incorporating Departure Time Choice into High-Occupancy/Toll (HOT) Algorithm Evaluation," submitted for publication in *Transportation Research Part C.*

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Integrated Traffic and Facility Motorway Management – the Greek evolution

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Modern motorways, especially those comprised of open road and tunnel sections, require complex E/M systems for their operation. Such systems have been historically divided in two categories: Facility Management and Traffic Management, and have been often designed and deployed as independent systems.

Facility Management Systems, also known as SCADA (Supervisory Control and Data Acquisition), are used primarily to manage the infrastructure elements (facilities) of the motorway such as buildings, tunnels, and other structures. Examples of such subsystems for the open road areas of the motorway include Open Road Lighting, Irrigation, and Power distribution.

Facility Management Systems however are mainly deployed at the tunnel sections of the motorway for the management of the environmental and driving conditions of the tunnel, as well as the response to fire emergencies. Examples of such subsystems include Ventilation and Lighting.

Traffic Management Systems aim to effectively detect and respond to traffic incidents by altering motorist behaviour. Typical TMS equipment includes CCTV, Loops Detectors, Variable Message Signs, and Lane Control and Speed Limit Signs. Furthermore, in recent implementations Traffic Management Systems also interface to Traffic Information Systems (Web site, social media, etc) in order to allow advanced driver notification.

Traffic and Facility Management systems have often been deployed independently as it has been traditionally seen that cooperation between such systems is not required; for example in an open road incident, response is managed only via the Traffic Management System.

However with the growing number of tunnels in the modern motorway network, and the safety concerns associated with tunnel traffic, an integrated approach is required to ensure an acceptable tunnel safety level.

This paper presents the main characteristics of an integrated Facility and Traffic Management system as a result of a common Motorway Functional Design effort, and the benefits that could be achieved in critical areas of a motorway's operation such as user's safety as well as operations costs.

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Off-ramp blockage on freeways

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Freeway congestion in many cases may spill back for several kilometers, blocking a number of on/off-ramps upstream of the congestion origin. As a result, the total off-ramp flow may substantially reduce, and vehicles bound for the blocked off-ramps are trapped in the mainstream congestion, causing the continuing spillback of congestion that blocks more off-ramps at the further upstream with similar effects and so forth. The off-ramp blockage effect is readily understood and its impact is empirically recognized, but there is a lack of analytical results to provide more insights. In this work [1] some flow conditions on bottleneck activation are first established, and the mechanism of the off-ramp blockage is theoretically explored. Macroscopic and microscopic simulations are conducted to demonstrate the analytical results obtained. To demonstrate the off-ramp blockage effect in particular, general relations between the total demand, total inflow, total off-ramp outflow, and the number of vehicles within the considered freeway system is examined in simulation. This work can shed some light on a side of traffic network dynamics that was not given enough attention before.

References

[1] Y. Wang., Y. Pang, X. Chen, Y. Kan, "Off-ramp blockage on freeways". *14th IFAC Symposium on Control in Transportation (CTS 2016)*.

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Using the Averaged Link Transmission Model for efficient control design of Large-Scale Urban

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In this lecture, we first formalize the mathematic sense in which the solutions of the continuous-time signalized T -periodic Link Transmission Model (LTM) are approximated by the solutions of its averaged version. In particular, we shown that the error norm between the solutions of the signalized and the averaged models is bounded, in both a finite and infinite time-intervals, by constant proportional to the ratio, between the traffic light time-cycle, and the considered road segment (link) length. This result confirms the intuition that the precision of the averaged models improves with the increase of traffic light frequencies and link road lengths. Then, we show that this model can be used to design efficient optimal controllers. We present a one-step head optimal controller, which can be formulated as a Linear program problem. Some animated simulations, using the microscopic simulator AIMSUM, of the Grenoble downtown will be also presented.

The talk is based on recent works [1], and [2].

References

[1] P. Grandinetti, C. Canudas-de-Wit and F. Garin, "An efficient one-step-ahead optimal control for urban signalized traffic networks based on an averaged Cell-Transmission model", *14th IEEE European Control Conference*, Jul 2015, Linz, Austria.

[2] C. Canudas-de-Wit "An Average Study of the Signalized Link Transmission Model", Submitted to *IEEE Trans. on Automatic Control*, 2016.

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Decomposing the Anticipatory Network Traffic Control Problem

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In the field of coordinated traffic control, a specific subset of works is that related to anticipatory traffic control policies. These approaches follow from theoretical works developed in the 70s [1] and the key contribution with respect to other control strategies is the fact that the road users' reactions to changes in traffic control conditions are taken explicitly into account when determining the control law. This property yields considerable benefits to the traffic controller, as it can place itself in the leading role of a Stackelberg interaction with the road users, allowing for greater efficiency [2], [3]. Model-based coordinated traffic control policies are though of considerable computational complexity, due to the possibly very high dimensionality (number of controllers being simultaneously coordinated) and the size of the underlying road network. This complexity becomes even steeper when considering the anticipatory control subset, where sensitivity information over the whole road network is necessary to correctly anticipate the users' behaviour.

Several researchers have been dealing with developing simplifications for the coordinated traffic control problem, we subdivide these works in three different categories:
- **Decomposition schemes**: frameworks that aim at subdividing a centralized, global problem into more tractable sub-problems, while still performing centralized computation and retaining globally valid dynamics of the original problem (see e.g. [4]);
- **Distribution schemes**: frameworks that subdivide a centralized, global problem into simpler sub-problems, and solve them separately, employing, if necessary, some central mechanism to ensure that the global dynamics of the original problems are retained (e.g. [5], [6]);
- **Decentralization schemes**: frameworks that subdivide a centralized, global problem into simpler sub-problems, and solve them fully separately. Unlike the distributed approaches, there is no explicit guarantee that the global dynamics of the original problem are retained, although they might emerge from the decentralized behaviour [7];

In this work, our main objective is to begin investigating if and how the *anticipatory* traffic control problem could be separated into simpler, smaller, eventually distributable problems. In order to do so, we develop a decomposition scheme, and study under which conditions this scheme is still able to retain globally valid dynamics and, therefore, yield the same level of optimality as a fully centralized anticipatory traffic control formulation. In order to ensure computational feasibility and ease of understanding, we perform this approach within the static time domain, although our focus for future research is that of extending these findings to the field of within-day dynamics.

References

[1] R. E. Allsop, "SOME POSSIBILITIES FOR USING TRAFFIC CONTROL TO INFLUENCE TRIP DISTRIBUTION AND ROUTE CHOICE," presented at the Transportation and Traffic Theory, Proceedings, 1974, vol. 6.
[2] H. Yan and W. H. Lam, "Optimal road tolls under conditions of queueing and congestion," *Transp. Res. Part Policy Pract.*, vol. 30, no. 5, pp. 319–332, 1996.
[3] G. E. Cantarella, G. Improta, and A. Sforza, "Iterative procedure for equilibrium network traffic signal setting," *Transp. Res. Part Gen.*, vol. 25, no. 5, pp. 241–249, Sep. 1991.
[4] S. Lin, B. De Schutter, Y. Xi, and H. Hellendoorn, "Efficient network-wide model-based predictive control for urban traffic networks," *Transp. Res. Part C Emerg. Technol.*, vol. 24, pp. 122–140, Oct. 2012.
[5] L. B. de Oliveira and E. Camponogara, "Multi-agent model predictive control of signaling split in urban traffic networks," *Transp. Res. Part C Emerg. Technol.*, vol. 18, no. 1, pp. 120–139, Feb. 2010.
[6] L. Du, L. Han, and X.-Y. Li, "Distributed coordinated in-vehicle online routing using mixed-strategy congestion game," *Transp. Res. Part B Methodol.*, vol. 67, pp. 1–17, Sep. 2014.
[7] F.-Y. Wang, "Agent-based control for networked traffic management systems," *IEEE Intell. Syst.*, vol. 20, no. 5, pp. 92–96, Sep. 2005.

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Decentralised extremum seeking in urban traffic network controllers

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There have been major developments in intelligent networked control of urban traffic lights over the last few decades driven by increasing availability of feedback on current traffic flow, coupled with the motivation to better utilise existing hard infrastructures. Whilst there is a diverse range of control architectures that have been proposed, they can largely be classified into model based or non-model based approaches. Each has potential strengths and weaknesses in terms of factors including potential transient performance of the network, stability guarantees, as well as the computational tractability and scalability of the approaches.

Irrespective of the individual architecture considered, common to all is the existence of parameters in the controller that are tuned to achieve best performance (in some desired sense). These parameters are typically implemented as constants, which can render the overall controller sub-optimal if the underlying traffic system changes due to environmental, infrastructure or behavioural conditions.

