ICCT Evaluation of Vehicle Simulation Tools

Summary Report

14-August-2009

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Project Background and Objectives

Project Background

- About 25% of CO_2 from motor vehicles is emitted from Heavy Duty Vehicles. Addressing GHG from this sector will require fuel economy improvements.
- In the context of potential future regulation of heavy-duty vehicle (HDV) fuel economy in the U.S. and other countries, ICCT is exploring technical and regulatory design issues related to developing and implementing fuel economy or greenhouse gas standards for HDVs. One among many issues that must be addressed for any regulation is to determine the test method(s) to be used to evaluate actual fuel use.
- Engine dynamometer testing in conjunction with vehicle simulation modeling is one method that might be used for regulatory certification of HDV fuel efficiency. This is the approach taken in Japan
- As vehicle simulation modeling is being considered for evaluating regulatory compliance and the feasibility of achieving standards for HDV fuel efficiency, an independent and balanced review of existing fuel economy simulation codes is needed. This study aims at identifying the existing simulation codes weaknesses and strengths in being used for this purpose.

Project Objectives

- Create a list of existing vehicle simulation codes to be considered for heavy duty vehicle fuel economy simulation
- Develop an evaluation matrix that can be used to perform a balanced comparative review of each simulation code
- Compare simulation codes and document results of overall weighted performance

Approach and Deliverables

Approach

- Identify available vehicle simulation codes based on in-house knowledge and literature search reviews. The codes of interest are required to:
  - Be suitable for modeling of typical HDV features such as APU, Stop-Start System, Electrical Accessories, etc…
  - Have demonstrable industry usage – so as to focus the evaluation on well-established simulation tools
  - Be continuously supported and updated by their developers
- Develop an Approach for Model Comparison by:
  - Creating an evaluation matrix with appropriate rating criteria and weighting factors based on Ricardo's in-house simulation expertise and consultation with other expert in the industry
  - Reviewing each code's documentation/manual as provided to Ricardo by the developers
  - Ranking the codes for each criterion based on the comparison between the literature review and the responses from a simulation user-based market survey conducted by Ricardo

Project Deliverables

- A final list of potentially relevant vehicle simulation tools/codes for evaluation
- A description of evaluation criteria and weighting factors
- A completed evaluation matrix for the selected codes and a PowerPoint report of the process, findings, and rank order assessment
- Presentation of a consolidated version of the final report via teleconference

HDV Codes Choice

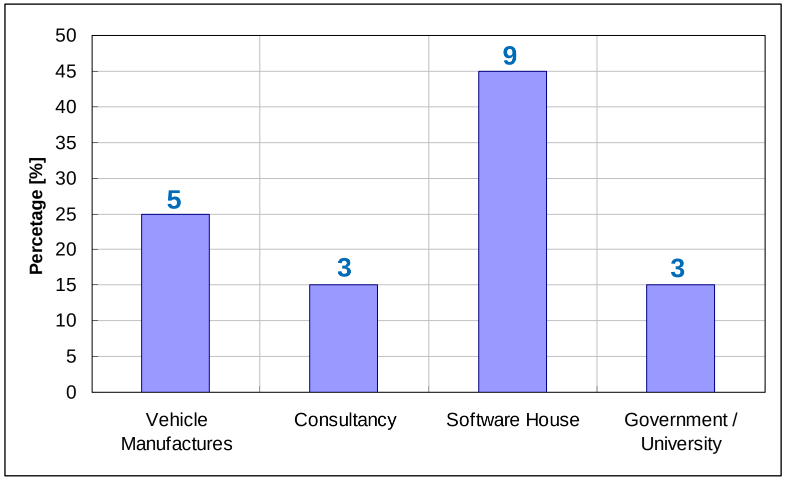
- **A list of 23 codes suitable for HDV simulation was compiled by Ricardo. Three identified simulation codes were removed from the final list to be evaluated because:**
  - The tool is too old and is/was not regularly updated
  - The tool is the previous version of a newer tool that retains all of the previous tool's capabilities
  - The tool is too simple to cover enough powertrain architectures even though it can be sufficient for some users
- **The three codes that were not included in the final evaluation are:**
  - **VPS (University of Michigan):** HE-VESIM / VESIM is based on the same principles and contains previously developed VPS tool (released in 1989)
  - **ADVISOR (AVL):** Latest ADVISOR version was released in 2004 with dependency on now old version of MATLAB/Simulink (R13 & R14). Even though it still used in some current project (or for comparison with new tools) all around the world, CRUISE is AVL primary tool for vehicle system simulation
  - **Spec-Manager (Detroit Diesel):** Based on current information, this tool is used for matching the engine to the transmission and FDR which greatly limits its use for more complex vehicle simulation.
- **Two other groups of tools were each evaluated as a single tool:**
  - HE-VESIM/VESIM and HEVSIM were evaluated as one tool since they are based on the same platform (MATLAB/Simulink™) and developed by the same authors
  - TruckSim and VEHSIM were evaluated as a single tool because VEHSIM is similar in its functionality and use as TruckSim [HD].

