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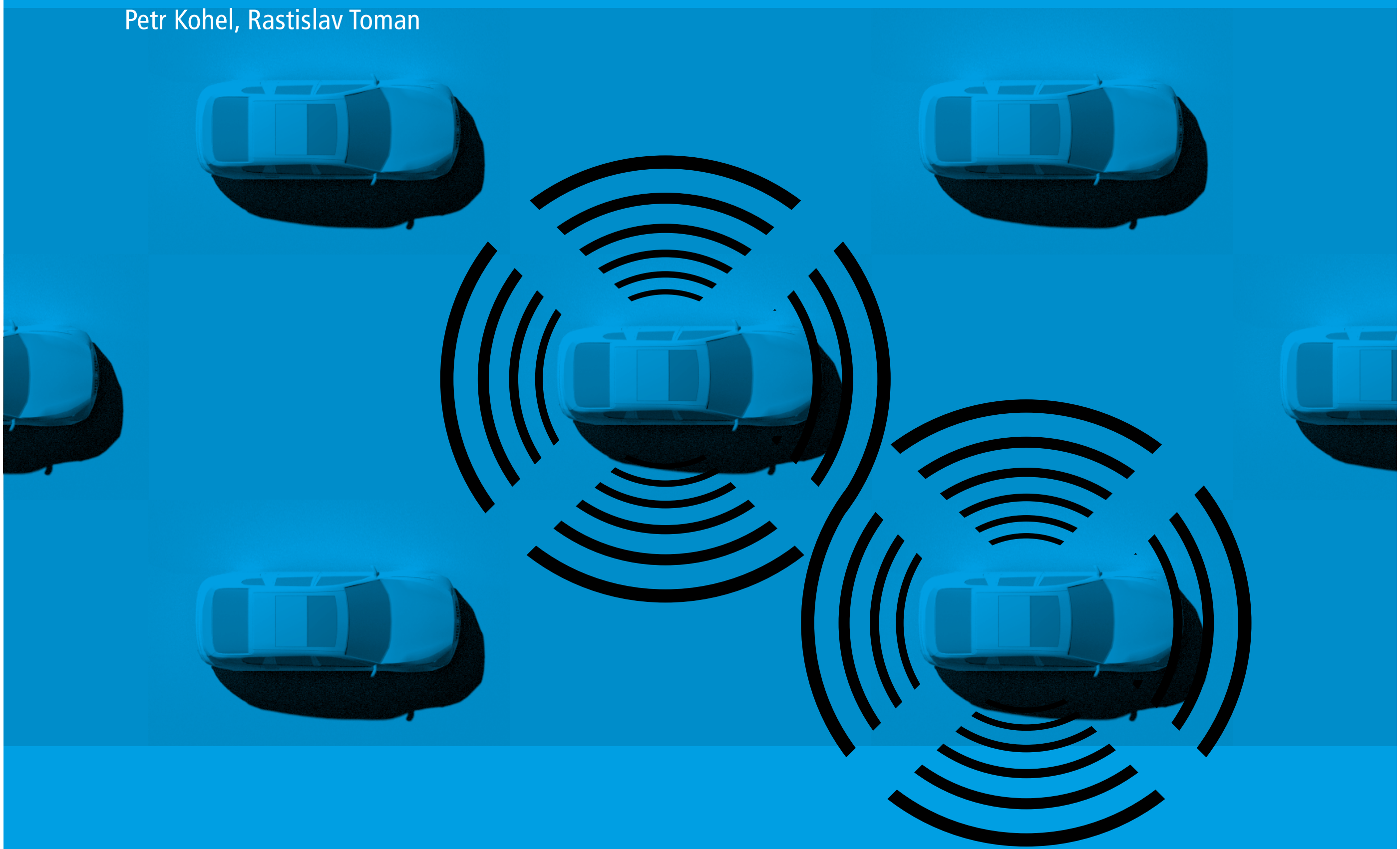

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THIS ISSUE IS FOCUSED ON RESEARCH IN: DESIGN OF VEHICLES

AIM

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AUTONOMOUS VEHICLES AND EUROPEAN DATA PROTECTION LAW

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ABSTRACT
Autonomous vehicles process a huge amount of data about the driver, or rather passengers of the vehicle, as well as about other persons (pedestrians and passengers of other vehicles). This is why the autonomous vehicles raise questions about the protection of personal data. In 2018 a new European data protection legislation came into force. The General Data Protection Regulation places new obligations on controllers of personal data and provides new rights to data subjects, which will relate to operations of autonomous vehicles and their infrastructure. The providers thereof will have to implement the principles of data protection legislation into their systems. In this context the personal data is not just data concerning the identity of the driver, a passenger or other persons, but any information relating to an identified or identifiable natural person who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, or even due to a peculiar behaviour in the vehicle. The paper will focus on the new legal regulation in relation to the operation of autonomous vehicles.
KEYWORDS: **AUTONOMOUS VEHICLES, DATA PROTECTION, GDPR, PRIVACY**

SHRNUTÍ
Autonomní vozidla zpracovávají velké množství údajů o řidiči vozidla, resp. cestujících ve vozidle, jakož i o dalších osobách (spolucestujících, chodcích a pasažérech v jiných vozidlech). To je důvod, proč provoz autonomních vozidel vyvolává řadu otázek týkajících se ochrany osobních údajů. V roce 2018 nabyla účinnosti nová evropská právní úprava regulující tuto oblast. Obecné nařízení o ochraně osobních údajů přináší nové povinnosti správcům osobních údajů, jakož i nová práva subjektům údajů, která se budou týkat provozu autonomních vozidel a infrastruktury. Výrobci a poskytovatelé služeb budou muset do svých systémů implementovat legislativu o ochraně osobních údajů. Osobními údaji nejsou pouze údaje týkající se totožnosti řidiče, cestujících nebo jiných osob, ale veškeré informace vztahujících se k identifikované nebo identifikovatelné fyzické osobě, kterou lze přímo nebo nepřímo identifikovat, zejména odkazem na identifikátor, jako je např. název, identifikační číslo, lokalizační údaje, nebo třeba i kvůli osobitému chování ve vozidle. Tento článek se zaměřuje na novou právní úpravu ve vztahu k provozu autonomních vozidel.
KLÍČOVÁ SLOVA: **AUTONOMNÍ VOZIDLA, GDPR, OCHRANA ÚDAJŮ, SOUKROMÍ**

1. INTRODUCTION

The operation of autonomous vehicles results in a huge amount of personal data being processed about drivers, or in the case of fully autonomous vehicles, about users (for the sake of simplicity the term driver is used for the driver as well as for the user of a fully autonomous vehicle). The processed data may also relate to third persons, e.g. fellow-passengers, pedestrians and drivers and passengers of other (autonomous) vehicles, in other words, the cameras, sonars and radars collects huge amount of data about their interior and exterior [1]. The legal framework for the protection of personal data was harmonized in the European Union on the basis of Directive 95/46/EC on the protection of individuals with regard to the processing of personal data and on the free movement of such data. Since the Directive has been transposed in national legal systems and the level of protection of personal data differed across the European Union, the protection of personal data is nowadays governed by the Regulation (EU) 2016/679 on the protection of individuals with regard to the processing of personal data and on the free movement of such data (hereinafter referred to as "the Regulation" or "GDPR"). The Regulation is directly effective in all Member States of the European Union. This means that in contrast to the Directive 95/46/EC the Regulation does not have to be transposed into the national laws because of its direct effect. This paper will focus on the new data protection regulation and its application with respect to autonomous vehicles.

2. PROTECTION OF PERSONAL DATA IN THE OPERATION OF AUTONOMOUS VEHICLES

According to art. 4 par. 1 GDPR, personal data is any information about an identified or identifiable natural person (a data subject). An identifiable person is a person who can be identified directly or indirectly, in particular by reference to an identifier such as name, identification number, location data, network identifier or one or more specific physical, physiological, genetic, psychological, economic, or social identifiers of a natural person. According to the Court of Justice of the European Union, a person is identifiable if the controller has means reasonably likely be used in order to identify the data subject, even with the assistance of other persons [2]. The personal data is, therefore, any information that can be related to the driver of an autonomous vehicle, to passengers, and to drivers or passengers of other vehicles with which the autonomous vehicle comes into contact. Such personal data could, for example, be the posture of the driver, his/her way of handling the vehicle, or his/her location or regular daily route from which a home and work address may be deduced.

Personal data may be processed only if the controller has a legal basis to perform such processing as enumerated in art. 6 GDPR. In the case of autonomous vehicles, the contract between the controller and the data subject will provide legal grounds for processing of the driver's data. According to the European Data Protection Board the aforementioned legal ground "will not cover processing which is useful but not objectively necessary for performing the contractual service or for taking relevant pre-contractual steps at the request of the data subject." [3]. If this is not the case, the controller will have to process the data under some other legal ground. Another legal ground for processing may be the fulfilment of a legal obligation of the controller. For example, a law might prescribe to the controller's obligation to process defined categories of data for specific purposes, e.g. insurance purposes, taxation, etc.

Beside that the controller is allowed to process the personal data when such processing is necessary to protect the vital interests of the data subject or of another natural person. For instance, in the case of an accident, the vehicle might evaluate some personal data essential for the saving of lives and transmit them to the controller for further processing in addition to data that are already programmed to be processed in such cases and are therefore processed under other legal grounds.

Other data may be processed if the processing is necessary for the purposes of the legitimate interests pursued by the controller or by a third party. As an example of such data could serve the data, which are indispensable for an examination of an accident and the determination of liability (provided that those data will not be processed for the fulfilment of the legal obligation). These interests can be overridden by the interests or fundamental rights and freedoms of the data subject (e.g. a right to privacy or interest in the protection of property).

Personal data may be also processed when the data subject has given consent to the processing of such data. Consent means a freely given, specific, informed and unambiguous manifestation of the data subject's wishes by which the data subject gives a declaration or other apparent confirmation of his/her consent to processing of personal data relating to him/her (art. 4 par. 11 GDPR).Such consent to processing will be typical for the driver's personal data that cannot be processed in accordance with the aforementioned legal grounds. Consent will also be typical for personal data necessary for providing additional services. The controller has to prove that the consent of the data subject has been given. The consent of the owner the vehicle could be attached to a contract of purchase. The controller may ask the driver for the consent during the operation of the vehicle. In the case of other vehicle's user, the controller will have to find a solution for the granting of consent and demonstration thereof.

There is a subtype of personal data that requires stricter protection, the "special categories" of personal data (art. 9 GDPR), and sensitive data according to the previous legislation. Those data relate in particular to a racial or ethnic origin, religious or philosophical beliefs, sexual orientation and health. Also sensitive according to the Regulation are biometric data for the purpose of uniquely identifying a person, for example, the identification of the driver or passenger. The processing of such data is forbidden unless the controller disposes with a legal ground pursuant art. 9 GDPR.

3. OBLIGATIONS OF THE CONTROLLER

A controller is a person who determines the purposes and means of the processing of personal data (art. 4 par. 7 GDPR). In relation to the operation of the autonomous vehicles, the data controller may be a manufacturer, a lessor (the owner of a fleet), or an operator of telecommunication or traffic infrastructure. In interconnected vehicles and infrastructure, it will be difficult to determine who are the controller and the processor of data. Besides the interconnected vehicles the autonomous ones might also be "self-contained". This means all the data will rest in the vehicle itself [4]. The interconnected autonomous vehicles and communication between vehicle and infrastructure is under research in this field now [5].

The controller may also be a driver of the vehicle that processes the personal data of third persons and this processing falls within the scope of the Regulation, such as the processing of personal data wholly or partly automatically. The driver may. for instance, be able to download data collected by cameras and sensors, to store them or to process them in any other way defined by art. 4 par. 2 GDPR. In such case, the driver has all the obligations of a data controller laid down by the Regulation. The controller may engage a processor who processes the personal data for the controller on the basis of a written contract, e.g. a provider of cloud computing services or other storage services for data processed during the operation of the autonomous vehicles. Nevertheless, it shall always be the controller who is responsible for personal data processing.

The controller must adhere to the data protection principles enumerated in art. 5 GDPR in order to be compliant with the Regulation. Personal data must be processed lawfully, fairly and in a transparent manner. The controller has to have legitimate purposes for the processing. The personal data must not be processed in a manner that is incompatible with the given purposes. However, further processing for scientific or historical research purposes or statistical purposes are not considered to be incompatible with the initial purposes. The controller must stick to the data minimisation principle. This principle means that the controller can only process data relevant to the given purpose and are limited in scope to what is necessary for that purpose. It is likely that the controller will manage to defend the processing of personal data relating to vehicle operation and its further use in the development of the autonomous vehicles, even in case that the personal data cannot be anonymized. The processed data have to be accurate and must not be stored longer that is necessary for the purpose. After the retention period, the data cannot be further processed.

One of the pivotal obligations of the controller and the processor is to ensure the integrity and confidentiality of the personal data. Pursuant to art. 32 GDPR the controller has to implement appropriate technical and organisational measures to ensure a level of security appropriate to the risk in relation to the rights and freedoms of natural persons. These risks include not just the threat to the right to privacy and data protection. The potentially infringing information may be the location where the vehicle is parked overnight, what is the usual route of the vehicle, etc. Based on the data, a detailed profile of the driver and his/her financial status, habits and preferences can be made [6].
The controller has to also assess the risk in relation to other rights, for instance the right not to be discriminated against in the case of profiling of a data subject. By selecting appropriate measures the controller will have to take into account the state of the art, the costs of implementation and the nature, scope, context and purposes of processing as well as the risk level in terms of likelihood and severity for the above-mentioned rights and freedoms. These measures include pseudonymisation and encryption, the ability to ensure confidentiality, integrity, availability and resilience of processing systems and services, the ability to restore the availability and access to personal data in a timely manner in the event of a physical or technical incident, and the implementation of a process for regularly testing, assessing and evaluating the effectiveness of technical and organisational measures for ensuring the security of the processing.

