


Researcher Links UK-Russia Workshop

Scientific and Technical Grounds of Future Low-Carbon Propulsion

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Model analysis of electrically driven vehicles by means of unknown input observers

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Research and development of vehicles with low-carbon powertrains at FSUE «NAMI»

Experimental electric vehicle with photovoltaic auxiliary energy system (2017-2018)

Hybrid powertrain of parallel type for heavy duty commercial vehicles (2012-2014)

Experimental range-extended electric vehicle (2014-2016)

Experimental hybrid vehicles (2007-2011)

Medium city bus with hybrid powertrain of series type

Truck with hybrid powertrain of series-parallel type

Large city bus with hybrid powertrain of series type

Researches of vehicle powertrains based on test data: problems and possible solutions

Availability of production hybrid and pure electric vehicles gives researchers an opportunity of studying the real-world implementations of these technologies, analyzing energy flows within powertrains of such vehicles, assessing their energy efficiency and comparing them with one another.

Such researches imply testing of vehicles and mathematical modelling of conducted tests in order to analyze powertrain operation in details, which are not provided by physical tests.

However, modelling of production vehicle tests is complicated due to the lack of information on control algorithms of the powertrain, which is the common case, because these algorithms constitute a property of their developer or vehicle's manufacturer and are protected or otherwise not available for reading.

Direct measurement of transmission torques may not be feasible especially in cases of vehicles that are «in use» and cannot be intervened by incorporation of sensors within their structure. In the same time, the full investigation of energy flows within powertrain requires knowing operating points of its driving units, which include both rpms and torques.

The question is: if there is a workaround for these problems? The answer is «yes». And this workaround may be provided by the control theory in the form of so called observers. An observer constitutes a mathematical system (model) used to identify non-measured variables of the object. There is a number of known observers, which identify output variables knowing input and state variables (Luenberger's observer) or identify state variables knowing input and output variables (Kalman's filter).

Another type of observer is a newer one and is called unknown input observer. It identifies non-measured inputs knowing measured outputs or state variables. In application to vehicle powertrains, input variables are usually constitute effort-type variables like torques or forces, or signals used to control them (i.e. throttle command, electric motor current command). Therefore, the functionality of unknown inputs observers may be used to cope with the described research problem.

The use of unknown input observers in tasks related to automotive powertrains: examples

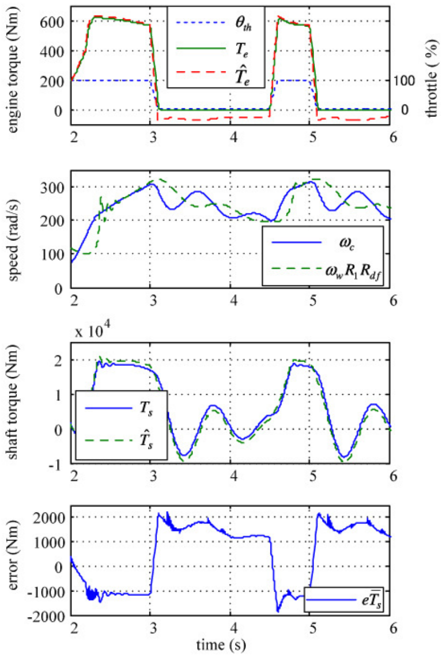
Observer intended for identification of the drive shaft torque [1]

The plant model:

$$\dot{\boldsymbol{y}} = \boldsymbol{F}(\boldsymbol{y}, u) + \boldsymbol{G}z + \boldsymbol{H}\boldsymbol{w}(\boldsymbol{y}, u, z),$$
$$\dot{z} = \boldsymbol{A}\boldsymbol{y},$$

Observer derived from the plant model:

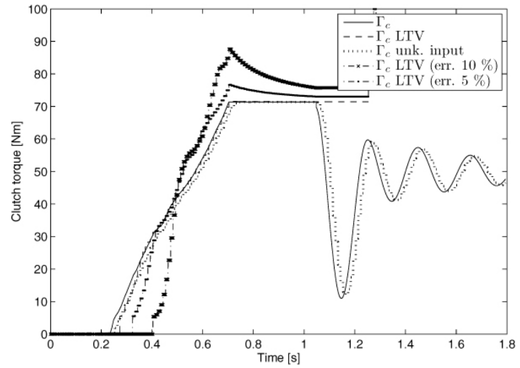
$$\dot{\hat{z}} = \boldsymbol{A}\boldsymbol{y} + \boldsymbol{L}(\dot{\boldsymbol{y}} - \boldsymbol{F}(\boldsymbol{y}, u) - \boldsymbol{G}\hat{z}),$$
$$\eta = \hat{z} - \boldsymbol{L}\boldsymbol{y},$$
$$\dot{\eta} = \boldsymbol{A}\boldsymbol{y} - \boldsymbol{L}\boldsymbol{G}(\eta + \boldsymbol{L}\boldsymbol{y}) - \boldsymbol{L}\boldsymbol{F}(\boldsymbol{y}, u).$$



Observer intended for identification of the clutch torque [2]

Observer is «incorporated» within the plant model:

$$J_e\dot{\hat{\omega}}_e = \hat{\Gamma}_e - \hat{\Gamma}_c + k_1(\bar{\omega}_e - \hat{\omega}_e)$$
$$\dot{\hat{\Gamma}}_c = k_2(\bar{\omega}_e - \hat{\omega}_e).$$