Final List of Codes Suitable for HDV Simulation

- The following list of heavy duty vehicle simulation tools will be evaluated:

#	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

Developers Grouping



- 40% of tools are based on MATLAB/Simulink™
- The remaining tools are based on Modelica language (or can load and run Modelica models) or in C/C++ and Fortran
- 90 % of tools can generate S-functions for Simulink export

s - MATLAB / Simulink™ based

m - Modelica language based

HDV Code Evaluation Approach

- Ricardo developed a list of 14 relevant Evaluation Criteria based on internal discussion among heavy duty vehicle departments in the US and Europe and the project team
  - Some criteria include several parameters/ aspects which are not be evaluated separately (e.g. ease of use includes units handling, quality of GUI, input data preparation, etc.)
  - "Results Accuracy" was not used as an evaluation criterion since it depends on the quality of input data, and Ricardo did not perform any hands on testing. The term "Validated Components" is used instead.
- The 14 criteria were grouped into three sets of related criteria reflecting:
  - the potential "**Complexity and Accuracy**" of the models and their results,
  - the "**Ease of Use**" for the tool, and
  - "**Other Factors**" such as cost and current industry acceptance
- Since each Evaluation Criterion does not have the same importance, weighting factors were also developed for each criterion to reflect their relative importance to each other
  - Weighting factors were set based on literature review and discussion among the project team

These criteria are listed on next slide →

Evaluation Matrix: Criterion Description

COMPLEXITY & ACCURACY OF RESULTS

- **Interaction with Controls**
  - Important for complex simulations with APU, Stop-Start system, WHR and also for tools without driver model (Simulink, Scicos, LabView, dSPACE)
- **Co-Simulation Availability**
  - Co-Simulation can be needed for some type of simulation (APU, detailed engine warm-up model, etc.) – MATLAB/Simulink became standard co-simulation interface (the evaluated tool must be able to use standard set/get functions)
- **Libraries / Model Complexity**
  - Default components distributed with the tool (number, physical models included, complex or simplified, etc.)
- **Validated Library Components**
  - Library components and their physical model should be validated to prevent any unrealistic results, tool components should be validated with experimental results or with other tool where the components were validated (Open Modelica Library and Advisor)

EASE OF USE

- **Interaction with Matlab**
  - Pre-processing and post-processing simplification, possibility of using MATLAB for control or other necessary calculation
- **Text Based User Model Writing**
  - Expansion of the tool library with user components, possibility for linking some other libraries (*.dll, *.lib), simpler than creating complex components from standard simple blocks (Simulink)
- **Parameterization / Automated Simulation**
  - Very important for intensive simulation projects, sensitivity study, design of experiment, decision making, etc.
- **Exporting Data**
  - Further post-processing, automated results export is necessary for automated runs (DOE, RSM, sensitivity, etc.)
- **Ease of Use**
  - Units handling, quality of GUI, input data preparation, etc.

OTHER FACTORS

- **Tool Support**
  - Software supplier helpdesk or quality of documentation (e.g. best practice)
- **Cost – Full Seat**
  - Price of overall software tool which is needed for HDV simulation (e.g. should include Matlab/Simulink if the tool is based on this environment + price of the libraries)
- **Customer Preferences**
  - HDV industry standard, no old or not supported tools
- **Hardware Requirements**
  - Necessary hardware to run the simulation model with acceptable CPU time, hardware price will be evaluated to reflect this parameter
- **Model Encryption**
  - Creation of S-function, MATRIXx function, dynamic-link library (*.dll), etc. for other users / parts suppliers

Evaluation Matrix: Weighing Factors and Rating

Evaluation Criterion		Weighting Factor
Complexity & Accuracy of Results	Interaction with Controls	0.9
	Co-simulation Availability	0.4
	Libraries/model Complexity	0.7
	Validated Library Components	1.0
	subtotal	***3.0***
Ease of Use	Interaction with MATLAB	0.5
	Text Based User Model Writing	0.3
	Parameterization/Automated Simulation	0.6
	Exporting Data	0.5
	Ease of Use	0.5
	subtotal	***2.4***
Other Factors	Tool Support	0.5
	Cost – Full Seat	0.0
	Hardware Requirements	0.1
	Customer Preferences	0.5
	Model Encryption	0.2
	subtotal	***1.4***