Online adaptation of these parameters may potentially improve the performance of the network controller despite these changes, but should not be implemented on an ad hoc basis. Over the past decade, extremum seeking has become a popular method of achieving online optimisation in nonlinear dynamical systems due to the development of rigorous theoretical results that underpin the basic technique, and its various incarnations. Consequently, approaching the online optimisation of traffic network controllers using extremum seeking would on the surface appear to be a natural approach, albeit one that is complicated by the high dimensionality of networked problems.

In this work, an overview of the recently developed Nash equilibrium seeking approaches will be provided, as these approaches present an intuitive framework for decentralising the extremum-seeking problem over large networked problems. The approach will then be demonstrated and assessed for online optimisation in multiple types of traffic network controllers through the use of a traffic micro-simulation. Future research directions will also be considered.

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The quest for an optimized road transportation system through autonomous vehicles

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The ontological complexity of the transportation system makes it very difficult to design (socially) optimal solutions addressing its inherent inefficiencies. The main origin of this complexity lies in its interaction with human behaviour. As an example, at the end of the 90s, the Intelligent Transport System paradigm promised to significantly contribute to increase road capacity by enabling a smarter demand management and avoiding excessive infrastructure investments (as a response to economic and physical constraints). This proved however to be not fully realizable since traffic forecasts do affect traffic as users react to traffic information in a way that is, most of the time, not fully predictable. With further technological development and the possible deployment of autonomous vehicles, the realization of an "ideal" transportation system management is becoming more likely. Autonomous vehicles, can untwine the relation between the transportation system and human behaviour *[1]* and this is the reason why they are currently attracting the attention of researchers in many fields.

To this aim new regulatory frameworks are necessary to allow these vehicles to flow over the existing road network (e.g. to address liability issues, the design of a new concept for driving licensing, etc.). Moreover, if these vehicles are connected to a central controller able to guide them on, e.g. by indicating the speed to keep, the path to follow and other decisions currently taken by drivers, then a step change in the optimization of the transportation system would be feasible. This would require evolving from the current "autonomous vehicle/driving" concept to the more complex Autonomous Road Transportation (ART) pursued with this proposal. An optimized ART could then be able to minimize the transportation system impacts on citizens and environment by setting the central controller to optimize a combination of travel time, travel costs, energy consumption, air pollution, collision risk etc.

Implementing an ART requires addressing a number of technical, political and social open issues, such as 1) how the central controller should optimize the transportation system (e.g. at which level? Urban, Regional, National? Which are the connected problems, also computationally?); 2) how the huge amount of data flows could and should be managed by the controller; 3) would drivers have in some cases the right and freedom to take his/her own decisions (for instance in relation to routing) or, on the contrary, they would be basically users of a system owned by the society that can impose the rules of driving based on a collective optimal solution; 4) which are the priority areas for the ART; 5) how to manage a mix of autonomous and normal vehicles; 6) how people would perceive the possibility to buy an autonomous vehicle.

All these issues will hardly hold a unique and simple solution. For this reason the European Commission – Joint Research Centre is performing an exploratory study on this subject. The aim is to achieve a clear understanding of a problem that is currently being tackled from many different perspectives. The final goal of the study is twofold: on the one hand the intention is to identify the political issues in order to support the development of the future legislations regulating this new transport paradigm. On the other hand the research will focus on the technical and methodological aspects of an ART, especially for what concerns the management of the information (big-data problem) and the models required to correctly reproduce the system (vehicle/system interaction and integration).

References

[1] U.S. DoT Releases Policy on Automated Vehicle Development". National Highway Traffic Safety Administration. 30 May 2013.

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Dynamic Demand Estimation And Prediction For Traffic Urban Networks

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Availability of accurate trip demand estimates plays a key role for both long term and short term traffic planning. Additionally, on line applications of intelligent management strategies require reliable forecasts of traffic demand so that users' response to varying flow conditions, both observed and communicated, in different locations and in different time intervals can be properly taken into account and anticipated. To guarantee consistency with respect to temporal and spatial dimensions, traffic demand estimates and predictions must reflect both time variability and network patterns. This calls for a problem known in literature as Dynamic Demand Estimation problem (DDEP); it can be formulated as an offline problem for medium to long term planning and design, or as an online problem for real time ATMS/ATIS [1].

Nowadays, demand information derive from advanced traffic surveillance systems that provide updated measurements of several heterogeneous traffic data, both in fixed locations and over specific corridors or paths. Such recent technology developments suggest new promising and challenging chances, not fully addressed yet. The present paper studies some of these opportunities within the DDEP, specifically: data heterogeneity, referring to different nature of data collected on wide spatial coverage that are integrated within the estimation framework, and on line detection of non-recurrent conditions, taken into account adopting a sequential approach for short-term predictions.

Starting from the analysis of Floating Car Data (FCD) collected in the "Eur" sub-area of Rome, Italy, during May 2010 (130,000 monitored trips, corresponding to 10,400,000 transmitted signals), several indications helpful for the DDEP have been obtained:

- The spatial distribution of OD flows generated by FCD is usually not representative of the real demand, since it depends from both the penetration rate and the specific features of the monitored fleet;
- FCD can contribute in reproducing aggregate demand values, as generated and attracted trips share;
- FCD can provide significant temporal information as the effective location of peak and off-peak hours as well as the real time interval in which vehicles are entering the road network;
- OD travel times and route choice probabilities can be derived from FCD.

Just the information on OD travel times and user's route choice behaviour from FCD are then coupled with fixed location observations (link flows) in the DDEP. Results show that link flows and OD travel times are able to work better than route choice probabilities on the not directly monitored ODs since they provide a "global" indication of traffic conditions overall network. Moreover, route choice probabilities are full of information respect to classical link flows, against a large difference in terms of OD coverage (12 ODs intercepted covering the 10% of the demand, against the 67% covered by traffic counts).

Finally, the possibility of adopting recent extensions on Kalman filter theory are evaluated for on line prediction [2].

References

[1] Antoniou C, Barceló J, Breen M, Bullejos M, Casas J, Cipriani E, Ciuffo B, Djukic T, Hoogendoorn S, Marzano V, Montero L, Nigro M., Perarnau J, Punzo V, Toledo T, van Lint H (2015). "Towards a generic benchmarking platform for OD flows estimation/updating algorithms: design, demonstration and validation". *Transportation Research. Part C*, Emerging Technologies, ISSN: 0968-090X, doi: doi:10.1016/j.trc.2015.08.009

[2] Nigro M, Mannini L, Cipriani E (2016). "A Local Ensemble Transformed Kalman Filter for the On-Line Estimation and Prediction of Dynamic Demand Matrices". TRB 95th Compendium of Papers, https://trid.trb.org/view.aspx?id=1393329

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Traffic Light Assistance Based on Low Frequency FCD

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Stops at traffic lights significantly influence the road network capacity and strongly impact the emissions of motorized traffic. On the one hand minimizing stops and hence reducing delays and emissions in road networks can be achieved by the optimization of traffic lights. One the other hand drivers can also contribute to the reduction of emissions while driving with foresight and using the advice of a Green Light Optimized Speed Advisory (GLOSA) [1]. However, assistance concepts like GLOSA or even simpler automatic start/stop functions need a reliable estimate of signal switching times at signalized intersections. Actual methodologies rely either on the provision of signalling information by a central traffic control system in combination with GSM data transmission or on the provision by a local controller in combination with short range communication between vehicle and infrastructure to transmit forecasted switching information[2]. Both concepts require significant modernisation and respective investments in the infrastructure. However, since such investments are unlikely to be covered by the road authorities, driver assistance systems including GLOSA are not included yet in the rising range of assistance systems which are offered by car manufacturers.

During the recent years the increasing availability of floating car data (FCD) caused by the popular use of modern smartphone navigation software offers a new and infrastructure independent approach to estimate signal timing information like cycle length and green/red time intervals based on this ubiquitous data source. Up to now there has not been much research focusing on signal timing estimation that considers temporary sparse probe vehicle data, so called low-frequency FCD, supplied typically by commercial data providers [3][4]. Therefore, we investigated the capabilities of signal timing estimation by using low-frequency FCD with low penetration rates only. To be able to infer signal timing information based on low frequency FCD, the approach assumes as a basic condition the daily repetition of signal plans, whereby time of the day intervals of similar workdays are aggregated to obtain a sufficient data density. The concept thus allows for an estimation using only a very small number of trajectories that covers typical sampling intervals between 15-45 seconds.