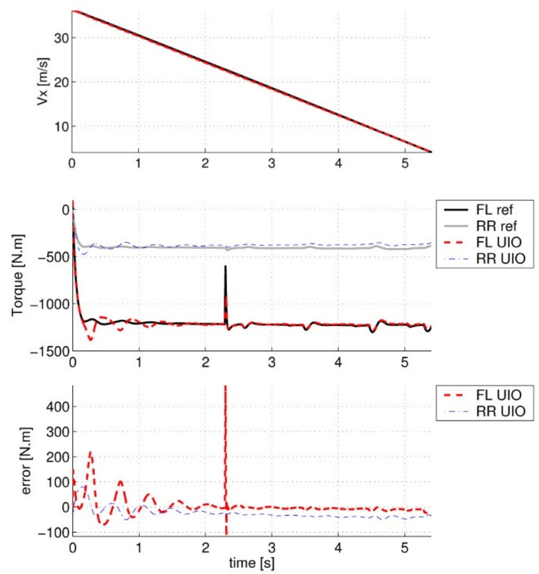
References:

1. Chen H., Gao B. Nonlinear Estimation and Control of Automotive Drivetrains. – Science Press Beijing, Springer-Verlag Berlin Heidelberg, 2014.
2. Dolcini P.J., de Wit C.C., Béchart H. Dry Clutch Control for Automotive Applications. – Springer-Verlag London Limited, 2010 .
3. Ouahi M., Stéphant J., Meizel D. Evaluation of Torque Observer in Automotive Context // Proc. of the 18th IFAC World Congress. – 2011.

Observer intended for identification of the wheel torques [3]

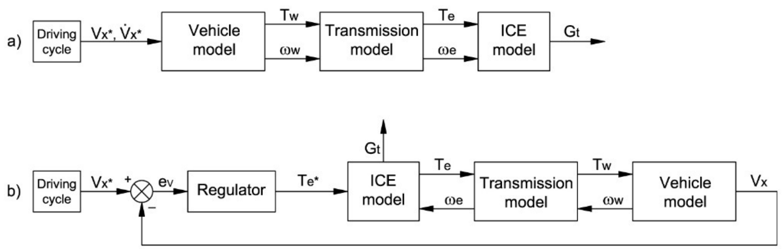
Observer is «incorporated» within the plant model:

$$\begin{cases} \dfrac{d\hat{\omega}_w}{dt} = \dfrac{1}{\hat{I}_w}\left[\hat{T}_w - \hat{R}_z \cdot \hat{\mu}_x \cdot \hat{R}_w\right] + 2L(\omega_w - \hat{\omega}_w) \\ \dfrac{d\hat{T}_w}{dt} = L^2\hat{I}_w(\omega_w - \hat{\omega}_w) \\ \dfrac{d\hat{V}_x}{dt} = \dfrac{\sum(\hat{R}_z \cdot \hat{\mu}_x)}{\hat{M}} \end{cases}$$



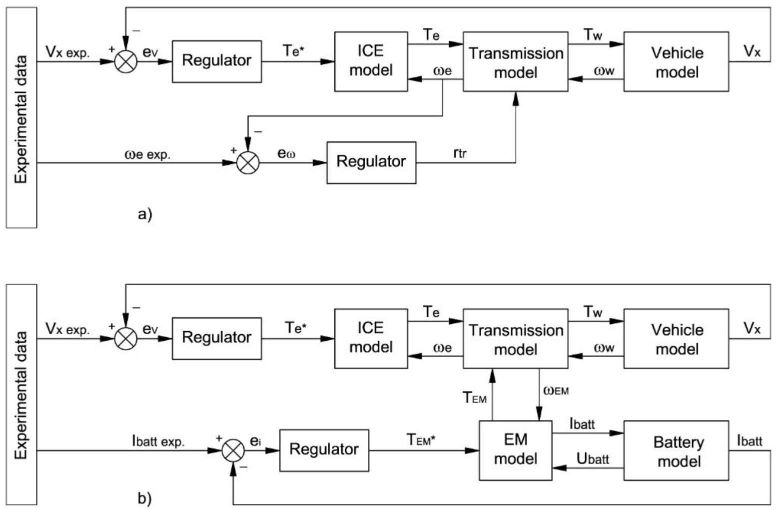
The proposed method for derivation of the unknown input observer for identification of unmeasured torques within automotive powertrains

Approaches to modelling of the vehicle dynamics:
a) back-facing approach b) forward-facing approach

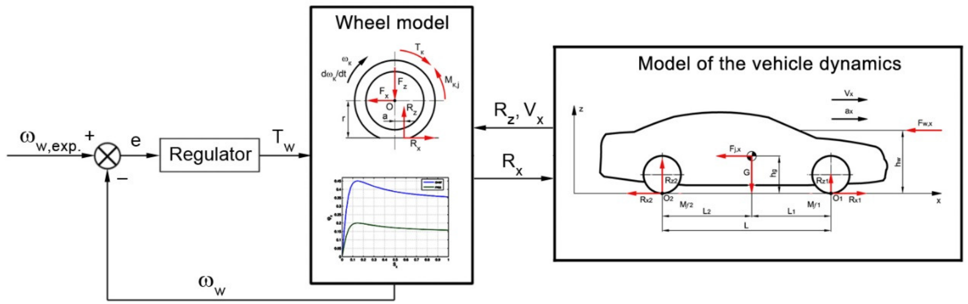


The observer's idea originates from the forward-facing approach

Observers intended for identification of powertrain operating regimes for:
a) Conventional powertrain with a CVT b) HEV with parallel topology