It can be assumed that companies and authorities engaged in the operation of autonomous vehicles will process a huge amount of personal data on numerous data subjects, their identifiers, daily habits and routines, profiles, connection with other persons etc. The right to privacy, data protection and other rights of those data subjects may be infringed by a breach of the integrity of the system and data leakage and loss. A controller that processes the personal data collected during the operation of autonomous vehicles will thus have to adopt strict measures to ensure the data security. A data breach may cause an intrusion into the private and family life of a user, his or her information self-determination or in some cases it might even affect his/her her personal safety in case that the information about the regular locations and habits has been compromised.

Assuming the probability that a personal data breach will result in a risk to the rights and freedoms of natural persons, the controller must without undue delay and, where feasible, within 72 hours of having become aware of it, notify the the supervisory authority (art. 33 GDPR).

Another obligation of some controllers is to carry out a data protection impact assessment pursuant to art 35 GDPR. Where a type of processing, especially one using new technologies, and taking into account the nature, scope, context and purposes of the processing, is likely to result in a high risk to the rights and freedoms of natural persons, the controller will, prior to the processing, carry out an assessment of the impact of the envisaged processing operations on the protection of personal data. A data protection impact assessment is in particular required in the case of a systematic and extensive evaluation of personal aspects relating to natural persons based on automated processing, including profiling or a systematic monitoring of a publicly accessible area on a large scale.

It can be assumed that the controllers processing the personal data in connection with the operation of autonomous vehicles will be obliged to carry out a personal data impact assessment before commencing processing. The reason for the obligation is the above-mentioned character of personal data processing during the operation of the autonomous vehicles. Moreover, the controllers will certainly systematically and extensively evaluate the personal data for safety or commercial reasons. Autonomous vehicles will also incorporate new technologies, or the current technologies will be used differently, so the risk to the rights and freedoms of data subjects is difficult to estimate at present. This fact represents an additional reason for a data protection impact assessment carried out by the operator prior to processing.

The controller in the case of personal data processing relating to the operation of the autonomous vehicle will have to designate a data protection officer (art. 37 GDPR). The data protection officer has to be designated when the core activities of the controller consist of processing operations which, by virtue of their nature, their scope and/or their purposes, require regular and systematic monitoring of data subjects on a large scale. Since the operation of autonomous vehicles represents the processing of a huge amount of personal data on a large scale as well as regular and systematic monitoring, there is no doubt about the obligation of the controller to appoint a data protection officer.

4. DATA PROTECTION BY DESIGN AND BY DEFAULT

According to the data minimisation principle, the controller processing personal data in connection with the operation of autonomous vehicle must take steps not to process more data than is necessary for the purpose for which the data are processed. In addition, art. 25 of the Regulation obliges the controller to take all possible steps to guarantee data protection by design and by default. This means that appropriate technical and organisational measures have to be implemented so that the data protection principles are safeguarded in order to meet the requirements of the Regulation, i.e. to protect the rights of data subjects and to ensure the security of the data processing.
When implementing data protection by design (sometimes also called privacy by design) the controller has to consider the data protection principles already at the stage of product or system development. According to its originator Ann Cavoukian privacy by design means "embedding privacy into information technologies, business practices, and networked infrastructures, as a core functionality, right from the outset – means building in privacy right up front – intentionally, with forethought. PbD may thus be defined as an engineering and strategic management approach that commits to selectively and sustainably minimize information systems' privacy risks through technical and governance controls." [7]. Autonomous vehicles have to be technically designed in a way compliant with the principles of personal data protection.

Data protection by default (or privacy by default) means that the manufacturer or designer applies the most stringent privacy settings which can only be subsequently changed only by the data subject. For Cavoukian privacy by default is one element of the privacy by design approach [8]. The data subject can later opt-in for a less stringent data protection setting. However, the opt-in should not be irreversible. German Verband der Automobilindustrie (VDA) supports the active involvement of the consumer in data processing options. "The members of the VDA are striving to enable customers to determine themselves the processing and use of personal data through various options. The members of the VDA will enable these options through contractual provisions, consents or technical features in the framework of optional features and choices that are given, through which the customer can activate or deactivate services, unless the processing is regulated by law." [9]. Data protection by design and the option for the user to change the privacy settings is advocated by the Data Protection and Privacy Commissioners in their Resolution on Data Protection in Automated and Connected Vehicles [10].

In the event of violation of the obligation, the supervisory authority may impose severe fines. The amount of the fine will depend in particular on the nature, severity and duration of the infringement. The supervisory authority will take into account the nature, extent or purpose of the processing, as well as the number of data subjects concerned and the extent of the damage caused to them. The imposed fine may be up to € 20 million or 4 % of total worldwide annual turnover.

5. RIGHTS OF THE DATA SUBJECT

The Regulation strengthens the rights of data subjects. Data subjects are the driver of the autonomous vehicle, a passenger or a third person outside the vehicle whose personal data are automatically processed during the operation of the vehicle.

A data subject, whether it is a driver, a passenger or persons whose personal data are processed in connection with the operation of an autonomous vehicle, has the following rights under the Regulation:

1. the right to information (art. 13 and 14 GDPR)
2. the right of access (art. 15 GDPR)
3. the right to rectification (art. 16 GDPR)
4. the right toerasure sometimes called the right to be forgotten (art. 17 GDPR)
5. right to restriction of data processing (art. 18 GDPR)

6. the right to data portability (art. 20 GDPR)
7. the right to object (art. 21 GDPR)
8. the right not to be subject to a decision based solely on automated processing, including profiling, which produces legal or similar effects concerning the data subject (art. 22 GDPR).

The right to data portability is the right to transfer the data between the controllers. This right can only be exercised when the data are processed on the basis of consent or a contract and the processing is carried out by automated means. This right may be applied in the case of changing the operator of an autonomous vehicle if the data subject is interested in transferring the personal data collected during the operation of the autonomous vehicle to another operator.

The data subject cannot claim the right to erasure when his/her data are processed on the basis of a legal obligation of the data controller. The right to erasure is not absolute. If the processing of the personal data is required by a law which enshrines the obligation of processing of certain data collected in connection with the operation of the autonomous vehicles, the data subject cannot claim the right to erasure of his/her personal data.

Profiling of the personal data is allowed in accordance with the Regulations. Pursuant to art. 4 par. 4 GDPR profiling is any form of automated processing of personal data involving the use of data to evaluate certain personal aspects related to a physical person, such as driving or reactions of the vehicle user or his or her habits for the marketing purposes. The right not to be subject to automated processing may be typically applied in the assessment of insurance risk. Profiling must not result in an automated decision. The right not to be subject to an automated decision will not apply if the automated processing is necessary for a performance of a contract or the automated decision-making is permitted by law or when this type of processing is based on the explicit consent of the data subject.

6. AUTONOMOUS VEHICLES AND EPRIVACY

The processing of personal data in the field of electronic communications is regulated in the European law by Directive 2002/58/EC concerning the processing of personal data and the protection of privacy in the electronic communications sector (Directive on Privacy and Electronic Communications). This directive applies to the processing of personal data in connection with the provision of publicly available electronic communications services or public communications networks.

At present, the legal framework for the protection of personal data in the electronic communications sector is being revised. The European Commission proposed a Regulation on Privacy and Electronic Communications (the "ePrivacy Regulation"), which will, along with the GDPR, be directly effective in all Member States of the European Union as well as the GDPR. Even though it is only at the draft stage and and the final wording is not yet set down [11], the ePrivacy Regulation will probably apply to the transmission of communication between machines. The recital 12 of the ePrivacy Regulation mentions explicitly that the regulation shall apply to machine-to-machine (M2M) communication. It is questionable what kind of M2M communication can be considered as an electronic communication service, the area regulated by the ePrivacy Regulation [12]. To assess whether the ePrivacy Regulation will enshrine the communication between autonomous vehicles and the vehicles and the infrastructure, a definition of the electronic communication service has to be taken into consideration. The definition of this service refers to the European Electronic Communications Code (Directive (EU) 2018/1972 establishing the European Electronic Communications Code). Pursuant to the art. 2 of the European Electronic Communications Code the electronic communications service encompasses, besides other things, services consisting wholly or mainly in the conveyance of signals such as transmission services used for the provision of machine-to-machine services. It is not clear whether the M2M communication of the autonomous vehicles and to what extant can be consider as the electronic communication service [13]. The clarification thereof is significant since the data processing in case of the provision of the service will be conditioned by compliance with the rules of the ePrivacy Regulation. Pursuant to the draft of the ePrivacy Regulation, service provider may provide the service primarily with the user's consent unless he will process the data under other legal grounds which are nevertheless limited in number.

7. CONCLUSION

The operation of autonomous vehicles will involve the processing of a huge amount of data. The GDPR will apply to the processing of personal data collected, transmitted, disclosed, used or profiled in connection with the operation of the vehicles. The manufacturers, the lessors and other personal data controllers will have to be compliant with the new legislation when they will process the personal data of the driver, passenger or third persons. In comparison with Directive 95/46/EC, the Regulation will set down new obligations of the controller, in particular, to appoint a data protection officer, to notify the supervisory authority of a data breach, to carry out a data protection impact assessment and to implement the privacy by design and by default into their products and processes. On the other hand, the Regulation provides the data subject with some new rights (the right to data portability, the right not to be subject to an automated decision and an enhanced right to data erasure). The rights of the data subject are aimed at ensuring greater transparency and control for the data subject over his/her personal data. However problematic issues may arise in practice, e.g. the finding of the appropriate legal ground of processing, a manner of obtaining the consent of data subject or appropriate data breach safeguards. A question whether the communication among vehicles and between the vehicles and the infrastructure will fall under the ePrivacy Regulation and if so, to what extent, still remains unclear.

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TESTING OF AUTOMATED DRIVING SYSTEMS

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ABSTRACT
The automated driving requires new testing approaches, which are more complex than the current testing systems. The complexity and requirements for accuracy is important, because of interconnection of virtual with physical testing. This paper presents a generic approach to testing of automated driving functions and demonstrates its implementation on measurement of two scenarios.
KEYWORDS: AUTOMATED DRIVING, TESTING, TESTING SCENARIOS

SHRNUTÍ
Automatizované řízení vyžaduje nové testovací přístupy, které jsou daleko komplexnější než současné testovací systémy. Komplexnost a požadavky na přesnost jsou důležité z pohledu na propojení fyzického a virtuálního testování. Tento článek prezentuje obecný přístup k testování funkcí automatizovaného řízení a demonstruje jeho implementaci na měřeních dvou scénářů.
KLÍČOVÁ SLOVA: AUTOMATIZOVANÉ ŘÍZENÍ, TESTOVÁNÍ, TESTOVACÍ SCÉNÁŘE

1. INTRODUCTION
The modern cars were invented as purely mechanical systems more than 130 years ago. However, since introduction of Antilock Brake Systems in 1970s the computerization of the vehicle driving started and computers played more and more significant role in the vehicles. The systems such as Antilock Brakes, Traction Control or Stability Control interrupt the direct connection between the driver and vehicle with the objective to reduce the possible risk, either to avoid the collision or at least to reduce the collision velocity in potentially dangerous situations.

In general, four groups of assistance systems can be recognized:
1. Comfort Systems such as Headlight or Rain Assistant – such systems take duties from drive, which are not directly connected with vehicle dynamic functions,
2. Information and Warning Systems such as Driver Alert, Lane Departure Warning or Traffic Sign Recognition Systems – such systems just inform driver about certain state of vehicle, driver or infrastructure,
3. Intervening Emergency Systems such as Stability Control or Automatic Emergency Braking – such systems take partial control over the vehicle in critical (near accident) situations,
4. Continuously Acting Systems such as Adaptive Cruise Control of Lane Keeping Assistance – such systems support driver in long time periods by taking part of his duties in standard situations.

The increasing computational power together with reducing purchase costs and as well as availability of low cost efficient and reliable sensors allow the manufacturers to implement functions such as lane keeping assistance or emergency braking options even to low cost cars, which are called Advance Driver Assistance Systems (ADAS). The logical consequence of the ADAS development is a vehicle which is either partly or even fully able to take the driver's duties. Such an automated driving (AD) vehicle will offer a co-pilot functions or drive even autonomously

TABLE 1: SAE levels of automated driving [1].
TABULKA 1: Úrovně automatizace řízení dle SAE [1].

SAE Level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
Human driver monitors the driving environment						
0	No Automation	the full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Drive Assistance	the driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task	System	Human driver	Human driver	Some driving modes
Automated driving system monitors the driving environment						
3	Conditional Automation	the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene	System	System	Human driver	Some driving modes
4	High Automation	the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene	System	System	System	Many driving modes
5	Full Automation	the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver	System	System	System	All driving modes

The Regulation 130 defines the approval tests for Lane Departure Warning Systems for vehicles categories N2, M2, N3, M3, i.e. trucks and buses. The test set-up is shown in Figure 1.

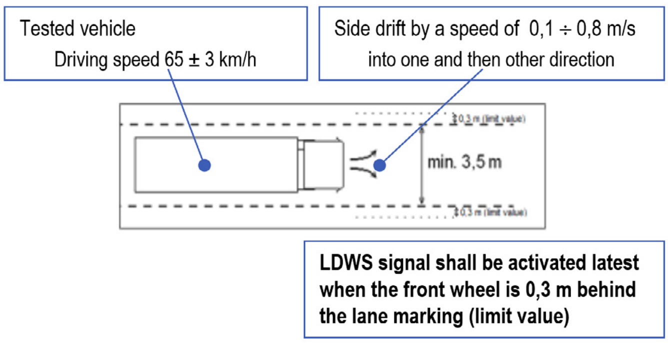

FIGURE 1: Test set-up according to UN ECE R 130
OBRÁZEK 1: Test setup dle předpisu EHK OSN 130

The Regulation 131 defines the timing and type of warning as well as automatic braking maneuver based on tests with a stationary and moving target, which represents a passenger car of category M1, class AA saloon. The initial velocity is defined to 80 km/h. The AEB system should at first warn the driver and if he does not react then to automatically brake the vehicle. The warning timings are different for various categories of vehicles, warning time for N2 is shorter than for M3. Further testing is focused on identification of failures and finally the driving in the gap between 2 parking vehicles, which are 4.5 meters side to side from each other as indicated in Figure 2.