In order to achieve this capability the developed method incorporates three processing stages. In a first stage the raw FCD are pre-processed and matched with the road network. Based on the map-matched data points the trajectories of the single trips can be derived using an appropriate routing algorithm. Further, the position of the stop bars are estimated from these data. In a second step the method calculates the specific moment when each trajectory crosses the stop bar position. The convolution of the considered time intervals over feasible cycle times in conjunction with a statistical data analysis then allows for the identification of the time of the day when the signal program remains unchanged. Finally, the last stage considers the precise estimation of red and green time intervals based on a histogram analysis.

Results gained by the application of the methodology for both real and simulated data sets provide statistically valid information on the quality of the estimation which can be achieved, taking into account signal programs with unknown changes over the time of the day and even traffic actuated control schemes. The results are evaluated against the requirements of GLOSA and other assistance systems like the automatic start/stop functions.

References

[1] Eckhoff, D., Halmos, B., German, R., “Potentials and limitations of green light optimal speed advisory systems”. *Proc. of IEEE-Vehicular Networking Conference (VNC)*, 2013.
[2] Barthauer, M., Friedrich, B., “Evaluation of a Signal State Prediction Algorithm for Car to Infrastructure Applications”. *Transportation Research Procedia, 3*, 982-991, 2014.
[3] Fayazi, S. A., Vahidi, A., Mahler, G., Winckler, A., „Traffic signal phase and timing estimation from low-frequency transit bus data”, 2014
[4] Liu, X., Zhu, Y., Li, M., Zhang, Q., “Pova: Traffic light sensing with probe vehicles”. *Proceedings IEEE -INFOCOM,* 2012.

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Throughput Analysis of a Horizontal Traffic Queue

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Rapid advancements in autonomous mobility and connected vehicle technologies present new opportunities for improving macroscopic traffic properties by design of appropriate microscopic interaction protocols between vehicles. There exists an extensive literature on relationship between local controllers and string stability of vehicle platoon under a variety of inter-vehicle communication networks. In this talk, we present results on the relationship between local car following rules and macroscopic traffic properties in a queuing theoretic framework.

We consider a horizontal traffic queue (HTQ) on a periodic road segment, where vehicles arrive according to a spatio-temporal Poisson process, delayed by an admission control policy akin to ramp metering. When inside the queue, vehicles travel according to a first order nonlinear car following model that avoids collision. In particular, the instantaneous speed of every vehicle is proportional to power $m > 0$ of the distance to the vehicle in front. Vehicles depart from the queue after traveling a distance that is sampled independently and identically from a spatial distribution. The throughput of such a queue is defined to be the maximum arrival rate under which the queue length remains bounded, possibly with a prescribed probability.

The proposed HTQ has a natural interpretation as a processor sharing queue, where the service rate associated with a vehicle is equal to its speed. However, the service discipline of HTQ cannot be modelled by a standard discriminatory processor sharing discipline. Indeed, the total service rate of HTQ, which is equal to the sum of speeds of all the vehicles, is state-dependent. For $m \in (0,1)$ (resp., $m > 1$), the total service rate is proven to be monotonically non-decreasing (resp., non-increasing) in between arrivals and departures. When $m = 1$, the total service rate is constant. Therefore, by a simple analysis of the dynamics in workload (i.e., cumulative distance remaining to be travelled by all the vehicles), one can show that, almost surely, the throughput for $m = 1$ is equal to the inverse of the time required by a solitary vehicle to traverse average travel distance.

We construct an M/G/1 queue which dominates HTQ in terms of queue length for $m > 1$. An extension of standard busy period calculations, including for non-zero initial condition, then gives a probabilistic lower bound on the throughput for $m > 1$.

The minimum inter-vehicle distance y_{min} can be easily shown to be non-decreasing at all times except arrivals. Therefore, a lower bound on y_{min} at the time of admission under the control policy, implies such a lower bound on y_{min} at all times. The choice of such lower bound involves trade-off between queue lengths of vehicles moving and vehicles waiting to be admitted. We show that, for every $m \in (0,1)$, for sufficiently small y_{min} at the time of admission, and a corresponding batch admission control policy, the throughput is unbounded almost surely. In summary, the proposed HTQ exhibits a phase transition in throughput from being unbounded to being finite, at $m = 1$.

We also present upper bounds on average travel time for the proposed HTQ, obtained as a by-product of our throughput analysis. Illustrative simulations showing extensions to car following under second order models, and under communication beyond nearest neighbors will also be presented. We conclude the presentation with discussion on derivation of macroscopic traffic flow model as a fluid limit of HTQ with a given car following model.

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Reliability of transit vehicle arrival prediction using connected vehicle data

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Reliable transit operations are an essential component of sustainable and efficient multimodal transportation systems, especially in busy urban environments. There are two ways that the reliability of transit systems can be improved: 1) providing more accurate transit arrival information to travelers and 2) reducing the variation in travel time between stops by providing preferential treatments to transit vehicles. While several examples in the literature have developed transit vehicle arrival prediction algorithms using historical data or a combination of historical with Automatic Vehicle Location (AVL) system data, very few have examined the inaccuracy of the arrival predictions due to measurement errors [1]. In addition, no research has explicitly used real-time traffic data (e.g., connected vehicle data) and traffic flow theory to predict transit vehicle arrival times and account for how uncertainty of inputs affects the accuracy of arrival time predictions.

The objective of this paper is to develop a method for predicting the arrival time of a transit vehicle at a downstream location based on real-time queue length estimates obtained from a subset of cars equipped with connected vehicle (CV) technology (i.e., vehicle-to-vehicle and vehicle-to-infrastructure communications). The location of interest may be an intersection (for transit signal priority systems) or a transit stop (for traveller information systems). Real-time queue length estimates can be used to improve predictions of transit arrival times, because they provide information about the current and expected traffic conditions along a transit route. The method is based on predicting the transit vehicle's position in queues and platoons as it progresses along a signalized arterial. During this estimation process, several sources of uncertainty arise that need to be taken into account, including measurement errors, incomplete observations of cars (e.g., not all vehicles are equipped with CV technologies), and turning vehicles along the corridor. The result is an expected value for the arrival time as well as the variance (and a confidence interval) associated with this prediction.

This research utilizes the maximum likelihood queue length estimation based on CV data presented in Argote et al. [2] and extends the formulation in Farid et al. [3] to account for uncertainty in the predictions of transit vehicle delays due to the sources of error described above. The method calculates a predicted delay for the transit vehicle's travel time for each link in a corridor, while providing updated input predictions for the next link. The predicted arrival time at the location of interest is based on the sum of delays and free flow travel times on the sequence of links leading to the location. Due to the sources of uncertainty described, the prediction of a transit vehicle's arrival time at a location is associated with a range of possible values. Although the method is general, we present a common case for transit vehicles that travel in mixed lanes at the same speed as car traffic.

The proposed method has been tested through microscopic simulation on a four-intersection segment of San Pablo Avenue in Berkeley, California, with a focus on route 72R, which is an express bus line that stops at every fourth intersection along the corridor. The microsimulation is used to generate realizations of transit arrival times at a bus stop that are compared to the arrival times predicted using the proposed method. This is useful for assessing the variance of transit vehicle arrival predictions, which must be accounted for when testing and implementing transit signal priority and traveller information systems. This paper presents a new method to utilize emerging CV technology along with traffic flow theory to improve the reliability and predictability of urban transit systems.

References

[1] F.W. Cathey, and D.J. Dailey, "A prescription for transit arrival/departure prediction using automatic vehicle location data". *Transportation Research Part C: Emerging Technologies*, vol. 11, pp. 241-264, 2003.
[2] J. Argote, E. Christofa, Y. Xuan, and A. Skabardonis, "Estimation of arterial measures of effectiveness with connected vehicle data". *Proceedings of the Transportation Research Board 91st Annual Meeting*, 22–26 January, Washington, D.C., Paper No. 12-1493, 2012.
[3] Y. Zeinali Farid, E. Christofa, and J. Collura, "A person-based evaluation of transit preferential treatments on signalized arterials". *Proceedings of the 93rd Transportation Research Board Annual Meeting*, 12–16 January, Washington, D.C., Paper No. 14-2995, 2014.

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Sharing based transport systems for given activity pattern

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Background and Objectives

When we discuss transport systems in the next generation, it is necessary to consider the development of the information and communication technologies and the changes in our life styles and social structures. Our society seems to be changing towards sharing economy in which properties and services are shared with individuals and organizations. Smartphones and information networks have been accelerating the peer-to-peer sharing economy. Traditional sharing transport systems such as car sharing and ride sharing have been improved by using those advanced technologies. The development of autonomous driving is another key technology in the future. Autonomous driving technologies will be involved into the traditional sharing transport systems. It is required for us to discuss the possibility of the advanced transport systems and to prepare the theories and methodologies for analysing and designing those new transport systems. The objectives of this study are to discuss a variety of the future society with different sharing systems, and to show an optimum vehicle/user routing model when autonomous driving is combined with sharing transport systems.