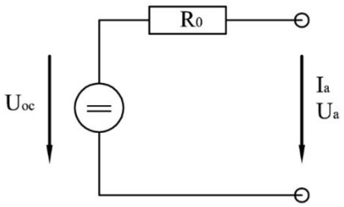
Observer intended for identification of the wheel torques considering the tyre-road adhesion



Modelling of powertrain components: traction batteries

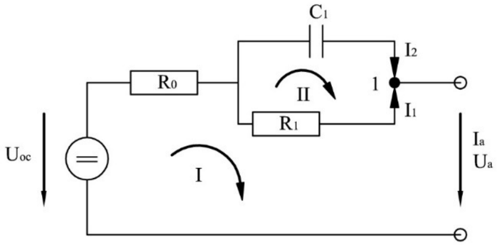
Modelling of battery voltage response by means of equivalent circuits

R-circuit



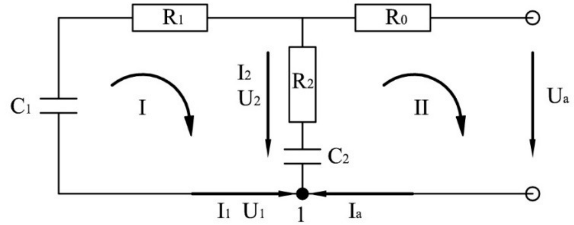
$$U_a = U_{OC} - R_0 I_a$$

Thevenin's circuit



$$\begin{cases} (R_1 C_1) \cdot \dot{U}_1 = I_{batt} \cdot R_1 - U_1 \\ U_{batt} = U_{OC} - I_{batt} R_0 - U_1 \end{cases}$$

Saft's circuit



$$\begin{cases} [C_1 (R_1 + R_2)] \cdot \dot{U}_1 = U_2 - U_1 - I_{batt} R_2 \\ [C_2 (R_1 + R_2)] \cdot \dot{U}_2 = U_1 - U_2 - I_{batt} R_1 \\ U_{batt} = (U_1 R_2 + U_2 R_1)/(R_1 + R_2) - \\ - I_{batt} (R_0 + R_1 R_2 / [R_1 + R_2]) \end{cases}$$

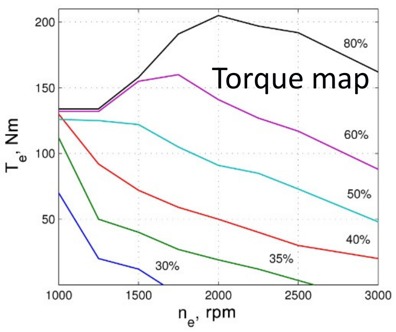
Calculation of the battery efficiency (a) and the state of charge(b):

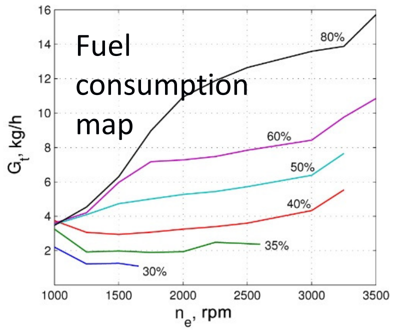
a) $$\eta_{batt} = \frac{|U_{batt} \cdot I_{batt}|^{\operatorname{sgn}(I_{batt})}}{(|U_{batt} \cdot I_{batt}| + \operatorname{sgn}(I_{batt}) \cdot I_{batt}^2 \cdot R_0)^{\operatorname{sgn}(I_{batt})}}$$

b) $$SOC = SOC_0 + \frac{100\%}{3600 \cdot Q_0} \int I_{batt} \cdot \eta_{batt}^{\operatorname{sgn} I_{batt}} \, dt$$

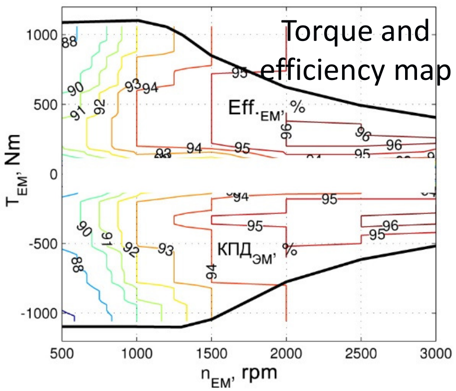
Modelling of vehicle and powertrain components: Internal combustion engine (ICE) and traction electric drive

Map-based model of the ICE



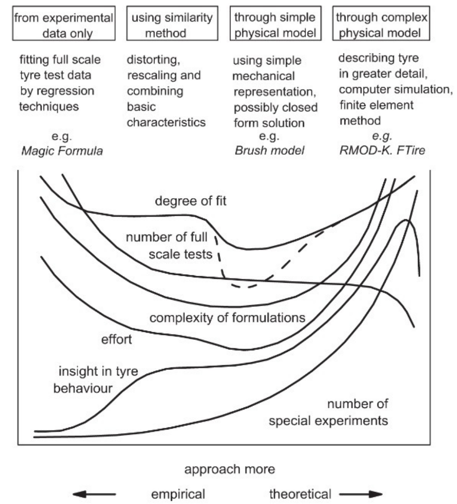


Map-based model of the traction electric drive



Tyre

Tyre models classification according to H. Pacejka [1]



