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How can a small research group of four senior researchers perform theoretical advanced research on design optimization of automotive drivelines, active safety algorithms for accident avoidance, automatic driving and at the same time apply the algorithms in real test driving?

The answer is, of course, cooperation. This article describes our research activities within the automotive area and how the activities are carried out in cooperation within the university, with organizations in our neighborhood and in international cooperation.

Like the international trend, the motivation of most of the research activities within the automotive area is to develop solutions for *safe, sustainable and efficient transportation*. For the research group, this general motivation is transformed into interesting and challenging engineering problems, typically formulated as *optimization* problems where modeling of dynamic properties are of importance. Often, it is *the formulation* of the optimization problem which is our research. It contains modelling and aspects such as modelling accuracy contra model complexity so that the optimization problem becomes feasible so that it can be solved in reasonable time. In automated driving and in active safety application this means that the optimization needs to be solved in real-time when the vehicle is running so that the algorithm always can deliver a safe solution at every instant. At the same time, the modeling of the vehicle and the traffic situation needs to be accurate enough for the solution to be valid.

In case of design optimization, computations can be done off-line and the challenge is instead to formulate the design problem in a way so that as many relevant design variables as possible can be incorporated at the same time as the optimization problem can be solved in a reasonable time. By formulating design and control problems as *convex optimization* problems we have been able to increase the number of design variables considerably and taken a clear step from toy-sized problems towards real world complexity. This can be, for example, to include gear-shifting, or engine on/off in the sizing of hybrid electrical vehicles. Examples and references are given bellow.

Driveline Optimization and Optimal Energy Management

Most of the driveline research concerns electro-mobility and hybrid electric vehicles. Most projects are connected to *Swedish Hybrid Centre*

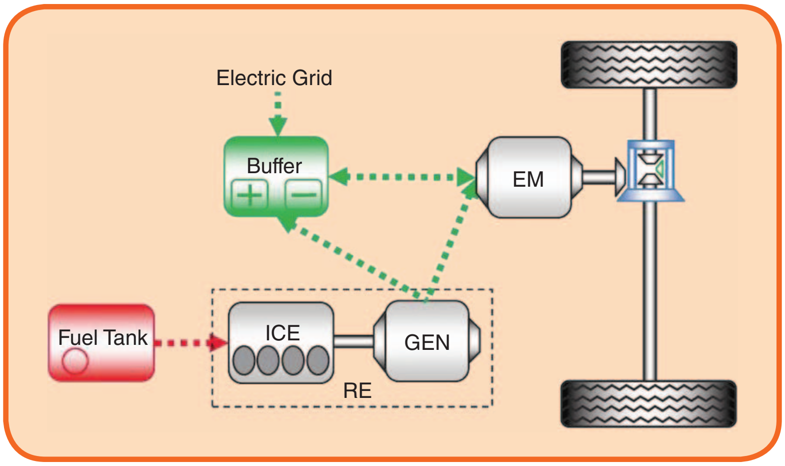

FIG 1 Series hybrid powertrain.

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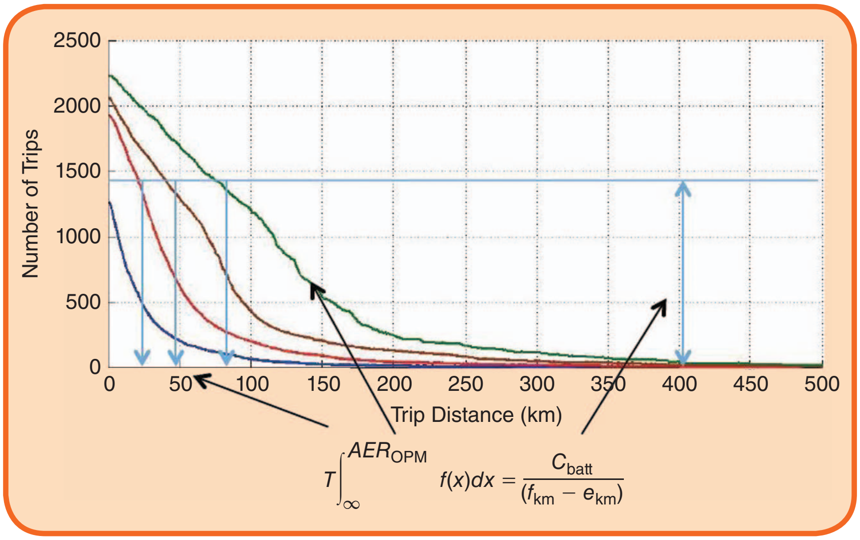


FIG 2 Driver statistics describing trip lengths from four different drivers and their individual optimal battery sizes described as All Electric Range (AER) the distance they can drive entirely electric before they need to start the combustion engine (the range extender).