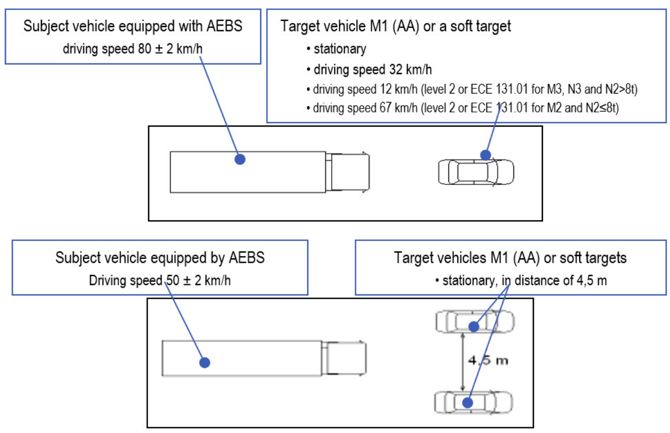

FIGURE 2: Test set-up according to UN ECE R 131
OBRÁZEK 2: Test setup dle předpisu EHK OSN 131

without a driver. According to SAE the development will be divided in several levels as indicated in Table 1.

In order to drive automatically, the vehicles must take responsibility from a human driver to its IT systems and control algorithms. Despite it is expected that driverless vehicles will be able to reduce significantly the number of accidents and fatalities, some sources expect even 90% or more, the initial stages of AD implementation will be accompanied by increase of accidents due to heterogeneous traffic of driverless and human driven vehicles and the insufficient maturity of AD systems [2].

Currently the regulatory bodies and consumer organizations define for some vehicle categories couple of physical proving ground tests to assess the functionality of ADAS. However, the testing procedures based on physical testing seem to be insufficient to cover the all possible cases and thus to evaluate the effectiveness and safety. To cover the vast number of possible scenarios, simulation methods are the only feasible way [3]. However, the physical tests will be still needed for verification and validation of these simulation models and set-ups.

The proper standardization and regulatory basis is important for all stakeholders. Since current regulations and inspection specifications are not sufficient or even not existing, several committees and project groups such as German project PEGASUS are developing new international regulations and standards.

To be able to implement complicated scenarios on a proving ground, new testing approaches must be developed and implemented, in which traffic simulation vehicles (TSV) and soft crash targets (SCT) together with other entities define repeatable environment for testing of so-called Vehicle Under Test (VUT). Such tasks are being solved within couple of projects and in an ISO level in ISO/TC 22/SC 33/WG 16 (Active Safety Test Equipment).

2. TYPE APPROVAL OF ASSISTANCE SYSTEMS

As usual, the development of standards and regulations is slower than the development of the technology itself.
The ADAS functions are implicitly addressed by the UN ECE Regulations 13 and 79 with Annexes on electronic systems. However, current Regulation 79 explicitly defines the requirements for systems up to automatic parking, i.e. with low velocities. Further development of Regulation 79 is in progress.
The vehicles of categories M2, M3, N2 and N3, i.e. trucks and buses with some exceptions are legislatively controlled by the Commission Regulation (EU) No. 351/2012 and 347/2012 to be equipped with

LDW and AEB functions since November 2015 [4, 5]. For AEB the deadline depends on the braking system and suspension. On the UN ECE level the Regulations 130 and 131 exist, which define the technical requirements and testing procedures.

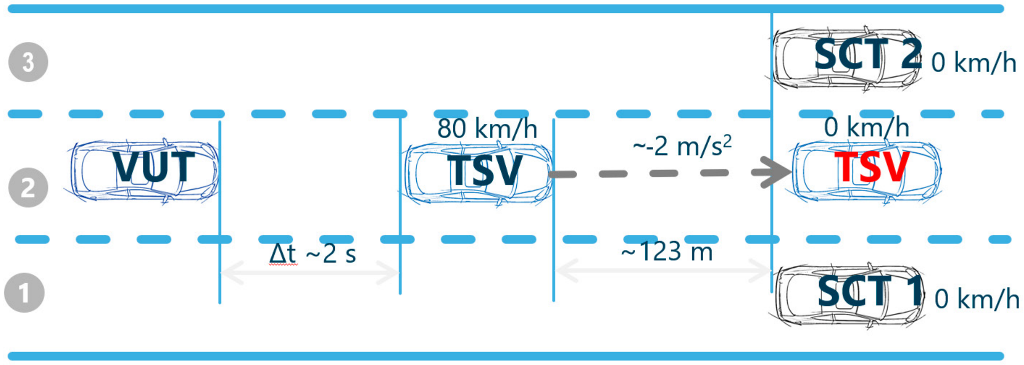

FIGURE 3: Scenario traffic jam tail end
OBRÁZEK 3: Scénář konec kolony

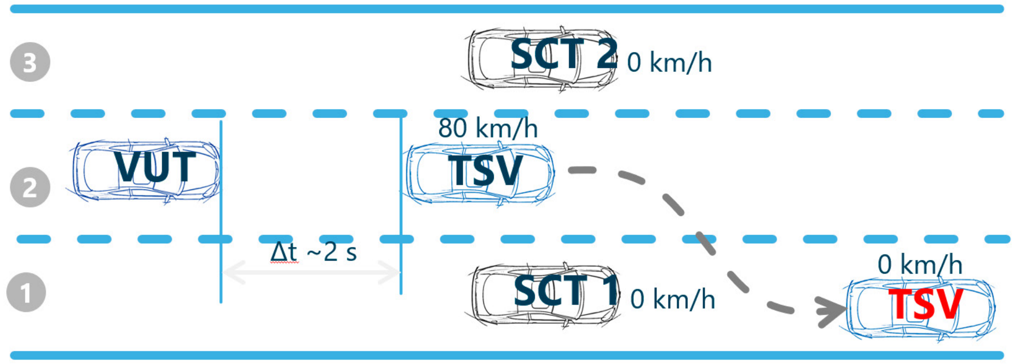

FIGURE 4: Scenario lane change
OBRÁZEK 4: Scénář změna jízdního pruhu

Two Soft Crash Targets (SCTs) were installed on the proving ground as indicated in Figure 5. SCT 1 was a balloon car from the EuroNCAP target for testing ADAS functions and SCT 2 was a model of a motorcyclist.

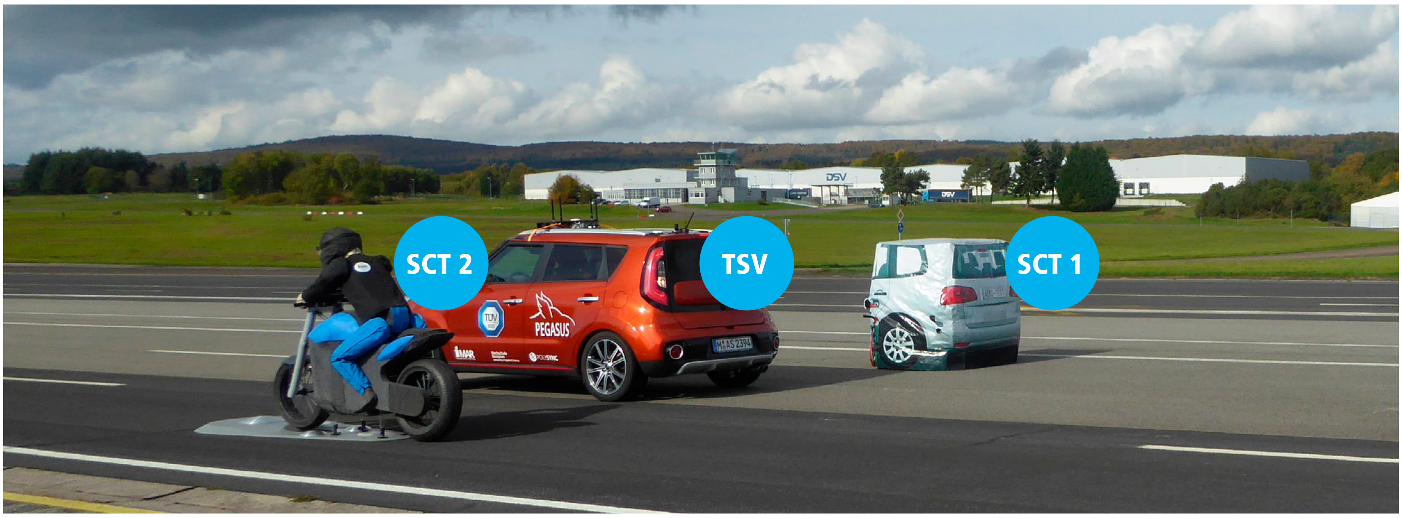

FIGURE 5: Soft Crash Targets
OBRÁZEK 5: Měkké cíle

3. CONSUMER TESTING

Currently the consumer organizations are focused on Advanced Emergency Braking (AEB) and Lane Departure Warning (LDW).

Consumer organization tests under the New Car Assessment Program (NCAP) [6], serves for the testing of AEB and LDW in passenger cars. Currently about nine different NCAP consumer organizations around the world exist, however not each has the AEB tests in its portfolio. The different NCAP test procedures demonstrate the heterogeneity of approaches in different countries and regions. While for example the US NCAP is based on tests drivers, the Euro NCAP uses driving and pedal robots along with accurate measurements of vehicle position. The advantages of the European approach are obvious: the higher accuracy in the position and higher repeatability the lower number of necessary tests to be performed.

Euro NCAP currently tests AEB systems in three areas: AEB city, AEB inter-urban and AEB pedestrian. Despite the complete set of velocities, this method considers only single, limited representative scenarios without considering the driver's behavior. This can be sufficient for consumer review to ensure comparability of different vehicles. However, for the vehicle safety and future type approval this is not enough, because realistic scenarios and driver and environmental influences are not included.

4. ENTITIES INVOLVED IN TESTING

To be able to generate the testing scenarios for both virtual and physical testing the possible set-ups should have a common basis. The presented structure has been developed in the project PEGASUS. The so-called generic approach for proving ground tests [7] summarizes the participants of the tests and defines the following entities [8, 9]:

1. Test Object
2. Basic Route
3. Guidance Infrastructure
4. Temporary Adjustments
5. Stationary Objects
6. Mobile Objects
7. Environment

The scenarios were performed in couple of runs in order to assess the repeatability and accuracy. The results achieved are presented in Figures 6 and 7. The first graph presents the velocity profile of the test; the second graph shows the lateral deviation. The results indicate that further development of the vehicle dynamic controllers is necessary in order to achieve the trajectory deviation better than +/- 0.1 m.

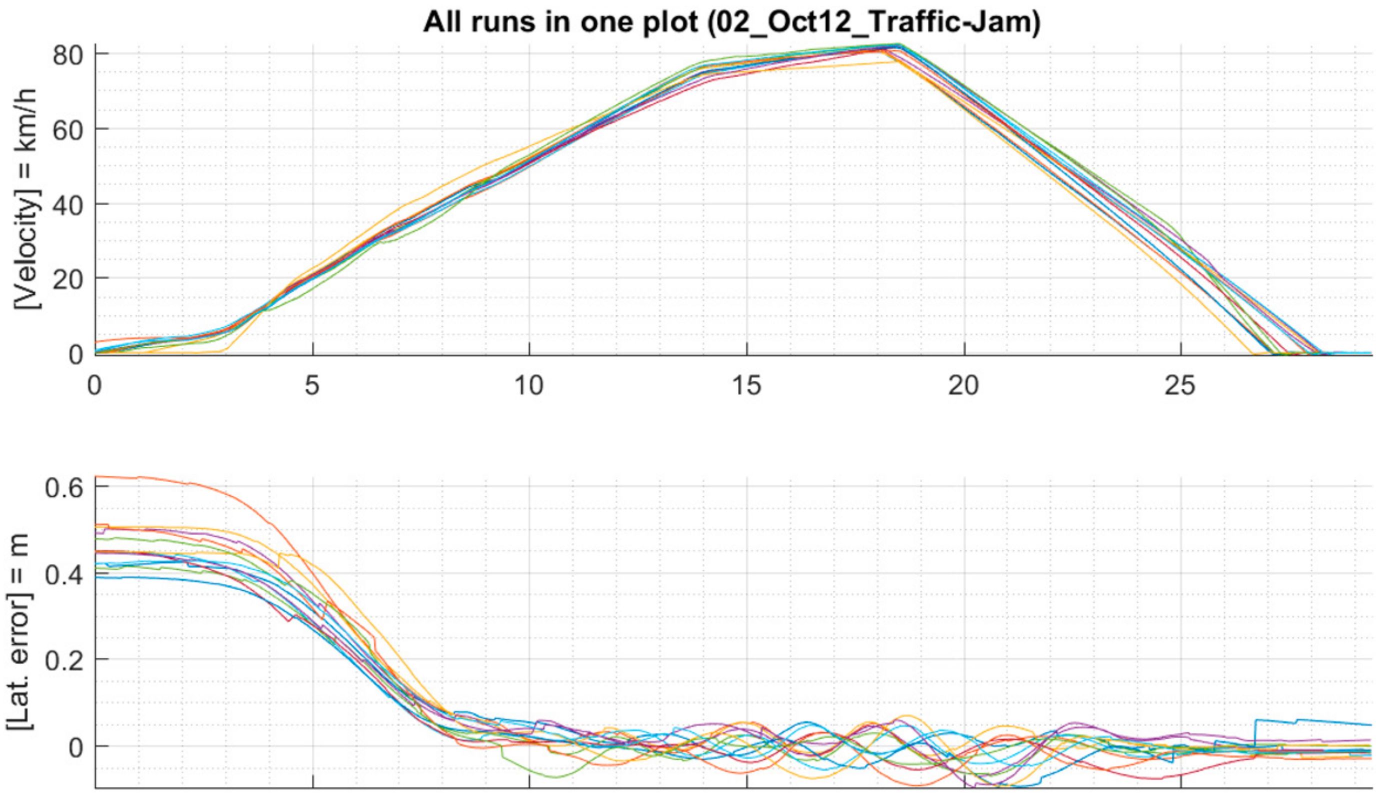

FIGURE 6: Measured data – traffic jam tail end
OBRÁZEK 6: Měření – konec kolony

FIGURE 7: Measured data – lane change
OBRÁZEK 7: Měření – změna jízdního pruhu

The testing scenario is then defined by a combination of different entities.
In order to implement the generic procedure of the scenarios on the proving a control center must implement all the tasks. The entire system should complete measurement equipment to perform tests of highly automated functions. Two types of scenarios are recognized: (i) time invariant and (ii) time variant. The time invariant test is synchronized by a Traffic Simulation Vehicle. In the time variant case the test is synchronized by the Vehicle Under Tests. The time variant case means that the TVS and SCT trajectories must be modified dynamically.
Very important feature of the control center is the wireless communication with low latency to all testing entities. All moving entities such as TSV, SCT and VUT must be equipped with a precise localization based e.g. on Real Time Kinematic (RTK) satellite navigation together with an inertial platform.
Since the trajectory of TSVs should be controlled, the vehicle must be actuated. Either it is possible to use external actuators such as steering and pedal robots of the internal actuators, which are already available in the vehicle. The second solution is of advantage because no additional devices must be installed in the vehicle. The current implementation uses direct control of internal vehicle actuators for steering and throttle and indirect control of deceleration by a braking robot. The system is in development and in the next version, it is expected that also the braking function will be actuated directly without installation of a braking robot.