A Variety of the Society with Smart Sharing Transport Services

Sharing transport is a general term of a demand-driven vehicle-sharing arrangement. At this moment, car sharing systems and ride sharing systems are thought to be independent. If they are combined within the same sharing transport scheme, it becomes possible to obtain large social benefit. When autonomous driving technologies are involved in those systems, a new public transport system would be established. A community or an organization owns a number of automated driving vehicles which are used for shared use. We discuss the development process of the transport society by using some extreme cases. A self-driving society is an extreme where everyone provides car transport service by the own vehicle. A taxi-dependent society is another extreme where all vehicles are taxis. A car sharing society is that all vehicles are owned by the community and a resident has to book a vehicle and drive to his/her destination. A ride sharing society is the one where vehicles are owned privately by some of the residents and a resident with a car must accept the ride share request from the residents without cars. A combined sharing transport society is defined as the one where car sharing and ride sharing are combined in a community. An automated driving society is the one where autonomous driving vehicles are introduced in a combined sharing society. It is expected to improve the mobility of the society with less number of vehicles if they are operated efficiently.

An Optimum Transport Model with Automated Driving Vehicles

An optimum transport model is formulated when autonomous driving is introduced in the combined sharing transport systems. We assume that the activity patterns of all travellers are given and fixed. In other words, a traveller presents origin, destination, the earliest departure time and the latest arrival time. A shared vehicle is assigned so that a traveller can complete his/her journey within given time constraint. We also assume that a vehicle has a limited number of seats and a traveller can change the vehicle on the way to the destination. When the number of vehicles is given, the problem is formulated to obtain the optimum set of routes for travellers and vehicles which can minimize the total travel times of vehicles and users in a network. In order to consider the movements of vehicles and travellers in a time-space domain, we introduce a three dimensional network named time-space network (TSN). It becomes possible to describe a staying at a node as well as a move along a link. The model formulated as an integer programming problem is solved by the Gurobi optimizer 6.5.0. The numerical performance of the model is examined by using a small scale network. The solution suggests that the shared transport system could save vehicle miles and travel times in the network.

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Shared Autonomous Electric Vehicle Systems: Relocation, Charging and Maintenance

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Electric cars and the development of highly automated driving are not only a marketing strategy of OEMs, but are also responses to people's changing mobility needs and urban developments, such as the sharing economy, the ever growing traffic congestions and urban pollution. Self-driving prototypes are already tested on streets and theoretical research about the impacts of autonomous vehicles is conducted. Results show, that it is in the nature of self-driving cars to have synergetic effects with electric vehicles. Shared autonomous electric vehicles have the potential to overcome the customer acceptance barriers associated with electric cars, such as charging management and range anxiety, and therefore contribute to a more sustainable traffic system.

Over the last five years free-floating carsharing systems like car2go and DriveNow have been implemented in several cities worldwide. These systems have some operational challenges. Empirical data show that demand-supply asymmetries occur. When vehicles are returned by customers in zones where there is no further customer demand, long vehicle idle times are observed. Thus these days all free-floating carsharing companies use manual relocation strategies to optimize their operation and to increase the profit. These are very cost intensive because one worker is necessary for one vehicle. A similar problem are vehicle loss times due to maintenance or refuelling/recharging. The vehicles cannot be booked by a customer during these time periods.

The technological advancements of automated shared electric vehicle are a huge chance to enhance free-floating carsharing companies. The system automatically adapts to the demand, relocations are conducted automatically all time. Also recharging and further maintenance processes can be easily integrated into the daily operations.

At the same time new competitors from different markets such as Google and Uber are also interested in automated carsharing systems. Various aspects have been discussed in urban scenarios and simulations. Researches focused on fleet management, customer waiting times, private car ownership, additional vehicle travel and the influence on the market potential. This work gives an overview of the current state of shared autonomous electric vehicles. It contributes to a better understanding of shared autonomous (electric) vehicles in the context of car-sharing business by summarizing and comparing current research results and highlighting present research gaps.

References

S. Weikl, K. Bogenberger, "A practice-ready relocation model for free-floating carsharing systems with electric vehicles – Mesoscopic approach and field trial results". *Transportation Research Part C: Emerging Technologies*, vol. 57, pp. 206–223, 2015.

T.D. Chen, K.M. Kockelman, J.P. Hanna, "Operations of a shared, autonomous, electric vehicle fleet: implications of vehicle & charging infrastructure decisions". *Presented at the 95th Annual Meeting of the Transportation Research Board*, 2016.

J. B. Greenblatt, S. Shaheen, „Automated vehicles, on-demand mobility, and environment impacts". *Current Sustainable/Renewable Energy Reports*, vol. 2, pp. 74 – 81, 2015.

K. Spieser, K. Treleaven, R. Zhang, E. Frazzoli, D. Morton, M. Pavone, „Toward a systematic approach to the design and evaluation of automated mobility-on-demand-systems. A case study in Singapore". *In Meyer, Beiker Road Vehicle Automation, Springer International Publishing*, pp. 229245, 2014.

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Towards Efficient Prioritisation of Public Transport Vehicles through Cooperative ITS technology

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Connected Vehicle (CV) technology, one of the main technological enablers of the emerging Cooperative Intelligent Transportation Systems (C-ITS) paradigm, will soon allow developing comprehensive, secure, and decentralised solutions improving the efficiency of Public Transport (PT) operations.

Most of the existing research in C-ITS focuses on improvements of general traffic efficiency. Very little work has been carried out for specific PT problems. The examples include CV-based Transit Signal Priority (TSP) [1], Green Light Optimal Speed Advisory (GLOSA) [2], and Green Light Optimal Dwell Time Advisory (GLODTA) [3]. These systems benefit from the access to Signal Phase and Timing (SPaT) information received from traffic light controllers [4]. Our framework integrates the three systems into a single cooperative concept. Its main objective is to provide PT vehicles with *adaptive priority*. That is, signal control addresses general traffic and PT vehicles in a single optimisation process. To achieve the goal not only it uses Vehicle-to-Infrastructure (V2I) communication between vehicles and traffic lights but also it takes the advantage of the Vehicle-to-Vehicle (V2V) communication between PT vehicles. Within the framework CV technology is also used to deploy a distributed Automatic Vehicle Location (AVL) system [5]. The main innovation of the framework lies in the *cooperation* of *traffic light control* and *SPaT-based advisory systems* located in PT *vehicles* to improve the efficiency of both traffic light and PT operations. On one hand, the two control domains negotiate a solution satisfying PT and general traffic performance objectives. On the other hand, the advisory systems allow more efficient use of received signal priority by PT vehicles. Moreover, such efficiency is further enhanced by *cooperative platooning* supported by V2V communication between PT vehicles—to minimise required green time the vehicles pass signalised intersections in platoons. Finally, bus bunching is mitigated via V2V-based *cooperative swap* application.

System evaluation is carried out in a simulated setting of one of Luxembourg's busiest urban arterials. Measures of effectiveness account for multi-modal level-of-service indicators, extended with TSP-related indicators. Since our problem involves multiple criteria decision-making, and the negotiation has co-evolutionary aspects we use multi-objective optimisation heuristics (NSGAII and SPEA2). Multi-scale and multi-modal network approaches are applied to properly evaluate traffic flows. All system's basic functionalities will be included in a developed generic research-based simulation tool as well as in commercial simulation tools (PTV-VISSIM, PTV-Visum and PTV-Balance). Preliminary performance evaluation of the framework will be given during the presentation using a microscopic simulation of a transit corridor.

References

[1] J. Hu, B. B. Park, and Y.-J. Lee, "Coordinated transit signal priority supporting transit progression under connected vehicle technology," Transportation Research Part C: Emerging Technologies, vol. 55, pp. 393–408, 2015.

[2] M. Seredynski, D. Khadraoui, "Complementing transit signal priority with speed and dwell time extension advisories", Proc. 17th International IEEE Conference on Intelligent Transportation Systems, 2014.

[3] M. Seredynski, D. Khadraoui, "Combining Speed and Dwell Time Advisories for Improving Bus Ride Comfort", Proc. 21st ITS World Congress, 2014.

[4] M. Seredynski, D. Khadraoui, F. Viti, "Signal Phase and Timing (SPaT) for Cooperative Public Transport Priority Measures", Proc. 22nd ITS World Congress, 2015.