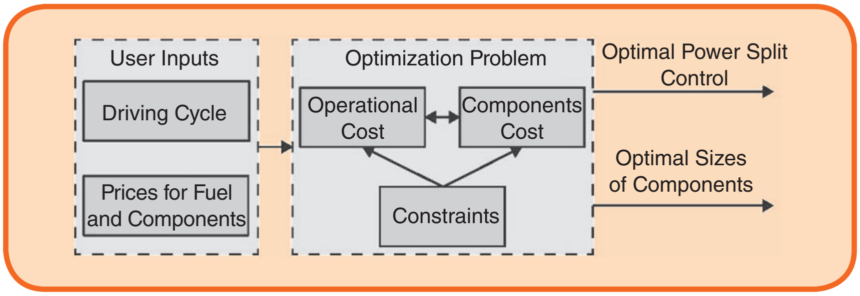


FIG 3 Optimization framework for simultaneous component sizing and energy management of a hybrid city bus. After user inputs are provided, the combined operational and components cost are minimized simultaneously, in order to obtain the optimal power split control and sizes of powertrain components.

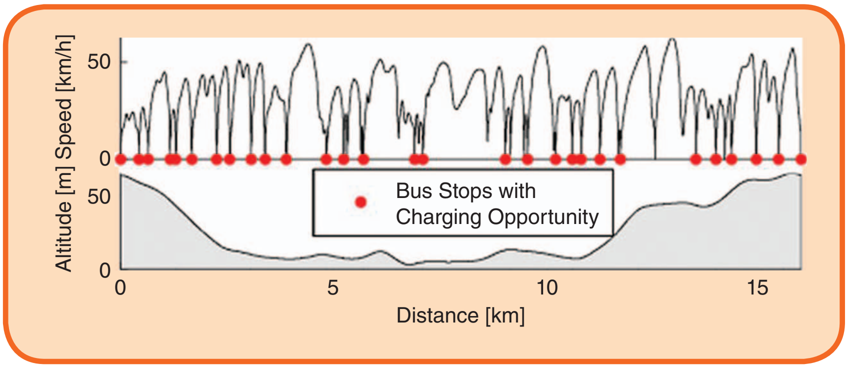


FIG 4 Model of a bus line, expressed by demanded vehicle velocity and road altitude. The initial and final velocities and road altitudes, respectively, are equal, thus conserving kinetic and potential energy of the vehicle. The bus line includes 29 stops on which it is possible to place electric chargers.

(SHC), http://hybridfordonscentrum.se/en/ where the Swedish vehicle companies Volvo AB, Volvo Cars and Scania are members together with several Swedish universities and the Swedish Energy Agency.

One such project is the EU-project Optimore, http://www.optimore-project.eu/, where we have been responsible for the optimal design of the sizing of components in range Extender Vehicles (RE). The idea behind a RE-vehicle is to have a design of a series hybrid, Figure 1, which can be charged from the grid. With a large battery, most of the driving can be done on cheap and environmental friendly electricity. The RE-engine is only started at long trips when the battery is empty. However the battery is expensive and its size is a key parameter in the design. Figure 2 illustrates the optimal size of battery for drivers with different trip length in their driver statistics.

The optimization becomes more challenging when design and optimal powersplit is considered for hybrid vehicles. A general approach is depicted in Figure 3.

It is only by re-formulating the problems as convex optimization problems that they become solvable. This makes it possible to enlarge the problem formulation into system level and in Figure 4 it is illustrated how the position of the charging stations for a bus line is considered together with the other design parameters, [2-c],[4-c].[5-c].[6-c]. So far we have applied our methods to FCHEV (Fuel-cell HEV) [3-c], Series, Parallel HEV, Parallel with CVT [7-c], Series-parallel HEV with a planetary gear [1-c].

