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COMPUTER AIDED MODELLING OF HYBRID MINI VAN

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The main advantage of hybrid vehicles and their electric drive systems that they reduce local pollutant emissions – especially in urban usage. The vehicle called E-VAN-09 was developed at Széchenyi István University which serves understanding and optimization potential of operational processes.

Keywords: AVL Cruise, model, validation, roller bench measurements, road tests

Introduction

The E-VAN-09 vehicle is based on a 2007 vintage Ford Transit with MWB chassis. The diesel engine drives the front wheels, while the rear wheels are driven by two electric motors connected in series. The two drives are not in operation at the same time, so the vehicle is purely electric or diesel powered.

This kind of propulsion system enables researchers to examine advantages and disadvantages of the different drives separately. Electric drive system and all vehicle control components (power electronics for e-motors, battery management system, etc.) were developed at the Széchenyi István University.

The synchronous machine is also an academic development, not available on the market. Besides the drive system, the on-board communication system was supplemented, and it had to be connected to the original system to add more functionality.

A speciality of the conversion is that the van was originally built with hydraulic power steering which had to be replaced by a electro-hydraulic part due to the electric mode. A completely new data bus had to be constructed connecting to the existing CAN-BUS network to control the units of electric drive system (Ford data bus, power steering, e-motor bus).

The schematic structure of the vehicle parts is shown in *Figure 1*.

Modelling tool

A number of companies are engaged in developing vehicle dynamics simulation software, which are capable of modelling electric vehicles. These software packages are complex systems and can be nested, so the results can be used for their development directly.

In addition to simulation results, these software give the possibility for establishment of HIL (Hardware in the Loop) sub-systems that is ready for testing given components (prototype device or new process management) under controlled conditions.

During the development, the so-called V model implementation steps are used. The model operates on the same vertical level. It may get to design and modification state again after implementation. In this way, the system can continue to improve until the final version is ready *(Figure 2)*.