[5] P. Smietanka, K. Szczypiorski, B. Lipinski, F. Viti, M. Seredynski, "Distributed Automatic Vehicle Location (AVL) System Based on Connected Vehicle Technology", Proc. 18th International IEEE Conference on Intelligent Transportation Systems, 2015

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Bimodal Traffic Control : Public Transport and Private Vehicles

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The development of surface public transportation networks is a major issue in terms of ecology, economy and society. To be more attractive, the bus service must have a good quality in terms of punctuality and vehicle frequency while at the same have low management costs. Unless the buses operate totally on exclusive or protected rights-of-way, like in the Bus rapid transit approach, the quality of surface public transportation service is related to urban traffic.

Without expensive specific infrastructures for buses, an alternative to improve route times of public surface transportation (buses, tramways, shuttles, etc.) is the use of regulation systems that apply strategies at junctions that grant priority to vehicles. These systems are referred to as Transit Signal Priority (TSP). They offer one of the most cost-effective approaches to enhance the effectiveness and efficiency of transit operations. However, the use of TSP systems is efficient when traffic is light or when used to improve a single congested bus route or buses on cross streets. TSP results in shorter travel times for buses but often to longer travel times for crossing traffic and traffic following the prioritized buses. Furthermore, reducing time of bus journey, although very important for operating a route, is not the sole factor considered by public transport operators whose obligation is to provide a good service to passengers and to respect bus schedules. Regular headways between buses are an important issue for transit agencies. Prioritizing buses at traffic lights in congested conditions may lead to irregular headways implying their irregular arrival at their stops, often in bunches.

The paper proposes three different strategies that regulate, in real time, the bi-modal traffic: private vehicles and public transport. The objective is to improve the global traffic, to reduce bus delays and to improve bus regularity in congested areas of the network. The first strategy, called NetPrior, consists in a Linear Quadratic control strategy for both private vehicles and public transport. It is based on a macroscopic linear model for the private vehicles and public transport. Its objective is to improve the traffic conditions on the whole of the network making more for the sections when and where public transport vehicles are present [1]. The second strategy is a Model Predictive Control strategy (MPC). It is based on a macroscopic modeling of private vehicles while the bus progression is microscopically modeled. For bus traffic, the strategy minimizes criteria that express the difference between the real positions of buses and the pre-specified positions to attain. The Particle Swarm Optimization method is used [2]. Finally, the third strategy called ASUR, is based on the multi-agent systems. Traffic regulation is obtained thanks to communication, collaboration and negotiation between heterogeneous agents. An important feature of ASUR is that it allows regulation at two levels: macroscopic level (for private vehicles) and microscopic (for public transport) [3].

References

- N. Bhouri, F.J. Mayorano, P.A. Lotito, H. Haj-Salem, J. P. Lebacque, Public Transport Priority for Multimodal Urban Traffic Control, *Cybernetics and Information Technologies*, 15, 5, pp. 766-771, DOI: 10.1515/cait-2015-0014. 2015.

- N. Bhouri, F. Balbo, S. Pinson. An Agent-Based Computational Approach for Urban Traffic Regulation, *Progress in Artificial Intelligence 1(2)*, pages 139-147, Springer-Verlag, 2012.

- S. Kachroudi and N. Bhouri, “A multimodal traffic responsive strategy using particle swarm optimization”, *12th IFAC Symposium on Control of Transportation Systems*. California, pp 531-537, September 2-4, 2009

Ridesharing in a Mobility-on-Demand System

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Mobility-on-demand (MoD) services have the potential for transporting passengers between locations efficiently and reliably, providing a service comparable to a private car, while removing many of the more burdensome aspects of ownership, e.g., maintenance and parking. Moreover, by collectively time-sharing use of the fleet, significant fixed costs are distributed over a large user base, drastically reducing the cost to access mobility. Although vehicle sharing services offer a number of benefits, they are plagued by the inefficiency of needing to rebalance empty vehicles to ensure the supply of vehicles remains aligned with the demand for transport. Rebalancing has the unfortunate side-effect of increasing the total vehicle mileage driven throughout the system, which raises concerns about worsening congestion on city streets. Recognizing that many vehicles can carry two or more passengers, one way to curb this effect is to incorporate ridesharing and permit vehicles to transport multiple passengers simultaneously. Services such as UberPool, Lyftline, and Via speak to, relatively recent commercial interest in building a carsharing platform capable of leveraging the efficiency gains of ridesharing.

Despite progress in resolving the core issues of carsharing and ridesharing independently, the associated results rarely extend to services that fuse carsharing and ridesharing functionality. For example, much of the ridesharing literature (see [1] for a detailed taxonomy) does not apply to carsharing systems because it assumes a private vehicle ownership model or ignores the issue of how to rebalance empty vehicles [2]. Similarly, much of the carsharing work, while accounting for rebalancing [3,4], assumes unit capacity vehicles[1]. As an alternative, software solutions that exploit ridesharing opportunities with real-time requests are discussed in [5]. There, a heuristic quality of service rule is used to match and route up to thousands of vehicles that are viable candidates sharing a ride. Throughout, we tacitly assume a door-to-door MoD service does not require riders to switch between vehicles.

This work makes an initial contribution to the literature by considering a MoD system, in which a shared fleet of vehicles, each capable of carrying two passengers at a time[2], is used to transport passengers. Inherent to the formulation are two important attributes: (i) the need to rebalance empty vehicles and (ii) the ability to identify lucrative ridesharing corridors by means of trip chaining. Note that although the later functionality is essential to capture ridesharing in its most general form, it is absent from the majority of existing works that, for a variety of reasons, limit the extent to which rides may be shared. We present a mixed-integer linear programming (MILP) formulation of the problem and show how a heuristic (feasible) solution to the problem can be obtained in polynomial-time by independently solving the ride-matching and rebalancing problems. This approximate solution can be used as a initial guess when solving the coupled problem via a MILP solver.

References

[1] N. A. H. Agatz, A. L. Erera, M. W. P. Savelsbergh, and X. Wing. Optimization for dynamic ride-sharing: A review. European Journal of Operational Research, 2012.
[2] P. Santi, G. Resta, M. Szell, S. Sobolvesky, S.H. Strogatz, and C. Ratti. Quantifying the benefits of vehicle pooling with shareability networks. PNAS, 2014.
[3] K. Spieser, S. Samaranayake, W. Gruel, and E. Frazzoli. Shared-vehicle mobility-on- demand systems: A fleet operator's guide to rebalancing empty vehicles. Proceedings of the 95th Annual Meeting of the Transportation Research Board, 2016.
[4] S. Ma, Y. Zheng, and O. Wolfson. T-share: A large scale dynamic taxi ridesharing service. Proceedings of IEEE ICDE, 2013.

[1] There is a large literature on these topics that we have not references to in this abstract due to space limitations.
[2] The model can be extended to the case of carrying more passengers, with the number of variables in the optimization problem increasing by a factor of N (the number of stations) per increase in occupancy.

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Switching CTM for mode dependent travel delay minimisation

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1. *Introduction*

The Lighthill-Whitham-Richards (LWR) model [1], [2] provides the most simple, first-order description of continuum traffic flow. The consistent numeric solution of the LWR model is the Godunov-scheme, leading to Cell Transmission model [3]. In the discrete model, state dynamics are represented through Godunov fluxes, the flow values between neighbouring segments. The non-continuous model has been formalized and analyzed as a switching system in a number of works, see e.g. [4], [5], [6]. Although these descriptions of the model have been used for control synthesis, they use simplifying assumptions on the initial or the boundary conditions. The model is formalized as a switching system in [7] for uncontrolled systems, assuming arbitrary initial and boundary conditions.

2. *Main result*

In this work, the switching system description of [7] is extended with Variable Speed Limit (VSL) control. The polyhedral representation of the Godunov flux function is reformulated, stating switching conditions as a function of the VSL signals. New operation modes are stated according to the relation of neighbouring VSL values. Assuming a triangular fundamental diagram, a switching mode linear parameter-varying description of state dynamics is derived. Among the operating modes, transitions are narrowed down to feasible ones.

Coordinated VSL sequence algorithm is developed according to the operational modes in order to minimize network travel time. Additional mode-dependent control input constraints (spatial and temporal control signal limits) are taken while postulating optimization problem. The proposed control system has low online computational demand. The developed control system is evaluated in a comparative simulation environment for a large-scale network.