Weighing Factors:

0 = Low Importance

1 = High Importance

Given highest weighting due to greater importance

Set to zero based on lack of data on actual cost

Tool / Code Rating

- **Each simulation tool/code was given a rating of 0 – 10 on each evaluation criterion**
  - **0 → tool performs poorly on this criterion**
  - **10 → tool performs well on this criterion**
- **The ratings were based on the survey results, review of manuals/documentation, and professional judgment of Ricardo in-house modeling staff**
  - **For some tools, no survey responses were received so ratings are based solely on Ricardo research and analysis**

Evaluation Matrix: Criterion Evaluation Methodology

Code Documentation: Ricardo | Market Survey Report: User 1, User 2

Evaluated Criterion — Set of questions

		Code Documentation: Ricardo	Market Survey Report: User 1	Market Survey Report: User 2	
# 1	Documentation	✓	✓	✗	Opposite answers in the survey report
# 2	Survey	✓	✓	✓	Complete agreement
# 3	Survey	?	✓	✓	No relevant information found in documentation
# 4	Documentation	✓	?	?	No respondents answers current question
# 5	Survey	✓	✓	?	Only some respondents answer current question
# 6	Survey	?	✗	✗	No relevant information found in documentation
# 7	Documentation	✓	✗	✗	Documentation and users responses ajar
# 8	Survey	✓	?	✓	Only some respondents answer current question
# 9	Survey	?	?	✓	No relevant information found in documentation

Survey Influence Percentage = 5/8 → 62.5%

- ? - not known
- ✓ - YES
- ✗ - NO
- → (blue) - Documentation based evaluation
- → (grey) - Survey based evaluation

Code documentation was used for:

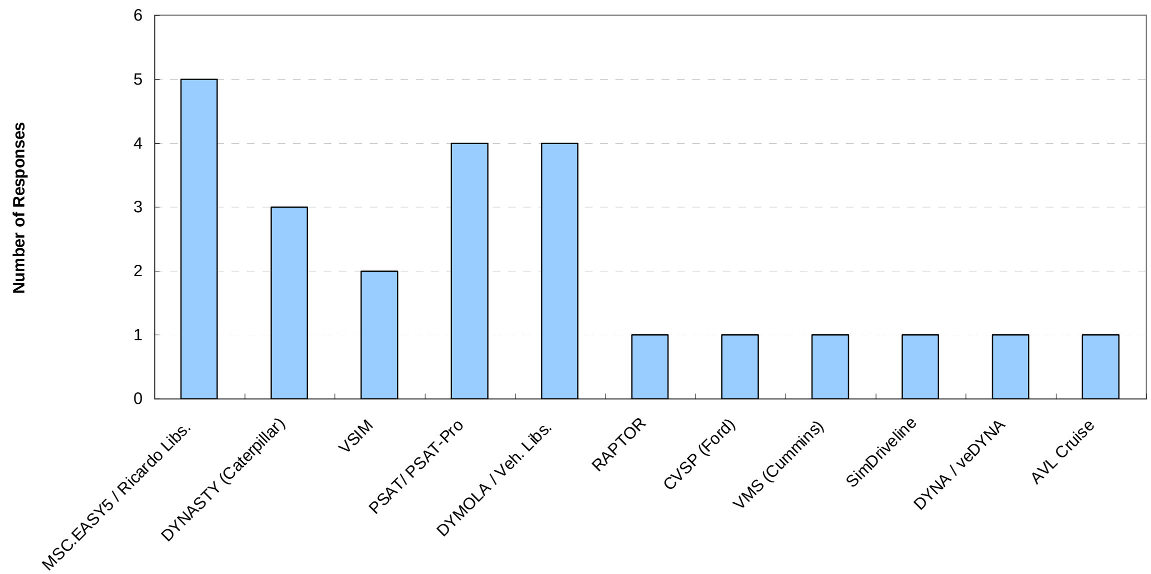
- Correction of survey responses if they were not in complete agreement
- As primary information source if none response was received
- Checking/complete survey responses for more complex questions

Market Survey Results

Objectives of Conducted Survey

- **To enhance Ricardo's evaluation of each tools with industry users' experience**
- **To maximise the response rate**
- **To obtain accurate user-based information on the complexity and ease of use for each tool**

- >100 respondents request sent / 24 respondents completed the survey
- 11 different companies / organizations
- 11 codes received at least 1 response
- Median survey time: 11 min 29 s