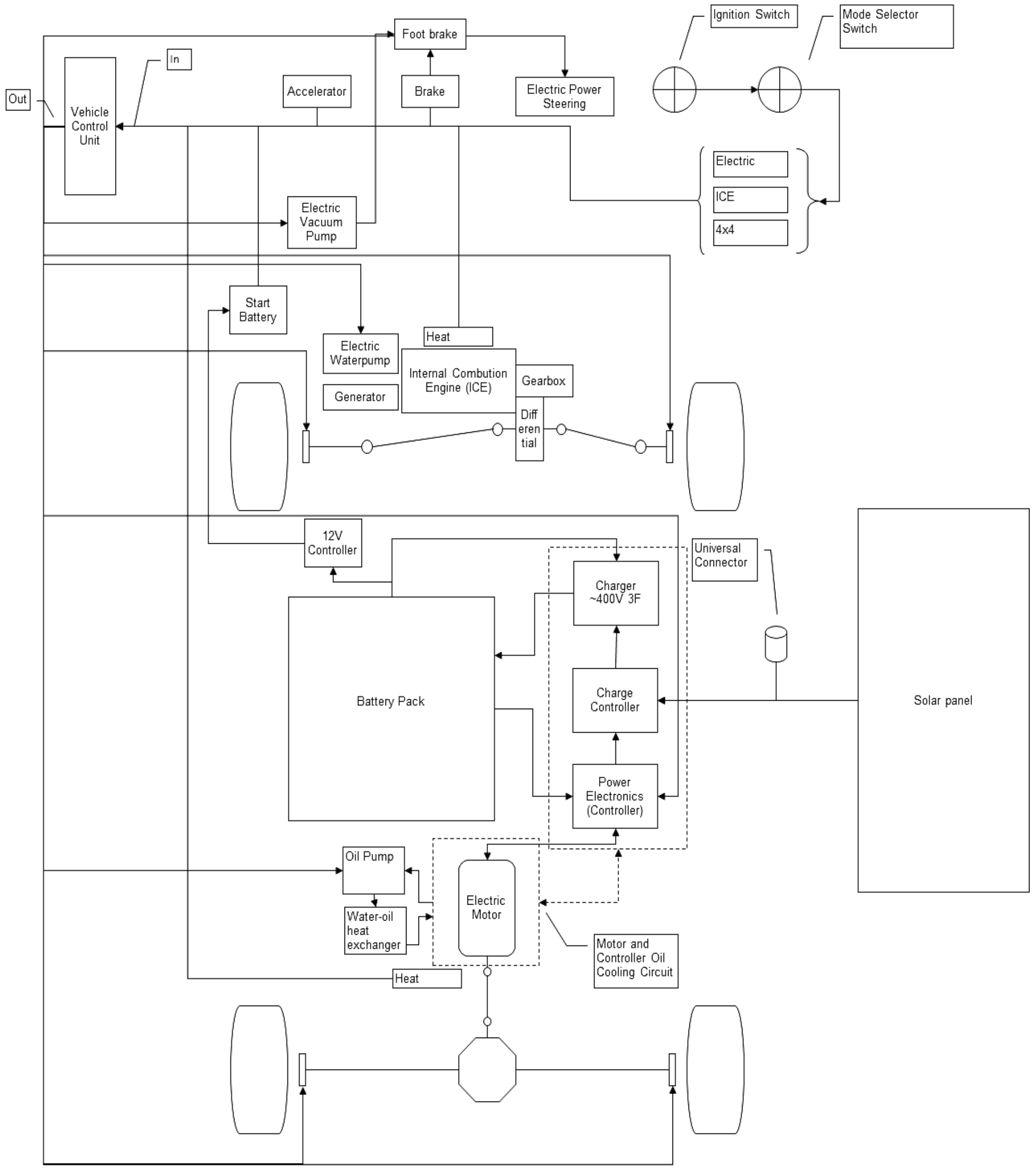

Figure 1: Block diagram of E-VAN-09

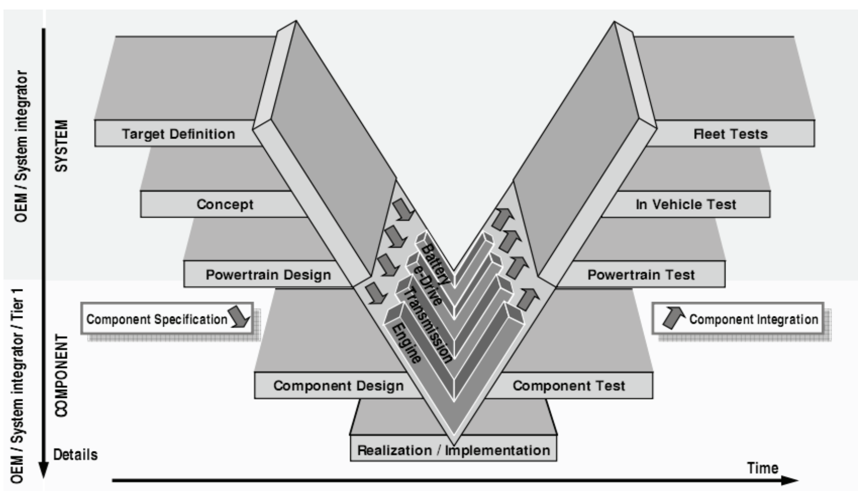

Figure 2: The development method proposed by AVL

All vehicle simulation software were ranked in 2009 by a UK-based engineering company called Ricardo. The common feature of these software packages is that they work together with other general-purpose simulation programs in their unique modular design (40% software are based on Matlab/Simulink and 90% are able to generate Simulink functions).