References

[1] M.J. Lighthill and G.B. Whitham. On kinematic waves II.: A theory of traffic flow on long crowded roads. Proc. of the Royal Society of London. Series A, Mathematical and Physical Sciences, 229: 317-345, 1955.
[2] P.I. Richards: Shock waves on the highway. Operations Research, (4) (1956): pp. 42-51.
[3] C.F. Daganzo, The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory, Transportation Research Part B: Methodological, 28(4):269-287, 1994,.
[4] D. Jacquet, J. Jaglin, D. Koenig and C Canudas de Wit: Non-local feedback ramp metering controller design. Proceedings of IFAC Symposium on Control in Transportation Systems, CTS 2006, pp. 6-12.
[5] G. Gomes and R. Horowitz: A study of two onramp metering schemes for congested freeways. IEEE American Control Conference, pp. 3756 – 3761, 2003.
[6] D. Pisarski and C. Canudas-de-Wit: Optimal Balancing of Road Traffic Density Distributions for the Cell Transmission Model. IEEE Conference on Decision and Control, pp. 6969-6974, 2012.
[7] J. Thai, A.M. Bayen: State Estimation for Polyhedral Hybrid Systems and Applications to the Godunov Scheme, IEEE Transactions on Automatic Control, 60(2): 311-326, 2015.

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Two-class freeway traffic control for reducing congestion and emissions: a computational analysis

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Different ramp metering controllers exist for freeway traffic regulation. One of the most widespread regulators is ALINEA [1], developed in the Nineties, which has shown to be very effective in real contexts. This type of feedback regulator provides a local strategy (the flow entering from one on-ramp only depends on the measurements downstream the on-ramp) and does not take into account any prediction of the system state evolution. In order to obtain predictive and coordinated ramp metering strategies, in the last decades different approaches, based on optimization or optimal control methods, have been developed. In most of the cases, the problem of controlling freeway networks with ramp metering strategies is faced by formulating and solving a discrete-time nonlinear optimal control problem. Such a problem can be either solved on line, in the case of MPC schemes [2], [3], or off line, for instance in hierarchical approaches [4] in which the optimal state trajectory is used to properly fix the set-points of several ALINEA controllers. One of the main difficulties for on-line applications of these optimization-based approaches in large freeway networks is related to the very high computational effort associated with the solution of the nonlinear optimal control problem. Objective of this work is to make a computational analysis of the solution of the optimal control problem, by using and comparing different nonlinear solvers.

In particular, the considered problem is the one discussed in [5] for jointly reducing traffic emissions and congestion in a traffic system where two classes of vehicles are explicitly modelled and controlled. In this work, different solvers for solving the nonlinear optimal control problem proposed in [5] are tested and compared. The analysed solvers are 1) the feasible direction algorithm with the derivative backpropagation method RPROP; 2) an algorithm based on Simulated Annealing and Local Search; 3) some optimization algorithms of the NLopt library for nonlinear optimization. In order to properly compare such optimization algorithms, different traffic scenarios (e.g. regular conditions, partly congested, highly congested) are considered and, for each scenario, a set of random instances are generated. For each instance, the solutions provided by the different solvers are compared, both in terms of computational time and in terms of quality of control. Other important aspects are investigated in the computational analysis; in particular, it is analysed how the computational complexity varies depending on the values of the weights in the cost function (especially those weighing the total time spent by the drivers in the freeway and those related to the traffic emissions) and depending on the bounds for the queue lengths at the on-ramps. Finally, another important aspect to examine is the dependence of the solution obtained by the solvers on the initial solution provided to them: to investigate this aspect, different sets of initial solutions are generated and tested.

References

[1] M. Papageorgiou, H. Hadj-Salem, J.-M. Blosseville, “ALINEA: a local feedback control law for on-ramp metering”. *Transportation Research Record*, vol. 1320, pp. 58-64, 1991.

[2] C. Caligaris, S. Sacone, S. Siri, “Model predictive control for multiclass freeway traffic”, *Proc. of the European Control Conference*, pp. 1764-1769, 2009.

[3] T. Bellemans, B. De Schutter, B. De Moor, “Model predictive control for ramp metering of motorway traffic: a case study”, *Control Engineering Practice*, vol. 14, pp. 757-767, 2006.

[4] I. Papamichail, A. Kotsialos, I. Margonis, M. Papageorgiou, “Coordinated ramp metering for freeway networks – A model-predictive hierarchical control approach”, *Transportation Research Part C*, vol. 18, pp. 311-331, 2010.

[5] C. Pasquale, I. Papamichail, C. Roncoli, S. Sacone, S. Siri, M. Papageorgiou, “Two-class freeway traffic regulation to reduce congestion and emissions via nonlinear optimal control”, *Transportation Research C*, vol. 55, pp. 85-99, 2015.

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A two-class traffic control scheme for reducing congestion, decreasing emissions and improving safety in freeway systems

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One of the most common and successful measures to control freeway traffic systems is ramp metering, i.e. the regulation of the flow entering from on-ramps into the freeway mainstream by means of traffic lights. Many control approaches developed in this field are optimization-based control schemes in which the traditional cost function is the reduction of the total time spent by the drivers in the freeway [1]. More recent works have introduced other objectives for freeway traffic controllers, in particular referred to the reduction of traffic emissions or fuel consumptions [2], [3]. Besides taking into account the congestion and environment-related factors, another crucial aspect to be considered is the improvement of safety in freeway networks. Some recent projects and research works have studied the relation between road safety (normally expressed as number of accidents in the freeway system) and traffic congestion (generally expressed as occupancy), based on real data of different areas, both in the US and in Europe, as described in [4], [5].

Objective of this work is to explicitly consider safety issues in the design of the traffic controller. In particular, a two-class control scheme is proposed, able to devise separate control actions for cars and trucks, in which three objectives are taken into account, i.e. the minimization of the total time spent by the drivers in the system (corresponding to the maximization of the throughput), the minimization of traffic emissions and the maximization of safety. Analogously to the approach proposed in [3], in which only the first two objectives are taken into account, the problem of regulating traffic via ramp metering is faced by solving a discrete-time nonlinear optimal control problem. In particular, the nonlinear structure of the problem is in this case due to the nonlinear state equations (the two-class Metanet model is adopted) and to the expression of the safety-related costs, which are typically represented by nonlinear functions.

The simulation analysis, regarding different traffic scenarios for a given test case, is devoted to evaluate the performance of the proposed control scheme, as well as to analyse the impact of the different objectives. In particular, the analysis regards the comparison of the solutions obtained by considering either the three cost functions separately or different combinations of them. The aim is to understand the relevance of the objective functions in any traffic condition and scenario and in which cases the objectives turn out to be conflicting.

References

[1] M. Papageorgiou, A. Kotsialos, “Freeway ramp metering: an overview”, *IEEE Transactions on Intelligent Transportation Systems*, vol. 3, pp. 271-281, 2002

[2] S.K. Zegeye, B. De Schutter, J. Hellendoorn, E.A. Breunesse, A. Hegyi, “Integrated macroscopic traffic flow, emission, and fuel consumption model for control purposes”, *Transportation Research C*, vol. 31, pp. 158171, 2013.

[3] C. Pasquale, I. Papamichail, C. Roncoli, S. Sacone, S. Siri, M. Papageorgiou, “Two-class freeway traffic regulation to reduce congestion and emissions via nonlinear optimal control”, *Transportation Research C*, vol. 55, pp. 85-99, 2015.

[4] P. Marchesini, W. Weijermars, “The relationship between road safety and congestion on motorways”, *Report R-2010-12*, SWOV Institute for Road Safety Research, The Netherlands, 2010.

[5] I.B. Potts, D.W. Harwood, C.A. Fees, K.M. Bauer, C.S. Kinzel, “Further development of the safety and congestion relationship for urban freeways”, *SHRP 2 Report S2-L07-RR-3*, Transportation Research Board, Washington D.C., 2015.

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Applications of Nonlinear Adaptive Control to Local and Coordinated Ramp Metering

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Ramp metering and mainline metering are effective control measures for freeway networks which aim at ameliorating traffic conditions by appropriately regulating the inflow from the on-ramps or the flow from one segment of a freeway to the next respectively. The goal of such control measures can only be achieved if driven by an opportune control strategy. For practical and other reasons, explicit feedback control strategies are the most direct and efficient methods towards this direction. Testing these strategies, under realistic traffic control scenarios and with sufficiently accurate freeway traffic flow models, may prepare and enhance their potential application in the field. This work aims to provide insights in the properties and performance of an Adaptive Control Scheme (ACS), recently proposed in the literature, which can be applied as a real-time ramp metering and mainline metering strategy at local or coordinated levels.

The proposed ACS has been developed on the basis of recent control theory advances and consists of two main components: i) a nominal feedback law, which guarantees the robust, global exponential stabilization of the desired equilibrium point of a general freeway model, when the model parameters are known; and ii) a nonlinear observer that performs the exact identification of the model parameters after a transient period. The combination of these two components guarantees the robust, global, exponential attractivity of the desired (unknown) uncongested equilibrium point.