5. PROVING GROUND TESTS

The first proving ground test has been performed in order to verify the implementation with selected test cases in real conditions. Two scenarios have been selected:

1. Traffic jam tail end
2. Lane change

Traffic jam tail end (Figure 3) is defined in the following steps:

a) SCTs in lanes 1 and 3 with v = 0 km/h represent the tail end of a traffic jam.
b) TSV, followed by VUT with ~2 s distance, drives with ~80 km/h in lane 2.
c) TSV decelerates ~123 m in front of SCTs with ~2 m/s² and stops beside the SCTs.

Lane change (Figure 4) is defined in the following steps:

a) SCTs in lanes 1 and 3 with v = 0 km/h represent the tail end of a traffic jam.

b) TSV, followed by VUT with ~2 s distance, drives with ~80 km/h in lane 2.
c) TSV changes lane into lane 1 behind the SCTs and stops. VUT accelerates in lane 2.

6. CONCLUSION

The proving ground testing will be a necessary part of the prove of effectiveness of the future automated driving functions. The complexity of the task requires to combine physical and virtual testing methods.

The objective of the proving ground testing equipment is to deliver accurate and repeatable testing environment for the automated driving systems. The paper presented a generic approach and an example of its implementation into the real environment together with some preliminary results based on predefined time invariant scenarios. The results indicate that further development of the trajectory controllers must be performed in order to achieve the acceptable motion of the traffic simulation vehicle.

Such complex systems as automated driving shall always be considered not only in terms of their effectiveness, but also functional safety and IT security issues are essential for the system overall rating.

The system is in development and the next generation will include full direct control of the vehicle using vehicle actuators as well as time variant capability. Furthermore, it is intended to integrate more traffic simulation vehicles together with moving platforms with soft crash targets for more complex scenarios.

ACKNOWLEDGEMENTS

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DEVELOPMENT OF A CONTROL ALGORITHM FOR A PARALLEL HYBRID POWERTRAIN

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ABSTRACT
The current legislation calls for fast electrification of vehicle powertrains, since it is necessary to fulfil the CO_2 requirements for the vehicle fleets. The hybrid electric vehicles (HEV) with parallel powertrain topologies – together with pure battery electric vehicles (BEV) – are the most common ways of electrification. However, the HEV powertrain – opposed to the BEV or conventional powertrain – poses an interesting challenge associated with the control system design to achieve the ideal power split between an internal combustion engine (ICE) and electrical machines (EM) during the whole vehicle operation.
The presented paper sums up the specific functions and requirements on a control system, together with the description of general control strategy options for a HEV powertrain. The proposed control strategy then combines heuristic rules with a suboptimal numerical control method, calculating the optimal power split ratio based on the efficiencies of ICE and EMs. This control strategy is built into a modular algorithm in Matlab/Simulink for two different parallel HEV powertrain topologies: P2 and P0P4. It is subsequently coupled with a vehicle models created in GT-Suite environment and tested on a WLTC homologation driving cycles. The following simulation tests show the fuel consumption reduction potential for chosen HEV topologies working in hybrid modes, in comparison to a base operation with conventional mode only. Yet, the heuristic rules can be further optimized to obtain even better overall results.
KEYWORDS: HYBRID ELECTRIC VEHICLE, PARALLEL HYBRID POWERTRAIN TOPOLOGY, ENERGY MANAGEMENT STRATEGY, HEURISTIC CONTROL STRATEGY, CONTROL ALGORITHM

SHRNUTÍ
Současná legislativa tlačí výrobce vozidel k okamžité elektrifikaci pohonu, protože je to v tuto chvíli jediná možnost, jak dostát požadavkům na flotilové emise CO_2. Nejběžnější formou elektrifikace pohonu jsou v dnešní době vozidla s paralelním hybridním pohonem anebo bateriové elektromobily. Nicméně hybridní pohon, na rozdíl právě od konvenčního nebo čistě elektrického pohonu, představuje zajímavé výzvy spojené s návrhem řídicího algoritmu, který musí v každém okamžiku zajišťovat optimální rozdělení výkonu mezi spalovací motor a elektromotor.
Tento článek v úvodu krátce shrnuje specifické funkce a požadavky na takový řídicí algoritmus, společně s obecným přehledem možných řídicích strategií hybridních vozidel. Následně je navržena řídicí strategie kombinující heuristická pravidla se suboptimální numerickou metodou, která vypočítává parametr optimálního dělení výkonu na základě účinností spalovacího motoru a elektromotoru. Na základě navrhnuté strategie je v programu Matlab/Simulink vytvořen modulární řídicí algoritmus pro dvě paralelní hybridní topologie: P2 a P0P4, který je následně propojen s modely vozidel vytvořenými v simulačním prostředí GT-Suite a testován v homologačním cyklu WLTC. Nakonec je prezentováno několik testů řídicího algoritmu, které demonstrují úsporu paliva vybraných topologií hybridního vozidla pracujících v hybridních režimech, ve srovnání s provozem pouze v konvenčním režimu pohonu. Avšak heuristická pravidla mohou být dále optimalizována, s cílem dosáhnout ještě příznivějších celkových výsledků.
KLÍČOVÁ SLOVA: HYBRIDNÍ VOZIDLO, PARALELNÍ HYBRIDNÍ POHON VOZIDLA, ENERGETICKÝ MANAGEMENT VOZIDLA, HEURISTICKÁ ŘÍDICÍ STRATEGIE, ŘÍDICÍ ALGORITMUS VOZIDLA

1. INTRODUCTION

One of the major characteristics of today's automotive sector is undoubtedly the shift to the more 'ecological' powertrain technologies, with the emission legislation becoming stricter all around the world. At least partial electrification of the future vehicle fleets is inevitable in order to meet all the legislative requirements.

One of the possible solutions are the battery electric vehicles (BEV). Local emission free service and possibility of brake energy recuperation are certainly their great advantages, however lower driving range, relatively long charging times, insufficient charging stations availability, and higher overall prices – all in comparison with conventional vehicles – obstruct the mass expansion of BEVs.

Therefore, the hybrid electric vehicles (HEV) seem to be an answer – at least for the short-term. There are plenty of various topologies of HEV powertrains, but with one feature in common: these powertrains try to combine the advantages of both electric and conventional vehicles. Brake energy recuperation, and in some cases pure electric drive for urban operation are available. The battery capacities are smaller, batteries cheaper, and the charging times of plug-in versions a lot shorter. At the same time, total driving ranges are comparable to conventional vehicles. Moreover, the coupling of an ICE and an EM allows for the ICE load point shifting (LPS), improving the ICE operation efficiencies.

Parallel HEV powertrain topologies are currently the most common solution for the case with regular use of an ICE, because of the relatively simple combination of electrical components with a conventional powertrain. During the HEV powertrain's development, the control strategy must be considered from the beginning: it is crucial for a thorough evaluation of different HEV concepts, component sizing, prediction of exhaust emission production etc. Therefore, this paper proposes a control strategy for a parallel HEV, that is easily adjustable for different vehicle component sizes, or even other topologies. The control strategy is then used for P2 and P0P4 parallel HEV powertrains, but since it is built as modular, it is extendable for other parallel topologies also. The 0D models of both P2 and P0P4 topologies are created in GT-Suite; the control strategy, that combines a heuristic approach with an innovative numerical "suboptimal" approach, and determines the power split ratio based on the efficiency maximization, is built within the supervisory control unit in Matlab/Simulink environment. Vehicle models and supervisory control units are then coupled to evaluate the general fuel consumption benefits of the two parallel HEV topologies. The paper also discusses some apparent differences between the two considered HEV topologies and suggests the areas for further control algorithm development and optimization.

1.1 OUTLINE OF THE PAPER

The paper is divided into 7 main sections. After the first introductory section, the section 2 summarizes the specific functions, and requirements on the HEV powertrain, describes the main control strategy types. The innovative numerical suboptimal method, that determines the power split ratio in combination with some heuristic rules, is briefly presented here as well. The following section 3 describes the 0D vehicle models created in GT-Suite, together with the lower level control units for the ICE and EMs. The section 4 then defines the powertrain modes and describes the proposed heuristic control strategy. The following section 5 presents the transformation of the control strategy into a control algorithm in Matlab/Simulink. The section 6 discusses the simulation results, and model sensitivities on different control algorithm parameters. Finally, the section 7 sums up the main conclusions, and adds some possible directions for the future work.

2. HYBRID ELECTRIC VEHICLE POWERTRAIN TECHNOLOGY: POINT OF VIEW FROM CONTROL UNIT

2.1 HEV-SPECIFIC FUNCTIONS

The basic HEV control function is a recuperation of vehicle kinetic energy. During the braking process, the EM is working in a generator mode, transforms the braking energy into the electric energy, and stores it into the battery. However, the brake energy recuperation is not always enough to fulfil the brake demand, therefore, all electrified vehicles must be still equipped with the conventional mechanical brakes. It means, the comprehensive recuperation strategy must be developed. The authors in [4] recognize serial and parallel recuperation strategies. When the serial strategy is embedded, the vehicle decelerates primarily using only recuperation. Friction brakes then connect when the requested deceleration power exceeds the capability of recuperation (i. e. maximal EM power in generator mode). Conversely, recuperation and friction brakes work always simultaneously when the parallel strategy is used.

Given the combination of at least two energy converters and energy sources, HEV powertrain also offers some specific functions to improve the fuel efficiency. The LPS is one of these fundamental HEV control functions. It aims to keep the ICE working point as close as possible to its optimum efficiency curve (see figure 1). The LPS is possible by the clever interaction between the ICE and the EM (or more EMs). We recognize two distinct LPS modes – load point decrease and load point increase. When the ICE load point is decreased, the missing

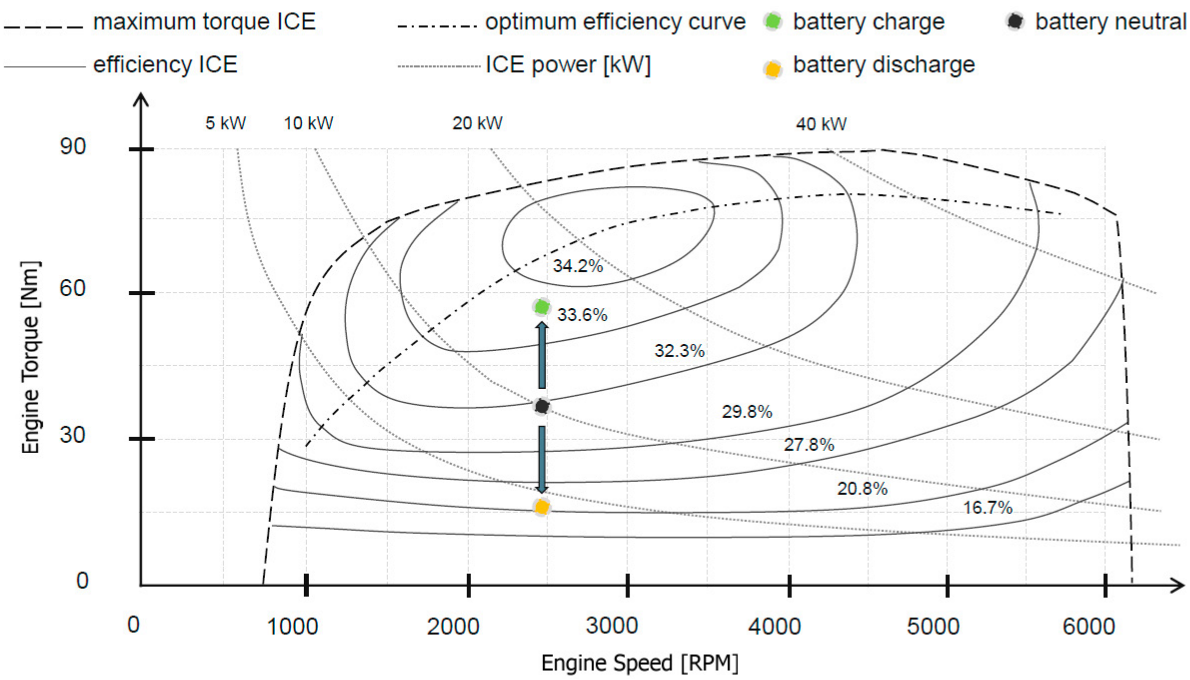

FIGURE 1: ICE load point shifting (modified from [3])
OBRÁZEK 1: Posun pracovního bodu spalovacího motoru (upraveno z [3])

energy is supplied by the EM. Vice versa, when the load point is increased, the excessive mechanic energy is transformed to the electric energy via EM in generator mode and stored into the battery.