#	Simulation Code Name		Code Developers
1	**VSIM**	s	Ricardo
2	**CVSP**	s	Ford
3	**HE-VESIM/ VESIM /HEVSIM**	s	University of Michigan / ARC / DoE
4	**PSAT/ PSAT-Pro**	s	Argonne National Lab. / DoE
5	**RAPTOR**	s	Southwest Research Institute
6	**SimDriveline**	s	Mathworks
7	**DYNA / veDYNA**	s	TESIS DYNAware
8	**AMESim**		LMS
9	**DYMOLA / Veh. Libs.**	m	Dassault Systemes / Dynasim
10	**SimulationX / ITI-Sim**	m	ITI
11	**MSC.EASY5 / Ricardo Libs.**		MSC.Software / Ricardo Inc.
12	**TruckSim / VEHSIM**		Mechanical Simulation
13	**AVL Cruise**		AVL
14	**GT-Drive / GT-Suite**		Gamma Technologies
15	**LVS**		Lotus Engineering Software
16	**VMS**		Cummins
17	**DYNASTY**	s	Caterpillar
18	**T-CAPE**		Navistar International
19	**Calculation Program for Heavy-duty Motor Vehicle Fuel Economy**		MLIT Japan

Table 1: Vehicle simulation software developers
(S – MATLAB / Simulink^{TM} based; m – Modelica based)
(source: RICARDO)

AVL Cruise power train simulation software is used at our University which is ranked fourth overall in the Ricardo report1. The ranking is based on the level of detail, mathematical background, data management, and user-friendly operation of the simulation modelling software.

Cruise developed by Graz-based AVL, Austrian company is used by auto-makers like Ford, GM, and Volvo. Besides simulation technology, AVL is also involved in the development of power-trains and building test systems meeting the needs of the automotive industry.

AVL Cruise software

The simulation model is modular, which guarantees fast and flexible modelling. The modules are connected through physical properties and data links. This modelling method is advantageous, because some of the processes can be parallelized and every sub-calculation can be optimized.

The modelling software enables us to reverse the direction of the simulation. In that way, velocity, acceleration values, and losses can be calculated backwards from the wheels to the motor. This process is fast, but gives inaccurate results because the electric motor can operate in a work point which is not realistic within the given time period.

Instead of that solution, the model chain is the reverse: the kinetic energy generated by the drive unit is reduced through mechanical connections (taking losses into account). This is the natural model of the physical system. For example, if an undersized engine or electric motor is given for the model, then the vehicle will not be able to reach or keep prescribed speed profile.

Sorted Overall Ranking

Evaluated Criterion	Interaction with MATLAB	Parametrisation / Automated Simulation	Interaction with Controls	Exporting Data	Cost - Full Seat	Co-Simulation Availability	Text Based User Model Writing	Libraries / Model Complexity	Tool Support	Customer Preferences	Ease of Use	Hardware Requirement	Validated Library Components	Model Encryption	Number of Points	Weighted Points	Complexity & Accuracy of Results	Ease of Use	Other Factors
DYMOLA / Veh. Libs.	9	10	10	10	0	10	10	10	10	10	5	5	10	9	118.0	63.3	30.0	21.0	12.3
PSAT/ PSAT-Pro	10	10	10	10	0	10	2	9	8	10	9	5	10	8	111.0	61.5	29.3	21.1	11.1
AMESim	9	10	8	10	0	10	5	9	10	10	9	5	10	9	114.0	61.3	27.5	21.5	12.3
AVL Cruise	10	10	10	10	0	10	0	9	8	9	9	5	10	9	109.0	60.6	29.3	20.5	10.8
MSC.EASY5 / Ricardo Libs.	9	7	8	8	0	10	10	10	10	10	7	8	10	8	115.0	59.5	28.2	19.2	12.4
RAPTOR	10	10	10	8	0	10	2	8	9	9	7	5	10	8	106.0	58.8	28.6	19.1	11.1
DYNASTY	9	5	8	7	0	10	10	8	10	9	7	5	10	8	106.0	55.9	26.8	17.5	11.6
GT-Drive / GT-Suite	9	10	8	8	0	10	0	9	8	9	9	5	10	0	95.0	55.5	27.5	19.0	9.0
VMS	10	7	10	7	0	10	2	9	10	9	2	5	10	8	99.0	55.2	29.3	14.3	11.6
TruckSim / VEHSIM	10	10	10	10	0	10	0	4	10	8	6	6	9	9	102.0	55.1	24.8	19.0	11.4
DYNA / veDYNA	10	7	10	6	0	10	2	7	10	8	7	5	8	8	98.0	53.3	25.9	16.3	11.1
SimDriveline	10	7	10	6	0	10	2	7	9	9	5	5	5	8	93.0	49.3	22.9	15.3	11.1
CVSP	10	7	10	7	0	10	2	6	5	6	2	5	10	8	88.0	49.1	27.2	14.3	7.6
VSIM	10	7	10	7	0	10	2	4	3	6	2	5	10	8	84.0	46.7	25.8	14.3	6.6
SimulationX / ITI-Sim	9	8	10	4	0	10	0	6	2	3	4	5	4	8	73.0	39.1	21.2	13.3	4.6
HE-VESIM/ VESIM/ HEVSIM	10	7	10	6	0	10	2	2	2	3	2	5	6	8	73.0	38.8	20.4	13.8	4.6
LVS	1	9	0	5	0	2	0	3	1	2	7	10	5	0	45.0	21.8	7.9	11.9	2.5
Fuel Sim (MLIT Japan)	1	0	0	3	0	0	0	0	10	2	5	10	2	0	33.0	13.0	2.0	4.5	7.0