The development of the proposed ACS has been based on freeway models that are generalizations of discretized LWR models. However, in this study, the second-order traffic flow model METANET is utilized as ground truth for the application of the ACS. This choice is justified by the fact that METANET is able to reproduce with high accuracy the traffic dynamics, thanks to the additional dynamic equation describing the speed evolution. For the simulation testing, realistic traffic scenarios are constructed involving non-constant entrance and on-ramp demand flows. The proposed ACS aims to maximize throughput of a pre-specified region, by estimating the capacity flow of that region, exploiting the knowledge of its critical density. To do so, an adequate number of density and flow measurements should be available.

The performance of the ACS is tested under two different control cases. The first case concerns testing of the performance of the ACS when a bottleneck exists far downstream of the controllable on-ramp (Section 1). The second case investigates the inherent characteristic of the ACS for coordinated control actions (Section 2). These two main control cases are described below in more detail.

1. *Local ramp-metering in case downstream bottlenecks are present*

This application test addresses the local ramp metering problem utilizing the proposed ACS. More specifically, the performance of the ACS is investigated with respect to the existence of bottlenecks downstream or further downstream from a metered on-ramp. Bottlenecks with lower capacity than the merging area may be present further downstream, due to the existence of upgrade, curvature, lane drop, tunnel, or even a downstream uncontrolled on-ramp. The proposed ACS aims to maximize freeway throughput downstream of that regions, by utilizing the critical density of the bottleneck. The results suggest that the proposed ACS responds very satisfactorily even for bottlenecks located several kilometers downstream of the on-ramp, leading to efficient control results compared also to other control strategies proposed in the literature and employed in the field.

2. *Coordinated ramp-metering - balancing on-ramp queue lengths*

As mentioned before, the structure of the proposed ACS incorporates the ability for taking coordinated actions for two or more controllable on-ramps. Coordinated ramp-metering strategies make use of all measurements collected in the network to control all metered on-ramps included therein. In case multiple bottlenecks on the freeway or restricted ramp storage spaces exist, coordinated strategies may be more efficient than the local ramp-metering strategies. In the particular example examined, two metered on-ramps are considered. The ACS succeeded to increase the achievable control benefit over the no-control case, leading to the maximization of exit flow downstream from the last controllable on-ramp by balancing the relative queue length created at the on-ramps.

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On macroscopic modelling of ACC/CACC traffic flows

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The incorporation of a novel macroscopic approach reflecting Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) traffic dynamics in a gas-kinetic (GKT) traffic flow model is presented. The proposed approach is based on the introduction of a relaxation term that satisfies the time/space-gap principle of ACC or CACC systems. The relaxation time is assigned on multiple leading vehicles in the CACC case; whereas in the ACC case this relaxation time is only assigned to the direct leading vehicle. The proposed modelling allows for the consideration of mixed traffic of manual and ACC/CACC vehicles. The resulting models is numerically approximated using an accurate and robust high-resolution finite volume relaxation scheme, where the nonlinear system of partial differential equations is first recast to a diagonalizable semi-linear system and is then discretized by a higher-order WENO scheme. Numerical simulations investigate the effect of the proposed ACC and CACC modelling to traffic flow macroscopic stability with respect to perturbations introduced in a single-lane ring road and to flow characteristics in open freeways with merging flows at an on-ramp. Additionally, we investigate the effect of the penetration rates of ACC and CACC equipped vehicles to traffic flow macroscopic stability, with respect to perturbations introduced in the ring road, and to flow characteristics in the open freeway with merging flow at an on-ramp. Following from the numerical results, it can be concluded that CACC vehicles increase the stabilization of traffic flow, with respect to both small and large perturbations, compared to ACC ones. Moreover, the proposed CACC approach can better improve the dynamic equilibrium capacity and traffic dynamics, especially at the on-ramp bottleneck, even at relatively low penetration rates.

References

[1] A.I. Delis, I.K. Nikolos and M. Papageorgiou, "High-resolution numerical relaxation approximations to second-order macroscopic traffic flow models". *Transportation Research Part C: Emerging Technologies*, vol. 44, pp. 318-349, 2014.

[2] A.I. Delis, I.K. Nikolos and M. Papageorgiou, "Adaptive cruise control for a macroscopic traffic flow model: development and numerical solution". *Computers and Mathematics with Applications*, vol. 70, pp. 1921-1947, 2015.

[3] I.K. Nikolos, A.I. Delis and M. Papageorgiou, "Macroscopic Modeling and Simulation of ACC and CACC Traffic". *Proceedings of the 18th IEEE International Conference on Intelligent Transportation Systems (ITSC 2015)*, Sept. 2015, 7313436, pp. 2129-2134, 2015.

[4] A.I. Delis, I.K. Nikolos and M. Papageorgiou, "Simulation of the penetration rate effects of ACC and CACC on macroscopic traffic dynamics". *Proceedings of the 19th IEEE International Conference on Intelligent Transportation Systems (ITSC 2016)* (submitted).

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Big Data Oriented Models for Intelligent Transport Systems

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Fast and accurate predictions of future traffic conditions are a crucial issue for reliable applications of Intelligent Transportation Systems devoted to traffic management and traveller information, whose intelligence is related to their capability to foresee future states of the system and individuate the most appropriate actions to undertake. Advances in Information and Communication Technologies are currently making available an unprecedented amount of measures of traffic variables from the road network that are a premise for introducing new models and methods for traffic predictions. Floating Car Data obtained by tracking GPS-enabled vehicles and mobile devices open new perspectives to develop novel predicting models. In fact, they provide a pervasive tool to explore the road network and get information related to theoretically any point of the network (Fusco and Colombaroni, 2013) and, in a near future, perform self-organizing monitoring techniques (Baiocchi et al., 2015). The drawback is that the information is collected from only a sample of vehicles that send their current positions and speeds. Thus, they provide ubiquitous but partial information, with unknown and variable sampling rates on different links. This requires a supplementary effort to process measures collected at different points and at different instants as well as efficient analysis methods to catch the most useful information embedded in such time-space big data. A large interest for machine learning methods arose in the last years in the literature on big data analysis. In addition to classical time-series approaches, many network-based approaches such as neural networks and Bayesian networks were proposed with the aim of exploiting existing correlations among measures collected at different time intervals and on different links of the network (*Cfr*. Vlahogianni et al. 2014 for a thorough review). Bayesian networks, which combines graph structure and Bayes approach to posterior probability from a priori estimate seems to offer a sound methodology for formulating short-term predictions from floating car data.

This paper aims at exploring the opportunities provided by floating car data to predict the evolution of road traffic and proposes a method to deal with statistical significance problems that arise from the sampling nature of data on the road network. The approach that we aim at following is that the nature of traffic congestion implicates that the computational methodologies of artificial intelligence must be transportation-inspired. Thus, we introduce different architectures of machine learning models based on different levels of exploration of the road network in order to catch possible spatial correlations among traffic measures taken on different links of the network. According to the Bayesian approach, we integrate an a priori estimation based on time correlation, represented by a consolidated Seasonal ARIMA model, with the spatial correlation estimated through a Bayesian Network. The specification of model variables tries to exploit all the available information about a traffic state; variances between individual velocities as well as the number of measures in each time interval on each link are considered to account for the time-variable accuracy of the measures. We also introduce specific error indexes that relate the accuracy of different prediction models with that of the measures.

References

[1] G. Fusco and C. Colombaroni, "An integrated method for short-term prediction of road traffic conditions for Intelligent Transportation Systems Applications", 7th *WSEAS European Computing Conference*, Dubrovnik, 25-27 July 2013.

[2] A. Baiocchi, F. Cuomo, M. De Felice, G. Fusco. "Vehicular Ad-Hoc Networks sampling protocols for traffic monitoring and incident detection in Intelligent Transportation Systems". *Transportation Research Part C: Emerging Technologies*, vol. 56, pp. 177-194, 2015.

[3] E.I. Vlahogianni, M.G. Karlaftis, J.C. Golias, "Short-term traffic forecasting: where we are and where we're going". *Transportation Research Part C*, vol. 43, pp. 3-19, 2014.

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Using motion planning techniques to improve traffic flow

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As we are moving to the era of automated transportation, new challenges and opportunities arise. Traditional traffic flow modelling and control methods may be amended, improved or even completely discarded in the near future, depending on the new capabilities of the infrastructure and vehicles. Particularly in the area of control, the vehicle automation and communication systems open a whole new chapter regarding the traffic control capabilities, since each individual vehicle can act as an actuator.