Approximation of tyre-road adhesion characteristics by the «Magic Formula» model [1]

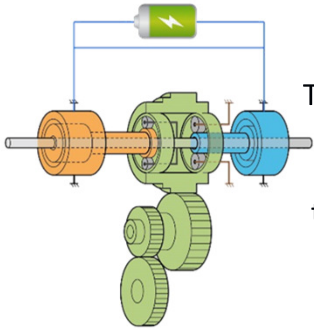
$$Y = D\sin\left[C \cdot arctg\left\{B \cdot X - E\left(B \cdot X - arctg\left(B \cdot X\right)\right)\right\}\right]$$

Reference:

1. Pacejka H.B., Besselink I. Tire and vehicle dynamics. – Third Edition. – Elsevier Ltd., 2012.

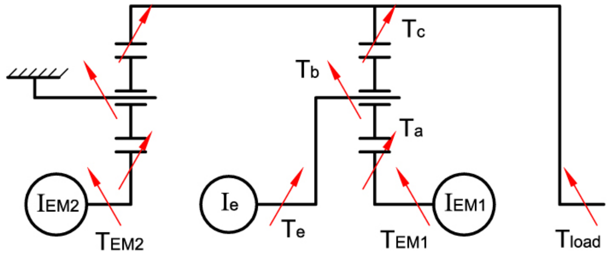
Case study 1: investigation of powertrain operating regimes in the production hybrid electric vehicle

The subject of the research: Toyota Prius HEV (test data from Argonne National Laboratory, USA*, no measurement of powertrain torques)



Toyota Hybrid System (THS) transmission

THS transmission schematics used for the model derivation

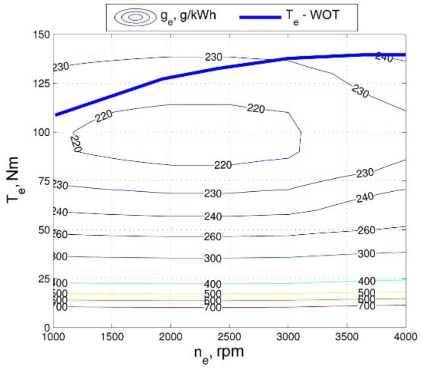


Equation system describing dynamics of the vehicle and THS transmission:

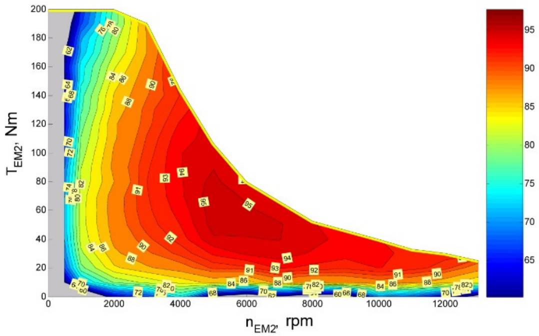
$$
\begin{cases}
\dfrac{d\omega_e}{dt} = \dfrac{T_e - T_b}{I_e} \\
\dfrac{d\omega_{EM1}}{dt} = \dfrac{T_{EM1} - T_a}{I_{EM1}} \\
\omega_c = \left[(k+1)\omega_e - \omega_{EM1}\right]/k \\
\dot{T}_c = c(\omega_c - \omega_0) + \gamma(\dot{\omega}_c - \dot{\omega}_0) \\
T_a = T_c / k \\
T_b = -T_c (k+1)/k \\
\dfrac{dV}{dt} = \dfrac{d\omega_0}{dt}\dfrac{R_w}{r_0} = \dfrac{(T_{EM2} \cdot r_{EM2} + T_c) r_0 / R_w - F_\psi}{M + \left(I_w n_{w1} + I_{EM2} r_0^2 \cdot r_{EM2}^2\right)/R_w^2}
\end{cases}
$$

Powertrain components' characteristics

Brake specific fuel consumption map of the ICE (calculated)