Bibliography: indicated by **[X-c] above, X replaced by integer.**

References

[1] N. Murgovski, X. Hu, and B. Egardt, "Computationally efficient energy management of a planetary gear hybrid electric vehicle," in *Proc. IFAC World Congr.*, Cape Town, South Africa, 2014.
[2] N. Murgovski, X. Hu, L. Johannesson, and B. Egardt, "Combined design and control optimization of hybrid vehicles," in *Handbook of Clean Energy Systems*, 2014.
[3] X. Hu, L. Johannesson, N. Murgovski, and B. Egardt, "Longevity-conscious dimensioning and power management of the hybrid energy storage system in a fuel cell hybrid electric bus," *Appl. Energy*, vol. 137, pp. 913–924, Jan. 2015.
[4] X. Hu, N. Murgovski, L. M. Johannesson, and B. Egardt, "Optimal dimensioning and power management of a fuel cell/battery hybrid bus via convex programming," *IEEE/ASME Trans. Mechatron.*, vol. 20, no. 1, pp. 457–468, 2015.
[5] L. Johannesson, N. Murgovski, E. Jonasson, J. Hellgren, and B. Egardt, "Predictive energy management of hybrid long-haul trucks," *Contr. Eng. Pract.*, vol. 41, pp. 83–97, 2015.
[6] L. Johannesson, M. Nilsson, and N. Murgovskij, "Look-ahead vehicle energy management with traffic predictions," in *Proc. IFAC Work-*

FIG 5 The experimental setup used in [2] to validate threat assessment algorithms for lane keeping applications.

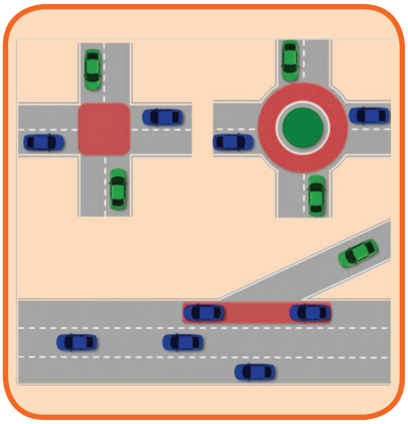


FIG 6 Cooperative driving scenarios where conflicts must be resolved.

shop Engine Powertrain Control, Simulation Modeling, Columbus, O.H., 2015.

[7] N. Murgovski, L. Johannesson, and B. Egardt, "Optimal battery dimensioning and control of a CVT PHEV powertrain," *IEEE Trans. Veh. Technol.*, vol. 63, no. 5, pp. 2151–2161, 2014.

Active Safety, Automated and Cooperative Driving

Since more than ten years, our group is engaged in research activities on active safety, automated and cooperative driving, which have led and will lead to exciting experimental activities.

In collaboration with Volvo Cars Corporation, we have contributed to the development of model-based threat assessment algorithm in lane keeping applications. The idea underlying our approaches is to resort to reachability analysis tools and set-invariance theory to calculate the set of states that can lead to a lane departure, based on a mathematical model describing the vehicle motion within the lane and the road geometry [1-a]. Our approach has been proven to successful trigger braking intervention, with the objective to prevent lane departures on low friction surfaces [2-a].

Recently, advances in ICT have encouraged a renewed interest in cooperative driving technology. In particular, initiatives like The Grand Cooperative Driving Challenge (GCDC) [3-a] have exposed our group to interesting open control problems in cooperative driving applications. We have approached the platooning control problem by resorting to Model Predictive Control (MPC) –based techniques [4-a], Linear Matrix Inequalities (LMI) –based robust control methods [5-a]–[8-a] and consensus paradigms [9-a]. Our research activities in cooperative driving include more complex scenarios as well like, e.g., the ones illustrated in Figure 3. We have particularly focused on traffic cross intersection scenarios, for which we have developed constrained optimal control-based approaches allowing a number of autonomous vehicles to negotiate the intersection while avoiding collisions and optimizing some performance index [10-a]–[12-a].

Our collaboration with the local automotive industry (Volvo Cars) has led to interesting results in automated overtaking maneuvers in highways driving, as depicted in Figure 8. In particular, we have developed MPC-based overtaking algorithms, where collision avoidance with surrounding vehicles is nicely enforced by newly developed linear constraints [13-a].