Vehicles with parallel or other HEV powertrain technology usually offer a boost function. For example, during the manoeuvres with high acceleration demand, the EM's instant torque allows for more powerful acceleration. This is the only case, when immediate availability of torque has higher priority than optimal energy consumption, hence it is usually not considered.
At last, pure electric drive is also one of the HEV functions: the driving range and maximal achievable vehicle speed then depend on specific HEV powertrain topology and battery capacity.

2.2 CONTROL STRATEGY OPTIONS FOR HEV POWERTRAINS

The hybrid electric vehicles are generally much more complex than the conventional and BEVs, since they essentially combine both systems. The manual control of EM and other specific components, together with the ICE control, would lead to driver overload, and moreover to operation states with low overall efficiency. Therefore, HEVs must be equipped with fully automatic control strategy, which manages the interaction between all powertrain components, and control units. The overall goal is to fulfil the driver's demands, while keeping the fuel economy at optimum. The following paragraphs present the main types of the control strategies: heuristic, optimal, and suboptimal.

Heuristic control strategies usually use a set of predefined rules and thresholds to determine the power split ratio, and the powertrain operation mode. Predefined rules and thresholds include various variables, such as the power demanded on the wheels, maximal EM torque, battery state of charge (SOC) etc. These strategies are generally simple and robust, which is why most car manufacturers currently rely on them [2], [8]. On the contrary, since the rules and thresholds are usually fixed (and optimized for homologation cycles), they cannot react to the actual traffic situation. The vehicle does not fully reach the fuel efficiency potential on an actual route then. Moreover, the heuristic control strategies must be calibrated separately for each vehicle configuration, which makes its development very time-consuming. Various realizations of the heuristic strategies were presented in [6], [7], and [8].

Optimal control strategies, according to [2] and [7], include methods of dynamic programming, and game theory. Main advantage of the optimal control strategies is the ability to determine the globally optimal power split ratios for the whole route or driving cycle, using numerical approaches. Nonetheless, that also requires the knowledge of the complete future drive profile for a real-time control, which makes them hardly applicable in combination with rather unpredictable human driver, but rather for autonomous drive. Results from the optimal control strategies are often used as a benchmark for thresholds setup in heuristic strategies. Dynamic programming, and game theory are specifically described in [2], [7], [12], [13], and [14].

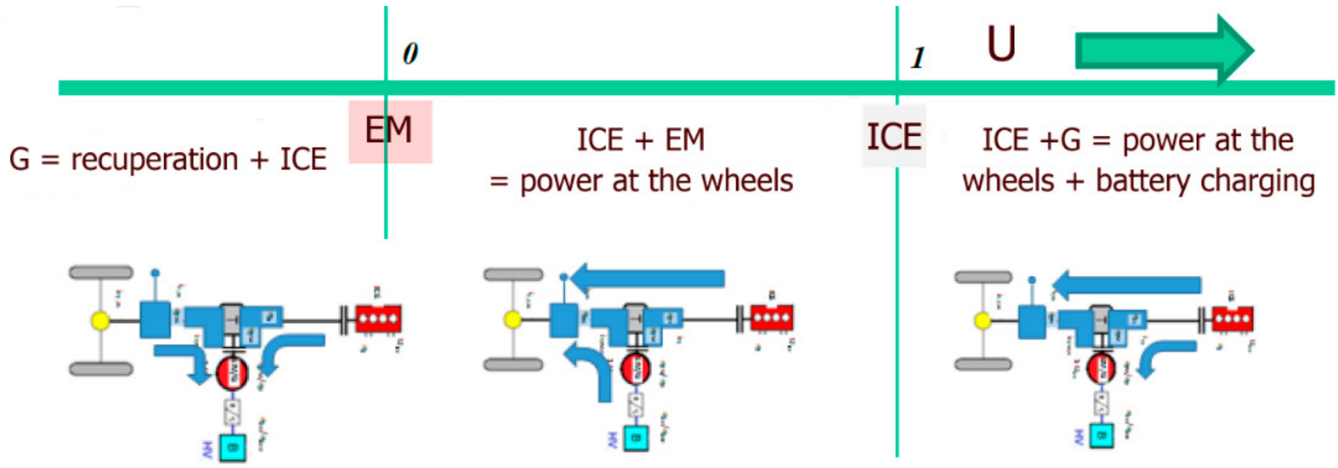

FIGURE 2: Range of U values (modified from [10])
OBRÁZEK 2: Rozsah hodnot parametru U (upraveno z [10])

A category of suboptimal methods contains mainly methods of equivalent consumption minimization strategy (ECMS), and predictive control. These methods also use numerical approaches to determine the optimal power split ratio, but only locally at a certain point in time, although sometimes they use information about the past powertrain states or try to predict the future operation. Suboptimal methods are also used for the real-time control of the HEV powertrain, since they are not so computationally demanding as optimal methods. The ECMS method, that is comprehensively described in [2], defines the energy consumption of all HEV power units as one variable, i.e. equivalent fuel consumption, and then it searches for a power split ratio with the minimal equivalent consumption.

The final two studies contain ideas, that inspired the proposed control strategy.

The first one is SOC-oriented suboptimal method from [5], that uses some heuristic concepts, rules. This method divides the battery into distinct charging fields, with different HEV powertrain behaviour in each field. Each charging field is then uniquely defined also by the charge and discharge power limits. The exact charge/discharge power limits are determined "off-line", using either the powertrain efficiency analysis or the ECMS method. The idea of different battery fields is used in the proposed method.

Another method, the OTHEV ([9], [10]), is a globally optimal method. However, in the proposed strategy, only its local level approach is used. The following chapter 2.3 presents the important OTHEV concepts, related to the local level.

2.3 OPTIMIZATION TOOL FOR HYBRID ELECTRIC VEHICLES (OTHEV)

The OTHEV method has two main features:

- A distinct local level with the powertrain units' efficiencies (ICE, EM) represented by regression formulas;
- A distinct global level, that searches for the optimal future drive profile by the "eco-routing" approach.

The first feature allows for the analytical search of the efficiency extreme values (or powertrain efficiency maxima), calculating the optimal power split ratio and transmission gear respecting the powertrain limits.

Since our proposed control strategy uses only the local level approach from OTHEV, the main ideas are shortly presented. The global level is explained in detail by the OTHEV authors in [9] and [10].

There are two main efficiency regression formulas: one for motor operation η_{MOT} (both for ICE and EM – equation 1), and for generator operation η_{GEN} (for EM only – equation 2). Both formulas use relative values of rotational speed ω_{rel}, torque p_{rel}, and power P_{rel} as their inputs. The exponents $x_{1,2}$, $y_{1,2}$, and $z_{1,2,g}$ are found by non-linear regression method in combination with the coefficients $A_{1\text{-}6}$ (these are determined by standard linear regression method at any non-linear regression approximation). The same formula with ad-hoc parameters can be used for each drive unit efficiency approximation.

$$\eta_{MOT} = \frac{1}{1+\frac{J_{MOT}}{P_{rel}}};\ J_{MOT} = \left(\begin{matrix} A_0 + A_1 p_{rel}^{y_1} + A_2 p_{rel}^{y_2} + A_3 \omega_{rel}^{x_1} \\ + A_4 \omega_{rel}^{x_2} + A_5 (P_{rel})^{z_1} + A_6 (P_{rel})^{z_2} \end{matrix}\right) * \omega_{rel}^{x_g} \tag{1}$$

$$\eta_{GEN} = 1 - \frac{J_{GEN}}{P_{rel}};\ J_{GEN} = \left(\begin{matrix} A_0 + A_1 p_{rel}^{y_1} + A_2 p_{rel}^{y_2} + A_3 \omega_{rel}^{x_1} \\ + A_4 \omega_{rel}^{x_2} + A_5 (P_{rel})^{z_1} + A_6 (P_{rel})^{z_2} \end{matrix}\right) * \omega_{rel}^{x_g} \tag{2}$$

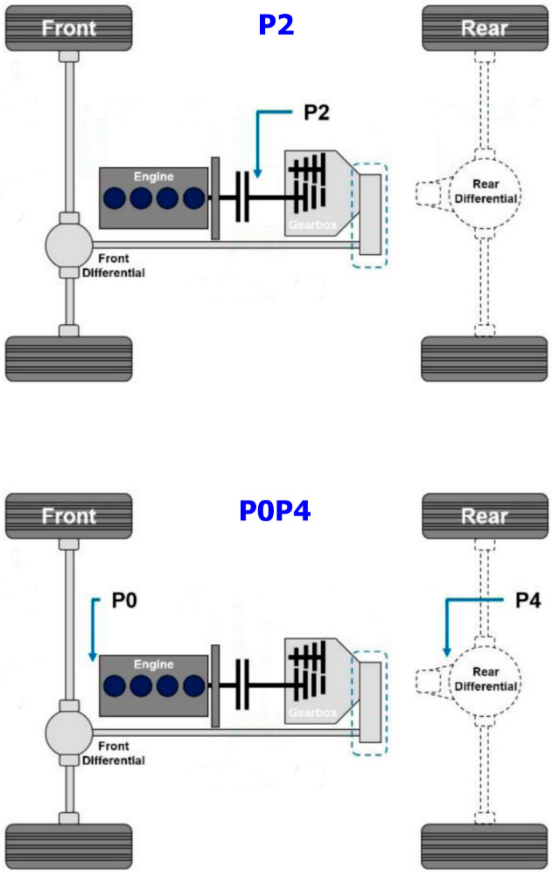

FIGURE 3: Parallel HEV topologies – EM position in P2 (top) and in P0P4 (bottom) (modified from [11])
OBRÁZEK 3: Paralelní topologie pohonu hybridního vozidla – pozice elektromotoru v P2 (nahoře) a v P0P4 (dole) (upraveno z [11])

$$U = \frac{P_{ICE}}{P_{total}} \tag{3}$$

The basic power split ratio U is defined as a ratio of ICE power to the total power (equation 3) – the remainder of the relative power (1-U) is then supplied by the EM. According to [10], the whole range of U values is shown on figure 2: values below zero represent brake energy recuperation mode combined with possible battery charge by the ICE; the interval <0÷1> represents the hybrid operation with LPS decrease; values higher than one represent the hybrid operation with LPS increase.
The optimization goal on the local level is to find the parameter U for the highest ICE efficiency possible. The equation describing the energy consumption is first defined for each powertrain operation mode (figure 2), with the only unknown variable in the energy equation being U. Its extreme value – the solution of minimal condition – is found using the Newton-Raphson iteration method. The validity of calculated U value is then checked by its comparison to the limit values of both drive units.

TABLE 1: Main vehicle parameters
TABULKA 1: Hlavní parametry vozidla

<table>
<tr><td colspan="4">VEHICLE</td></tr>
<tr><td>Topology</td><td>P2</td><td>P0P4</td><td></td></tr>
<tr><td>Vehicle mass</td><td>1450</td><td>1475</td><td>kg</td></tr>
<tr><td>Maximal speed</td><td colspan="2">220</td><td>km/h</td></tr>
<tr><td colspan="4">POWERTRAIN</td></tr>
<tr><td>Combined EM power</td><td colspan="2">54</td><td>kW</td></tr>
<tr><td>EM/ICE power ratio</td><td colspan="2">0,675</td><td>-</td></tr>
<tr><td>Total power</td><td colspan="2">134</td><td>kW</td></tr>
<tr><td colspan="4">ICE</td></tr>
<tr><td>Displacement</td><td colspan="2">1,5</td><td>dm³</td></tr>
<tr><td>Maximal power</td><td colspan="2">80</td><td>kW</td></tr>
<tr><td>Maximal torque</td><td colspan="2">150</td><td>Nm</td></tr>
<tr><td>Maximal speed</td><td colspan="2">6400</td><td>RPM</td></tr>
<tr><td colspan="4">EM P2</td></tr>
<tr><td>Maximal peak power</td><td>54</td><td>–</td><td>kW</td></tr>
<tr><td>Maximal peak torque</td><td>141</td><td>–</td><td>Nm</td></tr>
<tr><td>Maximal speed</td><td>8000</td><td>–</td><td>RPM</td></tr>
<tr><td colspan="4">EM P0</td></tr>
<tr><td>Maximal peak power</td><td>–</td><td>13,5</td><td>kW</td></tr>
<tr><td>Maximal peak torque</td><td>–</td><td>35</td><td>Nm</td></tr>
<tr><td>Maximal speed</td><td>–</td><td>8000</td><td>RPM</td></tr>
<tr><td>Fixed gear ratio</td><td>–</td><td>2,9</td><td>-</td></tr>
<tr><td colspan="4">EM P4</td></tr>
<tr><td>Maximal peak power</td><td>–</td><td>40,5</td><td>kW</td></tr>
<tr><td>Maximal peak torque</td><td>–</td><td>106</td><td>Nm</td></tr>
<tr><td>Maximal speed</td><td>–</td><td>8000</td><td>RPM</td></tr>
<tr><td>Fixed gear ratio</td><td>–</td><td>9,25</td><td>-</td></tr>
<tr><td colspan="4">TRANSMISSION</td></tr>
<tr><td>Type</td><td colspan="3">5-speed automatic</td></tr>
<tr><td colspan="4">BATTERY</td></tr>
<tr><td>Capacity</td><td colspan="2">7,7</td><td>kWh</td></tr>
<tr><td>Nominal voltage</td><td colspan="2">400</td><td>V</td></tr>
</table>

This whole calculation can be done either for a gear requested by the gear shifting strategy, or it can be repeated for all relevant transmission gear numbers to assure truly lowest fuel consumption.

