



SURFACE VEHICLE RECOMMENDED PRACTICE

J3049™

MAY2025

Issued 2015-08
Reaffirmed 2025-05

Superseding J3049 AUG2015

Model Architecture and Interfaces Recommended Practice
for Ground Vehicle System and Subsystem Dynamical Simulation

RATIONALE

Increasingly, global vehicle engineering teams span domains of engineering and physics within organizations and include external collaborations between commercial businesses (original equipment manufacturers (OEMs), and suppliers), government agencies, and research institutions. For increased efficiency, reduced costs, faster design iterations, and fewer hardware prototypes, these teams use math-based engineering methods to build and test virtual ground vehicles in simulation environments. These types of inter-organizational engineering collaborations require a common shared simulation model for an entire ground vehicle system and/or the related subsystems of which it is composed. Use of dynamical modeling and simulation for virtual engineering development and testing of the functional performance of ground vehicles by inter-organizational teams has increased and resulted in a need for standardizing the architecture and interfaces of a ground vehicle system model by partitioning it into subsystem models to enable plug-and-play of subsystem simulation models. A standardized ground vehicle system model with an architectural structure partitioned into subsystem models, and with defined subsystem model interfaces enables: (1) model reuse, (2) division of modeling tasks across multifunctional teams, (3) parallel model development, verification and validation, and (4) rapid and efficient integration of subsystem models for reduced development time and costs.

The recommended practice for model architecture and interfaces will: (1) create a common language, (2) increase productivity of processes, (3) promote uniform testing, (4) permit common interfaces, and (5) reduce costs.

SAE J3049 has been reaffirmed to comply with the SAE Five-Year Review policy.

FOREWORD

The word system is not an absolute term; it is a relative term, depending upon how it is used. Since, a system is an integration of parts assembled to perform a common functional purpose, and systems can be integrated together to form a larger system or to perform a greater purpose; then, a system taken as a whole unit or module can be called a system or a subsystem depending upon the context in which it is used. Thus, the use of the words system model and subsystem model are context or application sensitive, relative to where the model of a system module is used in a simulation model. If a system model module describes or models everything that is being simulated; it is the top-level model and the main subject of the simulation. Then, it is called a system model or the top-level system model. And, if it is one of the many interconnected supporting system model modules that contribute to the functionality of the entire simulation model under study; then, it is called a subsystem model.

In general, an architectural description for a simulation model of a system is a description of the structural organization of the fundamental building blocks from which it is assembled. The architecture description defines all of the fundamental subsystem building blocks, the purpose and function of the subsystems, and the connections between subsystems. Subsystem interfaces define the physical quantities and information that are passed between the subsystems. Together, the description of the model architecture and interfaces defines how to assemble and connect these subsystem blocks together in order to construct or build the overall system model.

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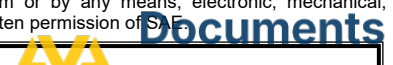


TABLE OF CONTENTS

1.	SCOPE.....	7
1.1	Purpose	7
2.	REFERENCES.....	8
2.1	Applicable Documents	8
2.2	Related Publications	8
3.	DEFINITIONS	10
3.1	Terms	10
4.	GENERAL MODEL ARCHITECTURAL STRUCTURE	16
4.1	Overview	16
4.2	Introduction	16
4.3	General Internal Architecture of a Subsystem	22
4.4	Architectural Conventions	25
4.5	Architectural Features for Flexibility	27
5.	HIERARCHICAL ARCHITECTURE OF A GROUND VEHICLE SYSTEM	32
5.1	Introduction and Overview	32
5.2	Top-Level Architectural Organization and Partitioning	32
5.3	Environment Subsystem Organization and Partitioning	33
5.4	Driver/Passengers Subsystem Organization and Partitioning	34
5.5	Vehicle Subsystem Organization and Partitioning	35
6.	DESCRIPTION OF THE FUNDAMENTAL SUBSYSTEMS OF A GROUND VEHICLE SYSTEM	46
6.1	Introduction	46
6.2	Top-Level Subsystems of a Ground Vehicle System	48
6.3	Environment Subsystem Internal Architecture.....	63
6.4	Driver/Passengers Subsystem Internal Architecture	73
6.5	Vehicle Subsystem Internal Architecture	83
6.6	Power Subsystem Internal Subsystems	111
6.7	Chassis Subsystem Internal Subsystems.....	156
6.8	Body-Frame Subsystem Internal Subsystems.....	198
6.9	Trailer i Subsystem Internal Subsystems.....	233
6.10	Trailer i Body-Frame Subsystem Internal Subsystems.....	271
7.	APPLYING THE MODEL ARCHITECTURE AND INTERFACES	305
7.1	General Application.....	305
7.2	Domain Specific Analysis Applications	305
7.3	Working with Spatially Distributed Models	306
7.4	Intelligent Transportation System Simulation Studies	306
8.	NOTES	308
8.1	Marginal Indicia	308
Appendix A	Definition of units for physical quantities	309
Appendix B	Definition of interface port types	310
Appendix C	Subsystem scope and content quick reference	343
Appendix D	Alternate ground vehicle system configurations	351

Figure 4-1	Definition of a hierarchical family of modular models	17
Figure 4-2	Definition of a nested hierarchical modeling organizational structure	18
Figure 4-3	Model abstraction flexibility requirements	19
Figure 4-4	Definition of a modular modeling structure with a level-2 subsystem	20
Figure 4-5	Hierarchical modeling structure with lower-level subsystems	21
Figure 4-6	General functional representation of the internal structure a subsystem	22
Figure 4-7	Subsystem partitioned into a controller, actuators, plant, and sensors architecture or CAPS architecture	23
Figure 4-8	Controller and plant architecture or CP architecture, where the plant subsystem has actuators, plant and sensors functions	23
Figure 4-9	Controller and plant architecture or CP architecture, where the controller subsystem has controller, actuators, and sensors functions	24
Figure 4-10	Simple subsystem with only a controller subsystem	24
Figure 4-11	Simple subsystem with only a plant subsystem	24
Figure 4-12	General subsystem architecture and controller bus structure	29
Figure 4-13	Higher-level subsystem architecture and controller bus structure	30
Figure 4-14	General hierarchical structure of a Vehicle Information Bus	31
Figure 5-1	Ground Vehicle System hierarchical organization into top-level subsystems	33
Figure 5-2	Environment Subsystem hierarchical organization	33
Figure 5-3	Driver/Passengers Subsystem hierarchical organization	34
Figure 5-4	Vehicle Subsystem hierarchical organization	35
Figure 5-5	Power Subsystem hierarchical organization	36
Figure 5-6	Chassis Subsystem hierarchical organization	37
Figure 5-7	Body-Frame Subsystem hierarchical organization	39
Figure 5-8	Trailer 1 Subsystem hierarchical organization	40
Figure 5-9	Trailer 1 Body-Frame Subsystem hierarchical organization	42
Figure 5-10	Trailer i Subsystem hierarchical organization	43
Figure 5-11	Trailer i Body-Frame Subsystem hierarchical organization	44
Figure 6-1	Ground Vehicle System hierarchical diagram of the top-level subsystems	48
Figure 6-2	Ground Vehicle System top-level connectivity diagram	49
Figure 6-3	Environment Subsystem hierarchical architecture location	50
Figure 6-4	Environment Subsystem top-level connectivity diagram	54
Figure 6-5	Driver/Passengers Subsystem hierarchical architecture location	54
Figure 6-6	Driver/Passengers Subsystem top-level connectivity diagram	58
Figure 6-7	Vehicle Subsystem hierarchical architecture location	58
Figure 6-8	Vehicle Subsystem top-level connectivity diagram	62
Figure 6-9	Atmospheric Subsystem hierarchical architecture location	63
Figure 6-10	Road/Terrain Subsystem hierarchical architecture location	66
Figure 6-11	Traffic/Surroundings Subsystem hierarchical architecture location	69
Figure 6-12	Remote HMI Subsystem hierarchical architecture location	71
Figure 6-13	Driver Subsystem hierarchical architecture location	73
Figure 6-14	Remote Driver Subsystem hierarchical architecture location	76
Figure 6-15	Remote Driver Subsystem and Remote HMI Subsystem hierarchical architecture locations	77
Figure 6-16	Passengers Subsystem hierarchical architecture location	79
Figure 6-17	Vehicle Subsystem high-level connectivity diagram	83
Figure 6-18	Vehicle Supervisory Control Subsystem hierarchical architecture location	84
Figure 6-19	Vehicle Supervisory Subsystem high-level connectivity diagram	89
Figure 6-20	Power Subsystem hierarchical architecture location	90
Figure 6-21	Power Subsystem high-level connectivity diagram	95
Figure 6-22	Chassis Subsystem hierarchical architecture location	96
Figure 6-23	Chassis Subsystem high-level connectivity diagram	103
Figure 6-24	Trailer 1 Subsystem hierarchical architecture location	104
Figure 6-25	Trailer 1 Subsystem high-level connectivity diagram	110
Figure 6-26	Power Subsystem internal architecture connectivity diagram	111
Figure 6-27	Power Supervisory Control Subsystem hierarchical architecture location	112
Figure 6-28	Power Supervisory Control Subsystem connectivity diagram	116
Figure 6-29	Electrical Subsystem hierarchical architecture location	117
Figure 6-30	Electrical Subsystem connectivity diagram	122
Figure 6-31	Thermal Management Subsystem hierarchical architecture location	122
Figure 6-32	Thermal Management Subsystem connectivity diagram	126

Figure 6-33	Fuel Subsystem hierarchical architecture location	127
Figure 6-34	Fuel Subsystem connectivity diagram	130
Figure 6-35	Propulsion Power Subsystem hierarchical architecture location	131
Figure 6-36	Propulsion Power Subsystem connectivity diagram	137
Figure 6-37	Transmission Subsystem hierarchical architecture location	138
Figure 6-38	Transmission Subsystem connectivity diagram	143
Figure 6-39	Driveline Subsystem hierarchical architecture location	144
Figure 6-40	Driveline Subsystem connectivity diagram	149
Figure 6-41	Auxiliary Power Subsystem hierarchical architecture location.....	150
Figure 6-42	Auxiliary Power Subsystem connectivity diagram	155
Figure 6-43	Chassis Subsystem internal architecture connectivity diagram.....	156
Figure 6-44	Chassis Supervisory Control Subsystem hierarchical architecture location.....	157
Figure 6-45	Chassis Supervisory Control Subsystem connectivity diagram.....	161
Figure 6-46	Steering Subsystem hierarchical architecture location	162
Figure 6-47	Steering Subsystem connectivity diagram	166
Figure 6-48	Braking Subsystem hierarchical architecture location	167
Figure 6-49	Braking Subsystem connectivity diagram	171
Figure 6-50	Wheels/Tracks Subsystem hierarchical architecture location.....	172
Figure 6-51	Wheels/Tracks Subsystem connectivity diagram	176
Figure 6-52	Suspension Subsystem hierarchical architecture location.....	177
Figure 6-53	Suspension Subsystem connectivity diagram	181
Figure 6-54	Body-Frame Subsystem hierarchical architecture location.....	182
Figure 6-55	Body-Frame Subsystem connectivity diagram	190
Figure 6-56	Power Take-Off Accessories Subsystem hierarchical architecture location.....	191
Figure 6-57	Power Take-Off Accessories Subsystem connectivity diagram.....	197
Figure 6-58	Body-Frame Subsystem internal architecture connectivity diagram.....	198
Figure 6-59	Body-Frame Supervisory Control Subsystem hierarchical architecture location.....	199
Figure 6-60	Body-Frame Supervisory Control Subsystem connectivity diagram.....	203
Figure 6-61	Under Body Subsystem hierarchical architecture location	204
Figure 6-62	Under Body Subsystem connectivity diagram	211
Figure 6-63	Upper Body Subsystem hierarchical architecture location	212
Figure 6-64	Upper Body Subsystem connectivity diagram	219
Figure 6-65	Cabin Interior Subsystem hierarchical architecture location	220
Figure 6-66	Cabin Interior Subsystem connectivity diagram.....	227
Figure 6-67	Cabin Climate Subsystem hierarchical architecture location.....	228
Figure 6-68	Cabin Climate Subsystem connectivity diagram.....	232
Figure 6-69	Trailer i Subsystem internal architecture connectivity diagram.....	233
Figure 6-70	Trailer i Supervisory Control Subsystem hierarchical architecture location.....	234
Figure 6-71	Trailer i Supervisory Control Subsystem connectivity diagram.....	238
Figure 6-72	Trailer i Steering Subsystem hierarchical architecture location	239
Figure 6-73	Trailer i Steering Subsystem connectivity diagram	242
Figure 6-74	Trailer i Braking Subsystem hierarchical architecture location	243
Figure 6-75	Trailer i Braking Subsystem connectivity diagram	247
Figure 6-76	Trailer i Wheels/Tracks Subsystem hierarchical architecture location	248
Figure 6-77	Trailer i Wheels/Tracks Subsystem connectivity diagram	251
Figure 6-78	Trailer i Suspension Subsystem hierarchical architecture location	252
Figure 6-79	Trailer i Suspension Subsystem connectivity diagram	255
Figure 6-80	Trailer i Body-Frame Subsystem hierarchical architecture location	256
Figure 6-81	Trailer i Body-Frame Subsystem connectivity diagram	264
Figure 6-82	Trailer i Power Take-Off Accessories Subsystem hierarchical architecture location	265
Figure 6-83	Trailer i Power Take-Off Accessories Subsystem connectivity diagram	270
Figure 6-84	Trailer i Body-Frame Subsystem internal architecture connectivity diagram.....	271
Figure 6-85	Trailer i Body-Frame Supervisory Control Subsystem hierarchical architecture location.....	272
Figure 6-86	Trailer i Body-Frame Supervisory Control Subsystem connectivity diagram.....	276
Figure 6-87	Trailer i Under Body Subsystem hierarchical architecture location	277
Figure 6-88	Trailer i Under Body Subsystem connectivity diagram	284
Figure 6-89	Trailer i Upper Body Subsystem hierarchical architecture location	285
Figure 6-90	Trailer i Upper Body Subsystem connectivity diagram	292
Figure 6-91	Trailer i Interior Subsystem hierarchical architecture location	293
Figure 6-92	Trailer i Interior Subsystem connectivity diagram	299

Figure 6-93	Trailer i Climate Subsystem hierarchical architecture location	300
Figure 6-94	Trailer i Climate Subsystem connectivity diagram	304
Figure 7-1	Intelligent Transportation System hierarchical organization for a single Ground Vehicle Subsystem	307
Figure 7-2	Intelligent Transportation System hierarchical organization for several Ground Vehicle Subsystems (1 to M)	307
Figure 8-1	Hierarchical architecture of the Vehicle Information Bus	330
Figure 8-2	Vehicle Subsystem top-level controller bus block diagram	331
Figure 8-3	Vehicle Supervisory Controller Subsystem input-output block diagram	332
Figure 8-4	Power Subsystem internal top-level controller bus block diagram	333
Figure 8-5	Power Supervisory Controller Subsystem input-output block diagram	334
Figure 8-6	Chassis Subsystem top-level controller bus block diagram	335
Figure 8-7	Chassis Supervisory Controller Subsystem input-output block diagram	336
Figure 8-8	Trailer 1 Subsystem top-level controller bus block diagram	337
Figure 8-9	Trailer 1 Supervisory Controller Subsystem input-output block diagram	338
Figure 8-10	Body-Frame Subsystem top-level controller bus block diagram	340
Figure 8-11	Body-Frame Supervisory Controller Subsystem input-output block diagram	340
Figure 8-12	Trailer 1 Body-Frame Subsystem top-level controller bus block diagram	342
Figure 8-13	Trailer 1 Body-Frame Supervisory Controller Subsystem input-output block diagram	342
Figure 8-14	Power Subsystem connectivity diagram for the baseline four-wheeled work truck application with an internal combustion engine (ICE)	352
Figure 8-15	Chassis Subsystem connectivity diagram for the baseline four-wheeled work truck application with an internal combustion engine (ICE)	353
Figure 8-16	Power Subsystem connectivity diagram for the baseline four-wheeled work truck with only primary power flow connections	354
Figure 8-17	Chassis Subsystem connectivity diagram for the baseline four-wheeled work truck with only primary power flow connections	355
Figure 8-18	Belted alternator starter (BAS) parallel hybrid configuration	356
Figure 8-19	Integrate starter generator (ISG) parallel hybrid	357
Figure 8-20	Electronically variable transmission (EVT) parallel hybrid	358
Figure 8-21	Parallel hybrid configuration with integrated electric machine at the output of the transmission to form a new Transmission Subsystem	359
Figure 8-22	Parallel hybrid configuration with integrated electric machine at the output of the driveline to form a new Driveline Subsystem	360
Figure 8-23	Power Subsystem for a parallel through the road hybrid configuration	361
Figure 8-24	Chassis Subsystem for a parallel through the road hybrid configuration	362
Figure 8-25	Flywheel parallel hybrid configuration with a flywheel integrated into the Transmission Subsystem	363
Figure 8-26	Flywheel parallel hybrid configuration with a flywheel integrated into the Driveline Subsystem	364
Figure 8-27	Parallel hydraulic hybrid configuration	365
Figure 8-28	Series electric hybrid configuration	366
Figure 8-29	Series hydraulic hybrid configuration	367
Figure 8-30	Electric vehicle configuration	368
Figure 8-31	Power Subsystem for an electric wheel hub motor configuration	369
Figure 8-32	Chassis Subsystem for an electric wheel hub motor configuration with all-wheel drive	370
Figure 8-33	Fuel cell electric vehicle configuration	371
Figure 8-34	Hydraulic series hybrid power transfer configuration	372
Figure 8-35	Power Subsystem for a Transmission Subsystem with a hydraulic powered power take-off providing mechanical power to the Chassis Subsystem	374
Figure 8-36	Chassis Subsystem for a Power Take-Off Accessories Subsystem powered by mechanical power from a transmission power take-off	375
Figure 8-37	Power Subsystem for a Transmission Subsystem with a power take-off providing hydraulic power to the Chassis Subsystem	376
Figure 8-38	Chassis Subsystem for a Power Take-Off Accessories Subsystem powered by hydraulic power from a transmission power take-off	377
Figure 8-39	Power Subsystem for a series hydraulic hybrid supplying hydraulic power to the Chassis Subsystem for powering wheel hub motors for propulsion	378
Figure 8-40	Chassis Subsystem for a series hydraulic hybrid with hydraulic powered wheel hub motors for propulsion	379
Figure 8-41	Power Subsystem for a rear-wheel drive vehicle configuration	381
Figure 8-42	Chassis Subsystem for a rear-wheel drive vehicle configuration	381

Figure 8-43	Power Subsystem for a front-wheel drive vehicle configuration	382
Figure 8-44	Chassis Subsystem for a front-wheel drive vehicle configuration	383
Figure 8-45	Power Subsystem for an all-wheel drive vehicle configuration	384
Figure 8-46	Chassis Subsystem for an all-wheel drive vehicle configuration	385
Table 1	Environment Subsystem interface connections	50
Table 2	Driver/Passengers Subsystem interface connections	55
Table 3	Vehicle Subsystem interface connections	59
Table 4	Atmospheric Subsystem interface connections	64
Table 5	Road/Terrain Subsystem interface connections	66
Table 6	Traffic/Surroundings Subsystem interface connections	69
Table 7	Remote HMI Subsystem interface connections	71
Table 8	Driver Subsystem interface connections	74
Table 9	Remote Driver Subsystem interface connections	77
Table 10	Passengers Subsystem interface connections	80
Table 11	Vehicle Supervisory Control Subsystem interface connections	85
Table 12	Power Subsystem interface connections	90
Table 13	Chassis Subsystem interface connections	96
Table 14	Trailer 1 Subsystem interface connections	105
Table 15	Power Supervisory Control Subsystem interface connections	113
Table 16	Electrical Subsystem interface connections	118
Table 17	Thermal Management Subsystem interface connections	124
Table 18	Fuel Subsystem interface connections	128
Table 19	Propulsion Power Subsystem interface connections	132
Table 20	Transmission Subsystem interface connections	139
Table 21	Driveline Subsystem interface connections	145
Table 22	Auxiliary Power Subsystem interface connections	151
Table 23	Chassis Supervisory Control Subsystem interface connections	158
Table 24	Steering Subsystem interface connections	163
Table 25	Braking Subsystem interface connections	168
Table 26	Wheels/Tracks Subsystem interface connections	173
Table 27	Suspension Subsystem interface connections	178
Table 28	Body-Frame Subsystem interface connections	183
Table 29	Power Take-Off Accessories Subsystem interface connections	192
Table 30	Body-Frame Supervisory Control Subsystem interface connections	200
Table 31	Under Body Subsystem interface connections	205
Table 32	Upper Body Subsystem interface connections	213
Table 33	Cabin Interior Subsystem interface connections	221
Table 34	Cabin Climate Subsystem interface connections	229
Table 35	Trailer i Supervisory Control Subsystem interface connections	235
Table 36	Trailer i Steering Subsystem interface connections	240
Table 37	Trailer i Braking Subsystem interface connections	244
Table 38	Trailer i Wheels/Tracks Subsystem interface connections	249
Table 39	Trailer i Suspension Subsystem interface connections	252
Table 40	Trailer i Body-Frame Subsystem interface connections	257
Table 41	Trailer i Power Take-Off Accessories Subsystem interface connections	266
Table 42	Trailer i Body-Frame Supervisory Control Subsystem interface connections	273
Table 43	Trailer i Under Body Subsystem interface connections	278
Table 44	Trailer i Upper Body Subsystem interface connections	286
Table 45	Trailer i Interior Subsystem interface connections	294
Table 46	Trailer i Climate Subsystem interface connections	301
Table 47	SI base units for measuring physical quantities	309
Table 48	Derived units created from the SI base units	309
Table 49	Power transfer port types	312
Table 50	Physical conditions port types	316
Table 51	Controller port types	319
Table 52	Human physical port types	327
Table 53	Vehicle Information Bus architecture definition	329
Table 54	Subsystem scope and content	

1. SCOPE

The “Model Architecture and Interfaces Recommended Practice for Ground Vehicle System and Subsystem Dynamical Simulation” defines the architectural structure of a ground vehicle system dynamical model by partitioning it into subsystem models and by defining subsystem interfaces required to enable plug-and-play operation of a dynamical simulation models. All types of ground vehicle were considered in the development of the architecture, such as, passenger cars, light and medium duty trucks, heavy duty tractor trailer trucks, and vehicles/equipment for military, farming, construction, and mining. Versatility of this architectural partitioning is demonstrated by showing how it can be applied to different vehicle configurations. Application examples of architecture are provided for a large number of the publicly known ground vehicle configurations in production, testing, or development.