Survey Results Influence in Ratings Evaluation:
- no responses in survey
- < 30 % from survey
- 30 - 60 % from survey
- > 60% from survey

Table 2: Simulation software evaluation summary table made by RICARDO (source: RICARDO)

The following calculation is valid for the simulation model:

1. Between the modules of the vehicle model – where connection is interpreted between two modules – the following non-linear differential equation is applied:

$$\begin{aligned} \dot{y} &= f(t, y) \\ y(0) &= y_0 \end{aligned} \quad . \tag{1}$$

2. This ordinary differential equation is converted into the following integral equation:

$$y = y_0 + \int_0^t f(\tau, y)\, d\tau \, . \tag{2}$$

3. The trapezoidal rule discretization leads to the following equation:

$$y_{n+1} - \frac{t_{n+1} - t_n}{2} f(t_{n+1}, y_{n+1}) = y_n + \frac{t_{n+1} - t_n}{2} f(t_n, y_n). \tag{3}$$

4. This non-linear system of equations is solved by the software in each cycle.

The software performs the prior interpolation of parameters (efficiency, torque, losses, fields, etc.). The program is using local bilinear interpolation.

Building up the drive-train model of e-van

CAD drawings of drive-train were used in the modelling process and the technical documentation. During validation, the unknown parameters were determined by characteristic values (from technical literature) and measurements, which were performed.

Since the two drive modes (electric and diesel) are available separately, during the development of the model, we had to stick to the principle, which says the diesel engine does not operate together with the electric motors and vice versa. Fortunately, the software provides the opportunity to handle drives separately as sub-systems.

This modelling method is practical because major physical parameters of the vehicles examined are the same, while the power-train may vary widely. Just think of the same model in different passenger cars with different internal combustion engines.

Modularity of Cruise model

The two subsystems created in the modular structure of Cruise is shown below:

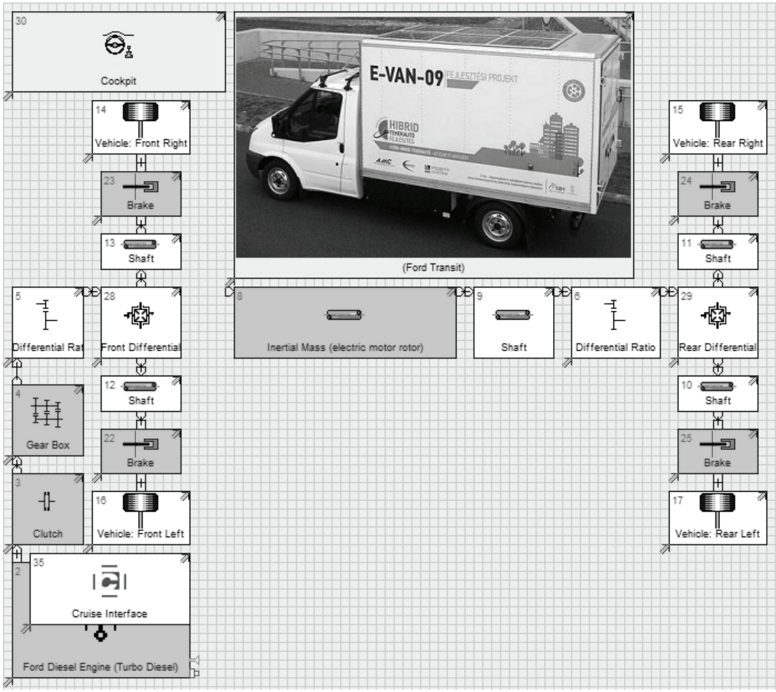

Figure 3: Diesel drive mode system of E-VAN-09 set up in AVL Cruise

Colour codes of diesel drive modules:

- white: components existing in both subsystems (power-train subsystem)
- grey: components of diesel driven system (brake modules for different methods of control subsystems)
- light grey: main parameters of the vehicle and „cockpit" symbolizing the driver.

The model of electric drive mode is the following:

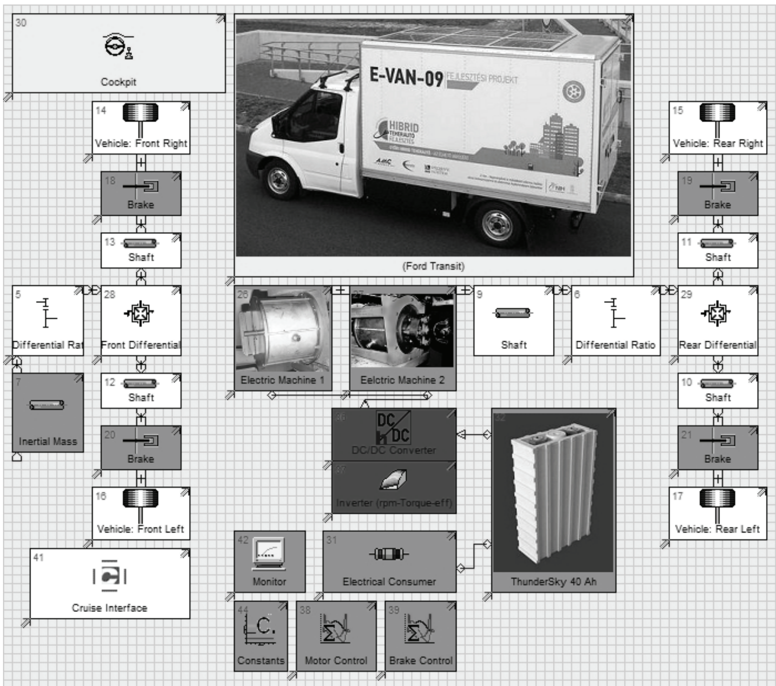

Figure 4: The model of electric drive system of E-VAN-09 set up in AVL Cruise software

The model of electric drive system of E-VAN-09 is set up in AVL Cruise software.

Colour codes of electric drive modules:

- white: components existing in both subsystems (power-train subsystem)
- grey: electric motors, energy source (high voltage battery cell pack), control units
- dark grey: inverter module
- light grey: main parameters of the vehicle and „cockpit" symbolizing the driver.