3. 0D VEHICLE MODELS OF CHOSEN PARALLEL HEV TOPOLOGIES

The supervisory control algorithm is conceived as modular from the beginning, applicable on various parallel HEV topologies

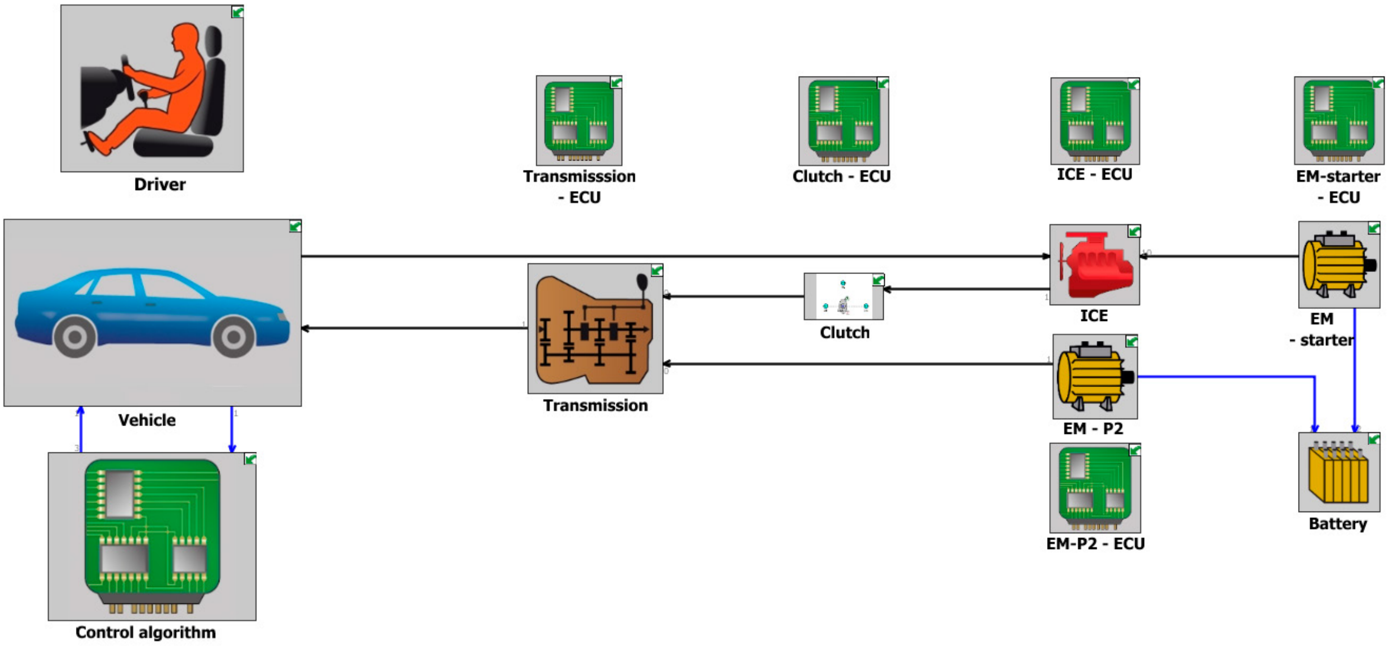

FIGURE 4: 0D model of P2 parallel HEV
OBRÁZEK 4: 0D model paralelního hybridního vozidla P2

TABLE 2: Powertrain operation modes
TABULKA 2: Provozní režimy pohonu

Operation mode	U value	Powertrain components states
Conventional	U=1	Vehicle powered by the ICE EM turned off
Hybrid 1	0<U<1	Both drive units power the vehicle simultaneously ICE load point decrease Power split defined by the U value Battery is discharged
Hybrid 2	U>1	Vehicle powered by the ICE ICE load point increase Excessive ICE power used in the EM Battery is charged
Pure electric	U=0	Vehicle powered by the EM ICE switched off
Recuperation	U<0	Always active, when possible Preferred way of vehicle braking
Boost	–	State of temporary vehicle power increase Active only when specific requirements are met ICE at full load, boosted by the EM

without a need of extensive changes. Two of the common parallel HEV options on the European market are the topologies P2 and P0P4 (figure 3).
The base vehicle for both HEV topologies is a C-class vehicle with a 4-cylinder natural aspirated, spark-ignition ICE, and 5-speed automatic transmission. The chosen battery capacity is standard for current plug-in HEVs: it allows for the pure electric drive mode as well. The main idea when deciding the EM sizes for both parallel topologies was to fix the ratio between the total EM power and ICE maximal power: P2 uses only one EM, the P0P4 splits the combined electrical power with a ratio 1:3 in favour of the P4 EM. The ICE, transmission, and battery are the same for both topologies, the vehicle mass is correspondingly adjusted. Table 1 summarizes all main vehicle parameters, together with gear ratios for P0 and P4 EMs.

The 0D models (figure 4 with P2 topology) are built as modular within the GT-Suite software. Therefore, main components (ICE, EM, and clutch) of the drivetrain have their own lower level control units. These control units ensure the correct function of all components, even when the architecture of the drivetrain changes. Moreover, the control units of the ICE and EM are programmed as templates within GT-Suite. It means that the user works with them in the same way, as he works with regular templates within the GT-Suite template libraries.

The ICE control unit determines the torque and power limits, controls injection, starting process, idle speed, and the minimum ICE runtime. The EM control unit defines the mechanical and electrical

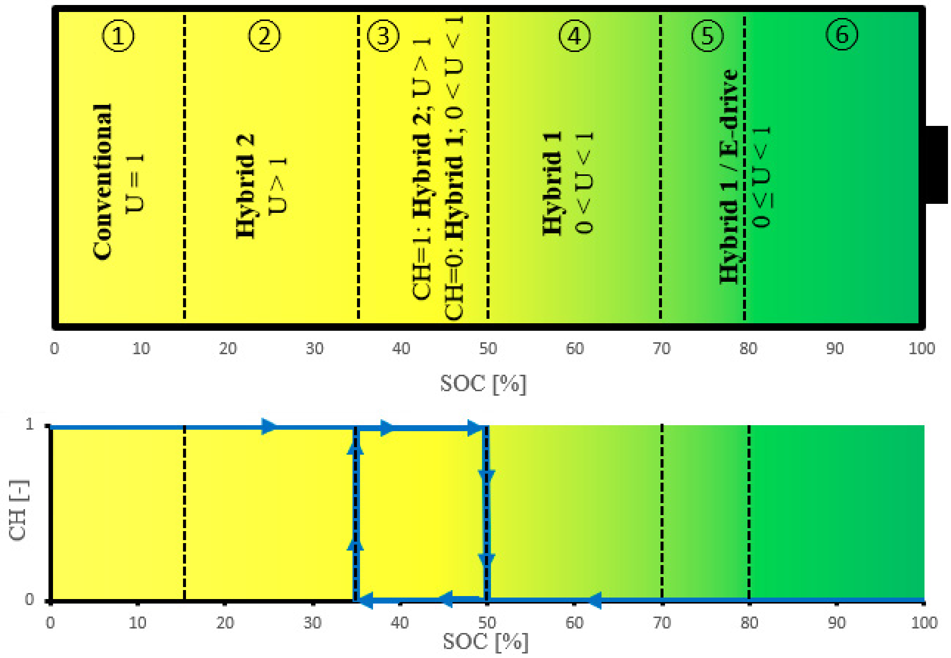

FIGURE 5: Control strategy in form of the battery charging fields
OBRÁZEK 5: Řídicí strategie ve formě dobíjecích polí baterie

limits of the torque and power, the peak torque availability, and controls the EM starter function (if applicable). The control unit of the transmission is embedded as a part of the main supervisory control strategy, and it is therefore not modelled in the 0D models.

4. SUBOPTIMAL CONTROL STRATEGY WITH HEURISTIC RULES

Our proposed control strategy uses the same U parameter and calculation method as the OTHEV from the chapter 2.3, figure 2. The value of U then uniquely defines five of six HEV powertrain operation modes. Only the Boost stands apart as an exception. All six powertrain modes, and the states of the main powertrain components are summarized in table 2.

In case of P2 topology, EM P2 supplies the requested electric power in all operational modes. On the other hand, the P0P4 topology has the specific EM assigned to each operational mode. EM P4 operates in Pure Electric, Hybrid 1, and Recuperation; the EM P0 in Hybrid 2 and Boost.

Recuperation mode is always active, using the serial recuperation strategy. It means the vehicle recuperates as much energy as possible during each deceleration phase. Boost can be activated only during the Hybrid 1 and Hybrid 2 modes, if driver demand is high. The only limit of the Recuperation mode is charge power limit; Boost mode maximizes the EM power, regardless of any power limitation. These two factors: charge/discharge power limits will be discussed in the following paragraphs.

The first set of heuristic rules in our control strategy is associated with the definition of six charging fields within the usable SOC range of the battery. Each field allows for a specific powertrain operation mode: their widths and positions are fully editable.

If the battery SOC is in the range of Field ① – the vehicle is driven conventionally by the ICE, with constant parameter U=1. As the SOC increases above the Field ②, the electric part of the drivetrain is always active. The OTHEV method [10] also defines a parameter CH, that is necessary for the final calculation of the correct U value. Here it is also used to distinguish between the modes Hybrid 1 (CH=0) and Hybrid 2 (CH=1). Field ② requires mode Hybrid 2, with constant battery charge by LPS increase. Field ③ is defined as transient – the selection of Hybrid mode depends on the value of parameter CH. Figure 5 shows CH value hysteresis in the Field ③, alternating the two Hybrid modes. Mode Hybrid 1 is always active in the following Field ④. The last two fields: Field ⑤ and Field ⑥, combine the use of Hybrid 1 and Pure electric modes.

Also, the available charge and discharge powers in all electrified modes (Hybrid 1, Hybrid 2, and Pure electric) are defined on SOC basis, defined as relative to the nominal EM power (see figure 6). These relative powers also belong to the editable heuristic rules, either directly connected to the charging fields, or independent from them.

Pure electric mode is limited by one last heuristic rule: the maximal vehicle speed in Pure electric mode (EV_{lim}). Figure 5 and figure 6

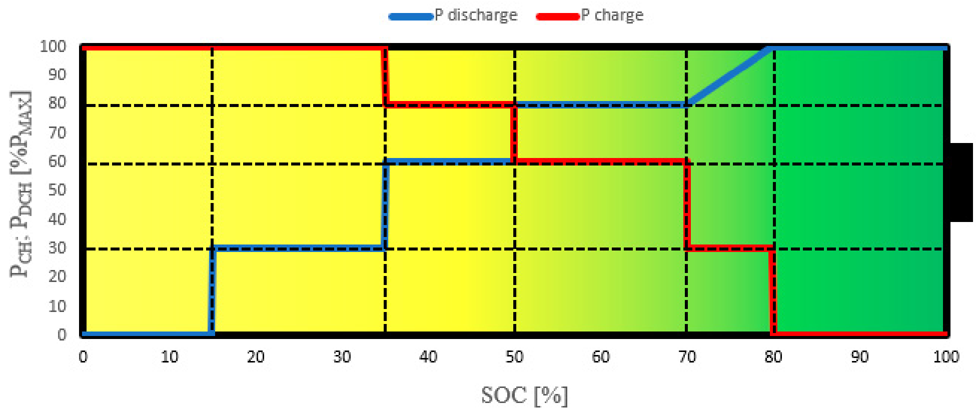

FIGURE 6: Charge and discharge power limits
OBRÁZEK 6: Dobíjecí a vybíjecí výkonové limity

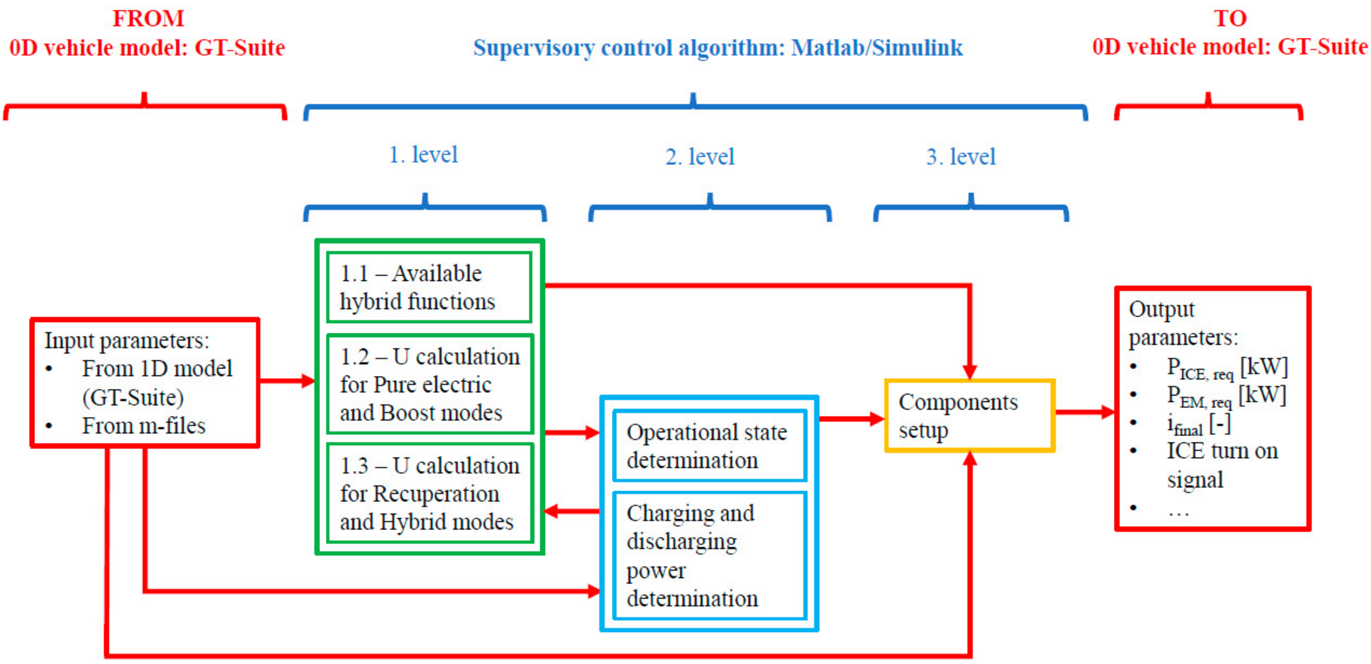

FIGURE 7: The main control algorithm structure
OBRÁZEK 7: Hlavní struktura řídicího algoritmu

show indeed the base settings of the heuristic rules, that is labelled as 'original' in the following simulation studies in chapter 6; the base value of EV_{lim} parameter is 50 km/h. These values were chosen manually to reflect the expected function of our HEV topologies, and the fact that the chosen battery size is for a plug-in HEV:

- The battery will be continuously discharging down to 35% SOC from the fully charged;
- The charging through the ICE LPS is available only up to 50% SOC;
- The fully charged state can be realistically achieved only by the external charging;
- The Pure electric mode is available for the urban drive, when the SOC is high enough;
- The Conventional mode should be used only in a case of emergency.