This recommended practice encompasses standards to enable seamless plug-and-play reusability of dynamical models for simulating the functional behavior of a ground vehicle system and its subsystems. A single ground vehicle system is the system of interest. The architecture and interfaces support vehicle models that describe vehicle motion in one dimension (longitudinal), two dimensions (longitudinal and lateral or longitudinal and vertical), and three dimensions (longitudinal, lateral, and vertical). The scope includes defining recommended practices for:

1. Model architectural structure, and interfaces that enable the plug-and-play development of: (1) a top-level ground vehicle system model from subsystem models, and (2) subsystem models from other subsystem models; and
2. Model architecture and interfaces for all hardware and controller interfaces; however, the internal structure of control algorithms and software will not be included in this recommended practice.

Since, other groups (such as, AUTOSAR) are addressing architecture and interfaces of models for control applications and software; they are not included in the scope of the recommended practice. However, in the future, the internal structure of control algorithms and software should be addressed for special issues of dynamical modeling and simulation of ground vehicle systems that are not covered by other standards groups.

1.1 Purpose

The purpose and benefits of defining a standard for dynamical simulation models of a ground vehicle system in terms of the architectural structure, the subsystem partitioning, the subsystem interfaces and implementation conventions are to:

1. Enable and facilitate exchange, reuse, and sharing of models across all disciplines of engineering and physics within organizations for enterprise-wide collaboration, and across the industry (between OEM's, suppliers, research laboratories, government agencies, and universities) for inter-organizational collaboration.
2. Reduce or eliminate duplication of modeling work products by defining the boundaries and scope of models.
3. Reduce the effort required to integrate models of all of the subsystems or components needed to create a functional system model for any ground vehicle.
4. Make models of varying fidelity or abstraction rapidly connectable and functional in an overall system, subsystem, or component model (i.e., ‘Make Models Pluggable and Playable’).
5. Reduce model development time and cost, and improve model quality.
6. Enable and facilitate management of large systems development projects through parallel development paths (i.e., decoupled development).

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE TSB003_199905 "Rules for SAE Use of SI (Metric) Units

SAE J670 Vehicle Dynamics Terminology.

SAE J3016 Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems

2.1.2 ISO Publications

Available from International Organization for Standardization, ISO Central Secretariat, 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41 22 749 01 11, www.iso.org.

ISO 80000-1:2009/Cor 1:2011, Quantities and units - Part 1: General.

ISO 8855:2011, Road vehicles - Vehicle dynamics and road-holding ability - Vocabulary, 2nd Edition, 2011.

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE Ground Vehicle Standards Committee Handbook

SAE J2546 Model Specification Process Standard

2.2.2 IEEE Publications

Available from IEEE Operations Center, 445 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

IEEE Standard 1076.1.1 – 2011; IEEE Standard for VHDL Analog and Mixed Signal Extensions – Packages for Multiple Energy Domain Support; IEEE, New York; 2011.

Fritzson, Peter; Principles of Object Oriented Modeling and Simulation with Modelica 2.1; IEEE Press; Wiley-Interscience; New Jersey; 2004.

Fritzson, Peter; Introduction to Modeling and Simulation of Technical and Physical Systems with Modelica; IEEE Press; Wiley; New Jersey; 2011.

2.2.3 Modelica Association

Available from Modelica Association, Linköping, Sweden, www.modelica.org.

Modelica Association; "Modelica – A Unified Object-Oriented Language for Modeling Systems, Language Specification, Version 3.3"; www.Modelica.org; 2012.

2.2.4 SPIE - The International Society for Optical Engineering

Available from SPIE Press, P.O. Box 10, Bellingham, WA 98227-0010 USA; Tel: +1 360 676 3290; <http://spie.org>.

Palmer, James M.; and Grant, Barbara G.; The Art of Radiometry; SPIE Press Monograph Vol. PM184; SPIE Press; Bellingham, Washington, December 2010.

2.2.5 Springer Verlag

Available from Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA, www.springer.com.

Borutzky, Wolfgang; Bond Graph Methodology – Development and Analysis of Multidisciplinary Dynamic System Models; Springer-Verlag London Limited; London, 2010.

Borutzky, Wolfgang (Editor); et al; Bond Graph Modeling of Engineering Systems – Theory, Applications and Software Support; Springer Science+Business Media LLC; New York, 2011.

3. DEFINITIONS

3.1 Terms

3.1.1 AUTOMATED VEHICLE¹

A vehicle equipped with an automated driving system.

3.1.2 AUTOMATED DRIVING SYSTEM²

The hardware and software that is collectively capable of performing all aspects of the dynamic driving task for a vehicle (whether part time or full time).

3.1.3 BUS

A method of using a single connection between model interfaces for organizing and exchanging a collection of interrelated information, and/or signals between interfaces. The single connection represents a structured organization of individual connections for each of the information, and/or signals that are carried on the bus between the models. This simplifies model diagrams and makes model operation easier to decipher and comprehend. It can be thought of as a bundle of wires or a column vector of items, where each element of the vector corresponds to a signal, or information arranged in a prescribed order with one item, stacked on top of another in the column.

3.1.4 BUS, STACKED

See definition of STACKED BUS.

3.1.5 COMPONENT

One part of the collection of parts that are assembled or integrated together to form a system or subsystem.

3.1.6 CONTROL SYSTEM

A mechanism that consists of a controller, actuators, and sensors, which is used to manage, regulate, and or govern the response of a system, mechanism or process (called a plant system) to changes in commands or conditions. The controller monitors the plant performance through sensing of critical variables and decides on actuator commands required to provide the desired or required performance. Then, the controller commands actuators to change plant variables that regulate the performance and return it to the desired response. This term may also be used to describe a mechanism that consists of a controller, actuators, plant, and sensors.

3.1.7 DYNAMIC DRIVING TASK³

All of the real-time functions required to operate a vehicle in on-road traffic, excluding the selection of destinations and waypoints (i.e., navigation or route planning) and including without limitation: (1) object and event detection, recognition, and classification; (2) object and event response; (3) maneuver planning; (4) steering, turning, lane keeping, and lane changing; (5) acceleration and deceleration; (6) enhancing conspicuity (lighting, signaling and gesturing, et cetera).

¹ SAE J3016_201401: "Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems", SAE International, Jan 16, 2014.

² SAE J3016_201401: "Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems", SAE International, Jan 16, 2014.

³ SAE J3016_201401: "Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems", SAE International, Jan 16, 2014.

3.1.8 FIDELITY⁴

The degree to which a representation, such as a model, captures the nature of the real object being represented.

3.1.9 GROUND VEHICLE

A mechanism for people to move themselves and their goods from one point to another on the surface of the earth (ground), or to perform work on their environmental surroundings.

3.1.10 GROUND VEHICLE SYSTEM

A system that describes the interaction of people (driver and passengers) with their environment through the use of a mechanism (vehicle) for them to move themselves and their goods from one point to another on the surface of the earth (ground), to perform work on the surface, and to affect their environmental surroundings. It describes and captures all of the interactions between the people, the mechanism, and the environment and their resulting effects on each other.

3.1.11 GROUND VEHICLE SYSTEM DYNAMICAL MODEL

A mathematical simulation model of the functional operation of a ground vehicle system that describes how its fundamental physical variables change with time, including transients.

3.1.12 GVS

An acronym for Ground Vehicle Subsystem. See definition of GROUND VEHICLE SYSTEM.

3.1.13 HMI (HUMAN-MACHINE INTERFACE)

An acronym for Human-Machine Interface. See definition of HUMAN-MACHINE INTERFACE.

3.1.14 HUMAN-MACHINE INTERFACE (HMI)

A means for a human being to monitor and control a system or subsystem. For a human to interact with a system to control it, many methods could be employed, such as, keypads, buttons, knobs, dials, touch screens, voice recognition, gesture recognition, et cetera. And, for monitoring a system, a human can be presented with display screens, graphs, flashing lights, alarms, sounds, messages, video, audio, vibration, et cetera.

3.1.15 HVAC

An acronym for heating, ventilation, and air conditioning. The climate control system for the interior of a vehicle is called a heating, ventilation, and air conditioning system and is referred to as an HVAC system.

3.1.16 ICE

An acronym for an internal combustion engine.

3.1.17 INTELLIGENT INFRASTRUCTURE SYSTEM

A control system for monitoring and controlling the flow of traffic to maximize the flow of traffic, minimize accidents, save energy, and efficiently utilize a transportation system. It uses sensors that measure the traffic flow and actuators that adjust the traffic control lights, change lane direction usage, adjust speed limits, and direct vehicles to underutilized routes.

⁴ SAE Ground Vehicle Standard J2546: "Model Specification Process Standard", SAE International, February 2002.

3.1.18 INTELLIGENT TRANSPORTATION SYSTEM (ITS)

A method for managing traffic and transit of ground vehicles to improve transportation safety, and increase traffic flow efficiency through the integration and coordination of intelligent vehicles and intelligent infrastructure that use vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications to operate as a single intelligently controlled, coordinated and managed transportation system.

3.1.19 INTELLIGENT VEHICLE SYSTEM

A controls system that monitors and controls a vehicle to make it function under some situations as an automated vehicle by monitoring the surrounding environment (e.g., surrounding vehicles, pedestrians, obstacles, intelligent infrastructure system, et cetera), detecting problems or potential accidents, and responding automatically to control the vehicle to avoid or mitigate a problem or a potential accident. It may be used to assist the driver or replace the driver completely. See definition of AUTOMATED VEHICLE.

3.1.20 ITS (INTELLIGENT TRANSPORTATION SYSTEM)

An acronym for an intelligent transportation system. See definition of INTELLIGENT TRANSPORTATION SYSTEM.

3.1.21 MODEL ARCHITECTURE

A description of the structure of a simulation model that organizes and partitions the model into the fundamental building blocks of subsystems (or components), and that defines how those building blocks are connected to each other and function together toward a common purpose. It defines the purpose and function of the subsystems (or components), and of the connections between them to provide the assembly instructions required to build the model.

3.1.22 MODEL INTERFACE

A means for a simulation model to exchange physical quantities and information with other models to support their coordinated and integrated operation within a system or subsystem.

3.1.23 MODEL INTERFACE PORT

A means for a simulation model to exchange physical quantities or information between subsystem models through an interface. Each type of interface port has a defined set of physical quantities or information that it provides. It is a means of specifying the information available from an interface that is independent of the modeling method.

3.1.24 MODEL INTERFACE PLUG-IN

A means to implement an interface port in simulation using a specific modeling method or language by providing a description of the port using the conventions of the modeling method. It plugs into an interface port to convert the port into the proper format required by the modeling method.

3.1.25 MODEL MODULE

A self-contained subsection or part of a model that performs a specific standardized function, for easy assembly, flexible integration, and reuse with other model modules to form more complex models of whole components, subsystems, and systems. Some examples of model modules, which can be interconnected to form more complex models, are: (1) subsystems used to form a system, (2) subsystems used to form larger subsystems, (3) components used to form a subsystem, and (4) math functions used to form components. See the separate definition of SUBSYSTEM given below.

3.1.26 MODEL PLAYABILITY

The ability of a model to work or function correctly in any simulation tool environment (using the same syntax and conventions) without requiring any additional processing or modification to the model.

3.1.27 MODEL PLUGABILITY

A property of models that follow the same conventions or syntax; so, they can be connected together. Thus, they can exchange the interface variables required to function together. However, it does not guarantee that they will work seamlessly together.

3.1.28 MODULAR MODEL

A type of model that is composed of a collection of units, called model modules, which perform specific standardized functions for easy assembly, integration, and reuse. See definition of MODEL MODULE.

3.1.29 N-TH LEVEL SUBSYSTEM

A coordinated assembly of interconnected components operating together to perform a function or functions that provide part of the functionality of the next level higher subsystem (i.e., the (N-1)-th level subsystem). See Figure 4-5.

3.1.30 PARAMETER

A quantity of a model that does not change explicitly with time. These quantities are functions, such as look-up tables, or model constants, whose values are set or fixed at the start of a simulation. They do not change explicitly with time over a simulation, but are only changed to configure a model to describe a different piece of hardware, algorithm or software that is governed by the same physical phenomena and equations described by the model or algorithm. The term PARAMETER is not to be used interchangeably with the term VARIABLE. See the separate definition for VARIABLE given below.

3.1.31 PLANT

The name given to the mechanism, process, subsystem, or system that is to be controlled. This term originated from chemical engineering where the process in need of control was a chemical manufacturing plant. Now, it is used as a general term to refer to any system that is being controlled.

3.1.32 PLUG-AND-PLAY

A property of models that follow the same conventions and syntax; so, they can be connected and work seamlessly together. This type of model can function correctly in any simulation tool environment (using the same conventions and syntax) without requiring any additional processing or modification to the model. See MODEL PLAYABILITY and MODEL PLUGABILITY for more details.

3.1.33 POWER TAKE-OFF (PTO)

A mechanism for extracting rotational mechanical power from the Propulsion Power Subsystem, Transmission Power Subsystem, and/or Driveline Subsystem. It diverts rotational mechanical power through arrangements of clutches and gearboxes, or belts and pulleys to power accessory equipment for providing additional features or functions for convenience or work, such as, a hydraulic pump for power steering assist, a compressor for air conditioning, or power for work equipment (e.g., winches, hoists, snow plows, tillers, spreaders, cherry pickers, hoists, et cetera).

3.1.34 PTO (POWER TAKE-OFF)

See definition of POWER TAKE-OFF.

3.1.35 SET OF CONNECTIONS

The description for a single connection between model interfaces that represents a collection of physical interfaces of the same physical type. This single connection is a group of individual connections that is not organized or structured in a rigorous fashion, which could limit flexibility for different vehicle applications or implementations. This simplifies model diagrams and makes model operation easier to decipher and comprehend.

3.1.36 SIGNAL

A method of conveying information through an interface connection, where the physical quantities, and/or information is represented or encoded in another form, such as, an analog or digital voltage.

3.1.37 SIMULATION ENVIRONMENT

A software tool that enables a user to manage and control the simulation of models. Typically, it enables a user to configure a simulation by creating and connecting models, to execute (or run) a simulation, and to use simulation results for analysis and reporting. It may also provide other functions to manage a complete process of modeling and simulation.

3.1.38 SOFTWARE MODEL

A model that emulates either the behavior or the implementation of software code in the physical vehicle. It could be the actual in-vehicle software code generated by hand-coding or auto-coding.

3.1.39 STACKED BUS

A structured organization of a collection of busses that are stacked one on top of the other to form a single connection between models, which simplifies model diagrams and makes model operation easier to decipher and comprehend. It can be thought of as a column vector, where each element of the vector is a bus connection. And, each bus is a column vector, where each element of the vector represents a connection for information or signals.

3.1.40 SUBSYSTEM

A coordinated assembly of interconnected components operating together to perform a function or functions that provide part of the functionality of a larger system. It may also provide part of the functionality of a larger subsystem.

3.1.41 SUBSYSTEM MODEL

A mathematical simulation model of a subsystem.

3.1.42 SYSTEM

A coordinated assembly of interconnected components or subsystems operating together to perform a common function or functions, which provides greater functionality than any individual component or subsystem provides alone.

3.1.43 SYSTEM MODEL

A mathematical simulation model of a system. It may be used as a system or subsystem model depending on how the model is used in a simulation. If a model module describes or models everything that is being simulated, it is the main subject of the simulation, and thus, called a system model. And, if it is one of the many interconnected supporting model modules that contribute to the functionality of the entire simulation under study; then, it and the modules interconnecting with it are all called subsystem models.

3.1.44 TOP-LEVEL SYSTEM MODEL

The highest level mathematical simulation model of the entire system being simulated.

3.1.45 TELEOPERATION

A method for controlling the operation of a vehicle remotely from a distant location that is outside and typically out of sight of the vehicle. Control is accomplished through a communications link, which transmits vehicle control commands to the vehicle and receives vehicle status information from the vehicle.

3.1.46 UNIBODY

A type construction for a vehicle body structure that integrates body enclosure and frame structural functions together into a single body structure, which has incorporated structural features to serve the purpose of a frame.

3.1.47 VALIDATION

The process of checking that the model adequately describes the functionality of the real physical system, algorithm, or software in sufficient detail to support the intended use. The fundamental questions being answered by this process are: were the right things modeled and are the model requirements sufficiently complete? These questions are answered through a process of physically testing the hardware, algorithm or software over a set of test cases, and then simulating the model over the same set of test cases (which represent the intended use cases) to confirm that the model was designed and calibrated correctly to reproduce the required behavior or functionality, sufficiently. For example validation may reveal additional features, functions, or behaviors the model does not describe or requirements it does not meet, which causes unacceptable or inadequate performance. It should be noted that before validating the model, the model must be verified to ensure that the model is performing its calculations correctly as it was designed. See definition of VERIFICATION.

3.1.48 VARIABLE

A quantity of a model that changes as time progresses during a simulation. This is not to be used interchangeably with the term PARAMETER. See the separate definition for PARAMETER.

3.1.49 VERIFICATION

The processing of determining that the model was implemented correctly as it was designed. Model verification is the process of simulating the model over a set of test cases to confirm that the design requirements have been achieved.

4. GENERAL MODEL ARCHITECTURAL STRUCTURE

4.1 Overview

This section serves as an introduction to the principles of hierarchical modeling, which are used in this standard. It defines a hierarchical modeling structure, and a general architectural structure for any subsystem of a system. In addition, architectural conventions for subsystem models are defined (1) for coordinate systems used to describe the spatial orientation of a vehicle, subsystem, or component relative to the earth, vehicle, and other subsystems of a ground vehicle; (2) for units of measure for physical quantities, and (3) for the types of physical and information interfaces that models may have. Finally, architectural features are introduced that provide flexibility to support any type of partitioning of control functions between subsystems, and any type of information sharing between subsystems.