The accuracy of simulation depends on the determination of the critical parameters of two main components. The energy storage system (in this case the lithium-ion battery cell pack) is the subsystem which defines the usability of electric vehicles. The main obstacle to the spread of electric vehicles is the low energy density and efficiency of batteries – besides high price of technology. Despite energy storage difficulties, the balance tips for systems with electrical equipment of high efficiency (internal combustion engines with 20–30% efficiency value compared to nearly 90% efficiency at electric machines in almost every work point).

During setting up the model, we conducted battery tests[2]. Not only capacity but also internal resistance has to be defined, because energy charging and discharging bring losses. This resistance value is only mΩ per cell, but for a full battery pack it can reach decimal or integer value. Internal resistance indicators show significant advantage at lithium-ion batteries compared to nickel-metal hydride batteries.

The battery internal resistance test values were higher than it was shown on the data sheets. On the other side larger capacities were measured.

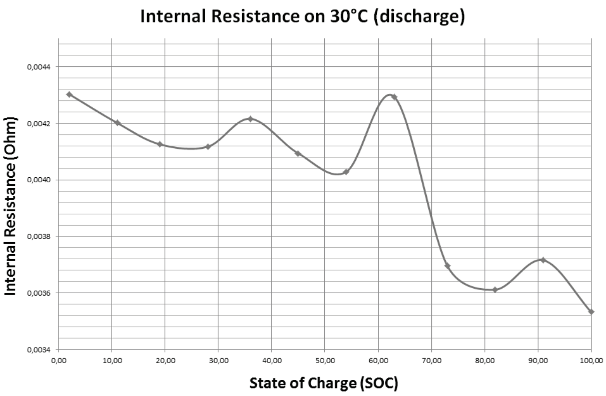

Figure 5: ThunderSky 40 Ah battery internal resistance measurement results made with Current off method

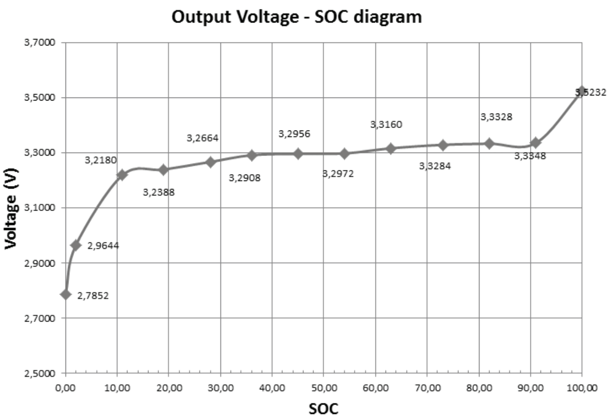

Figure 6: ThunderSky 40 Ah battery output voltage at 0,5 C discharge

Main characteristics of the battery cell pack:

- 128 pcs ThunderSky WB-LYP40AHA battery cells in series (8 pcs battery blocks)
- Nominal voltage: 3,2 V
- Continuous load: 3 C (120 A)
- Pulse load: 20 C (800 A)
- Capacity: 40 Ah
- Operating temperature range: -40°C – 80°C

PMSM module

Performance and efficiency data of the electric motor were provided by MotorSolve software, which has given around 200 work points.