These heuristic rules can be adjusted and optimized for different component sizes, or desirable powertrain function. Likewise, the number of charging fields and their assigned powertrain modes can be easily adjusted, allowing for many different studies.

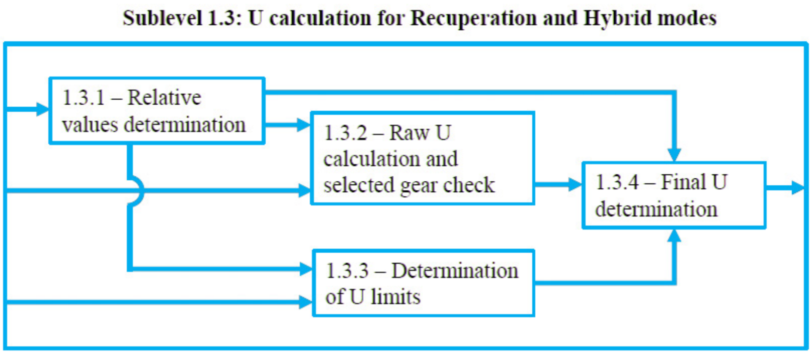

FIGURE 8: Sublevel 1.3 of the control algorithm
OBRÁZEK 8: Podúroveň 1.3 řídicího algoritmu

5. SUPERVISORY CONTROL ALGORITHM: IMPLEMENTATION IN MATLAB/SIMULINK

The proposed control strategy presented in the previous chapter, is built-in into a modular supervisory control algorithm in Matlab/Simulink. The algorithm receives the input signals from GT-Suite 0D vehicle model, and sends back the calculated output signals, such as ICE power demand $P_{ICE,req}$, or requested transmission gear ratio i_{total}. The supervisory control algorithm itself is then divided into three main levels, as shown in the figure 7. These three main levels are further subdivided.

The essential task of the first main level is to constantly calculate the value of U for each powertrain mode. The figure 7 shows its subdivision. The first sublevel 1.1 defines the available hybrid functions, that were briefly discussed in chapter 2.1. In our case, the P2 and P0P4 topologies have all mentioned hybrid functions at their disposal. The second sublevel 1.2 determines the values of U for Pure electric mode (U=0) and Boost mode.

The third sublevel 1.3 is the most complex one, figure 8 shows its detail. It calculates the value of parameter U for both Hybrid modes and for Recuperation, using the OTHEV approach. It also searches for the transmission gear ratio with the lowest fuel consumption. Sublevel 1.3.1 determines first the relative values of rotational speed and power, then the 1.3.2 calculates the raw value of U. Sublevel 1.3.2 includes the function of the transmission gear ratio modification as well: the raw power split ratio U and energy consumption are calculated for the actual transmission gear ratio 'i', one above the actual 'i+1', and one below the actual 'i-1'. These calculations run simultaneously for both Hybrid modes. After the 1.3.2 calculates the possible consumptions, and sublevel 1.3.3 determines the limits of U, 1.3.4 chooses the final value of U. If it is suitable, the transmission gear ratio is overridden, and the new gear ratio is sent to the transmission control unit to shift to a corresponding gear.

The second main level checks for the additional heuristic rules (end of chapter 5) and then selects final powertrain operation mode from those calculated in the former main level. This level then specifies the maximal discharge and charge powers, based on figure 6.

The third main level calculates the final operation parameters for all the powertrain components, using the outputs from the first two main levels (U value, operational state, charge/discharge power limits etc.). The ICE required power, ICE on/off signal, EMs requested power, modified transmission gear ratio, and other signals are specified here. The calculated EM powers are compared and eventually modified according to the maximal charge or discharge power limits here as well. Finally, also the braking process is determined in this level, using the already mentioned serial recuperation strategy. Three braking scenarios can happen: the vehicle brakes only by the recuperation, by the friction brakes only, or by the combination of both. This main level also determines the correct setting of topology-related functions: e.g. the LPS or Pure electric mode is executed differently for P2, then for P0P4.

6. SIMULATION RESULTS

This chapter presents some of the supervisory control algorithm's simulation tests. The first test is testing the overall algorithm functionality over the course of several WLTC Class 3 homologation drive cycles, starting at fully charged battery and "Charge depleting" mode (CD – i.e. SOC generally decreases), and shifting into "Charge sustaining" mode (CS – i.e. SOC at the driving cycle start equals the SOC at the end).

The next tests are all conducted in CS mode, also in WLTC Class 3. First of them tests one of the individual algorithm's functions: the transmission gear ratio modification function. The final two tests are studying the control algorithm's sensitivities on some of its heuristic rules.

6.1 OVERALL FUNCTION TEST

The first study shows the overall function of the HEV powertrain P2, with the battery fully charged at the beginning of the test (figure 9). The test lasts for 5400s, the vehicle drives through three WLTC Class 3 cycles consecutively. The upper part of figure 9 shows the evolution of SOC and the lower part values of the power split ratio U along the test.

The control strategy in the overall function test uses the base heuristic rules setting, that are listed at the end of the chapter 4. The vertical dashed line denotes the changes of powertrain mode with the SOC variation – dividing the whole test into five stages:

- The first two stages are in CD mode, the next stages in CS;
- Pure electric mode is available in the first stage (if the conditions are met);
- Control strategy allows only for the Hybrid 1 mode in the second stage;
- Hybrid 1 and Hybrid 2 modes are alternating in the CS stages, keeping the battery charge within the range of charging Field ③;
- The alternation of Hybrid modes would eventually continue till the user recharges the battery from the grid.

The algorithm works similarly for the vehicle with the P0P4 powertrain topology, but the average fuel consumption is slightly higher in comparison to the P2. This is due to the overall efficiencies of the P0P4 topology in comparison with P2:

- The P0P4 EMs are probably working with lower efficiency at the similar total loads;
- There is an additional conversion efficiency implied when charging the battery through the P0 EM and then using it on the P4 EM to drive the vehicle.

6.2 TEST OF TRANSMISSION GEAR RATIO MODIFICATION FUNCTION

The next functional test, shown on the figure 10, tests the function of the transmission gear ratio modification, from supervisory control algorithm's sublevel 1.3.2.

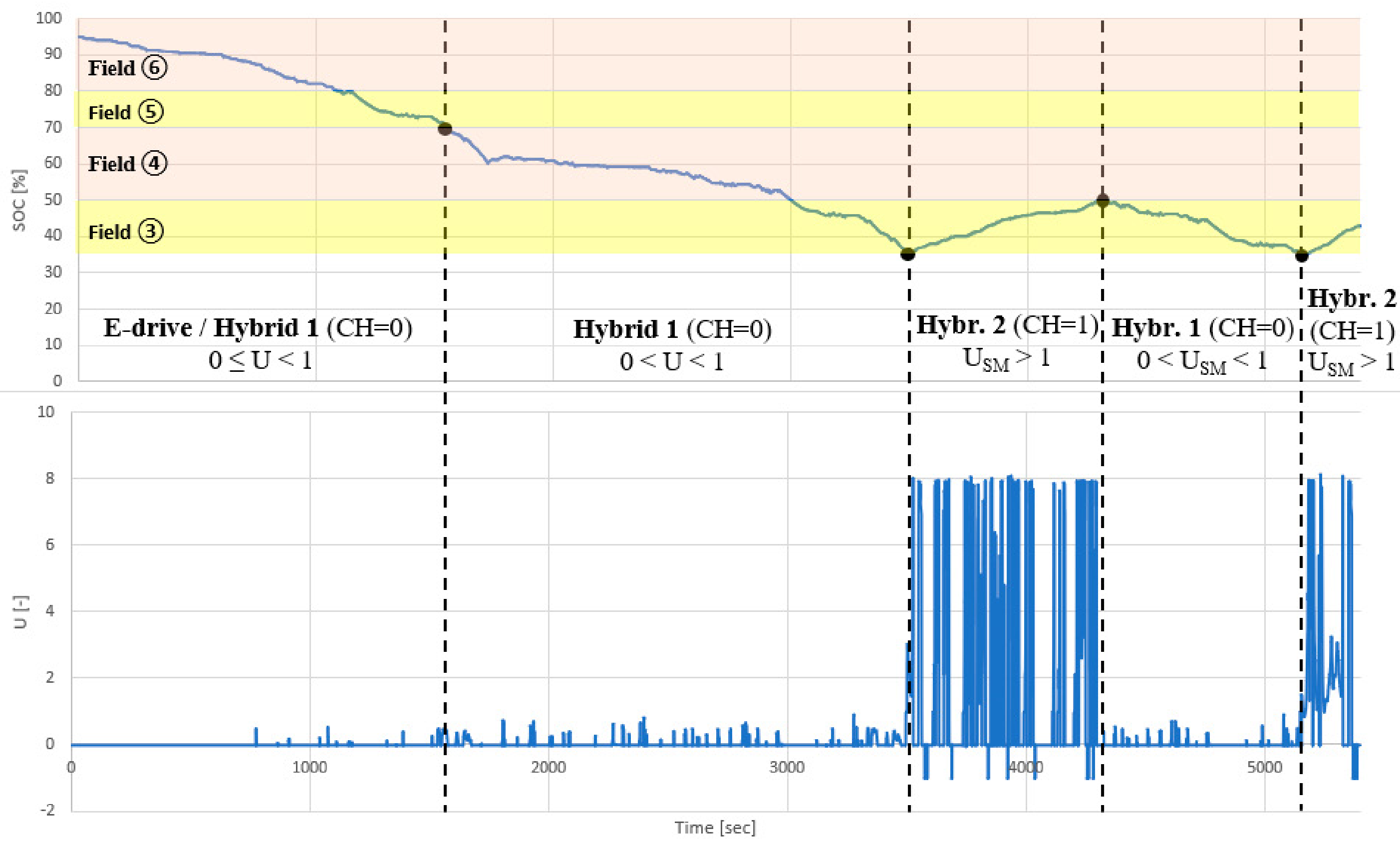

FIGURE 9: Overall function test of the topology P2
OBRÁZEK 9: Test celkové funkcionality topologie P2

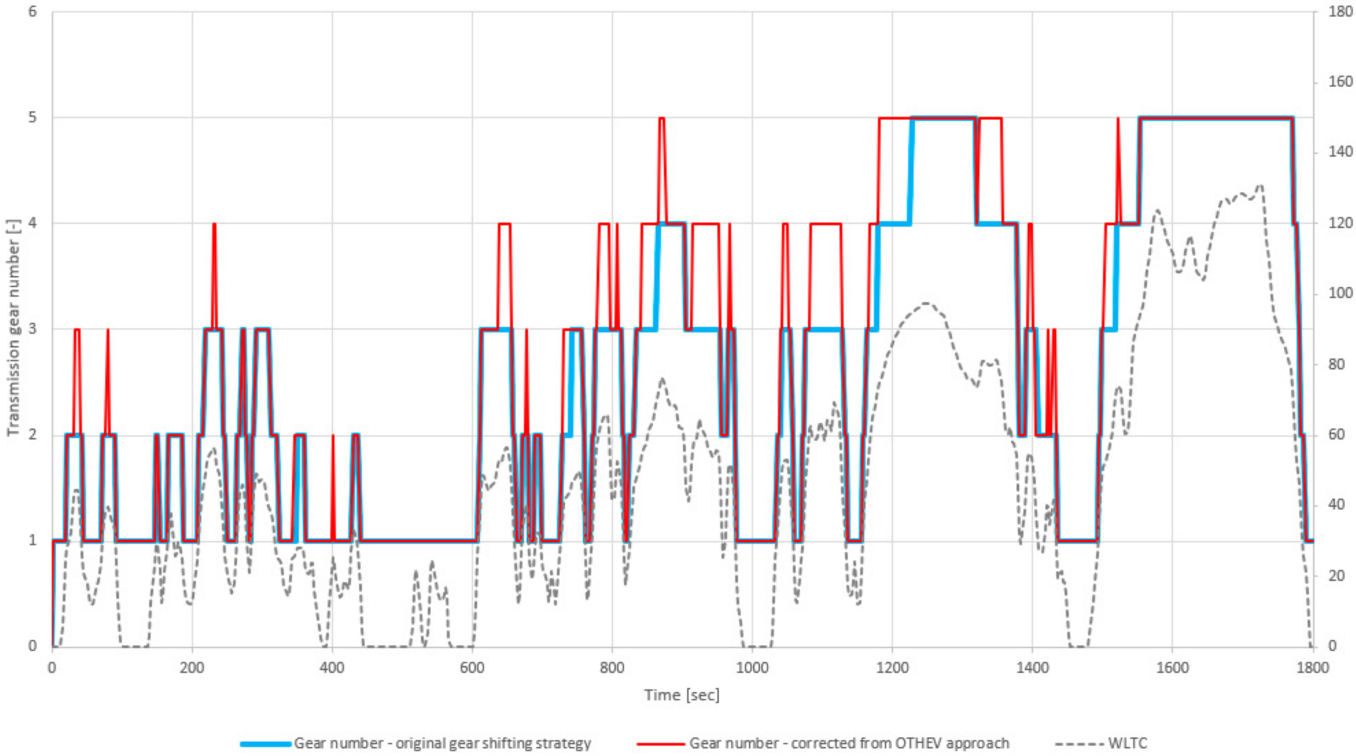

FIGURE 10: Test of transmission gear ratio modification function
OBRÁZEK 10: Test funkce změny převodového stupně

The transmission gear numbers are derived from the basic gear shifting strategy (saw diagram), when the function is turned off: these are shown in blue. The OTHEV modified gear numbers are shown in red. It is evident, that the control block prefers to shift to higher transmission gear numbers, as it is expected. The resulting fuel saving potential in CS WLTC Class 3 for the P2 topology is 0,54 l/100km.