4.2 Introduction

The structure of the model architecture selected for representing a Ground Vehicle System (GVS) is based on proven and well tested modeling and simulation methods and principles, which were developed for modeling and simulation of the dynamical functional operation of complex systems, composed of many subsystems and components. These general methods have been developed and successfully applied for over fifty years for modeling and simulation applications in electrical, electronics, integrated circuit design, and aeronautical and aerospace engineering. In general, standard methods for modeling and simulation of the physical operation for a system are enabled by the following four main fundamental concepts of modeling:

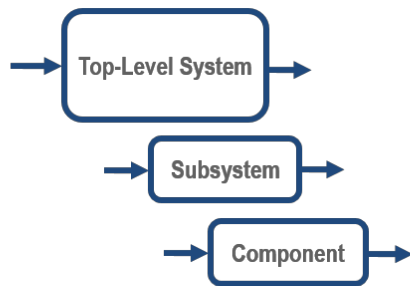
1. Modularity,
2. Hierarchy,
3. Abstraction, and
4. Encapsulation.

The idea of modularity is to partition complex system models into a small collection of subsystem modules, which are collections of subsystems or components that work in concert to provide some larger common functional purpose. Having fewer pieces to describe the system model makes it easier to learn and comprehend. This modular representation helps facilitate the understanding of the functions performed by an interconnection of several modules, and of the relationship of each module to the greater functionality of the whole system.

Converting a complex system into modules starts with identifying components that work in concert to provide a function or group of functions. This collection of components forms a module called a subsystem. Next, the subsystems can be organized into a collection of subsystems that work together to provide a higher function to form a larger subsystem module. Or, a collection of subsystems performing similar functions could be collected together to form a larger subsystem module based on commonality of function. By continuing this process, it is possible to arrive at high level description of a ground vehicle system that is composed of three to ten subsystem modules that describe the fundamental physics of any ground vehicle system. This process of collecting components to form subsystems modules and collecting subsystems modules to form larger subsystem modules results in a tiered model organization called a hierarchical model structure.

The concept of model modularity applied recursively leads to a hierarchical organization of functional operation, which results in a model that is described by a hierarchy of modules, where modules at each level in the hierarchy provide a higher level of functionality than a module in the level below it. Figure 4-1 below shows a hierarchy of modules that progress from the highest level of functionality of a top-level system to the lowest level of functionality provided by a component. The modules are defined by a nested hierarchy of models (e.g., top-level system, subsystem, and component) where the models at each level are composed of an interconnection of models from the next lower level in the hierarchy as is shown in Figure 4-2.

Hierarchy of Modular Models for Partitioning Complex System Models



- Models are partitioned:
 - according to physical hardware components & connections,
 - and to provide proper functional behavior, simultaneously,
 - or when both requirements are not possible,
 - then at least to provide proper functional behavior

Figure 4-1 - Definition of a hierarchical family of modular models

Partitioning of a model into modules is guided by a primary goal that the model should reflect the physical structure of the hardware components and their connections, while simultaneously describing the proper functional behavior of the hardware. If both of these conditions cannot be met (because of other requirements or constraints); then, the model must at least provide the proper functional behavior or operation. Modeling of the functional operation is of paramount importance. However, it is also important to maintain the physical structure of the hardware to enable the models to be replaced by physical hardware components to support Hardware-in-the-Loop (HIL) simulation capabilities. An additional benefit of building models according to the physical components and connections is that the resulting model diagram provides a schematic or topological picture of the system being modeled. Thus, the model diagram becomes a visual representation that also provides insight into the structure and operation of the physical system. Hence, models can be representationally correct either physically and functionally, or functionally, depending on organizational, physical, or other requirements and constraints.

The ability to use models with varying abstraction to represent any hierarchical model module is an important fundamental concept for functional modeling and simulation. Abstraction flexibility is a key concept that helps define the interfaces for a given module. If the interfaces for a model module are based on the physical function that the module performs; then, a simple model can be directly replaced by a highly detailed model as illustrated in Figure 4-3. By selecting the module interfaces based on the fundamental physical function it performs, one model module can be replaced by another model module without requiring any changes to the interface, which enables the ability to plug-and-play models of vary levels of fidelity, complexity or abstraction.

Encapsulation is another fundamental modeling concept, which operates in concert with abstraction flexibility to provide plug-and-play capability. Encapsulation involves the concept of 'information hiding' or keeping information internal and isolated from the model interfaces. The idea of identifying variables that do not need to be passed to surrounding model modules is fundamental to the ability to support abstraction flexibility. For example, a piece of hardware could be characterized with different levels of fidelity by plug-and-play substitution of models, such as, a static or steady-state model, a simple dynamical model with one state variable, or a high-fidelity dynamical model with many state variables; because, the state variables can be encapsulated internal to the model without affecting the fundamental information required by other model modules that interact with it.

Hierarchical Model Organization

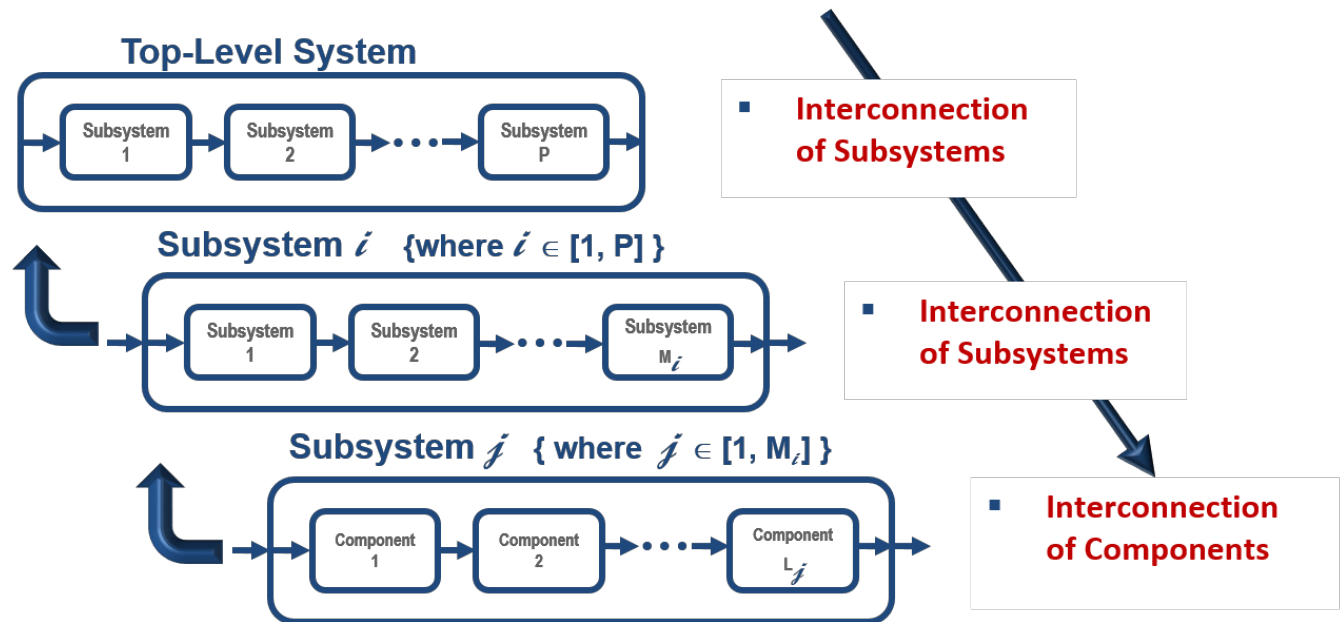


Figure 4-2 - Definition of a nested hierarchical modeling organizational structure

Selectable Level of Abstraction

- Plug-and-Play model complexity
 - Replacing simple concept models directly with physical models or production hardware requires
 - External model interfaces must match hardware interfaces
 - Model interfaces based on physical function of the hardware

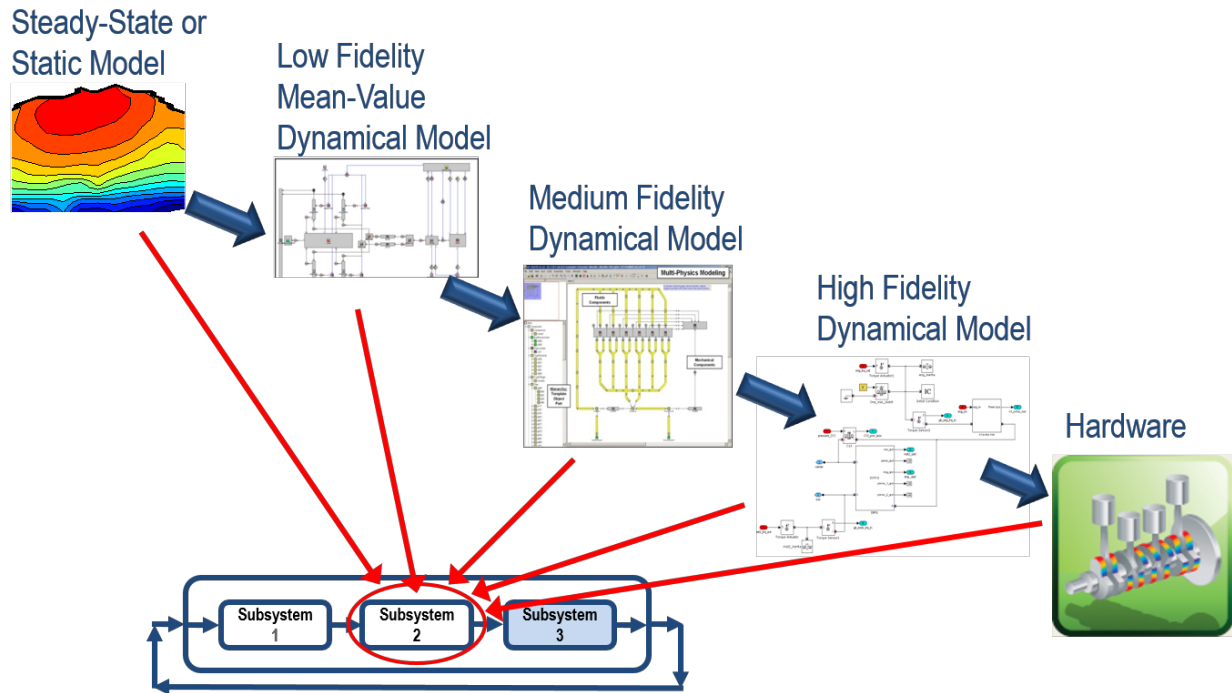
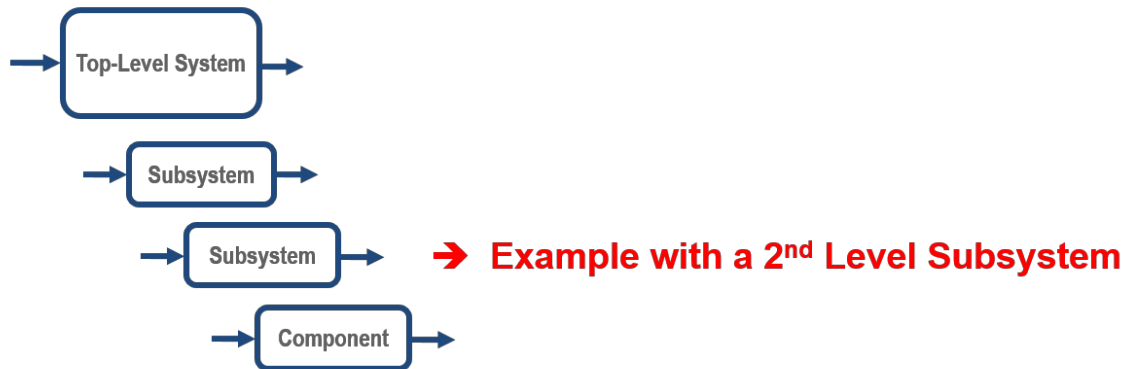


Figure 4-3 - Model abstraction flexibility requirements

For even more complex systems, there may be a need for lower-level subsystem modules below the subsystem level as shown in Figure 4-4 below. These lower-level subsystems are referred to as level-2 subsystems, level-3 subsystems and so on down to a level-N subsystem at the lowest level, where N is the number of subsystem levels or layers required to describe the subsystem being modeled.

A hierarchical modeling organizational structure for a system with nested lower-level subsystems down to level-N subsystems is shown below in Figure 4-5.

Modular Model Structure



- Model external interfaces (inputs and outputs) based on:
 - ability to plug-and-play models with different fidelity, complexity, or abstraction
 - physical connections between components,
 - fundamental physics of the hardware's function, and
 - generalized power defined by effort and flow variables for energy conversion devices

Figure 4-4 - Definition of a modular modeling structure with a level-2 subsystem

Hierarchical Model Organization with Lower Level Subsystems

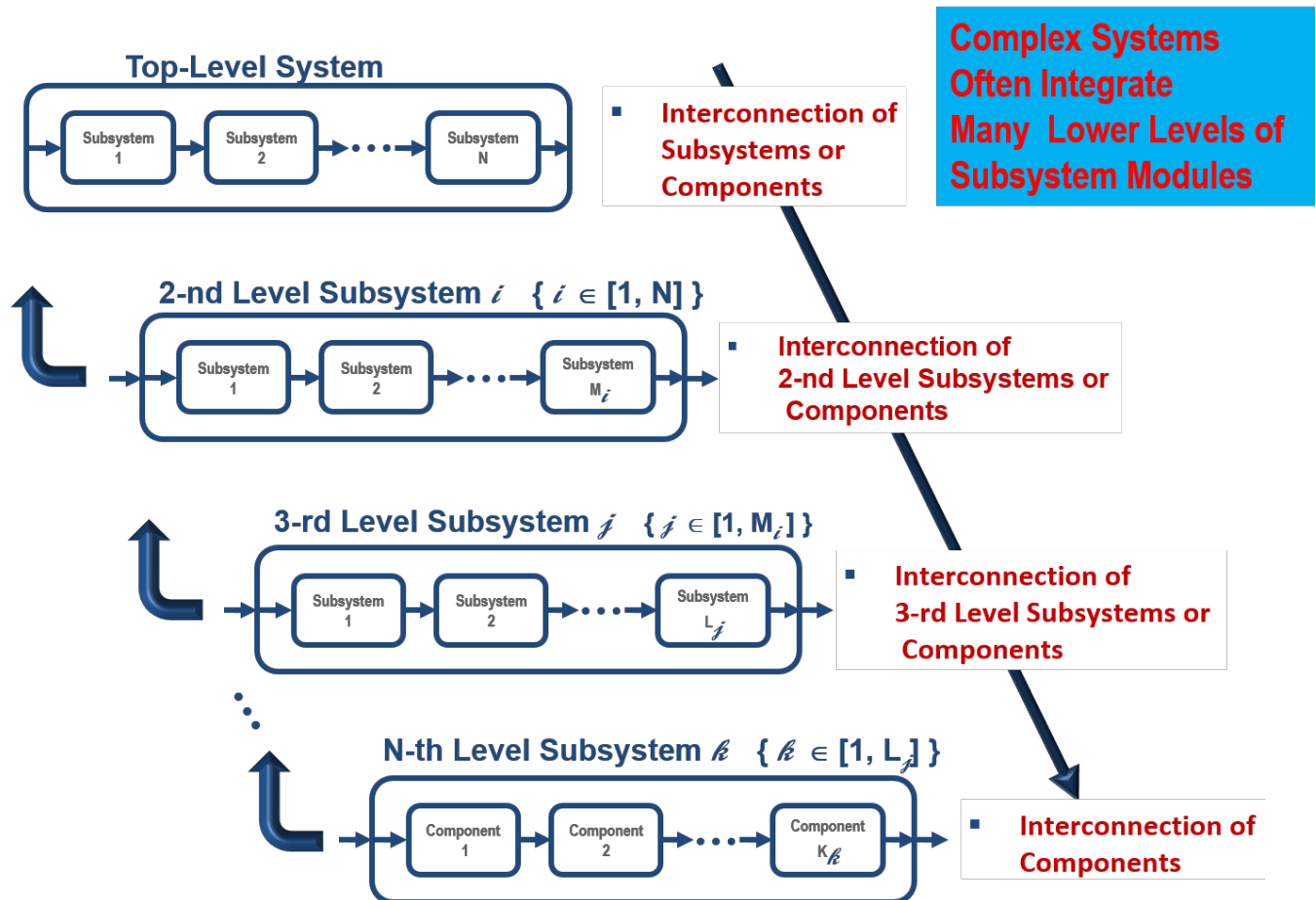


Figure 4-5 - Hierarchical modeling structure with lower-level subsystems

In summary, modeling and simulation of the functional operation of dynamical systems is simplified by:

1. Partitioning a hardware system into modular models according to the functional operation and physical structure of the hardware being modeled,
2. Organizing these modular models into groups that function together to provide higher-level functions to arrive at a nested hierarchy of higher-level models that progresses from the highest functionality of a top-level system to the lowest level functionality of a component (e.g., a top-level system, subsystems, and components),
3. Identifying and encapsulating the variables of model modules that are not needed by surrounding modules, and
4. Defining the model interfaces that will enable models of varying levels of abstraction to be used rapidly for any model module without requiring changes in the interfaces, thus, enabling the capability to plug and play models of varying fidelity, complexity, or abstraction.

A hierarchical architecture is recommended for representing a ground vehicle system model; because, it reduces the complexity of individual graphical diagrams of the model of the system, and the subsystems from which it is constructed. This modeling approach breaks the model in to smaller modules or pieces that are less complicated, and hence, easier to learn, comprehend, and remember. Consequently, the top-level model of the system is a high level abstract representation of the fundamental functional operation; while, the lowest level of the hierarchy represents the physical partitioning and operation.

However, the lowest level of the model, where the implementation of the subsystem would be defined, is not included in the definition of the architecture; because, it needs to be flexible enough to support many different possible implementations used by original equipment manufacturers (OEMs). Hence, the architecture is a structural organization of the fundamental building blocks of a ground vehicle system only; it does not define the implementation of the structure in terms of components or the underlying mathematical equations that describe component behaviors. Otherwise, the usefulness of the architecture would be severely limited.

On any layer of a hierarchical model, it is recommended that the number of model blocks in any diagram should typically be limited to about 5 to 10 blocks for rapid comprehension, if possible. The upper limit on the number of blocks is not a hard constraint and could be higher depending on the system being modeled. However, if the number of blocks becomes too large; then, it is more difficult to understand the relationships between blocks. For more complex systems, a hierarchical modeling structure of modular models enables the use of multiple layers of model diagrams. Thus, the top-level system model would show the interconnection of the major subsystems with the next layer of model diagrams under each major subsystem describing an interconnection of about 5 to 10 subsystems or components and so on. By limiting the amount of information or number of model blocks in any layer, the user can more easily remember and understand the structure and function of the block being modeled with respect to the blocks it connects with.

4.3 General Internal Architecture of a Subsystem

In general, any subsystem can be partitioned internally into at most four functional elements, namely, controller, actuator, plant, and sensor functions (see Figure 4-6). Each of these functions can be thought of as a subsystem; so, in the most general sense, any subsystem has an internal structure consisting of a controller subsystem, actuators subsystem, plant subsystem, and sensors subsystem, as shown in Figure 4-7. This partitioning structure is sometimes called a controller, actuators, plant, and sensors architecture or CAPS architecture. For smart sensors or actuators subsystems with internal controllers, they can also be represented internally by a CAPS architecture.