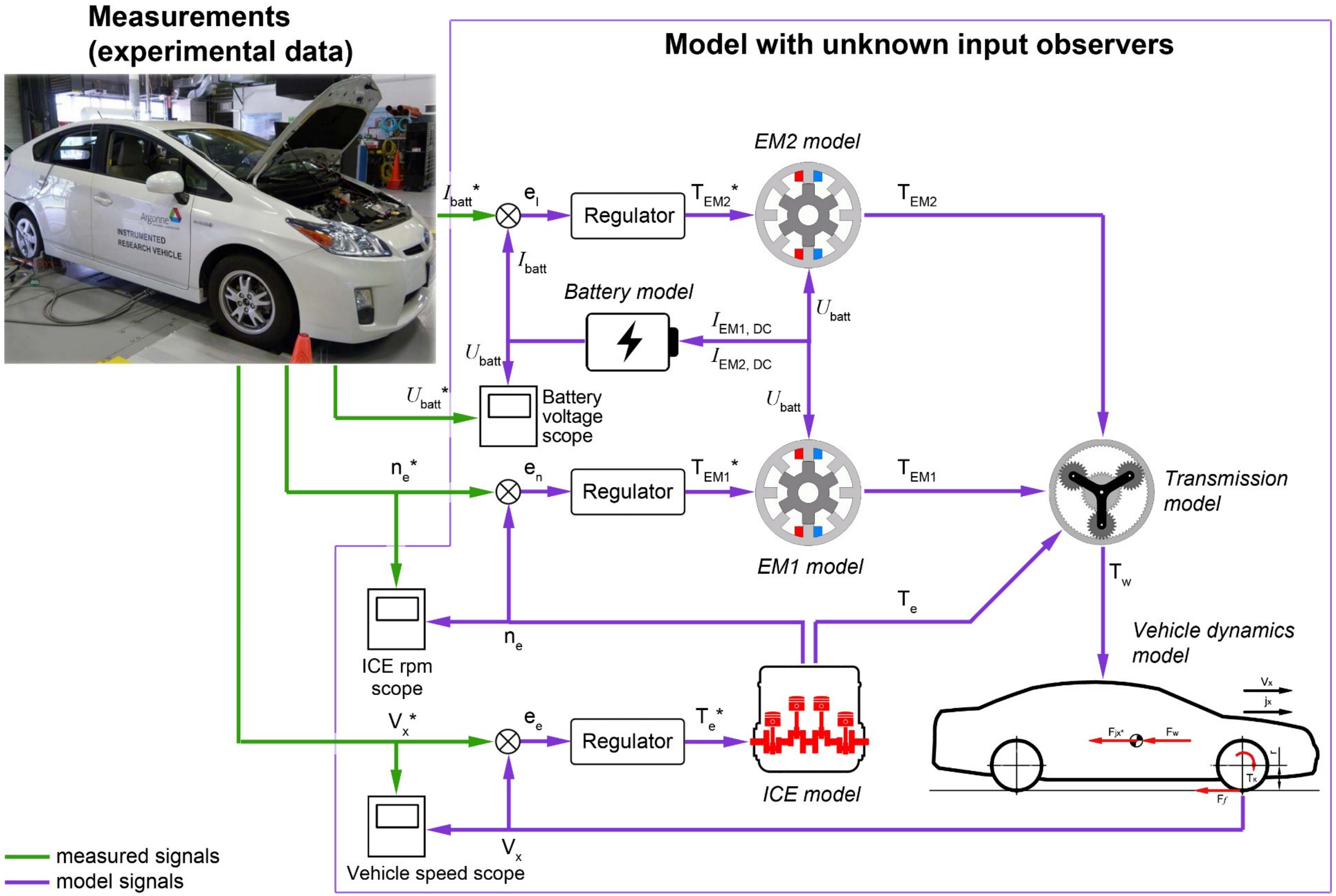
Efficiency map of the traction electric drive [1]



* Used experimental data is from the Downloadable Dynamometer Database and was generated at the Advanced Powertrain Research Facility (APRF) at Argonne National Laboratory under the funding and guidance of the U.S. Department of Energy (DOE).

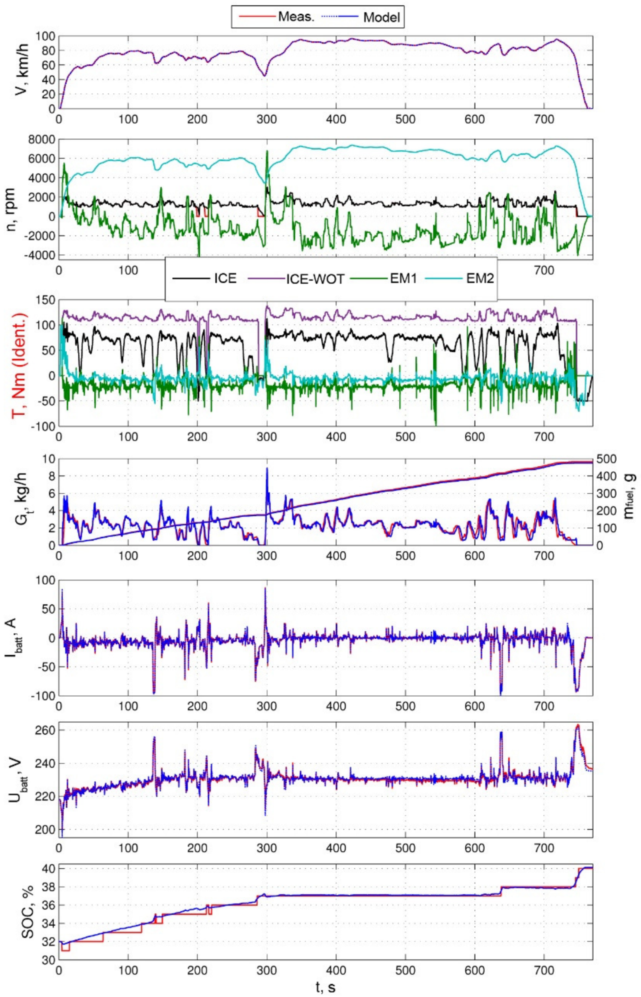
1. Burress T. A., Campbell S. L., Coomer C. L., Ayers C. W. et. al. Evaluation of 2010 Toyota Prius Hybrid Synergy Drive System: Report / Oak Ridge National Laboratory, 2011.