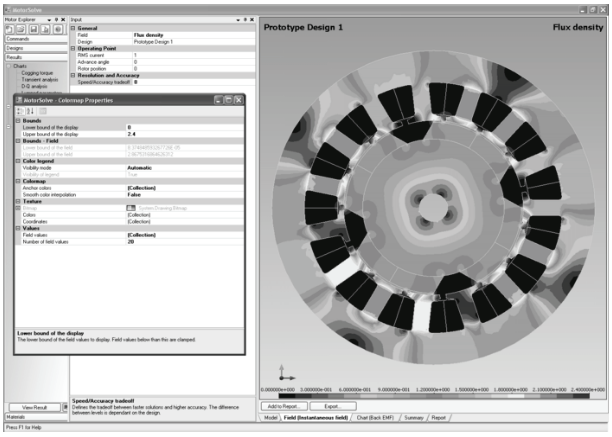

Figure 7: MotorSolve simulation

Table 3: Parameters of vehicle

Vehicle:	
Gas Tank Volume (m^3)	0.08
Pressure Difference Engine/Environment (mbar)	0
Temperature Difference Engine/Environment (K)	0
Distance from Hitch to Front Axle	4549
Wheel Base	3504
Net Weight	2690
Gross Weight	2925
Frontal Area (m^2)	4.458
Drag Coefficient	0.42
Tire Inflation Pressure Front Axle	4.3
Tire Inflation Pressure Rear Axle	4.5
Single Ratio Transmission (front axle):	
Transmission Ratio	4.23
Inertia Moment in / out	0.009/0.016
Efficiency	0.97
Single Ratio Transmission (rear axle):	
Transmission Ratio	4.27
Inertia Moment in / out	0.009/0.016
Efficiency	0.97
Differential (front axle):	
Torque Split Factor	1

Inertia Moment In / Out	0.02/0.02/0.02
Differential (rear axle):	
Torque Split Factor	1
Inertia Moment In / Out	0.02/0.02/0.02
Brake (front):	
Brake Piston Surface (mm^2)	3619
Friction Coefficient (0-1)	0.27
Specific Brake Factor (disc = 1)	1
Effective Friction Radius	150
Efficiency	0.99
Inertia Moment	0.136
Brake (rear):	
Brake Piston Surface (mm^2)	1810
Friction Coefficient (0–1)	0.27
Specific Brake Factor (disc = 1)	1
Effective Friction Radius	140
Efficiency	0.99
Inertia Moment	0.072
Wheel (front):	
Inertia Moment	1.137
Friction Coefficient of Tire	0.95
Wheel Load Correction Coefficient	0.02
Static Rolling Radius	330
Dynamic Rolling Radius	350
Wheel (rear):	
Inertia Moment	1.137
Friction Coefficient of Tire	0.95
Wheel Load Correction Coefficient	0.02
Static Rolling Radius	330
Dynamic Rolling Radius	350

Table 4: Centre of Gravity calculation

COG (Center of Gravity)	
Wheelbase [mm]	3504
Front Axle Load [N] (Fa)	15210
Rear Axle Load [N]	13380
Wheel Radius [mm]	306
Lifting Height [mm] (hem)	324
Front Axle Load after Lifting [N] (Fb)	15550
COG distance to front axle [mm]	1639.857293
COG distance to rear axle [mm]	1864.142707
COG height [mm]	229.2646558
COG distance to ground [mm]	535.2646558
Net Weight [N]	28590
Front Axle Load (%)	0.532004197
Rear Axle Load (%)	0.467995803

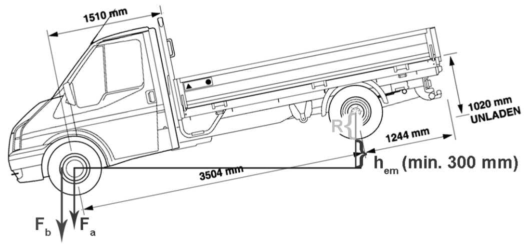

Figure 8: Centre of gravity of the vehicle

Validation tests

The validation of the model we set up in AVL Cruise software required measurements performed on road tests and roller bench tests. The road tests were focusing on the examination of vehicle's driving dynamics in order to achieve validation properties.

Road tests

Each operation data was logged during the road test on highway and city traffic performed through on-board CAN system with special data logger equipment.

Roller bench measurements

The following measurement cycles were performed on the roller test bench:

- Definition of drive-line inertia (reduced to roller bench axis)
- Examination of steady (stationary) operating conditions. This cycle is normally used for consumption and emission measurement tests.
- Acceleration engine-power measurement cycle. Determination of maximum engine power is carried out with this cycle.

During the roller bench measurements the following parameters were recorded:

- Vehicle speed
- Traction power
- Performance (power)
- All traffic took place in CAN network.