Functional Partitioning: Controller, Actuators, Plant, and Sensors Functions

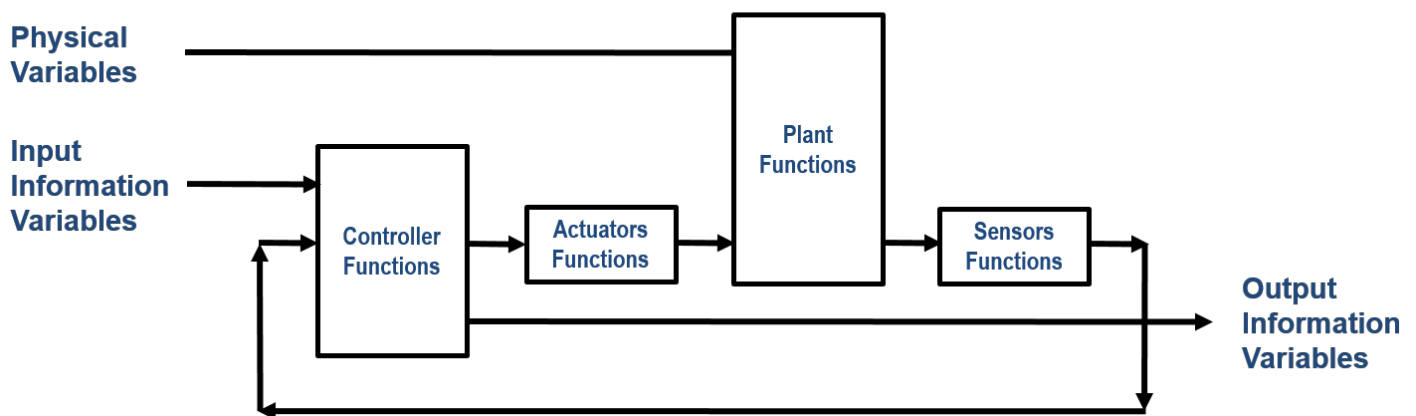


Figure 4-6 - General functional representation of the internal structure a subsystem

CAPS Structure: Controller, Actuators, Plant, and Sensors Subsystem

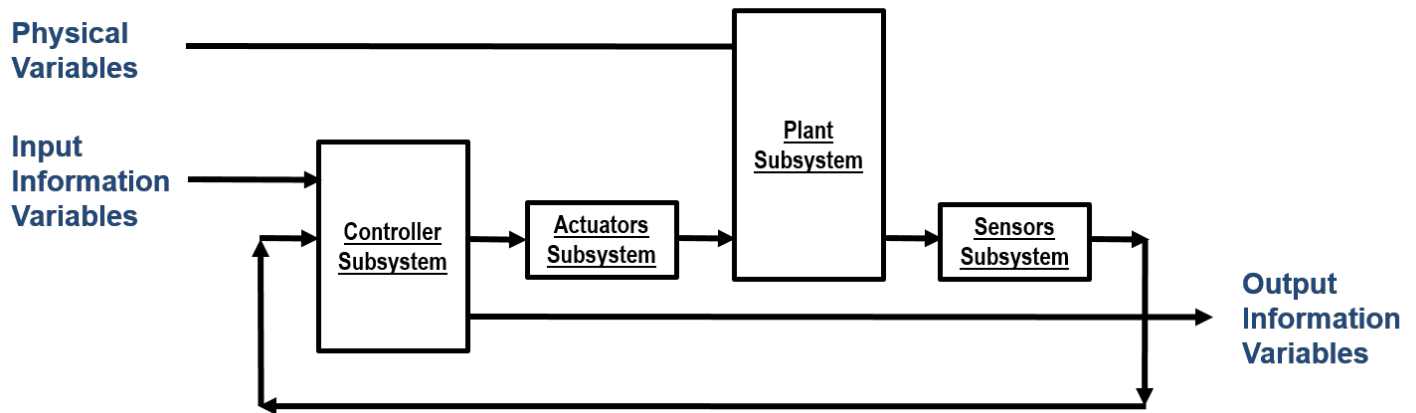


Figure 4-7 - Subsystem partitioned into a controller, actuators, plant, and sensors architecture or CAPS architecture

Alternate arrangements of these four functions are common, where the sensors and actuators functions are incorporated into either the plant subsystem or the controller subsystem for a controller and plant architecture or CP architecture. So, the resulting internal structure of the subsystem consists of either: (1) a controller subsystem and a plant subsystem (which includes the actuators, plant, and sensors functions) as in Figure 4-8, or (2) a controller subsystem (which includes the controller, actuators, and sensors functions) and a plant subsystem as in Figure 4-9.

CP Structure: with Plant, Actuators and Sensors Functions in a Plant Subsystem

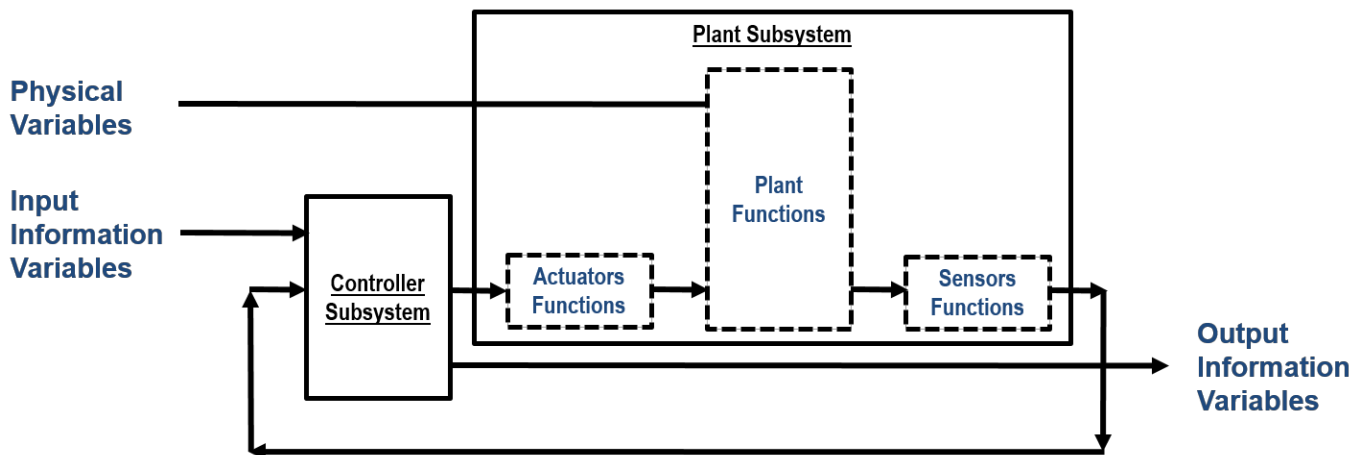


Figure 4-8 - Controller and plant architecture or CP architecture, where the plant subsystem has actuators, plant and sensors functions

CP Structure: with Controller, Actuators, and Sensors Functions in a Controller Subsystem

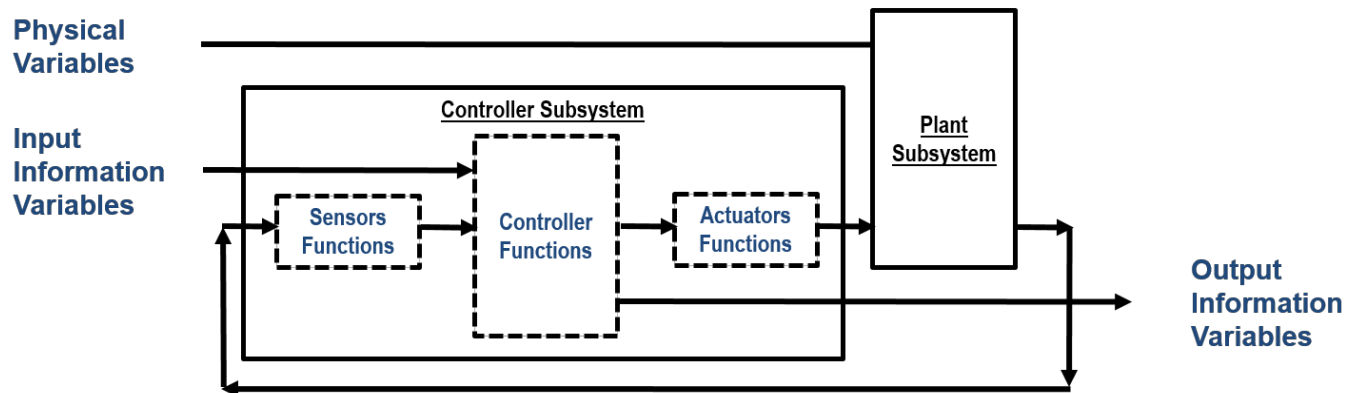


Figure 4-9 - Controller and plant architecture or CP architecture, where the controller subsystem has controller, actuators, and sensors functions

In addition, there may be some subsystems with just a plant subsystem or a controller subsystem without any actuators or sensors functions. Hence, they do not require an internal architecture description, which is illustrated in Figure 4-10 and Figure 4-11.

Controller Subsystem without Actuators, Plant, and Sensors Functions

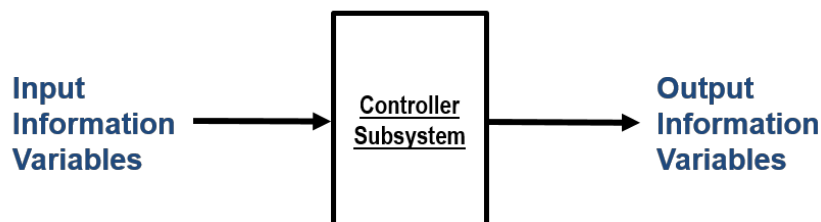


Figure 4-10 - Simple subsystem with only a controller subsystem

Plant Subsystem without Controller, Actuators, and Sensors Subsystem

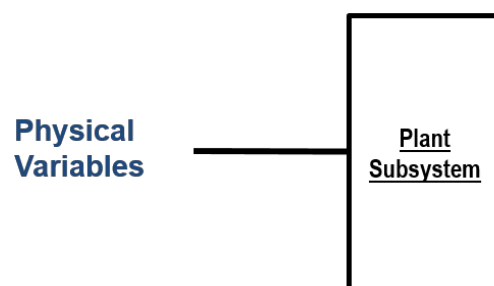


Figure 4-11 - Simple subsystem with only a plant subsystem

By including models of controller, actuators, plant, and sensors subsystems all together inside a single subsystem, it encapsulates all of the variables that the controller needs to interface with the actuators, plant, and sensors. This means the controller will have a minimal impact on the external interfaces of the subsystem, where it is internally located. The only impact of the controller on the interface is the variables that the controller needs to share with other subsystem controllers, such as between the engine and the transmission subsystems or between the engine and chassis subsystems. These external interfaces are illustrated in Figure 4-7 as 'input information variables' and 'output information variables'.

Controllers (such as electronic control modules) are considered as internal subsystems of the subsystems they control. This is done for facilitating plug and play of models of varying fidelity, for simplicity of model diagrams, and for improved understanding of the functional operation of the system or subsystem. For example, by combining a gas internal combustion (IC) engine with its controller in a single model module, then it is easier to replace one gas IC engine with another gas IC engine technology even though they have a different number of sensors and actuators.; because, the connections between the engine plant subsystem model and the models of sensors, actuators, and controller are encapsulated inside the engine subsystem model module and the external interfaces are the same for any gas IC engine. Thus, the models can be quickly substituted with no or minimal reconfiguration of external connections.

4.4 Architectural Conventions

4.4.1 Reference Coordinate Systems

Standard reference coordinate systems are needed to facilitate the exchange and reuse of models. Defining the translational and rotational position and movement of components and subsystems of a ground vehicle system through three-dimensional space, requires several reference coordinate systems to define their relative motions.

The recommended reference coordinate systems are established in ISO8855:2011. It covers a wide range of vehicles from passenger cars and light trucks to heavy duty commercial vehicles with multiple axles that are towing multiple trailers with multiple axles. However, for applications of passenger cars and light trucks with two axles that are towing a single axle trailer, SAE J670_200801 (with the Z-Up orientation) is equally valid. Also, the combination of both ISO8855:2011 and SAE J760_200801 are recommended to provide a complete and precise reference for ground vehicle vocabulary, terminology, coordinate systems, measurement definitions and references, vehicle dynamics, and ride characteristics.

Fundamentally, five reference coordinate systems are defined: (1) earth, (2) vehicle, (3) wheel, (4) tire, and (5) intermediate. These coordinate systems establish right-handed Cartesian axis coordinate systems with three orthogonal directions X, Y, and Z. The coordinate systems for the earth, vehicle, wheel, and tire are defined with an origin tied to a reference point within each of them. Consequently, a separate coordinate system is needed for each wheel, tire, and articulating vehicle section or unit (i.e., chassis and trailers).

For every wheel, tire, and vehicle unit coordinate system, there is also a corresponding intermediate coordinate system. It is used as a reference for measuring rotation (yaw, pitch, and roll) of every vehicle unit, wheel, and tire coordinate system relative to the earth coordinate system. Each intermediate coordinate system has: (1) an origin that is fixed to the origin of every vehicle unit, wheel, and tire coordinate system, (2) a positive Z-axis that is parallel to the positive earth Z-axis, (3) an X-axis and Y-axis that are perpendicular to the gravitational vector, and (4) a plane formed by the positive X-axis and Z-axis that contains the positive X-axis of the vehicle unit, wheel, or tire being referenced by the intermediate coordinate system.

As an example of coordinate system conventions, the coordinate system for a vehicle unit is defined next. For the vehicle coordinate system with the origin located at the vehicle center of gravity, the positive X-axis points in the forward longitudinal direction of the vehicle, the positive Y-axis point to the left, and the positive Z-axis points in the upward direction. And, for the rotational orientation of the vehicle, a positive yaw angle is a counterclockwise rotation around the positive earth Z-axis from the positive earth X-axis direction to the positive intermediate X-axis, a positive pitch angle is a counterclockwise rotation around the positive intermediate Y-axis from the positive intermediate X-axis to the positive vehicle X-axis, and a positive roll angle is a counterclockwise rotation around the positive vehicle X-axis from the positive intermediate Y-axis to the positive vehicle Y-axis. The definitions and details of the other coordinate systems are provided in ISO8855:2011.

4.4.2 Units of Physical Quantities

A standard for the units of all physical quantities, such as variables and parameters, is required; because, it minimizes errors in using and converting units, and reduces computation time for simulations by eliminating unnecessary repeated unit conversion calculations at each time step of the simulation solver. The International System of Units or SI Units is used for measurements. All physical quantities are represented in coherent SI units using the meter-kilogram-second convention as described in SAE TSB003_199905. For reference, APPENDIX A provide a listing of the base units and derived units from the SI Units that are used in this standard recommended practice.

However, non-SI units may be used for monitoring and recording quantities that are produced after the simulation has completed, when post processing of data generated by the simulation.

Also, internal quantities within controller models may use non-SI units, when implementing algorithms or software models of code that use non-SI units in calculations. However, these controllers must convert their inputs from SI to non-SI units and convert their outputs from non-SI units to SI units for compatibility with the rest of the ground vehicle subsystems they are connected.

4.4.3 Subsystem Interface Types

A standard for interface types facilitates parallel and distributed development of models, and efficient and rapid exchange and reuse of models. Interfaces allow a subsystem to connect with other subsystems and exchange the key quantities needed for them to coordinate and function together. Subsystems require three general types of interfaces: (1) Physical Interfaces for exchanging physical quantities between subsystems, (2) Controller Interfaces for exchanging signals, and information between controller subsystems, and other subsystems, and (3) Human Interfaces for the driver and passengers to interact with the subsystems of a Ground Vehicle System through physical means to control and monitor them.

4.4.4 Physical Interfaces

Physical interfaces are classified into to two types: (1) Power Transfer Interfaces, and (2) Physical Conditions Interfaces (non-power transfer interfaces). The purpose of the Power Transfer Interfaces is to describe and emphasize the operation of the interconnected subsystems in terms of the power or energy that is exchanged between subsystems in order for the system to propel the vehicle or perform work functions. And, the purpose of the Physical Conditions Interfaces is to provide physical quantities that describe the state of a subsystem to other subsystems that require these quantities to operate.

Different modeling methods have either formally, through standards, or informally, through common practice, adopted conventions for exchanging power or energy between subsystems. In general, there are physical interface types defined for physical quantities, such as: (1) electrical power, (2) magnetic power, (3) magnetic energy, (4) translational mechanical energy, (5) translational mechanical power, (6) rotational mechanical energy, (7) rotational mechanical power, (8) three-dimensional mechanical energy, (9) thermal power, (10) radiant power, (11) simple fluid flow power, (12) hydraulic power, (13) pneumatic power, (14) thermo fluid flow power, (15) enthalpy flow power, (16) thermodynamic power, (17) chemical power. This list is not meant to be complete, i.e., there can be other power or energy types depending on the modeling approximations, and on the types of power or energy being used, analyzed, and modeled.

For example, the study of noise or sound is important for Ground Vehicle System modeling, analysis, and design. But, acoustical power is not included in the list of power transfer interface types; because, acoustical modeling typically deals with the study of perturbational changes in pressure and velocity of sound waves which do not transport mass. However, because GVS applications require the study of noise and sounds through environments with mass flow; these physical effects are represented in this standard by using simple fluid flow power connections.

Although, some of the physical interfaces describe the transfer of energy, the vast majority of interfaces describe the transfer of power. Hence, the interfaces that deliver power or energy will be collectively referred to as Power Transfer Interfaces. Appendix B.2 provides a table summarizing commonly used Power Transfer Interface types with a listing of the physical quantities that are commonly exchanged through the different forms of power or energy listed above. The summary also describes formulas for calculating either the power or energy exchanged through a physical interface by using the physical quantities available at the interface. In addition, this appendix also provides a table summarizing commonly used Physical Conditions Interface types with a listing of the kinds of physical quantities (other than power or

energy) that are exchanged between subsystems (e.g., atmospheric conditions, physical properties, position coordinates, performance, and ride and handling properties or metrics, et cetera).

4.4.4.1 Controller Interfaces

Besides physical interfaces for exchanging physical quantities between subsystems, controller interfaces are required for exchanging information, data, or signals between subsystems. Controller interfaces are needed to exchange: (1) signals between controllers (e.g., controller commands, controller status, sensor measurements, calculated variables, et cetera) (2) signals between controllers and subsystems (e.g., actuator command signals, sensor signals, et cetera), and (3) information describing conditions of traffic, roads, terrain, and environmental surroundings.

Controller interfaces used for connections between the subsystems of a Ground Vehicle System (GVS) are defined in Section 6, where the purpose of each interface used by each subsystem is described. The controller interface types are summarized and illustrated in Appendix B.3, where a description of the type of information passed through each type is defined.

4.4.4.2 Human Interfaces

Additionally, interfaces are needed for driver and passengers to control and monitor controller subsystems and other vehicle subsystems. The interfaces for human interaction with vehicle subsystems involve physical mechanisms. They may control vehicle operation through the application of physical effort from the hands or feet being applied to pedals, levers, buttons, knobs, steering wheels, touch screens et cetera. Or, they may control the vehicle through voice commands, motions or gestures, et cetera. And, they may monitor the operation of the vehicle through gauges, displays, lights, annunciators, vibrators, alarms, etcetera, which they detect physically through their senses of seeing, hearing, balance, feeling, et cetera. The human interface type is summarized and illustrated in Appendix B.4 where a description of the type of physical mechanisms involved are illustrated.

4.5 Architectural Features for Flexibility

At a high level, the architecture of any ground vehicle can be generalized; because, all types of ground vehicles use the same fundamental physical phenomena or methods to perform work functions and to provide transportation. However, the detailed low-level architecture of the control subsystems and controller subsystems cannot be generalized; since, each manufacturer has different ways of partitioning the control functions between subsystems and groups of subsystems. Hence, the model architecture for a Ground Vehicle System must include flexible features for supporting a range of possible control or controller subsystem architectures.

The model architecture accomplishes this through two features: (1) a general controller architectural structure that defines a network of controllers, and (2) the definition of information busses for facilitating the exchange of information between any of the controller subsystems in the model architecture. The remainder of this section provides an introduction to these two features.

4.5.1 Controller Organizational Structure

The control of a ground vehicle system and subsystems utilizes many controllers or control subsystems that are distributed throughout the vehicle. These controllers may work independently or may be coordinated with each other through a communication network. Since, there is no standard method or architecture for organizing controllers, the model architecture must have a structure that is flexible enough to support a broad range of potential configurations of controllers.

Hence, controller subsystems are assumed to be present in every subsystem in the architecture as described in Section 4.3. In addition, 'supervisory control subsystems' are included in the architecture. These are high level control subsystems. They are used to coordinate and control the controller subsystems within the other subsystems on the same level of the hierarchy with them. These 'supervisory control subsystems' are intended to coordinate and manage the operation of all of the subsystems that work together on that level of the hierarchy. They are not all needed in every Ground Vehicle System model implementation; but are required in the architecture to provide flexibility to support the broad range of controller configurations used across the automotive industry.

A 'supervisory control subsystem' has a controller subsystem as a minimum configuration, but, may also include an actuators subsystem and a sensors subsystem. It does not have a plant subsystem internal to it; since, the plant it is

controlling consists of the other subsystems (on the same level of the hierarchy) and their internal controller subsystems. Hence, the 'supervisory control subsystems' have the word 'control' in their name rather than 'controller' to emphasize that they may also have sensors and actuators to enable them to provide additional higher-level control functions that coordinate and control a collection of subsystems on the same level of the hierarchy.