Bibliography: indicated by [X-a] above, X replaced by integer.

References

[1] P. Falcone, M. Ali, and J. Sjöberg, "Predictive threat assessment via reachability analysis and set invariance theory," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1352–1361, Dec. 2011.

[2] M. Ali, P. Falcone, C. Olsson, and J. Sjoberg, "Predictive prevention of loss of vehicle control for roadway departure avoidance," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 56–68, 2013.

[3] R. Kianfar, B. Augusto, A. Ebadighajari, U. Hakeem, J. Nilsson, A. Reza, R. Tabar, N. V. Irukulapati, C. Englund, P. Falcone, S. Papanastasiou, L. Svensson, and H. Wymeersch, "Design and experimental validation of a cooperative driving system in the grand cooperative driving challenge," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 3, pp. 994–1007, Sept. 2012.

[4] R. Kianfar, P. Falcone, and J. Fredriksson, "A control matching-based predictive approach to string stable vehicle platooning," in *Proc. 19th World Congr. Int. Federation Automatic Control*, Cape Town, South Africa, Aug. 24–29, 2014.

[5] H. Köroğlu and P. Falcone, "State feedback synthesis for homogenous platoons under the leader and predecessor following scheme," in *Proc. European Control Conf.*, Strasbourg, France, June 24–27, 2014, pp. 2655–2660.

[6] H. Köroğlu and P. Falcone, "New LMI conditions for static output feedback synthesis with multiple performance objectives," in *Proc. 53rd IEEE Conf. Decision Control*, Los Angeles, C.A., Dec. 15–17, 2014, pp. 866–871.

[7] H. Köroğlu and P. Falcone, "Joint synthesis of dynamic feed-forward and static state feedback for platoon control," in *Proc. 53rd IEEE Conf.Decision Control*, Los Angeles, C.A., Dec. 15–17, 2014, pp. 4503–4508.

[8] H. Köroğlu and P. Falcone, "Controller synthesis for a homogenous platoon under leader and predecessor following scheme," in *Proc. American Control Conf.*, Portland, O.R., June 4–6, 2014, pp. 1463–1468.

[9] M. di Bernardo, P. Falcone, A. Salvi, and S. Santini, "Design, analysis and experimental validation of a distributed protocol for platooning in the presence of time-varying heterogeneous delays," *IEEE Trans. Contr. Syst. Technol. appear*, no. 99, p. 1, June 2015.

[10] H. Wymeersch, G. R. de Campos, P. Falcone, L. Svensson, and E. G. Ström, "Challenges for cooperative ITS: Improving road safety through the integration of wireless communications, control, and positioning," in *Proc. Int. Conf. Computing, Networking*

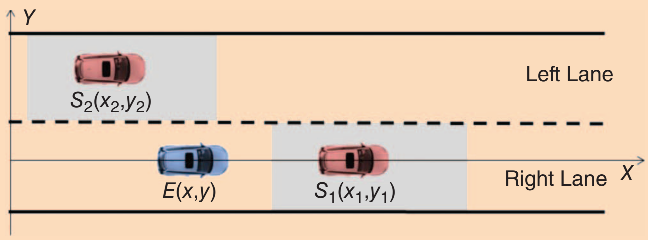


FIG 7 Overtaking on highway scenarios.

Communications, Anaheim, C.A., Feb. 16–19, 2015, pp. 573–578.
[11] E. Steinmetz, R. Hult, G. R. de Campos, M. Widemeersch, P. Falcone, and H. Wymeersch, "Communication analysis for centralized intersection crossing coordination," in *Proc. 11th Int. Symp. Wireless Communications Systems*, Barcelona, Spain, Aug. 26–29, 2014, pp. 813–818.
[12] G. R. de Campos, P. Falcone, H. Wymeersch, R. Hult, and J. Sjöberg, "Cooperative receding horizon conflict resolution at traffic intersections," in *Proc. 53rd IEEE Conf. Decision Control*, Los Angeles, C.A., Dec. 15–17, 2014, pp. 2932–2937.
[13] J. Nilsson, M. Ali, P. Falcone, and J. Sjöberg, "Predictive manoeuvre generation for automated driving," in *Proc. 16th Int. IEEE Annual Conf. Intelligent Transportation Systems*," The Hague, The Netherlands, Oct. 6–9, 2013, pp. 418–423.