Respondents
Ricardo, Plc.
Caterpillar
ArvinMeritor
Modelon AB
Southwest Research Institute
Cummins Inc.
Kenworth Truck Co.
Paccar Technical Center
Argonne National Laboratory
Oak Ridge National Laboratory
MAGNA Steyr Fahrzeugtechnik AG & Co KG

HDV Code Rating Results

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

Evaluation Matrix: "Top 10" Rated Tools

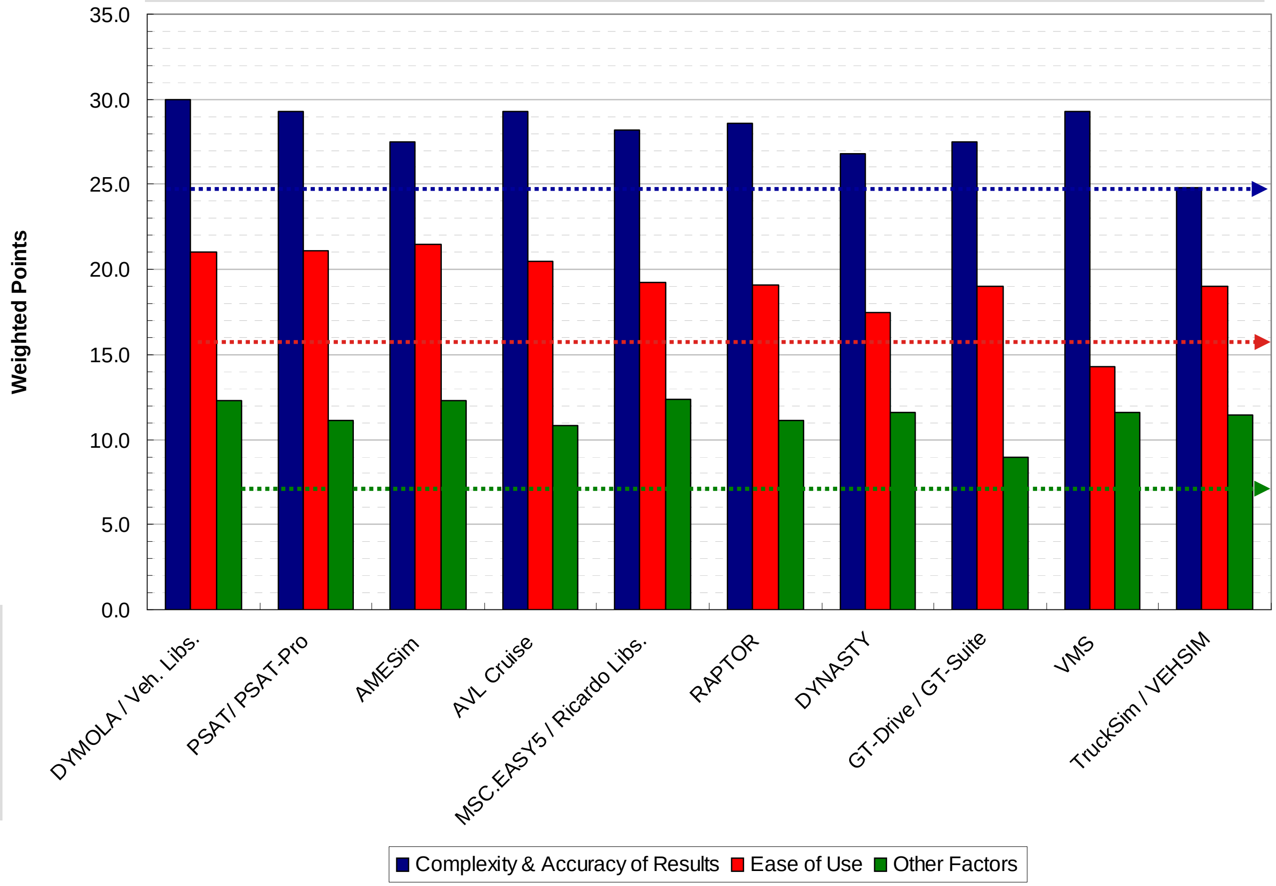
Total Weighted Points

1	**DYMOLA / Veh. Libs.**	63.3
2	**PSAT/ PSAT-Pro**	61.5
3	**AMESim**	61.3
4	**AVL Cruise**	60.6
5	**MSC.EASY5 / Ricardo Libs.**	59.5
6	**RAPTOR**	58.8
7	**DYNASTY**	55.9
8	**GT-Drive / GT-Suite**	55.5
9	**VMS**	55.2
10	**TruckSim / VEHSIM**	55.1

Difference in total weighted rating among top tools:

Top 6 - 7.1%
Top 10 - 13.0%

Total Weighted Points by Criteria Groups



Evaluation Matrix: "Top 6" Rated Tools Ranking by Different Groups of Criteria

RANK	RATING CRITERION				
	Over-all		Complexity & Accuracy	Ease of use	Other Factors
		Weighted Points			
#1	DYMOLA / Veh. Libs.	63.3	DYMOLA / Veh. Libs.	AMESim	MAC.EASY5 / Ricardo Libs.
#2	PSAT/PSAT-pro	61.5	PSAT/PSAT-pro	PSAT/PSAT-pro	AMESim
#3	AMESim	61.3	AVL Cruise	DYMOLA / Veh. Libs.	DYMOLA
#4	AVL Cruise	61.1	VMS	AVL Cruise	DYNASTY
#5	MAC.EASY5 / Ricardo Libs.	61.1	RAPTOR	MAC.EASY5 / Ricardo Libs.	VMS
#6	RAPTOR	60.6	MAC.EASY5 / Ricardo Libs.	RAPTOR	TruckSim / VEHSIM

The same tools generally fall into the "Top 6" whether one uses all 14 criteria or one of the sub-groups of criteria for evaluation.

Note that the top 2 rated tools (DYMOLA/Veh. Libs and PSAT/PSAT-Pro), as well as MSC.EASY5/Ricardo Libs., all had multiple respondents to the survey. The other top-rated tools had 0 – 1 survey responses.

Evaluation Matrix: Major Users of “Top 6” Rated Tools

Major Users			Simulation Codes Used					
			DYMOLA	PSAT/PSAT-Pro	AMESim	AVL Cruise	MSC.EASY5	RAPTOR
Major Heavy-Duty Truck Manufacturers (NOTE1)	Ford		✔	✔		✔		
	GM			✔	✔	✔		
	PACCAR	Kenworth		✔				
		Peterbuilt		✔				
	Navistar			✔				
	Volvo	Volvo	✔			✔		
		Mack						
	Daimler Trucks NA	Freightliner				✔		
		Sterling						
		Western Star						
Other Heavy-Duty Truck Manufacturers (U.S. Market)	Mitsubishi/FUSO						✔	
	Isuzu						✔	
	Hyundai			✔				
	Oshkosh							
	UD Trucks							
	Hino						✔	
Heavy-Duty Engine Manufacturers (NOTE 2)	Caterpillar			✔	✔			
	Cummins			✔				
	Detroit Diesel							
	Mack							
	Volvo		✔			✔		
Component Suppliers	Arvin Meritor			✔				
	DANA			✔				
	Motorola							
	Delphi				✔			
	Bosch				✔			
	Siemens				✔			
	ZF		✔					
	Denso							✔
	GKN driveline						✔	
	Michelin					✔		
Government	Department of Energy			✔				
	US ARMY							✔

NOTE 1: 91% U.S. market share in Class 3 - 8 (2003 - 2007; R.L. Polk & Company; based on new vehicle registrations)

NOTE 2: 97% U.S. market share in new heavy-duty engine sales (2005; Diesel Progress North America, R.L. Polk & Company)

Conclusions

- There are a number of simulation tools that could potentially be used for regulatory evaluation of HDV fuel economy
  - There was only a 7% difference in the overall weighted ratings of the “Top 6” rated tools
- The most highly rated tool was DYMOLA / Veh. Libs, followed by PSAT / PSAT-pro
  - The DYMOLA tool is not widely used in the U.S. HDV manufacturing industry so acceptance of this tool as a regulatory standard might be difficult
  - PSAT / PSAT-pro is much more widely used, by truck and engine manufacturers as well as government agencies, and might therefore be the most likely candidate for use in support of HDV fuel economy regulation
- Other highly rated tools that are currently widely used by the U.S. HDV manufacturing industry include AMESim, AVL Cruise and MSC.EASY5
  - These tools do not show any real limitations for fuel economy simulations, but are missing some features which can make these tool less easy to use and then less efficient in comparison to the top rated two
  - All details for each tool are described in separate Word document: “Simulation_Tools_Description.doc”
- The feasibility for advanced future fuel economy simulation in the reviewed tool was not evaluated
  - The capability for traffic fuel economy simulation or fuel economy simulation with detailed geographical data were not evaluated
- This project used market survey as one of the information sources even though low response rates were expected
  - Low response rate depreciated the usage of market survey results Tools’ documentation and manual pages were used as supplementary information source to complete, check (and correct as needed) the survey responses
- FUTURE WORK
  - Hands on testing of “Top 6” rated simulation tools and direct comparison based on real usage (input data needed, building of the model, accuracy of results, ease of model correlation, etc.)