The most important parameters are:

- Battery voltage
- Electric motor voltage
- Electric motor current
- Throttle angle

Power output of electric drive-train was tested on roller bench by 25–40 km/h speed. Motor reverse speed limit is set to 40 km/h, so it was not exceeded.

The tests were carried out on the two engines connected mechanically in series. Further validation procedures are planned to be done in a way that only one electric motor will be examined, which has power traction. From this measurement, clarification of required parameters validation is expected.

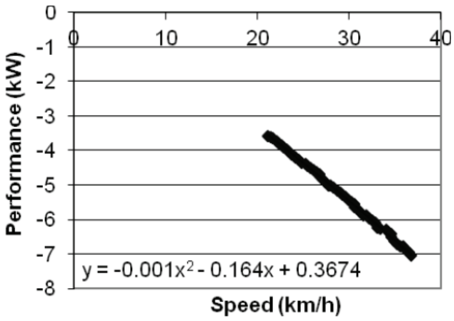

Figure 9: Performance losses measurement with free running test

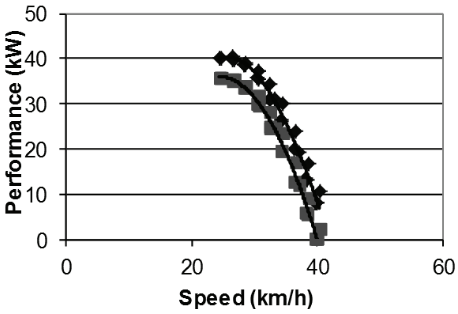

Figure 10: Full load power characteristic curve of E-VAN-09

Performance-speed characteristic curve shows that electric motor's maximum power is 40 kW. This power was measured at 27 km/h speed. At lower speeds power output was reduced.

As *Figure 11* shows, more than 5 kN traction force is registered at this speed. The slope of the curve shows if speed is increasing traction force is drastically decreasing. This means that the vehicle would lose velocity on rising road sections – when operating under real life circumstances. Unfortunately, these conditions also have safety risks.

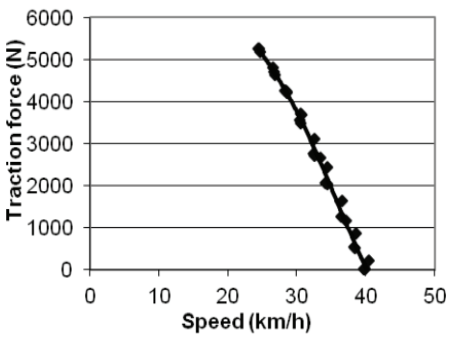

Figure 11: Full load traction power characteristic curve of E-VAN-09

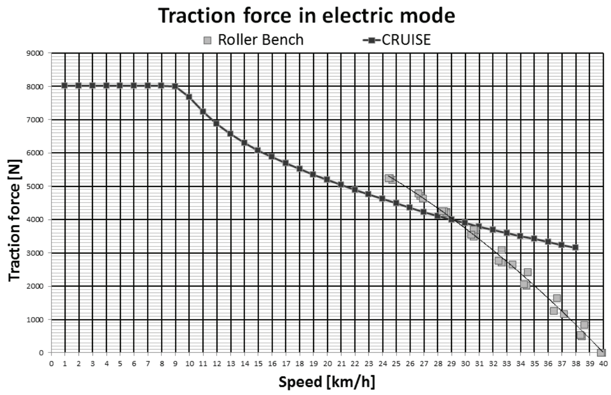

Figure 12: Characteristic curves of Cruise model and real drives

Summary

The model construction and validation of E-VAN-09 is an important part of the project within the target of electric vehicle development. The models are used to facilitate the development process and highlight its trends or directions. Validation process has not been finished yet *(Figure 12)*, but the measurements and parameters have already been identified, which ensure that the result and the process can be successfully carried out.

Acknowledgements

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