Model of chassis dynamometer testing with unknown input observers identifying the unmeasured torques within the powertrain



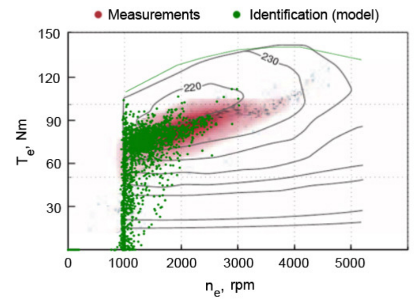
Modelling and identification results. Validation. Powertrain operation analysis

Modelling of a chassis dynamometer test in the HWFET driving cycle with identification of unmeasured torques

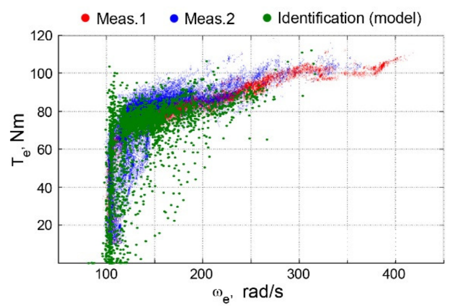


ICE operating points: identification vs measurements

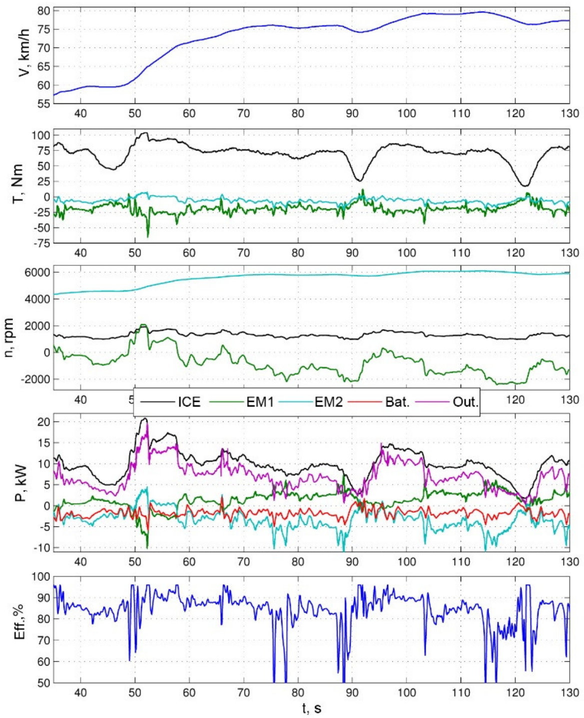
Test data from IFP Energies Nouvelles [1]



Test data from Argonne National Lab. [2]



Using of modelling results: Analysis of power flows and efficiency of the powertrain



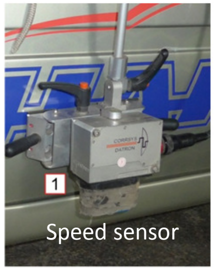
References:

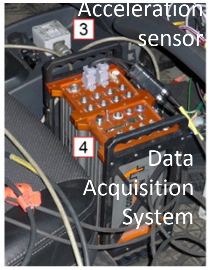
1. Badin F. Ed. Hybrid Vehicles: From Components to System. – Editions Technip, Paris, 2013.
2. Kim N., Rousseau A., Rask E. Autonomie Model Validation with Test Data for 2010 Toyota Prius. – SAE Technical Paper. – 2012. – no. 2012-01-1040.

Case study 2: investigation of the regenerative braking system operation in the electric vehicle

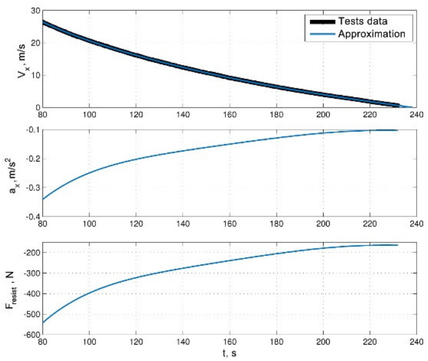
The subject of the research: range extended electric vehicle developed at NAMI (test data from road tests with no torque measurements)