The controller subsystems and 'supervisory control subsystems' models may represent: (1) a separate electronic controller (i.e., physical hardware) with dedicated software functions for the subsystem being controlled, (2) a separate control subsystem (which could include controller, actuators, sensors, and software functions), (3) control algorithms models for the subsystem being controlled, (4) dedicated software code for the subsystem being controlled, or (5) software code for the subsystem being controlled along with software code for other subsystems (for sharing controller resources efficiently). This structure of 'supervisory control subsystems' and controller subsystems that are distributed throughout the GVS architecture is included to provide the flexibility for supporting different hardware and software implementations, and software that is distributed across several controllers, such as by the automotive software architecture called AUTOSAR (AUTomotive Open System Architecture).

4.5.2 Vehicle and Subsystem Information Busses

In general, a bus is an organized collection of connections between subsystems, where each connection is used to provide, receive or exchange a signal or information. It can be thought of as a bundle of wires or a column vector of items, where each element of the vector corresponds to a signal or information arranged in a prescribed order with one item, stacked on top of another in the column. Similarly, a collection of busses can be combined together to form a larger bus of connections by stacking busses one on top of another to form a larger column vector, where each element of the vector is a bus. This ordered column vector of vectors or ordered bus of busses will be called a 'stacked bus'.

As stated in Section 4.5.1, the architectural structure of the control and controller subsystems are defined as a hierarchical network of interconnected controllers. The controllers are organized into groups that work closely together through a 'supervisory control subsystem'. Also, 'supervisory control subsystems' on the same level of the hierarchy are organized into groups that are managed as a group by another 'supervisory control subsystem' that resides at the next level higher in the hierarchical architecture. To support this coordination and sharing of control functions, an information bus structure is defined with a hierarchical structure that follows the hierarchical structure of the controllers and 'supervisory control subsystems'.

Any controller subsystem may need to share information with other controller subsystems in the system. So, a bus from the controller subsystem is needed to organize the information that each controller needs to share with other controllers within the vehicle system. A subsystem controller bus is defined as a bus structure that is a collection of information from the controller subsystem, which is arranged with one item stacked on top of the other. Similarly, each controller subsystem may need to receive information from other controllers in the system to coordinate their operation. Figure 4-12 shows that 'Subsystem X' Controller receives information from the rest of the vehicle through a 'Vehicle Information Bus', a 'Group-Subsystem Supervisory Bus', and a 'Group-Subsystem Information Bus'; and provides information to the rest of the system through a 'Subsystem Information Bus' (or the 'Subsystem X' Controller Bus). The 'Group-Subsystem Information Bus' provides any information that 'Subsystem X' needs to receive and share with other controllers that it must work with in the same group of subsystems. And, the 'Group-Subsystem Supervisory Bus' provides 'Subsystem X' with commands to supervise and coordinate it with other subsystems in the group and in the rest of the Ground Vehicle System. Finally, the 'Vehicle Information Bus' provides information that 'Subsystem X' needs to share and receive from any controllers outside of the group-subsystem.

'Subsystem X' Architecture with Controller Information Busses

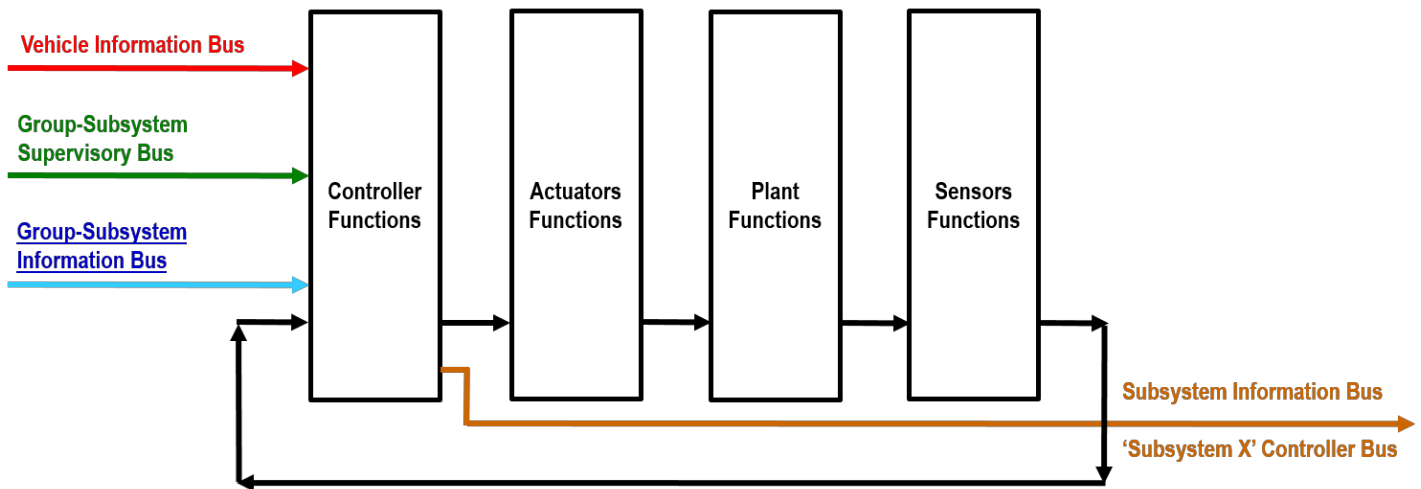


Figure 4-12 - General subsystem architecture and controller bus structure

Depending upon the analysis being done, a subsystem model may require a more in-depth model with components replaced by subsystems that provide more details about the inner workings of the components. Under these conditions, a subsystem model may be represented as a higher-level subsystem model that requires several hierarchical layers of subsystems, before the general subsystem architecture in Figure 4-12 is needed. The higher-level subsystem model has the same external interfaces as the subsystem shown in Figure 4-12; consequently, a higher-level model can easily replace a subsystem model. However, the internal architecture is different and is composed of a 'Supervisory Control Subsystem' that coordinates a group of subsystems.

The general architecture for a higher-level subsystem is shown in Figure 4-13. In this diagram 'Subsystem X' has the same external interfaces as the general subsystem model in Figure 4-12, where it receives information from the 'Vehicle Information Bus', a 'Group-Subsystem Supervisory Bus', and a 'Group-Subsystem Information Bus', and provides information to the other subsystems in the vehicle through the 'Subsystem X Controller Bus'. However, internally, it is composed of a 'Subsystem X Supervisory Controller Subsystem' (i.e., the controller of the 'Subsystem X Supervisory Control Subsystem'), which creates a 'Subsystem X Supervisory Bus' to supervise and coordinate the control of the internal subsystems numbered from 1 to N, and a 'Subsystem X Information Bus' for information that needs to be shared between the controllers inside and outside of 'Subsystem X'.

The 'Subsystem X Supervisory Controller Subsystem' also creates a 'Subsystem X Supervisory Controller Bus' for information that it produces and needs to share with other controllers. This bus is contained inside the 'Subsystem X Supervisory Controller Subsystem', and does not appear in Figure 4-13. The 'Subsystem X Supervisory Controller Subsystem' combines the 'Subsystem X Supervisory Controller Bus' with controller busses that it receives from each of the top-level controllers of 'Subsystem X', and produces a 'Subsystem X Information Bus'. And, the 'Subsystem X Information Bus' is shared internally with all of the top-level controllers of the 'Subsystem X' Subsystem and externally with outside controllers on the 'Subsystem X Controller Bus'. Again, as stated in in Section 4.5.1 for controller architecture flexibility, every subsystem is assumed to have an internal controller subsystem. Each of the N+1 controllers (i.e., 'Subsystem X Supervisory Control Subsystem' controller, and the controllers of the N subsystems) may place information on the 'Subsystem X Information Bus' that they need to share with controllers inside or outside of the 'Subsystem X' Subsystem. They receive information that they need from controllers inside 'Subsystem X' Subsystem on the 'Subsystem X Information Bus', and from controllers outside of the 'Subsystem X' Subsystem on the 'Vehicle Information Bus' (See Table 51 for a description of the 'Subsystem X' busses.).

External to the 'Subsystem X' Subsystem, the 'Subsystem X Information Bus' is called the 'Subsystem X Controller Bus'. The reason for this convention is to maintain the consistency of the model architecture and interfaces of the controller bus structure, when a lower-level subsystem model is replaced with a more detailed higher-level model that has an internal structure composed of several subsystems. This convention supports flexibility and expandability of the architecture to support plug-and-play of models and to support any controller network configuration or partitioning of controller functions.

Higher-level models may also be used to represent several subsystems that function independently but are located within the same higher-level subsystem. In this situation, the higher-level subsystem model is used to provide a flexible controller bus structure to integrate all of the subsystems into the overall Vehicle Information Bus structure for sharing information with controllers outside of the subsystem where they reside. In general, a higher-level subsystem can represent a collection of subsystems that work in concert to provide a common function, that work independently, or that combine some integrated and some independent subsystems.

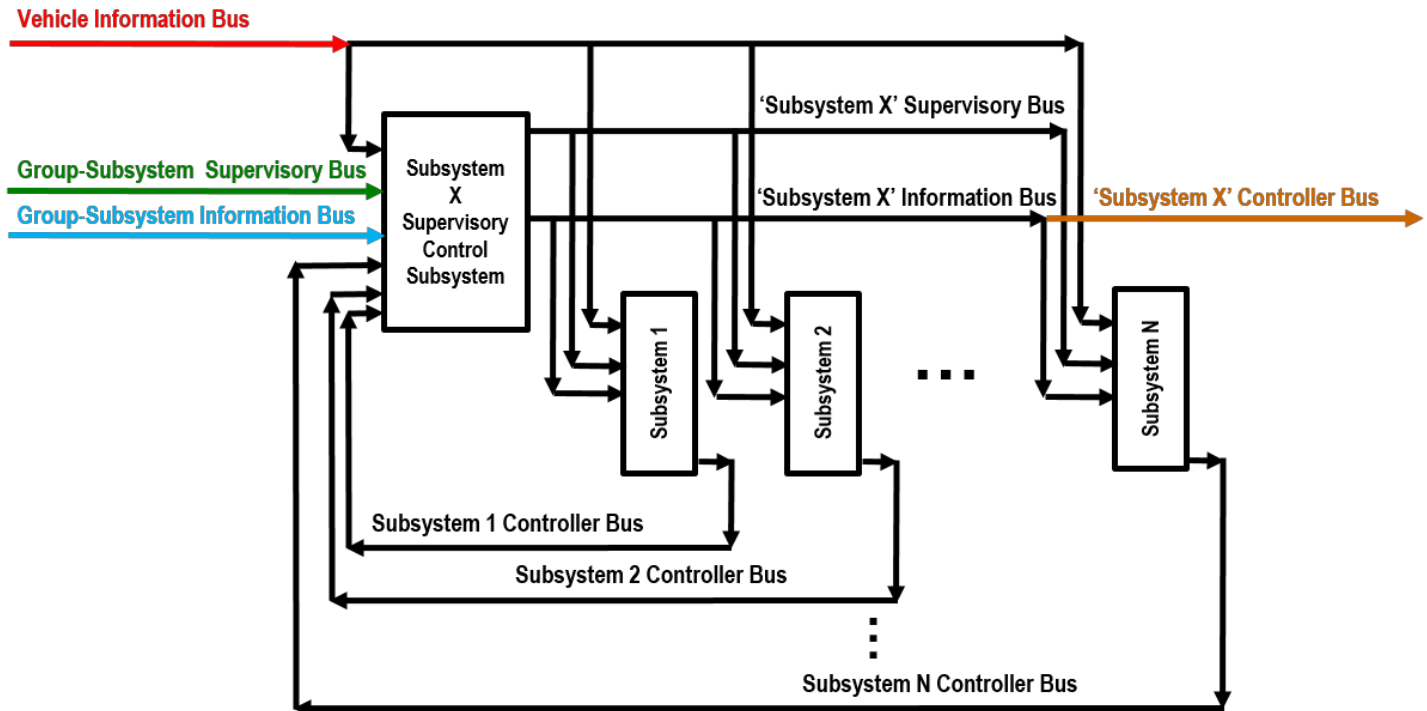


Figure 4-13 - Higher-level subsystem architecture and controller bus structure

Figure 4-14 depicts the general architecture of the 'Vehicle Information Bus'. In this diagram, the construction of the hierarchical information bus for an entire vehicle system starts at the lowest level in the lower right corner and progresses to the left and upward as busses are collected and combined by stacking one on top of the other to define higher-level busses. Each subsystem may have a Subsystem Controller Bus (which is shown in the lower right corner of the diagram) to supply information it needs to share with other controllers within the vehicle system. To the left of the Subsystem Controller Bus in Figure 4-14, a group of subsystem controllers that work together to provide a greater function are combined in an orderly fashion to form a bus to share information between the controllers as need for them to work together. This bus is composed of the Subsystem Controller Bus for each of the subsystems in the group stacked one on top of the other with the Group-Subsystem Supervisory Controller Bus placed on top of this to form a 'Group-Subsystem Information Bus'. The subsystem controllers in the group will extract only the information that they need from this local shared bus. Similarly, all of the controller information from all of the Group Information Busses are stacked on top of each other in an orderly fashion. Finally, a 'Vehicle Supervisory Controller Bus' is stacked on top of this collection of busses to form the 'Vehicle Information Bus', which is located at the upper left corner of the diagram. It is a stacked bus of all of the information that needs to be shared between all of the controllers in the entire vehicle system.

The 'Vehicle Information Bus' defines an organized bus structure for exchanging information between controllers, where each controller subsystem has an assigned location within the bus for transferring information required by other controllers within the vehicle system. Although, the 'Vehicle Information Bus' contains all of the shared information, the subsystem controllers requiring the information only take the information that they need.

Figure 4-12 shows that the 'Vehicle Information Bus' may be connected to the controller subsystem of any general 'Subsystem X'; so, any controller in the system can extract only the information that it needs from controllers outside of the group-subsystem, where it resides. The 'Subsystem X' Controller may receive and share information with all of the other controllers within the same group-subsystem through a 'Group-Subsystem Information Bus'. These information busses are structured in a hierarchical manner to complement the hierarchical model architecture. The 'Vehicle Information Bus' may provide the 'Subsystem X' Controller with information about controllers outside of the local group.

The 'Group-Subsystem Supervisory Bus' may coordinate the group-subsystem with the vehicle and with the other controllers inside the group. And, the 'Group-Subsystem Information Bus' may share information primarily between controllers within the group, and secondarily with any controller in the vehicle system. This hierarchical information bus structure enables tighter control within the local group by reducing delays in information between controllers that work closely together; so, the local group can operate more responsively.

Vehicle Information Bus

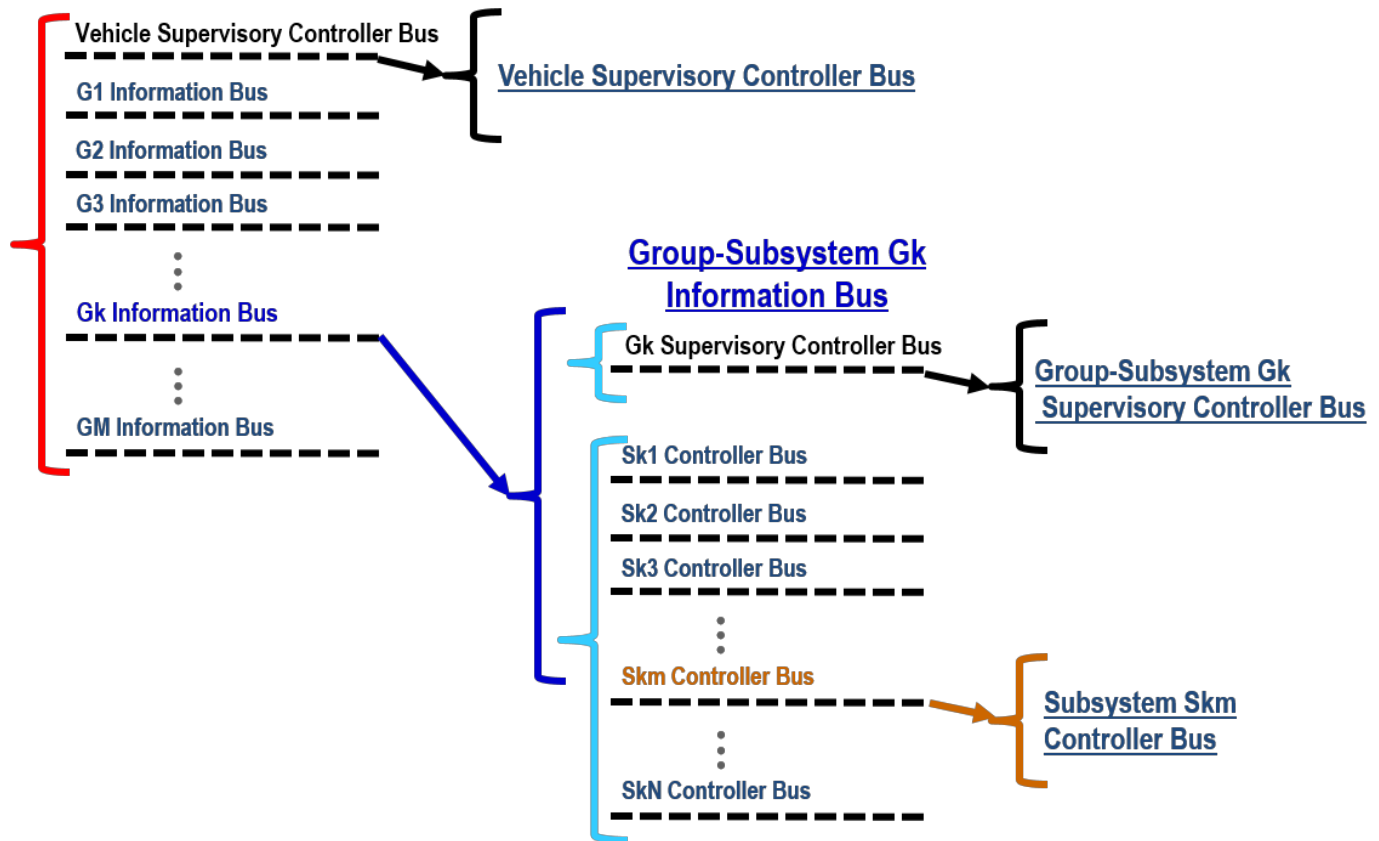


Figure 4-14 - General hierarchical structure of a Vehicle Information Bus

Thus, the 'Vehicle Information Bus' carries only the information that needs to be shared between other controller subsystems in the vehicle architecture. For reference, the 'Vehicle Information Bus and all of the 'subsystem information buses' from which it is constructed are defined in Appendix B.5, where the architectural organization of the busses is defined. This hierarchical bus structure for the Vehicle Information Bus enables information to be shared between any controller subsystems in the model architecture, which provides the flexibility needed in the architecture to support any type of controller or control subsystem partitioning of controller software functions required by AUTOSAR.

5. HIERARCHICAL ARCHITECTURE OF A GROUND VEHICLE SYSTEM

5.1 Introduction and Overview

This section provides an overview of the architecture for a Ground Vehicle System (GVS) model. It defines the partitioning of the GVS into subsystems, which are the fundamental building blocks of the system. Some of the subsystems are partitioned further into a collection of subsystems, which work in concert to provide the function of the greater subsystem containing them.

A hierarchical organization diagram is used to introduce the fundamental subsystems of a GVS and to show the relationships between them. This diagram is structured similar to the organization chart of a company, which shows the hierarchical structure of the company partitioned into layers, where each layer describes the partitioning of the company into smaller operating units. The layers of the organization chart proceed from the company at the top level followed on successive levels by divisions of the company, departments under each division, groups in each department, and people within each group.

Similarly, the hierarchical organization diagram of a Ground Vehicle System shows a partitioning of layers of subsystems, which define the fundamental building blocks of the architecture. Starting at the top of the diagram with a Ground Vehicle System, lines connect the GVS to a collection of subsystems on the next level below it, which defines the partitioning of the GVS. Some of these subsystems are connected by lines to a collection of subsystems on the next level below them, which defines the subsystems contained within the subsystem on the layer above. This structure continues from one layer to the next until all of the fundamental subsystems of the GVS are defined.

The architecture defines all of the subsystems that could be present in a model of a Ground Vehicle System. The structure of the architecture is designed with flexibility to support modeling of all types of ground vehicles, analyses, modeling methods, modeling assumptions, and model complexity. Not all of the subsystems shown in the architecture are needed for every simulation model. Hence, only a subset of subsystems would be needed for a specific model, depending upon the modeling and simulation task.