Verification of Active Safety Systems and Self-Driving Vehicles

An effective verification process is one important part in the development of automotive systems, to ensure system safety and reliability. The objective of the verification is to quantitatively assess the system and show, for example, customers and authorities, that the system will solve all situations equally well, or better than the traditional system. Systems are traditionally verified by testing a subset of situations where the system is active. This ensures that the system performs according to specification in that specific situation.

The problem of verifying automotive safety systems with large uncertainties is not an easy task and is not extensively treated in the literature, see e.g. [1-b]. The aim of the group's work in the area is to develop computational methods for efficient verification of automotive safety systems. Computational verification methods are treated as methods that predict a system's performance by using mathematical models and/or recorded experimental data as input. Developed methods include, for example, estimating performance bounds of the system, see [2-b], developed methods for efficient testing using augmentation techniques, see [3-b], and system performance verification using reachability analysis, see e.g. [4-b] and [5-b]. The work is to a large extent performed in cooperation with Volvo Car Corporation.

A big challenge for self-driving vehicles is that the system must be able to handle all situations that arise, unlike traditional active safety systems, which focus on a specific subset of situations, [1-b]. Automated driving systems handles a much larger variety of situations, which makes testing very time consuming, cost inefficient and difficult. In the *Trust-Me* project, the Mechatronics research group together with Volvo Car Corporation are cooperating on developing new methods for verification of self-driving vehicles. The project is financed by the Vinnova and the FFI-programme.

Bibliography: indicated by [X-b] above, X replaced by integer.

References

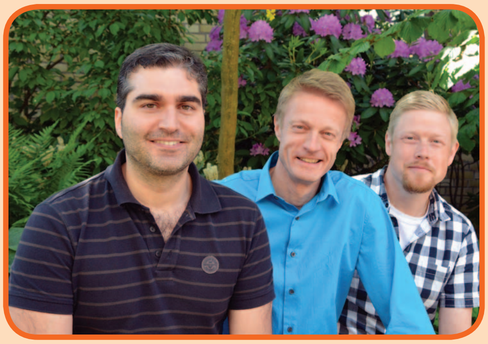
[1] J. Nilsson, "Computational verification methods for automotive safety systems," Ph.D. dissertation, Chalmers Univ. Technology, Gothenburg, Sweden, 2014.
[2] J. Nilsson, A. C. E. Ödblom, and J. Fredriksson, "Worst case analysis of automotive collision avoidance systems," *IEEE Trans. Veh. Technol.*, no. 99, p. 1, 2015.
[3] J. Nilsson, A. C. E. Ödblom, and J. Fredriksson, A. Zafar, and F. Ahmed, "Performance evaluation method for mobile computer vision systems using Augmented Reality," in *Proc. IEEE Virtual Reality Conf.*, Waltham, M.A., 2010, pp. 19–22.
[4] J. Nilsson, J. Fredriksson, and A. Ödblom, "Verification of collision avoidance systems using reachability analysis," in *Proc. 19th IFAC World Congr.*, Cape Town, South Africa, 2014.
[5] R. Kianfar, P. Falcone, and J. Fredriksson, "Safety verification of automated driving systems," *IEEE Intell. Transp. Syst. Mag.*, vol. 5, no. 4, pp. 73–86, 2013.
[6] Trust-Me. [Online]. Available: http://www.vinnova.se/sv/Resultat/Projekt/Effekta/2009-02186/Tidseffektiv-RobUSt-verifiering-av-auTonoma-fordon---teori-och-MEtoder--TRUST-ME/

Networking Activities

In connection to the research, the networking and community activities have also resulted in the receiving the main responsibility for the organization of two major conferences:

- FAST-zero 15, http://fastzero15.net
- IEEE Intelligent Vehicle symposium 2016, http://iv2016.org/

Of course, this responsibility is carried out in cooperation with several other research groups at the university, international program committees and the organizations we have close contact with.



Jonas Sjöberg surrounded by Paolo Falcone (left) and Jonas Fredriksson (right).

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