Measurement equipment

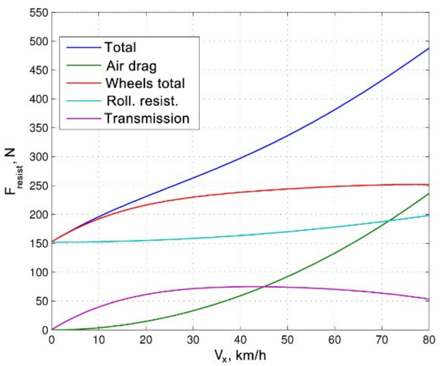




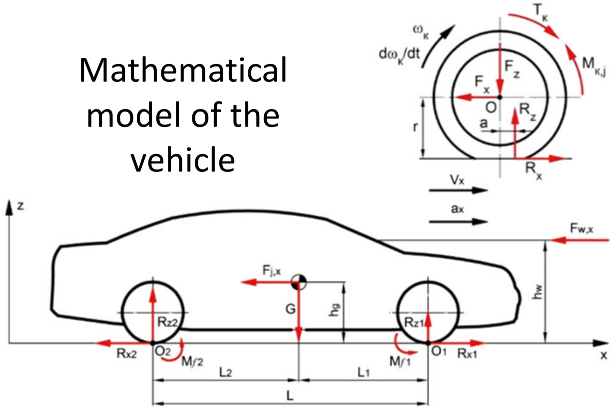
Results of the «coasting» test



Components of road resistance



Mathematical model of the vehicle



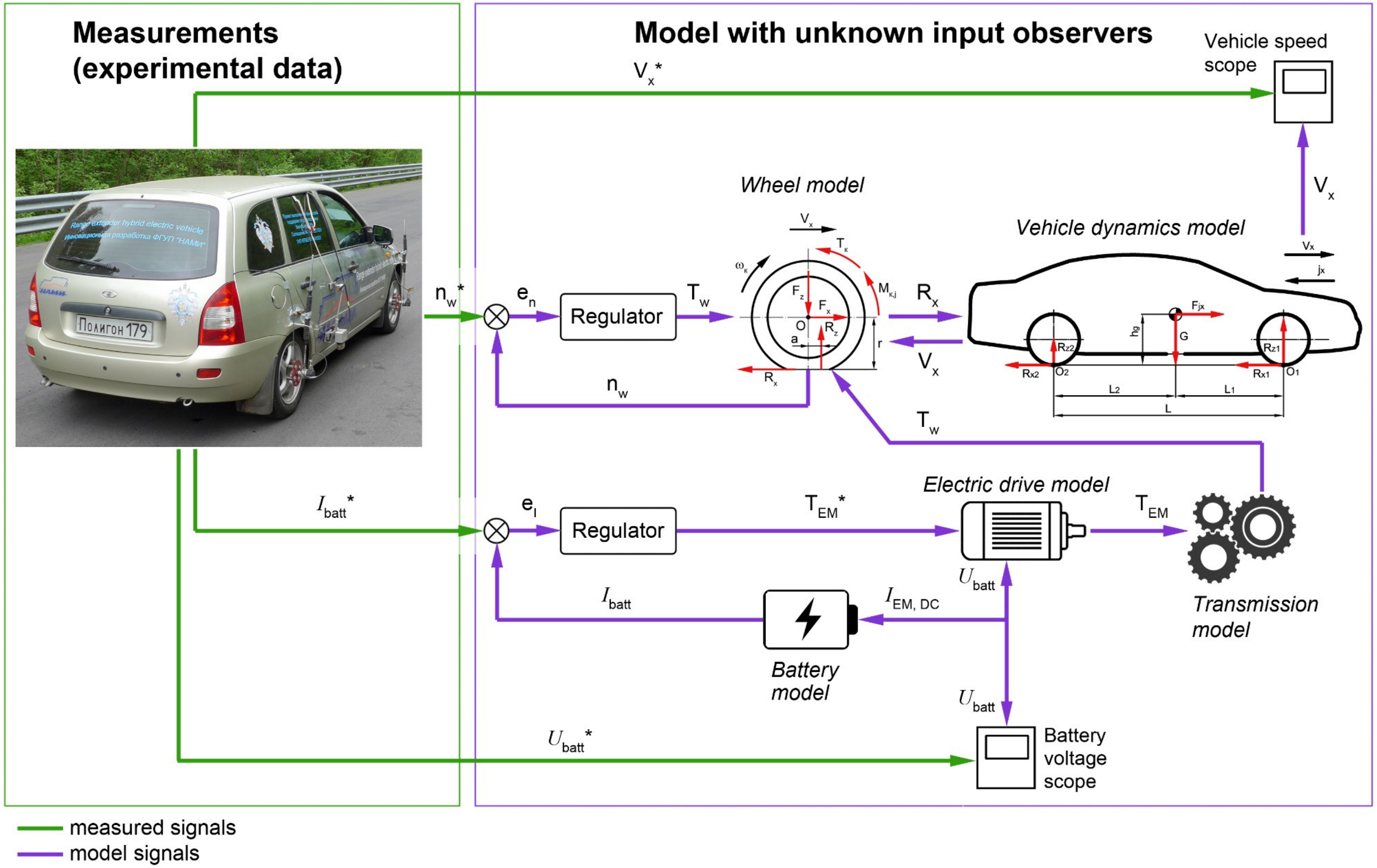
Equation system describing dynamics of the vehicle and its wheels

$$\begin{cases} \dfrac{d\omega_{w1}}{dt} = \dfrac{T_{EM} \cdot r_0 - T_{brakes1} - (R_{z1} \cdot \mu_{x1} + R_{z1} f_1 + F_{loss}) R_w}{n_{w1} I_w + I_{EM} \cdot r_0^2} \\ \dfrac{d\omega_{w2}}{dt} = \dfrac{(R_{z2} \cdot \mu_{x2} - R_{z2} f_2) R_w - T_{brakes2}}{n_{w2} I_w} \\ \dfrac{dV_x}{dt} = \dfrac{R_{z1} \cdot \mu_{x1} - R_{z2} \cdot \mu_{x2} - F_{w,x}}{M} \end{cases}$$

Calculation of the wheel normal forces

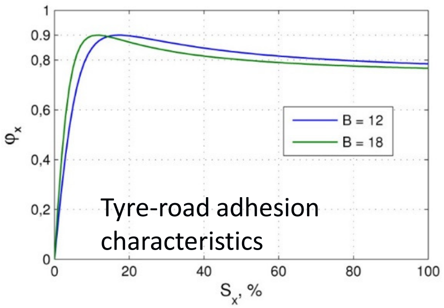
$$\begin{cases} R_{z1} = \dfrac{G \cdot L_2 - M \cdot a_x h_{cg} - F_{w,x} h_w - R_{z2} f_2 \cdot R_w}{L + f_1 \cdot R_w} \\ R_{z2} = G - R_{z1} \end{cases}$$

Model of a road test with unknown input observers identifying the unmeasured torques at the wheels and at the electric motor shaft