In the remainder of Section 5, the entire hierarchical organization of the Ground Vehicle Subsystem is introduced, starting at the top and progressing through the diagram to the next level down, then from left to right across each level, and continuing this process to the end of the diagram. After, the hierarchical diagram for a GVS is defined, it will serve as a high-level road map of the architecture for the rest of this specification. The intention of this section is to provide only a big picture of the entire partitioning of the GVS. Hence, the names and high-level description of the subsystems are only defined here. The purpose, function, and interfaces of each subsystem are defined in more detail in Section 6.

5.2 Top-Level Architectural Organization and Partitioning

The top-level of the hierarchical diagram for a Ground Vehicle System describes the system at the most basic level of functional operation. It is a functional partitioning that captures the fundamental purpose or mission of the system. For a Ground Vehicle System, the top-level diagram is shown highlighted in light blue in Figure 5-1, which consists of the following three subsystems:

1. Environment Subsystem,
2. Driver/Passengers Subsystem, and
3. Vehicle Subsystem.

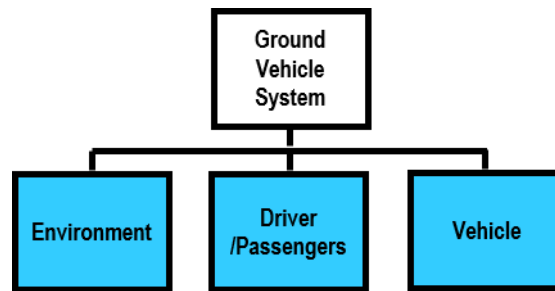


Figure 5-1 - Ground Vehicle System hierarchical organization into top-level subsystems

The Environment Subsystem encompasses the space surrounding the driver, passengers, and vehicle. And, the Driver/Passengers Subsystem defines the humans that control and monitor the functioning of the vehicle and the subsystems it contains, as it is operated by the driver and passengers in the environment. The Vehicle Subsystem defines the means for humans to be transported through the environment or to perform work on it. This partitioning describes the essential purpose of a Ground Vehicle System at the highest level of functional abstraction, which is to provide a means for people to move through their environment. More generally, a ground vehicle is a means for people to transport themselves and their goods from one point to another, or to perform work on their environmental surroundings. The remainder of Section 5 defines the partitioning of these three subsystems in terms of their internal subsystems and continuing on to lower-level subsystems until the hierarchical architecture is completely defined.

5.3 Environment Subsystem Organization and Partitioning

The subsystems of the Environment Subsystem consist of the following four subsystems, which are highlighted in light blue in Figure 5-2:

1. Atmospheric Subsystem,
2. Road/Terrain Subsystem,
3. Traffic/Surroundings Subsystem, and
4. Remote Human-Machine Interface (HMI) Subsystem.

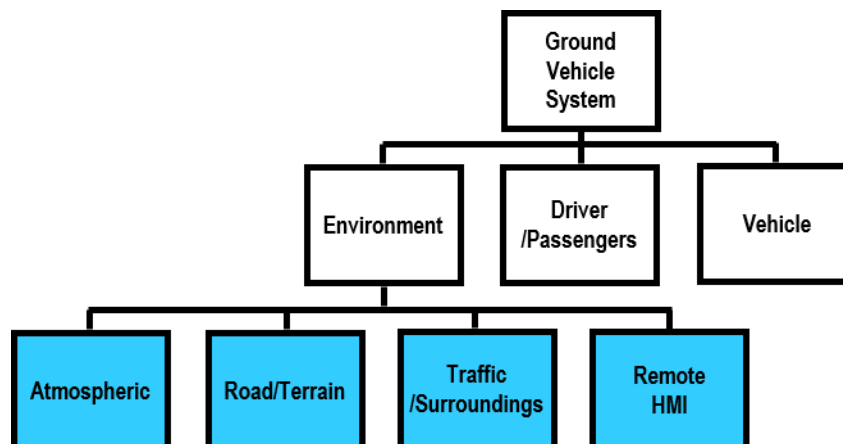


Figure 5-2 - Environment Subsystem hierarchical organization

Moving from left to right in Figure 5-2, the four subsystems define the fundamental characteristics of the environmental surroundings of the vehicle and driver in terms of: (1) the state of the atmosphere, which the Atmospheric Subsystem describes, (2) the surface conditions of the ground on the road or terrain under the vehicle, which the Road/Terrain Subsystem defines, (3) the state of the traffic (vehicles and pedestrians) and the traffic infrastructure and natural features around the vehicle, which the Traffic/Surroundings Subsystem models, and (4) the interface and surroundings from which a remotely located driver controls the vehicle, which the Remote HMI Subsystem describes. The Remote HMI Subsystem may be located quite a distance from the immediate environment of the vehicle and is only required for applications with teleoperation.

5.4 Driver/Passengers Subsystem Organization and Partitioning

The Driver/Passengers Subsystem is partitioned into the following three subsystems, which are highlighted in light blue in Figure 5-3:

1. Driver Subsystem,
2. Remote Driver Subsystem, and
3. Passengers Subsystem.

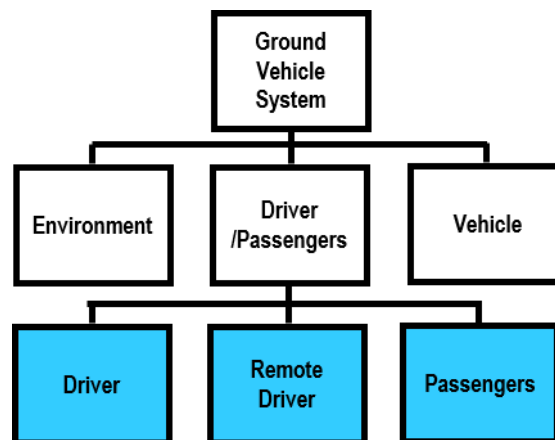


Figure 5-3 - Driver/Passengers Subsystem hierarchical organization

These subsystems describe the human beings who control the vehicle and the vehicle subsystems. The Driver Subsystem describes the actions of the human controlling vehicle motion, work functions, and other features and functions. And, the Remote Driver Subsystem, which is only required for applications using teleoperation, defines the actions of a human controlling the vehicle from a remote location outside of the vehicle. Both a Driver Subsystem and a Remote Driver Subsystem are needed; because there are applications that require both of them to be able to control the vehicle. For these applications, both drivers may be controlling the vehicle in the transition periods when control responsibility is transferred between drivers. Finally, the Passengers Subsystem models the action of human occupants in controlling vehicle work functions, and other features and functions, but not vehicle motion.

5.5 Vehicle Subsystem Organization and Partitioning

The Vehicle Subsystem can be described at the highest level of functional abstraction as consisting of the following four subsystems highlighted in light blue in Figure 5-4:

1. Vehicle Supervisory Control Subsystem,
2. Power Subsystem,
3. Chassis Subsystem, and
4. Trailer 1 Subsystem.

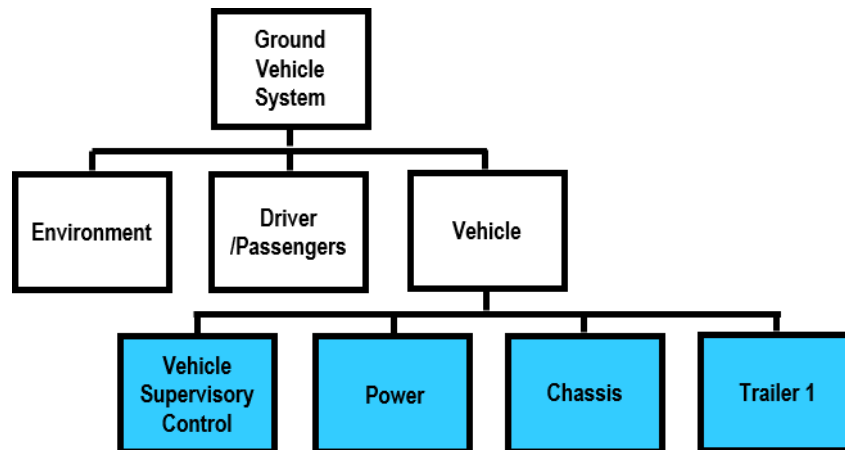


Figure 5-4 - Vehicle Subsystem hierarchical organization

These subsystems work together to provide the primary functions of a ground vehicle. The Vehicle Supervisory Control Subsystem is a high-level controller that monitors the capabilities of the Vehicle Subsystem and coordinates the requests of the humans controlling the vehicle with the capabilities of all of the other subsystems of the Vehicle Subsystem at this level of the hierarchy. Supplying the power needed to provide all the functions and features of a vehicle, such as transporting people and goods, performing work tasks, and providing safety, convenience, and infotainment, is the main function of the Power Subsystem. The Chassis Subsystem provides the means for carrying the driver, passenger, and their goods in an enclosed safe and comfortable environment, for converting power into motion, and for controlling the motion and direction of the vehicle. For some vehicles, additional capacity for carrying goods or performing additional work functions are provided by the Trailer 1 Subsystem, which would be towed behind the chassis. The Trailer 1 Subsystem has the number '1' included in the name to establish a consistent name for vehicles that may be towing several trailers connected sequentially one after the other in a line. Hence, additional trailers are named with a number corresponding to their location in the line of trailers behind the chassis. The additional trailers are named 'Trailer i Subsystem', where $i \in [2, N]$ for a trailer train with N trailers. And, for this case, additional trailer subsystem blocks would need to be added to the right of the Trailer 1 Subsystem in Figure 5-4.

5.5.1 Power Subsystem Organization and Partitioning

The Power Subsystem is composed of the following eight subsystems, which are highlighted in light blue in Figure 5-5:

1. Power Supervisory Control Subsystem,
2. Electrical Subsystem,
3. Thermal Management Subsystem,
4. Fuel Subsystem,
5. Propulsion Power Subsystem,
6. Auxiliary Power Subsystem,
7. Transmission Subsystem, and
8. Driveline Subsystem.

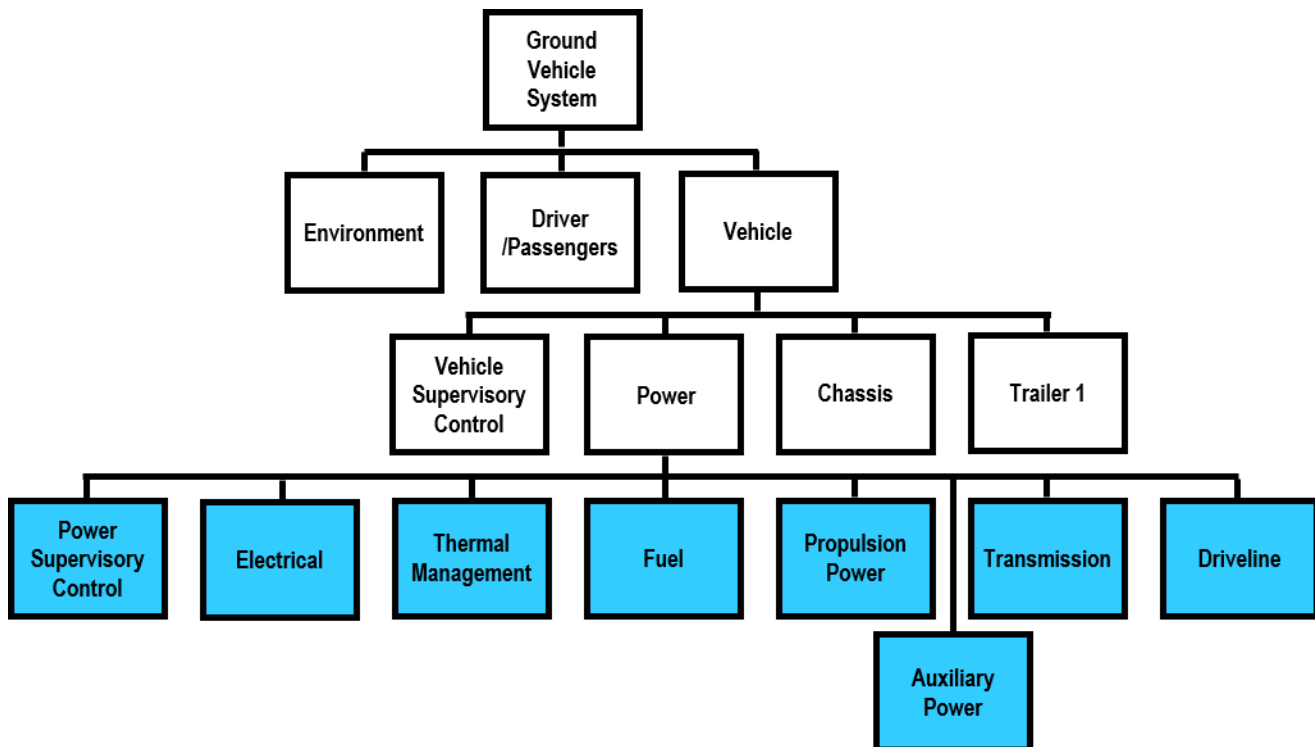


Figure 5-5 - Power Subsystem hierarchical organization

These subsystems are interrelated and work together to provide the primary power for propelling the vehicle and secondary power for auxiliary functions. The Power Supervisory Control Subsystem is a high-level controller that monitors the capabilities of the Power Subsystem and coordinates the requests of the human controlling the vehicle with the capabilities of all of the other subsystems of the Power Subsystem at this level of the hierarchy. The electrical power required for all of the subsystems of the GVS is stored, conditioned, and distributed by the Electrical Subsystem. Power production creates heat that is managed by Thermal Management Subsystem. This includes cooling of power producing components for proper operation and durability, supplying heat to the cabin for comfort, or supplying heat to selected components to ensure efficient and proper operation. Fuel is stored, monitored, conditioned, pumped, and distributed by the Fuel Subsystem to the subsystems requiring it.

The subsystems of the Power Subsystem introduced so far provide functions necessary to support the Propulsion Power Subsystem, which is the primary source of mechanical power for propelling the vehicle and powering many of the accessory functions. The propulsion power produced is transformed by the Transmission Subsystem to provide the proper torque and speed required to launch, accelerate, or decelerate the vehicle, while maintaining the Propulsion Power Subsystem at desired operating conditions for durability, component protection, and efficiency. Finally, the Driveline Subsystem distributes the mechanical power to the wheels or tracks of the vehicle to propel the vehicle.

For some applications, power is needed for non-propulsive work functions, and/or functions for the comfort and convenience of the driver or passengers for extended periods when the vehicle is parked or stationary at work sites or during driver rest periods. Under these conditions, it is more efficient to have a separate power source, called an Auxiliary Power Subsystem to produce the power in place of the Propulsion Power Subsystem, which is designed to provide the power necessary to propel the vehicle at full load on steep grades. Since, the Auxiliary Power Subsystem is not common for all ground vehicle applications; it is shown on a separate row of the hierarchical organization chart to emphasize this fact.

5.5.2 Chassis Subsystem Organization and Partitioning

The Chassis Subsystem is partitioned into the following seven subsystems, which are highlighted in light blue in Figure 5-6:

1. Chassis Supervisory Control Subsystem,
2. Steering Subsystem,
3. Braking Subsystem,
4. Wheels/Tracks Subsystem,
5. Suspension Subsystem,
6. Body-Frame Subsystem, and
7. Power Take-Off (PTO) Accessories Subsystem.

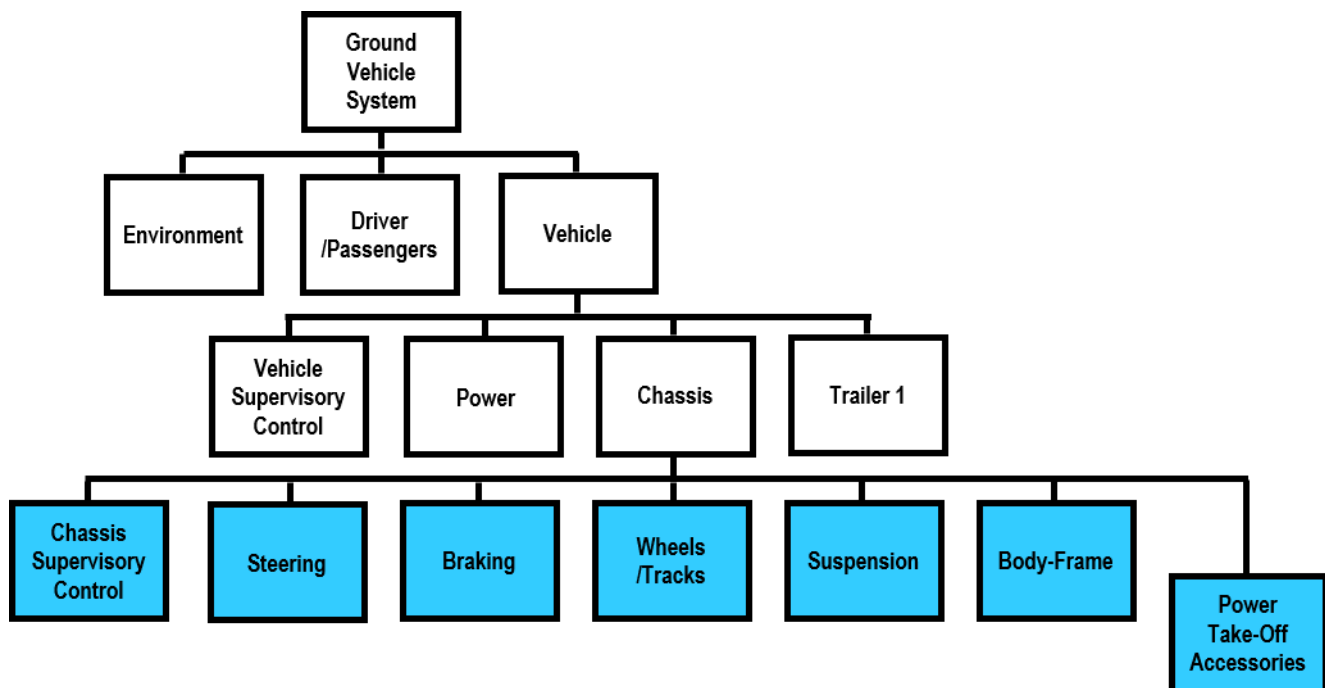


Figure 5-6 - Chassis Subsystem hierarchical organization

These subsystems are interrelated and work together to provide the means for carrying the driver, passengers, and their goods in an enclosed, safe, and comfortable environment. They convert the propelling power produced by the Power Subsystem into translational motion, reduce the effect of rough surface conditions on ride comfort, provide a means for slowing and stopping, and provide the means for changing the direction of travel. The Chassis Supervisory Control Subsystem is a high-level controller that coordinates the operation of all of the subsystems of the Chassis Subsystem by monitoring the capabilities of these subsystems and coordinating the requests of the human controlling the vehicle with the capabilities of all of the other subsystems of the Chassis Subsystem at this level of the hierarchy.

The lateral direction of travel of the Chassis Subsystem is controlled by the Steering Subsystem. The chassis motion is decelerated or stopped by the Braking Subsystem. The chassis is propelled by the Wheels/Tracks Subsystem, which receives rotational mechanical power from the Propulsion Power Subsystem of the Power Subsystem and converts this into translational mechanical power to move the vehicle along the ground surface. A Suspension Subsystem transfers the translational mechanical power from the wheels/tracks to the Body-Frame Subsystem. The Body-Frame Subsystem provides a protected and comfortable enclosure for transporting people and their goods. Vertical motion of the wheels/tracks is transferred to the Suspension Subsystem, which filters out the motion to provide a smoother ride for occupants and goods. For some applications, there are accessories mounted on the Body-Frame Subsystem for providing work functions, such as hoists, lifts, winches, cherry pickers, snow plows, et cetera. These accessories are contained in the Power Take-Off (PTO) Accessories Subsystem. Since, the Power Take-Off Accessories Subsystem is not common for all ground vehicle applications; it is shown on a separate row of the hierarchical organization chart to emphasize this fact.

5.5.2.1 Body-Frame Subsystem Organization and Partitioning

The Body-Frame Subsystem is comprised of the following five subsystems, which are highlighted in light blue in Figure 5-7:

1. Body-Frame Supervisory Control Subsystem,
2. Under Body Subsystem,
3. Upper Body Subsystem,
4. Cabin Interior Subsystem, and
5. Cabin Climate Subsystem.