6.3 SENSITIVITY TO THE VARIATION OF HEURISTIC RULES FOR THE PURE ELECTRIC MODE SELECTION

The selection of Pure electric mode depends mainly on the battery SOC level (lower SOC limit of Field ⑤ – SOC_{low5}), and the maximal vehicle speed in Pure electric mode (EV_{lim}). The sensitivity is presented for both HEV topologies with three different control strategy settings (table 3).

TABLE 3: Test setup and results for the sensitivity on heuristic rules related to Pure electric mode
TABULKA 3: Nastavení a výsledky testu citlivosti na heuristická pravidla související s Elektrickým módem

	Pure electric mode heuristic rules		Setting 1 (original)	Setting 2	Setting 3
	SOC_{low5}	[%]	70	35	35
	EV_{lim}	[km/h]	50	50	90
Topology	Results				
P2	Conventional mode FC	[l/100km]		5,83	
	CS test FC	[l/100km]	5,56	5,2	4,91
	ΔFC (CS – Conventional)	[l/100km]	-0,27	-0,63	-0,92
P0P4	Conventional mode FC	[l/100km]		5,95	
	CS test FC	[l/100km]	5,67	5,93	5,73
	ΔFC (CS – Conventional)	[l/100km]	-0,28	-0,02	-0,22

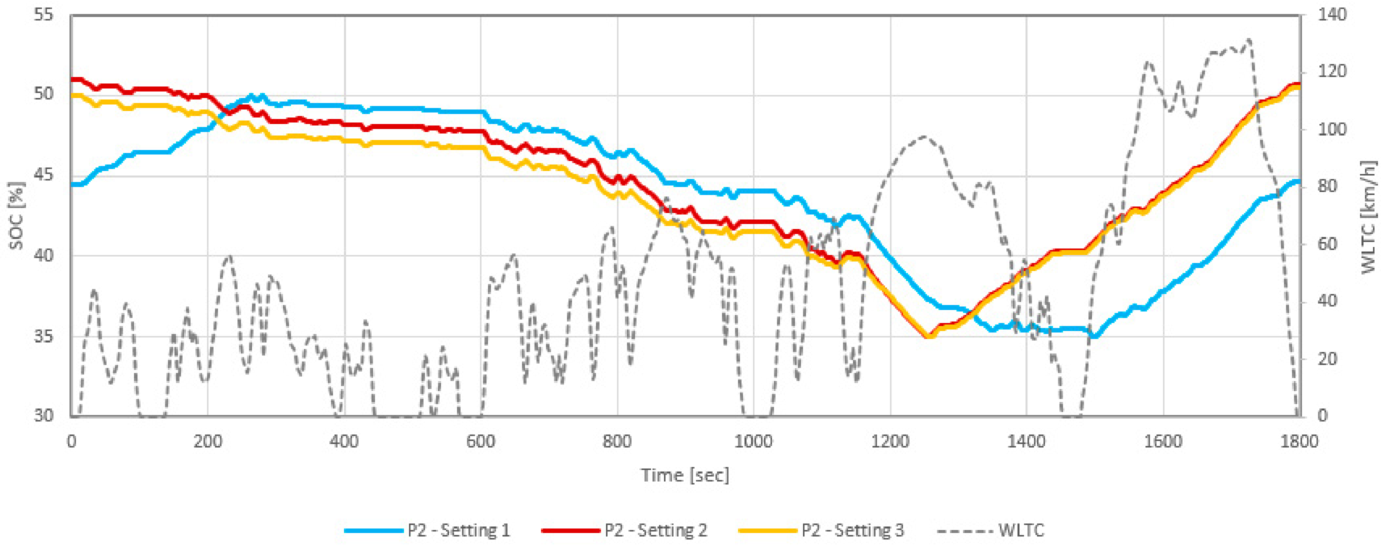

FIGURE 11: Topology P2 – SOC curves for different heuristic rules related to Pure electric mode
OBRÁZEK 11: Topologie P2 – SOC křivky pro různé varianty heuristických pravidel souvisící s Elektrickým módem

Setting 1 is the base setting of the control strategy (chapter 4); Setting 2 and Setting 3 then allow for the Pure electric mode down to SOC 35%, with a variation of the EV_{lim} limit.

The initial estimation of the heuristic rules in Setting 1 is clearly not optimal for the P2 topology, although the same does not apply for the P0P4. The positive result is that all tested settings show some fuel consumption (FC) reduction potential. The Conventional mode FC serves here as a benchmark.

- P2 topology achieves the highest FC reduction potential of 0,92 l/100km using the Setting 3, and only 0,27 l/100km with the original Setting 1;
- P0P4 topology achieves the highest FC reduction potential of 0,28 l/100km with the original Setting 1, Setting 2 achieves FC reduction potential of only 0,02 l/100km.

The P0P4 topology reaches generally lower fuel savings compared to the P2. This is caused by the already mentioned lower nominal powers of electric machines P0 and P4. Especially P0 is significantly smaller than P2 and its charging in generator mode lasts longer and probably runs with a worse overall efficiency.

The SOC curves for the P2 topology test (figure 11) show the powertrain's CS behaviour and the alternation of the Hybrid modes. The Pure electric mode is never active with Setting 1, the other two settings work in a very similar way.

6.4 SENSITIVITY TO THE VARIATION OF THE CHARGING FIELD ③

The second of the sensitivity tests is aimed at the charging Field ③ setup, where the modes Hybrid 1/Hybrid 2 are alternating. The results (table 4) are presented again for both topologies with four different Field ③ sizes, and fixed upper SOC limit (SOC_{high3}). Width 3 is the base setting of control strategy from chapter 4. Even though the powertrain SOC behaviour differs, the use of suboptimal method in Hybrid 1/Hybrid 2 modes ensures almost optimal operation and prevents high FC deviations from the original setting. None of the settings brings substantial FC

TABLE 4: Test setup and results for the sensitivity on Field ③ variations
TABULKA 4: Nastavení a výsledky testu citlivosti na změny Pole ③

	Field ③ setup		Width 1	Width 2	Width 3 (Original)	Width 4
	SOC width	[%]	5	10	15	20
	SOC_{low3}	[%]	45	40	35	30
	SOC_{high3}	[%]	50	50	50	50
Topology	Results					
P2	CS test FC	[l/100km]	5,56	5,59	5,56	5,68
	ΔFC (CS – Original)	[l/100km]	0	+0,03	-	+0,12
P0P4	CS test FC	[l/100km]	5,63	5,61	5,67	5,87
	ΔFC (CS – Original)	[l/100km]	-0,04	-0,06	-	+0,2

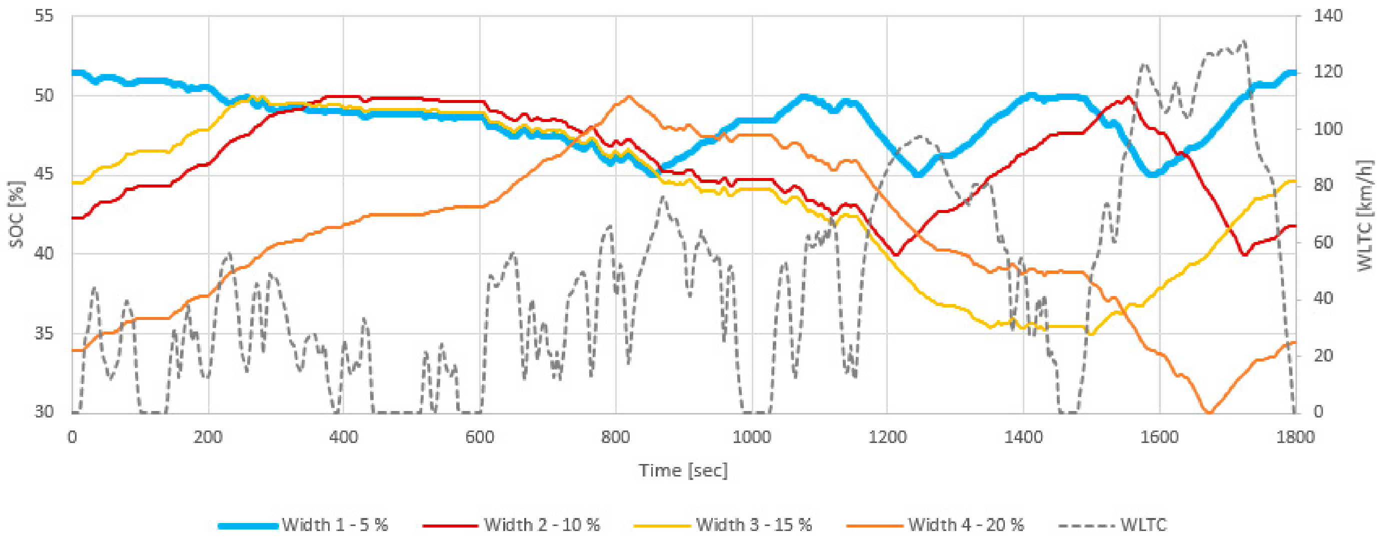

FIGURE 12: Topology P2 – SOC curves for different charging Field ③ widths
OBRÁZEK 12: Topologie P2 – křivky SOC pro různé šířky dobíjecího Pole ③

savings in comparison with the original setting, neither for P2 topology, nor for P0P4. However, detailed optimization could lead to some improvement:

- P2 achieves the same (Width 1), or worse FC compared to original;
- P0P4 achieves FC reduction potential of 0,04 and 0,06 l/100km for narrower Field ③ (Width 1, Width 2), and worse FC for wider Field ③ (Width 4);

The FC variations are generally associated with different durations of Hybrid 2 mode, in which the ICE is charging the battery with its excessive power, and with overall powertrain components efficiencies.

The charging Field ③ width variation is evident on the SOC curves for the P2 topology test (figure 12), with the alternation of modes Hybrid 1 (curve is descending) and Hybrid 2 (curve is ascending) being well obvious.

7. CONCLUSIONS

The paper presents the development of a new modular supervisory control algorithm, that combines SOC-oriented heuristic rules with suboptimal numerical approach to determine the locally optimal power split ratio. The control algorithm is then coupled with GT-Suite 0D vehicle models of two common parallel HEV topologies – P2 and P0P4 with plug-in size battery – and tested, in order to evaluate the fuel consumption reduction potentials, and the control algorithm's functionality.

The control algorithm is built as modular; therefore, it is easily adjustable for other parallel HEV topologies. Since it uses also a suboptimal approach, it creates a tool, which is particularly suitable in the early stages of the vehicle development for the component sizing, HEV topology fuel consumption potentials evaluation, comparison of control strategy variants etc.

The control algorithm tests show the overall potentials of the parallel HEV powertrain technology on the fuel consumption, despite majority of control algorithm's rules, and vehicle parameters were only roughly estimated, and not optimized. Following conclusions can be deducted from the two tests of algorithm functionality:

- The control algorithm behaves as expected for a plug--in size battery, changing from charge depleting mode when starting the route with fully charged battery, later shifting to a charge sustaining (CS) mode;
- The transmission gear ratio modification function also works as expected, choosing the higher gear when possible, leading to a significant fuel consumption reduction.

The subsequent sensitivities showed these main conclusions:

- Both topologies achieve lower fuel consumption in CS mode compared to the same vehicle driving in Conventional mode;
- The heuristic rules connected to Pure electric mode have great impact on a CS mode fuel consumption;
- The topology P2 shows higher fuel consumption reduction potential in comparison with the topology P0P4 in Pure electric mode test;
- The sensitivity on the size of one of the SOC charging fields show only slight impact on the fuel consumption results; the exact trends of potentials are not very clear for both topologies and this sensitivity.

The whole control algorithm and its test show a good promise and satisfying results. The future work should focus on following points:

- Thorough calibration and optimization of all the heuristic rules (optimally also in different driving cycles, for different vehicle classes etc.), as well as optimization of the powertrain behaviour to avoid frequent speed or load changes (hysteresis for shifting and on-off switching of the ICE);
- Algorithm extension for other parallel HEV topologies;
- Implementation of a prediction control model, with which the algorithm could adapt its behaviour according to a future road inclination or curvature (discharging battery before a long downhill drive, charging battery before a long climb, etc.);
- Implementation of the OTHEVs global level approach to further increase the accuracy of the power split ratio calculation;
- Implementation of the thermal management of the whole powertrain (ICE, EM, battery etc.), since the lower level control units (in GT-Suite, described in the chapter 3) are already prepared for that. The exhaust gas aftertreatment should be implemented as well.

LIST OF NOTATIONS AND ABBREVIATIONS

BEV	Battery electric vehicle
CD	Charge depleting
CS	Charge sustaining
ECMS	Equivalent consumption minimization strategy
EM	Electric motor
FC	Fuel consumption
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
LPS	Load point shifting
OTHEV	Optimization tool for hybrid electric vehicles
SOC	State of Charge
WLTC	Worldwide harmonized light vehicles test cycle

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