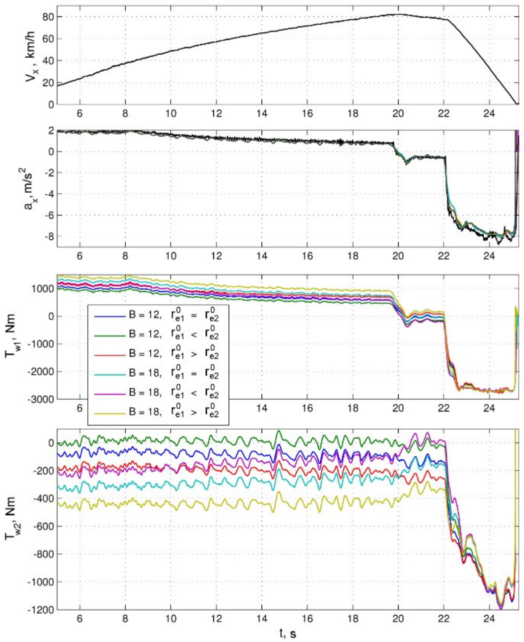


Modelling and identification results. Validation. Powertrain operation analysis

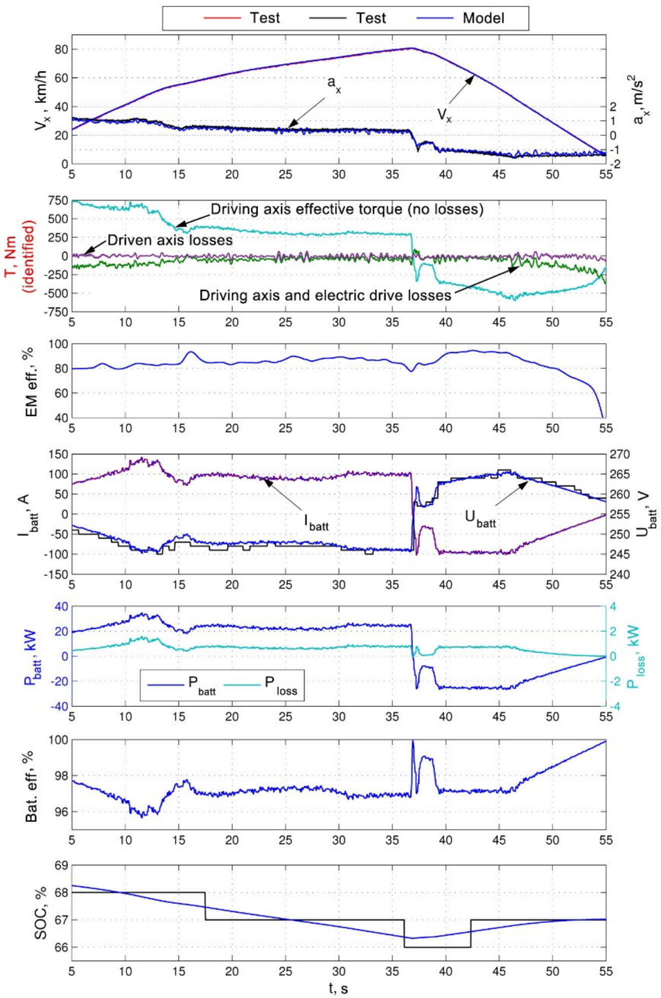
Identification of the model parameters



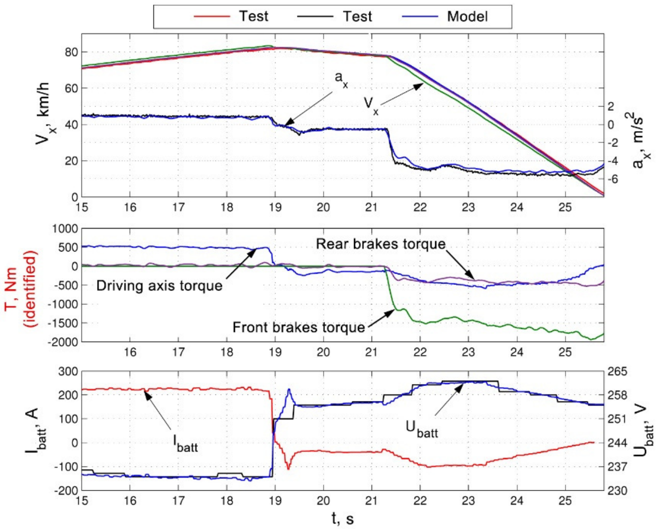
Influence of tyre model parameters on the adequacy of wheel torques identification



Test with pure regenerative braking



Test with «blending» of regenerative and mechanical braking



Conclusions

- The lack of torque measurements in tests of electrically driven vehicles or their powertrains can be compensated by employing unknown input observers, which are able to identify non-measured torques using other measured quantities and mathematical modelling.
- A form of unknown input observer can be proposed, which is simple, logical and does not make any changes within the basic structure of the plant's model. This observer constitutes a feedback control system, which uses the measured signal as the command and its calculated counterpart as the feedback. Compensating difference between these two signals, the regulator calculates non-measured torque.
- Two case studies show that proposed observer is able to reconstruct unknown operating regimes of powertrain components if there is sufficient number of measured variables, which can be used as commands for regulators.
- Direct and indirect verifications of simulation results demonstrate sufficient adequacy of identification provided by the torque observers. These results allow for more thorough and comprehensive studying of powertrains including their operating regimes and efficiency.

Researcher Links UK-Russia Workshop

Scientific and Technical Grounds of Future Low-Carbon Propulsion

19th - 22nd November 2018, Northumbria University at Newcastle, UK

Thank you for your attention
Ready to answer your questions

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