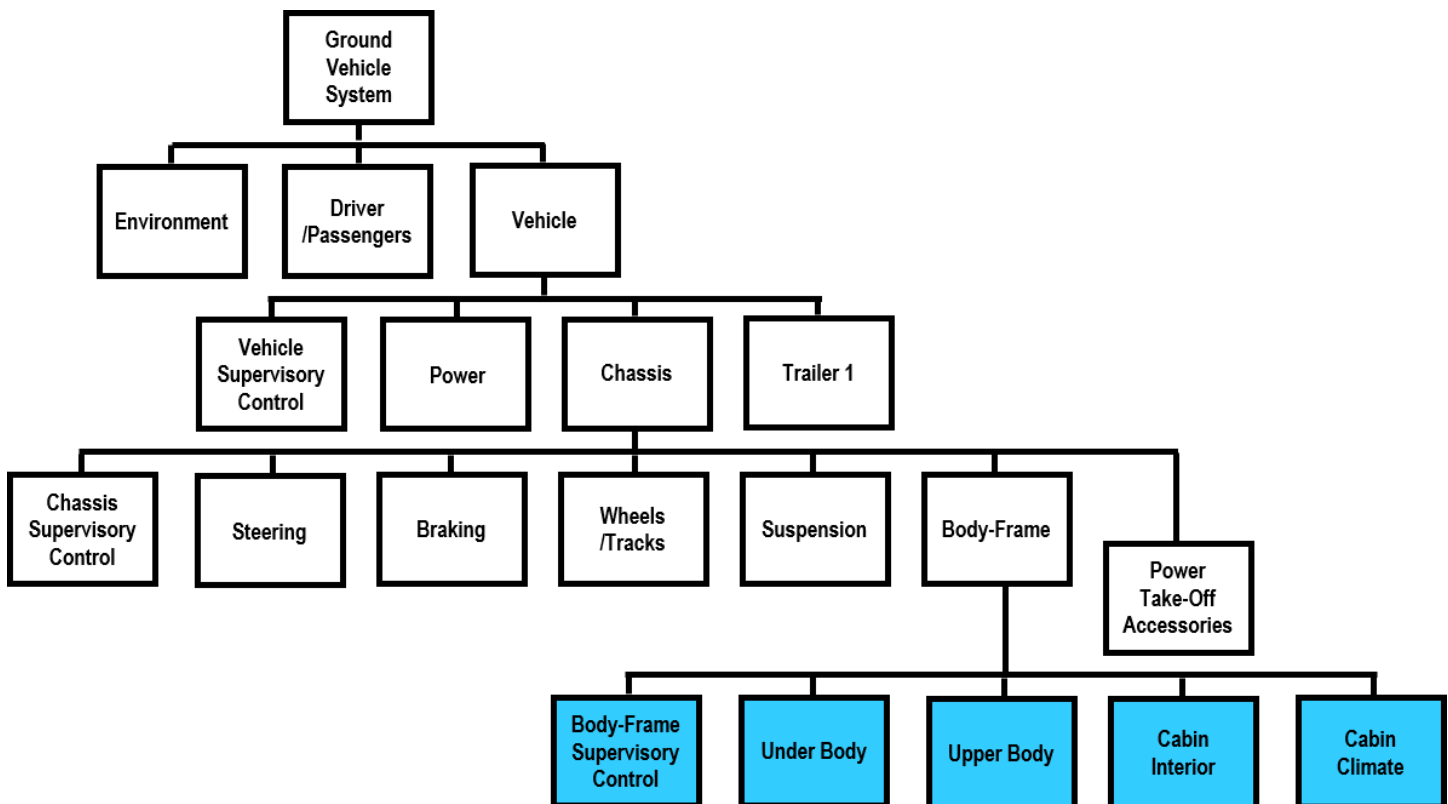


Figure 5-7 - Body-Frame Subsystem hierarchical organization

These subsystems are interrelated and work together to provide an enclosed space that is protected from the elements of the weather, with seating for transporting people, storage areas for transporting goods, and subsystems for controlling the climate of the enclosed space. The Body-Frame Subsystem Supervisory Control Subsystem supervises and coordinates the control of all of the subsystems in the Body-Frame Subsystem. In addition, it provides a flexible controller information bus structure for coordinating all of subsystem controllers in the Body-Frame Subsystem with each other and with controllers throughout the Vehicle Subsystem, as needed. It is a high-level controller that coordinates the operation of all of the subsystems of the Body-Frame Subsystem by monitoring the capabilities of these subsystems and coordinating the requests of the human controlling the vehicle with the capabilities of all of the other subsystems of the Body-Frame Subsystem at this level of the hierarchy.

The lower portion of the Body-Frame Subsystem that is connected to the Suspension Subsystem is called the Under Body Subsystem. It is connected to the Upper Body Subsystem, which forms the upper portion of the Body-Frame Subsystem. The Cabin Interior Subsystem describes the interior parts of the structure that are mounted to and enclosed by the under and upper body to form a compartment or cabin for the driver and passengers. These three subsystems together provide a complete description of the structural aspects of the chassis. And, the structure created provides a means for mounting and integrating all of the vehicle subsystems and components into the Vehicle Subsystem. They also form an interior space that creates an enclosed environment called the Cabin Climate Subsystem, which contains subsystems for controlling the interior environment to provide a comfortable local climate for transporting people and their goods.

5.5.3 Trailer 1 Subsystem Organization and Partitioning

The Trailer 1 Subsystem is structurally similar to the Chassis Subsystem, and hence, is partitioned similarly into the following seven subsystems, which are highlighted in light blue in Figure 5-8:

1. Trailer 1 Supervisory Control Subsystem,
2. Trailer 1 Steering Subsystem,
3. Trailer 1 Braking Subsystem,
4. Trailer 1 Wheels/Tracks Subsystem,
5. Trailer 1 Suspension Subsystem, and
6. Trailer 1 Body-Frame Subsystem, and
7. Trailer 1 PTO Accessories Subsystem.

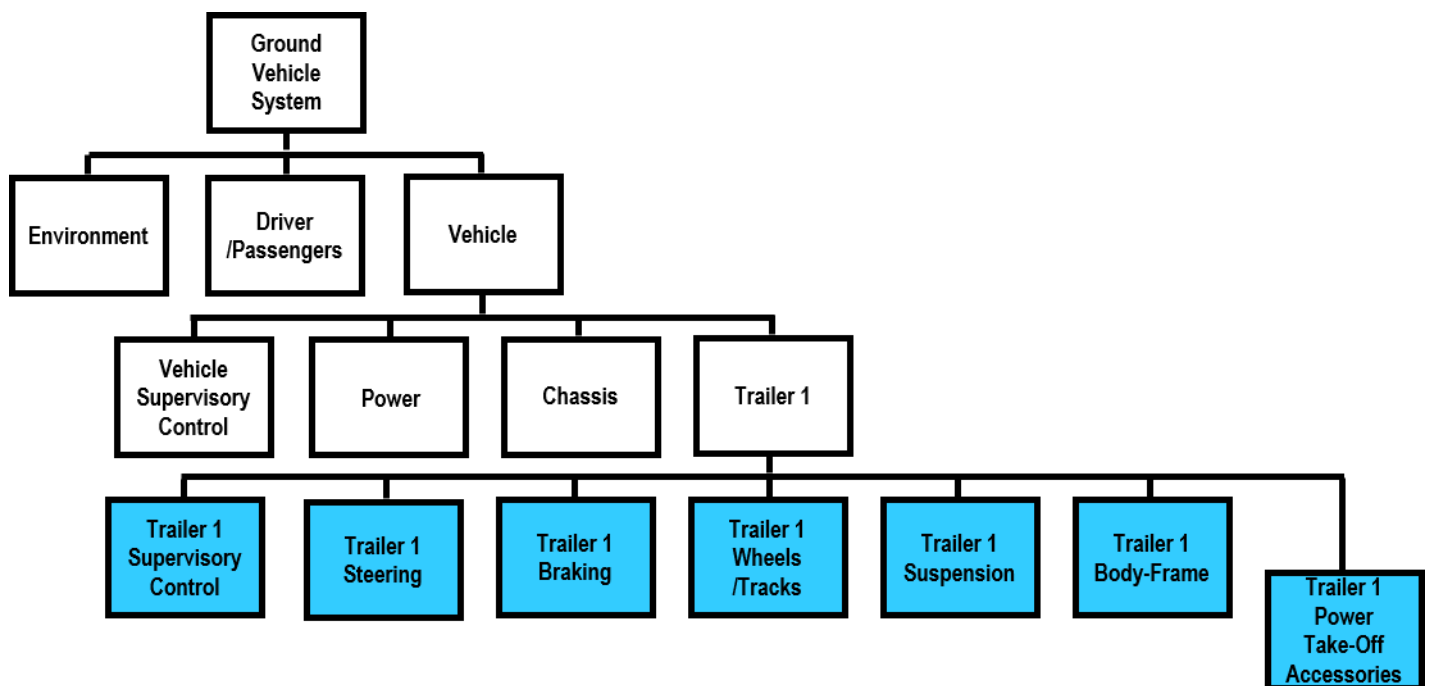


Figure 5-8 - Trailer 1 Subsystem hierarchical organization

These subsystems are interrelated and work together to provide the means for carrying additional goods and/or passengers in an enclosed, safe, and comfortable environment. They transfer the translational motion and pulling power of the Chassis Subsystem into translational motion of the trailer, reduce the effect of rough surface conditions on ride comfort, provide a means for slowing and stopping, and provide the means for changing the direction of the travel. The description and purpose of each of these subsystems of the Trailer 1 Subsystem is the same as the similarly named subsystems of the Chassis Subsystem described in Section 5.5.2. The identifier Trailer 1 is added to the beginning of the name of each of the subsystems to make the subsystem names unique. Again, the Trailer 1 Power Take-Off Accessories Subsystem is not common for all ground vehicle applications; hence, it is shown on a separate row of the hierarchical organization chart to emphasize this fact.

5.5.3.1 Trailer 1 Body-Frame Subsystem Organization and Partitioning

The Trailer 1 Body-Frame Subsystem is comprised of the following five subsystems, which are highlighted in light blue in Figure 5-9:

1. Trailer 1 Body-Frame Supervisory Control Subsystem,
2. Trailer 1 Under Body Subsystem,
3. Trailer 1 Upper Body Subsystem,
4. Trailer 1 Interior Subsystem, and
5. Trailer 1 Climate Subsystem.

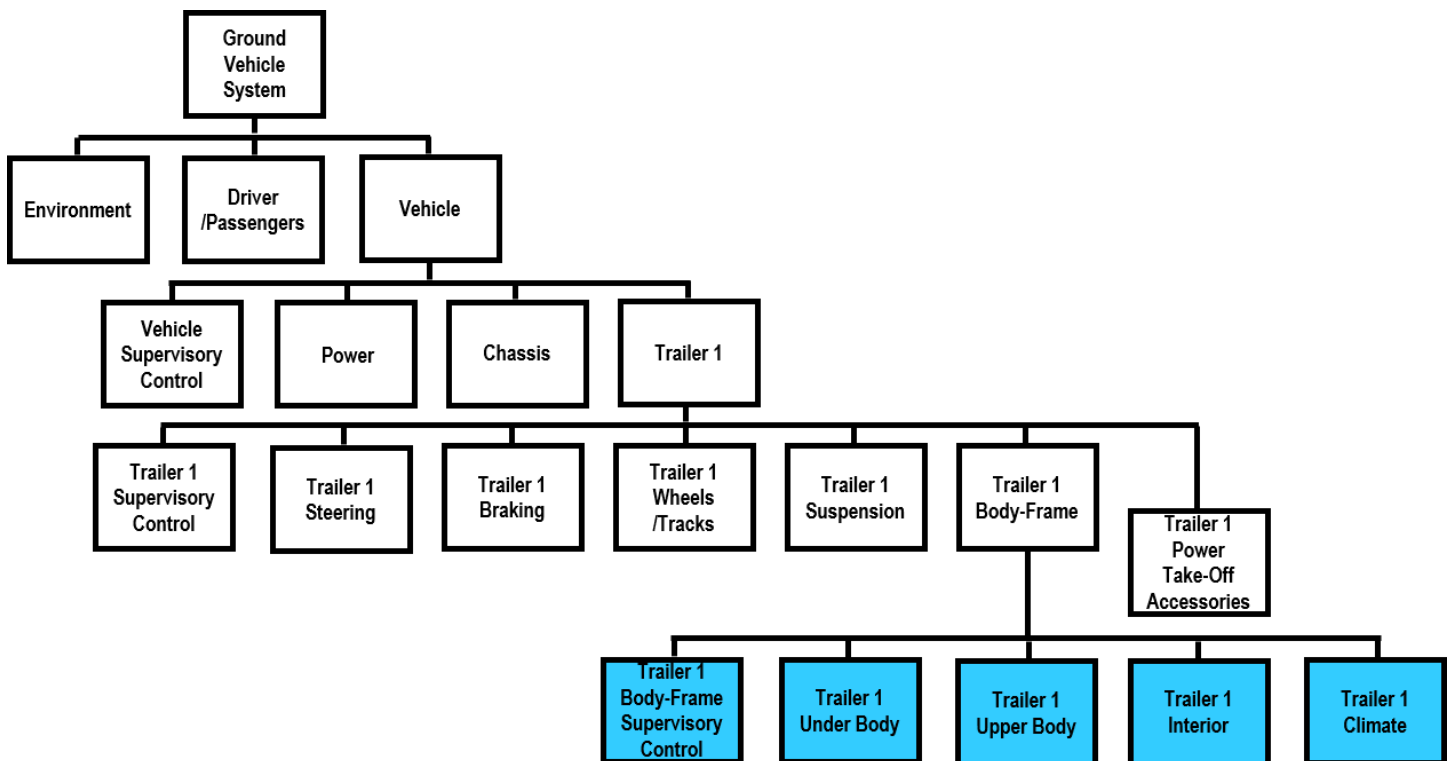


Figure 5-9 - Trailer 1 Body-Frame Subsystem hierarchical organization

These subsystems are interrelated and work together to provide an enclosed space that is protected from the elements of the weather, with seating for transporting people, storage areas for transporting goods, and subsystems for controlling the climate of the enclosed space. The Trailer 1 Body-Frame Subsystem Supervisory Control Subsystem supervises and coordinates the control of all of the subsystems in the Trailer 1 Body-Frame Subsystem. In addition, it provides a flexible controller information bus structure for coordinating all of subsystem controllers in the Trailer 1 Body-Frame Subsystem with each other and with controllers throughout the Vehicle Subsystem, as needed. It is a high-level controller that coordinates the operation of all of the subsystems of the Body-Frame Subsystem by monitoring the capabilities of these subsystems and coordinating the requests of the human controlling the vehicle with the capabilities of all of the other subsystems of the Body-Frame Subsystem at this level of the hierarchy

The lower portion of the Trailer 1 Body-Frame Subsystem that is connected to the Trailer 1 Suspension Subsystem is called the Trailer 1 Under Body Subsystem. It is connected to the Trailer 1 Upper Body Subsystem, which forms the upper portion of the Body-Frame Subsystem. The Trailer 1 Interior Subsystem describes the interior parts of the structure that are mounted to and enclosed by the under and upper body to form a compartment for carrying goods, and/or passengers. These three subsystems together provide a complete description of the structural aspects of the trailer. And, the structure created provides a means for mounting and integrating all of the trailer subsystems and components into the Trailer 1

Subsystem. They also form an interior space that creates an enclosed environment called the Trailer 1 Climate Subsystem, which contains subsystems for controlling the interior environment to provide a comfortable local climate for transporting goods and/or occupants.

5.5.4 Trailer i Subsystem Organization and Partitioning

For some vehicle applications, several trailers may be pulled behind a tractor chassis. To ensure unique names for each trailer and their internal subsystems, the identifier 'Trailer i' is used at the beginning of the name of each of the subsystems of the 'Trailer i' Subsystem, where 'i' is an integer that represents the sequential location of the trailer behind the chassis (where $i \in [1, N]$ for a vehicle pulling N trailers). Each trailer has the same architectural structure as the Trailer 1 Subsystem and the Chassis Subsystem, and hence, is partitioned into the following seven subsystems, which are highlighted in light blue in Figure 5-10:

1. Trailer i Supervisory Control Subsystem,
2. Trailer i Steering Subsystem,
3. Trailer i Braking Subsystem,
4. Trailer i Wheels/Tracks Subsystem,
5. Trailer i Suspension Subsystem,
6. Trailer i Body-Frame Subsystem, and
7. Trailer i PTO Accessories Subsystem.

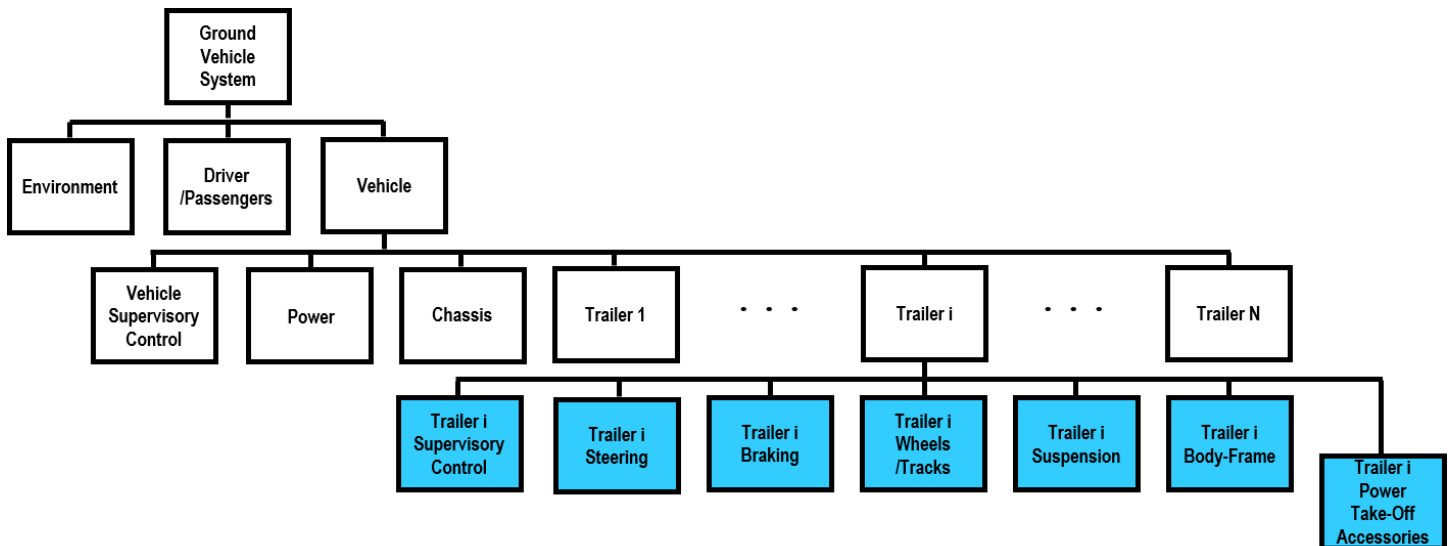


Figure 5-10 - Trailer i Subsystem hierarchical organization

The description and purpose of each of these subsystems of the 'Trailer i' Subsystem is the same as the similarly named subsystems of the 'Trailer 1' Subsystem described in Section 5.5.3. For a model of a double bottom or tandem trailer configuration, where 'N' has a value of two, a Trailer 2 Subsystem is added to the Vehicle Subsystem. Similarly, when additional trailer subsystems are added from the Trailer 2 Subsystem to the Trailer N Subsystem; the model represents a Vehicle Subsystem of a trailer train configuration with N trailers being pulled behind a Chassis Subsystem.

5.5.4.1 Trailer i Body-Frame Subsystem Organization and Partitioning

The Trailer i Body-Frame Subsystem is comprised of the following five subsystems, which are highlighted in light blue in Figure 5-11:

1. Trailer i Body-Frame Supervisory Control Subsystem,
2. Trailer i Under Body Subsystem,
3. Trailer i Upper Body Subsystem,
4. Trailer i Interior Subsystem and,
5. Trailer i Climate Subsystem.