In this environment, motion planning for automated vehicles can serve the objectives of efficient traffic flow in various driving scenarios. This contribution will provide an overview of how motion planning can be utilized as an actuator for control techniques that among others aim at optimizing the traffic flow. Emphasis will be given to complex driving scenarios that usually trigger traffic breakdowns, such as highway merging.

In addition, parts from on-going work will be presented, which focus on trajectory planning of individual vehicles. An appropriate problem formulation along with a numerical solution method will be presented along with some initial findings and remarks on the methodology.

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Coordinated risk-aware ramp metering

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1. Introduction

As one of the indisputable causes of congestions in motorways, traffic incidents are regarded as an important factor in reducing throughput of motorway networks. Congestions created by non-recurrent traffic conditions might have serious long-lasting effects and block upstream off-ramps and on-ramps. Hence, one of the most important challenges for traffic engineers and scientists is to create Intelligent Transportation Systems (ITS) solutions resilient to off-nominal traffic condition. In this direction, analysing the traffic behaviour in occurrence of incident has been targeted in numerous studies [3, 4, 5]. In one of the recent works, it has been shown how to connect incident traffic flow models to driver behavior with the help of novel incident parameterisation for macroscopic flow models [1]. Having such parameterisation in macroscopic model is especially beneficial when traffic management and control is targeted.

2. Main result

Even if traffic incident as off-nominal traffic condition is recognized, the need for a proper and effective traffic management strategy is still inevitable. With risk-aware traffic management strategy, it is possible to influence traffic flow by taking traffic incident information into account. In this note, a distributed and incident-parameter triggered coordinated ramp metering is proposed to minimize the throughput degradation cause by incident at motorways. The benefit of such control strategy is twofold.
First, the ramp meter has to be aware of incident parameters. In this way, the incident effect can be encountered into the synthesis. Assuming that the incident parameters can be reconstructed from online measurement of traffic variables [1], ramp actions can adapt to changing incident levels. Risk aware ramp decision logic can therefore be developed. On the other hand, the incident parameter inclusion of traffic flow model in [1] gives rise to novel flow control objective by means of fictitious density parametrization. The paper hence proposes to develop and use incident aware ramp solutions where incident inclusion is formulated by direct scheduling and indirect throughput performance degradation.
Rather than developing local risk aware traffic flow control solution, the paper suggests to coordinate incident knowledge in a novel, distributed way for superior motorway capacity. In this note, inspired from**Error! Reference source not found.**, coordination is limited to ramp meters communicating with their neighbours. Therefore, in contrast to local ramp meters in which decision-making is only based on the local traffic and incident conditions, by use of partial communication between the ramp controllers herewith, we suggest a novel risk aware topology. In such cases, it is possible to inform the controller of each segment about traffic situation and incidents from the upstream and downstream segments to enhance network level motorway throughput.

The developed synthesis result will be evaluated in simulated case study aiming at analysing the importance of risk awareness.

References

[1] A. Dabiri, B. Kulcsár, "Freeway traffic incident reconstruction – A bi-parameter approach". *Transportation Research Part C: Emerging Technologies*, vol. 58, pp. 585–597, 2015.
[2] A. Dabiri, B. Kulcsár, H. Köroglu, "Distributed LPV state-feedback control with application to motorway ramp metering". In *Proc. to European Control Conference (ECC)*, pp.1480-1485, July 2015.
[3] V. Knoop, H. Zuylen, S. Hoogendoorn, *Microscopic traffic behaviour near incidents*, Transportation and Traffic Theory: Golden Jubilee, Springer, US (2009), pp. 75-97.
[4] A. Dabiri, B. Kulcsár, "Incident parameter estimation". In: *Proc. to European Control Conference (ECC)*, pp. 3518–3523, 2013.
[5] Y. Wang, M. Papageorgiou, A. Messmer, P. Coppola, A. Tzimitsi, A. Nuzzol, "An adaptive freeway traffic state estimator". *Automatica*, vol. 45 (1), pp. 10–24, 2009.

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Feedback-Based Integrated Motorway Traffic Flow Control

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The development and deployment of simple, yet efficient, coordinated and integrated control tools for motorway traffic control remains a challenge. A generic integrated feedback-based motorway traffic flow control concept is proposed in this presentation. It is based on the combination and suitable extension of control algorithms and tools proposed or deployed in other studies, such as ramp metering or VSL (Variable Speed Limit)-enabled cascade-feedback mainstream traffic flow control, and allows for consideration of multiple bottlenecks. The new controller enables coordination of ramp metering actions at a series of on-ramps, as well as integration with VSL control actions, towards a common control goal, which is bottleneck throughput maximization. While doing this, the approach considers a pre-specified (desired) balancing of the incurred delays upstream of the employed actuators, via a suitably designed knapsack problem. Despite the multitude of the offered configurations, options and possibilities, the generic control algorithm remains simple, efficient and suitable for field implementation. The control algorithm is demonstrated and evaluated using a validated METANET macroscopic traffic flow model for a number of scenarios for a motorway stretch in the United Kingdom. The feedback controller is robust as there is no need, neither for any predictions of the demand nor for any model calibration or parameter identification. Practical and safety constrains have been considered, and, as a result, the concept is appropriate for field implementations.

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Stability Results for a Monotonic Ramp Metering Controller

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We consider the freeway ramp metering problem, based on the Asymmetric Cell Transmission Model. In ramp metering, one seeks to minimize travel time or maximize throughput on a freeway by regulating the inflow from onramps onto the mainline. Proposed controller designs for this problem can often be classified in one of two categories: In a first approach, model knowledge is assumed and a global, finite horizon optimization problem is solved. Conversely, other approaches assume only very limited model information and rely on local measurements for each controlled onramp to maximize bottleneck flows. Practical experience suggests that the performance of both approaches is similar in many instances, but a theoretical confirmation of such conjectures is lacking, since many practically successful ramp metering strategies are difficult to analyze from a control point of view. For instance, in the case of the popular ramp metering strategy Alinea, even proof of stability has only been achieved for a limited, special case [2]. In recent work, we proposed a decentralized controller as a proxy to better understand popular ramp metering strategies. The conceptually simple controller aims to track the local critical density at the metered onramps similar to popular ramp metering strategies, but uses additional model knowledge to a limited extend. In particular, knowledge of parts of the freeway dynamics allows the controller to counterbalance the nonlinear freeway dynamics, such that the theoretical analysis of the closed loop becomes tractable. Results suggest that optimality of local ramp metering strategies is related to monotonicity properties of the freeway dynamics. We extend these results and also present a proof of global asymptotic stability of the closed loop comprised of this controller and monotonic CTM freeway models, for feasible traffic demand patterns.

1. Results

For traffic density $\rho(t)$, upstream flow ϕ^{in} and downstream flow ϕ^{out}, the metering rate at each onramp for a time interval of length Δt is chosen such as to move the traffic density in a cell of length l to the critical density ρ^c, while counteracting the disturbances by upstream and downstream flow:

$$r(t) = \left[\frac{l}{\Delta t}(\rho^c - \rho(t)) + \phi^{out} - \phi^{in} \right]_{\underline{r}(t)}^{\bar{r}(t)} \tag{1}$$

Here, the operator $[\cdot]_{\underline{r}(t)}^{\bar{r}(t)}$ symbolizes saturation at an upper bound for the metering rates $\bar{r}(t)$ and a lower bound $\underline{r}(t)$. These bounds may arise from limitations on the queue length or the maximal throughput of the onramp and typically vary over time. Boundary conditions for time-varying demand patterns under which the control strategy (1) achieves global minimization of the travel time have been derived in previous work. These conditions are almost always satisfied in a case study involving real-world traffic demands and a monotonic freeway model. The results suggest that there is little benefit of using model- and optimization based control strategies for ramp metering if the controller relies on a monotonic freeway model. We extend the analysis and consider the closed loop system under constant boundary conditions, i.e. traffic demands, which makes the analysis of equilibria and their stability properties meaningful. We show that the closed loop system itself is monotonic. In the presence of feasible demands, it follows that the closed loop is asymptotically stable and all equilibria exhibit favorable properties in the sense of [1].

References

[1] M. Schmitt et al, "Flow-maximizing equilibria of the cell transmission model." *Proceedings of the European Control Conference (ECC)*, pp. 2634-2639, 2015.

[2] Y. Wang et al, "Local ramp metering in the presence of a distant downstream bottleneck: Theoretical analysis and simulation study". *IEEE Transactions on Intelligent Transportation Systems,* vol. 15.5, pp. 2024-2039, 2014.

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