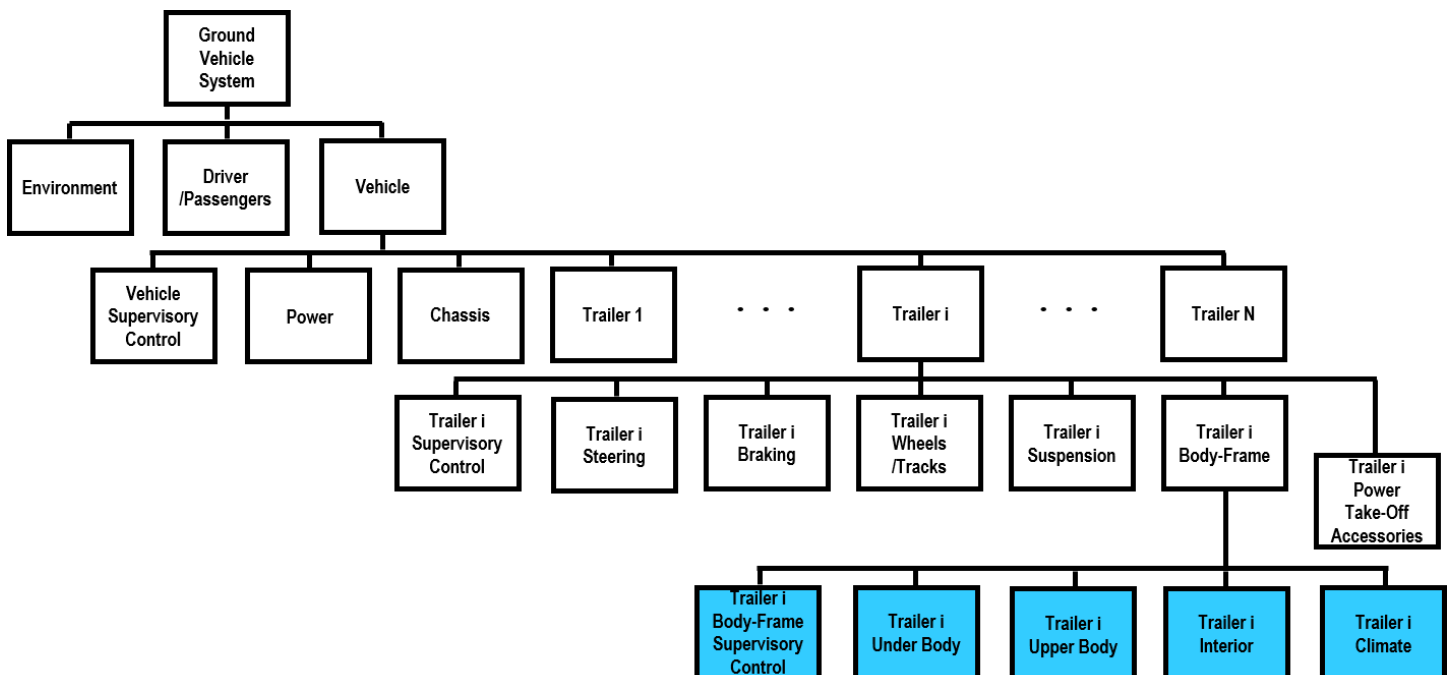


Figure 5-11 - Trailer i Body-Frame Subsystem hierarchical organization

These subsystems are interrelated and work together to provide an enclosed space that is protected from the elements of the weather, with seating for transporting people, storage areas for transporting goods, and subsystems for controlling the climate of the enclosed space. The 'Trailer i' Body-Frame Subsystem Supervisory Control Subsystem supervises and coordinates the control of all of the subsystems in the 'Trailer i' Body-Frame Subsystem. In addition, it provides a flexible controller information bus structure for coordinating all of subsystem controllers in the 'Trailer i' Body-Frame Subsystem with each other and with controllers throughout the Vehicle Subsystem, as needed. It is a high-level controller that coordinates the operation of all of the subsystems of the Body-Frame Subsystem by monitoring the capabilities of these subsystems and coordinating the requests of the human controlling the vehicle with the capabilities of all of the other subsystems of the compartment for goods and/or passengers. Body-Frame Subsystem at this level of the hierarchy.

The lower portion of the 'Trailer i' Body-Frame Subsystem that is connected to the 'Trailer i' Suspension Subsystem is called the 'Trailer i' Under Body Subsystem. It is connected to the 'Trailer i' Upper Body Subsystem, which forms the upper portion of the Body-Frame Subsystem. The 'Trailer i' Interior Subsystem describes the interior parts of the structure that are mounted to and enclosed by the under and upper body to form a compartment for carrying goods, and/or passengers. These three subsystems together provide a complete description of the structural aspects of the trailer. And, the structure created provides a means for mounting and integrating all of the trailer subsystems and components into the 'Trailer i' Subsystem. They also form an interior space that creates an enclosed environment called the 'Trailer i' Climate Subsystem, which contains subsystems for controlling the interior environment to provide a comfortable local climate for the goods and/or occupants.

The lower portion of the 'Trailer i' Body-Frame Subsystem that is connected to the 'Trailer i' Suspension Subsystem is called the 'Trailer i' Under Body Subsystem. It is connected to the 'Trailer i' Upper Body Subsystem, which forms the upper portion of the 'Trailer i' Body-Frame Subsystem. The 'Trailer i' Interior Subsystem describes the interior parts of the structure that are mounted to and enclosed by the under and upper body to form a trailer compartment for goods and/or passengers. These three subsystems together provide a complete description of the structural aspects of the trailer. The interior forms an enclosed volume environment called the 'Trailer i' Climate Subsystem, which can be controlled to provide a comfortable local climate for goods and/or occupants.

6. DESCRIPTION OF THE FUNDAMENTAL SUBSYSTEMS OF A GROUND VEHICLE SYSTEM

6.1 Introduction

6.1.1 Overview

All of the fundamental subsystems of a Ground Vehicle System (GVS) were introduced in Section 5 along with the concept of the hierarchical organization diagram to describe the architectural structure and hierarchical relationships between the system and the subsystems from which it is composed. This section is a reference section with a section devoted to each subsystem, where the subsystem is described in more detail than was presented in Section 5. Each subsystem is described according to hierarchical location, purpose and function, and interfaces. The hierarchical organization diagram, introduced in Section 5, is used in this section as a road map to keep track of the location of the subsystem within the GVS and to keep track of the progress of the review of the subsystems. In addition, this section expands on the description of the purpose and function of the subsystem that was briefly introduced in Section 5.

The scope of each subsystem is generally defined by the description of the function and purpose of the subsystem, which is presented below where each subsystem is defined in a separate subsection of Section 6. A detailed description of the subsystem scope is difficult to provide; since, each subsystem can be implemented with different technologies, and configurations of subsystems and components. However, as a means of making the scope more understandable in terms of practical implementations, examples of the typical content included in each subsystem is listed in APPENDIX C for some typical configurations.

In the following sections, the subsystems are presented in order of their appearance in the hierarchical diagram starting at the top of the diagram, proceeding across each row from left to right, progressing down to the next row, and continuing this pattern to the bottom of the diagram. In order to describe the subsystem location and to keep track of the progress in defining the subsystems within the GVS, the subsystem being described in each section is highlighted in a light blue color and is shown in a hierarchical diagram at the beginning of each section. Hence, the hierarchical diagram is used as a road map that defines the GVS and the relationship of each subsystem to the other subsystems and to the whole system.

6.1.2 Interfaces and Interface Tables

In each subsystem description section below, a description of the interfaces that may be needed for that subsystem is presented in a table. For each interface connection listed in the table, a number is assigned for that connection as a unique identifier, which is listed in column 1. The second column of the table lists the name of the subsystems that are connected to the subsystem being defined. For each row of the table, the third column describes the type of physical or information interface port that the connection represents. These interface port types are defined in reference tables in APPENDIX B. A fourth column describes the function or purpose of the connection, which includes contextual information about quantities that are transferred, exchanged, provided, or received between the two connected subsystems. And, a fifth column is provided as a checklist that can be used for building subsystem models for a Ground Vehicle System.

When building a model, the interface tables can be used as a list of possible connections to consider. A copy of the interface table can be used as a checklist to define the connections that are needed; or not needed. The choice of the connections required by a model depends upon the analysis being performed, the physical phenomena or effects of interest, the resolution of the time scale required, the model fidelity required, et cetera. After each connection is reviewed, a character can be added in the fifth column to indicate the connection was reviewed, accepted, or rejected. As an example, the following convention could be used: (1) a minus sign can be added for connections that are not needed, and (2) a plus sign can be added for connections that are needed. Hence, the interface table can be used as a tool to establish a specification for the model interfaces needed and to confirm that all possible connections have been reviewed. Then, this list can also be used when integrating the model to ensure that all connections have been made. An additional character, such as an asterisk, can be added after the plus sign to indicate that the connection has been completed.

In the interface tables, when two internal subsystems are connected together at the same level of the hierarchy within the same parent subsystem; the name of the destination subsystem for the connection is listed in the second column of the interface table. However, when two subsystems from different parent subsystems or at different levels of the hierarchy are connected; then, the name of the destination subsystem for the connection is listed in the second column at the end of a sequence of subsystem names. The subsystem name preceding it is the parent subsystem; and, the one before that is the grandparent subsystem etcetera. For these cases, the name of the destination subsystem for the connection will be defined in the following format: 'High-Level Subsystem Name' → 'Next Lower-Level Internal Subsystem Name' → 'Next

Lower-Level Internal Subsystem Name' et cetera, where the last subsystem name in the list is the name of the subsystem destination for the connection. This subsystem-path notation shows the hierarchical path to the destination subsystem. In addition, for high-level subsystems, the connected subsystem is listed as another high-level subsystem at the top of the table cell and may represent several connection destinations, which are listed below it in the subsystem-path notation. This convention is used to remind the user where the connected subsystem is located in the GVS hierarchy.

For each subsystem, the interface description tables list some of thermal connections between subsystems. Thermal coupling between subsystems may be through conduction, convection, or radiation. Rather than specify, the specific mechanisms for thermal coupling, thermal Power Interface Ports are described as being a set of heat transfer connections, which could consist of as many of the three kinds of thermal coupling mechanisms as needed. This is done to avoid specifying an architecture that could limit the implementation of a subsystem by designating specific types of thermal connections.

Also, with regard to Thermal Power interfaces, not all of the possible thermal interface connections are listed in the tables. Specifically, thermal radiation connections between subsystems are difficult and cumbersome to specify completely; since, these connections are not made through physical contact, but by coupling through air or space between two subsystems that are within direct view of each other. Consequently, the physical implementation of the subsystems and the arrangement of their components will determine whether the subsystems are exposed to each other and coupled through thermal radiation. The radiating components or surfaces will couple thermal power to any subsystem components that are within view of the surface or component. This means that there can be an almost infinite number of connections required to specify all of the possible thermal radiation connections to other subsystems. Therefore, specific interfaces for thermal radiation are not listed in the interface tables; and, the user is advised to add the specific connections for thermal radiation to the subsystems when and where radiation mechanisms are required for the specific modeling analysis being performed.

In addition, when two subsystems are physically connected to each other through the mounting of the components of one subsystem to the other; there is an interface created for the transfer of thermal power and mechanical power, which includes mechanical vibration. For these situations, the interface connection is described in the interface tables as consisting of 'a set of heat transfer connections' for thermal power coupling, or 'a set of force and displacement connections' for the translational mechanical coupling that occurs at the mounting, coupling, or contact points or surfaces of the components. The intention of the 'set of connections' term is to describe all of the component connections between the two subsystems without specifying each component connection. This is also done to support any type of physical implementation of the components, and to avoid specifying a specific physical implementation, which would limit the usefulness of the architecture.

Any physical contact between subsystems or components (such as mounting or coupling) provides a path for the transfer of heat, and vibration. And, any vibrating surface that interfaces with a gas or liquid provides the opportunity for acoustical power production. Again, the need for including sound transfer connections in a model must be evaluated for each implementation, or analysis and cannot be specified explicitly.

Also, different ground vehicle configurations may require additional thermal management for components by supplemental liquid or gas cooling. Hence, connections for Enthalpy Flow Power cannot be generalized and must be considered for each implementation.

Thus, not all of the connections between subsystems can be explicitly specified in the interface tables for the following types of power transfer: (1) Thermal Power for radiation, (2) Thermal Power for convection and conduction, (3) Translational Mechanical Energy for vibration, (4) Simple Fluid Flow Power for sound, and (5) Enthalpy Flow Power for cooling. These connections are dependent upon implementation; so, their inclusion in a model must be based on each individual vehicle configuration and on the requirements of the analysis being performed. Hence, they cannot be specified a priori. So, they are listed at the end of each table as a reminder to the model developer that they may be needed and must be evaluated on a case-by-case basis.

In the interface summary tables, connections for the transfer of heat (thermal power) and vibration (translational mechanical energy) are listed explicitly for the primary functions of propulsion, performing work, mounting a subsystem to the body or frame of the vehicle, and climate control. In general, they are listed to provide the physical quantities required for the driver and passengers to evaluate comfort, handling, ride, and performance feel.

6.1.3 Subsystem Connectivity Diagrams

The interface tables provide a definition of the interfaces that a subsystem may require. All of the interfaces are not required for every model. So, the interface tables provide an organized checklist for building a subsystem model to ensure that all of the possible connections have been considered and evaluated for inclusion in the model. However, they do not provide a graphical picture of the relationships and connections between subsystems. Hence, after the interface table for a subsystem is presented, a 'subsystem connectivity diagram' is shown for that subsystem to provide a graphical view and summary of the subsystem and the interface connections it makes with other subsystems.

A 'subsystem connectivity diagram' provides a single graphical view of a subsystem with all of the primary interface connections it makes to other subsystems. These types of diagrams are useful for examining and understanding relationships between subsystems and for understanding the operation of the overall subsystem or system in which they are contained. For this type of graphical description of a subsystem, the controller information bus connections, the mechanical connections, thermal connections, and acoustical connections associated with the mounting or coupling of components have been omitted to simplify the diagrams and to improve comprehension and understanding of the primary functional operation and power transfer mechanisms of each subsystem. They are also omitted because these connections are implementation specific and cannot be generalized for all Ground Vehicle Systems. However, some mechanical vibration and thermal coupling connections related to driver and passengers are included for their primary role in the perception and evaluation of ride, handling, performance, quality, and climate control and comfort. Finally, to simplify the diagrams, the connections for the driver and passengers are combined into a single driver/passengers connection.

6.2 Top-Level Subsystems of a Ground Vehicle System

The top-level subsystems define a Ground Vehicle System (GVS) at the most basic and abstract level of purpose and function. As shown in Figure 6-1, the GVS is partitioned into a Driver/Passengers Subsystem, which is the top-level controller or control subsystem of the Ground Vehicle System; a Vehicle Subsystem, which is a mechanism for the driver and passengers to control for performing transportation and work; and an Environment Subsystem, which is a place for the driver and passengers to use the vehicle for transporting themselves and their goods from one place to another, or for performing work functions on. These three subsystems are shown in a high-level connectivity diagram in Figure 6-2, where the primary connections between them are depicted.

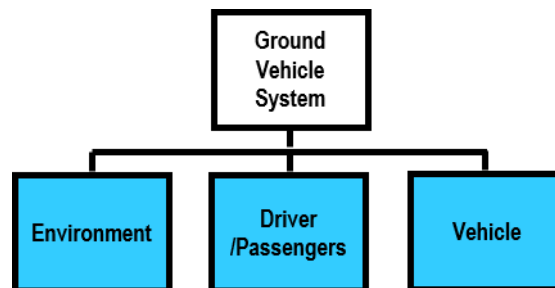


Figure 6-1 - Ground Vehicle System hierarchical diagram of the top-level subsystems

Ground Vehicle System Architecture – Total System Connectivity Diagram

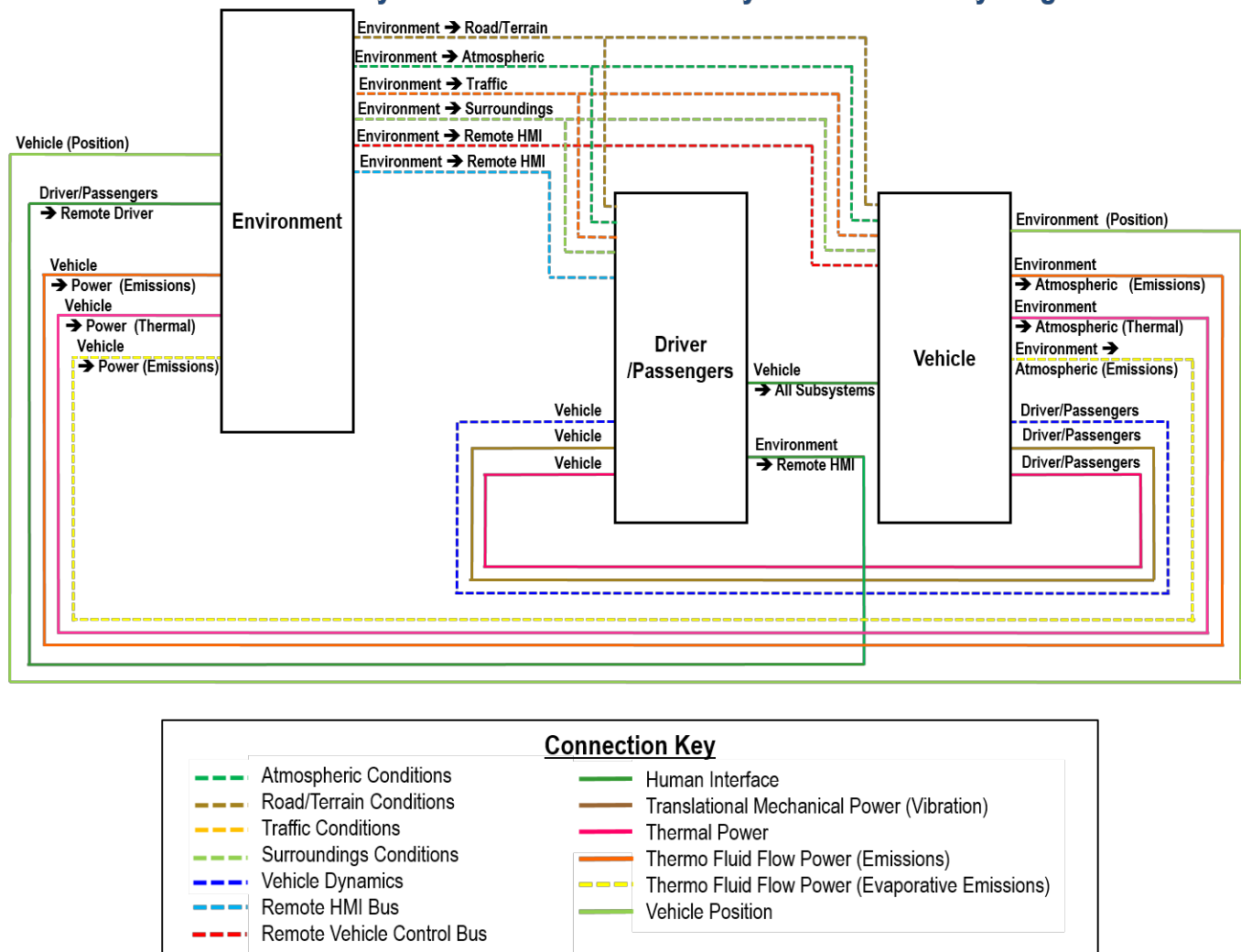


Figure 6-2 - Ground Vehicle System top-level connectivity diagram

Although the driver and passengers are typically located inside the vehicle and within the cabin or passenger compartment, they are not always located there for every ground vehicle application. For some military and medium or heavy duty work equipment applications, the driver may be located outside and at some remote location from the vehicle. Also, the passengers may be located in trailers or cargo compartments of the vehicle with or without work equipment. Hence, the Driver/Passengers Subsystem is located at the top level of the hierarchy, which allows them to control and interact with any subsystem of the vehicle from any location in the environment or vehicle.

Regardless of where the driver and passengers are physically located in the architecture, they will always have the same connections to control and monitor the same subsystems. With them at only one place and at the highest level in the architecture; there is a single and consistent place where they are always located. Thus, all GVS applications can be modeled with only one architectural structure. If they were located in the architecture according to physical location; then, different architectures would be needed for each location and/or application.

6.2.1 Environment Subsystem Overview

Figure 6-3 shows the location of the Environment Subsystem within the hierarchy of the GVS and Table 1 defines the possible interface connections to other subsystems of the GVS.

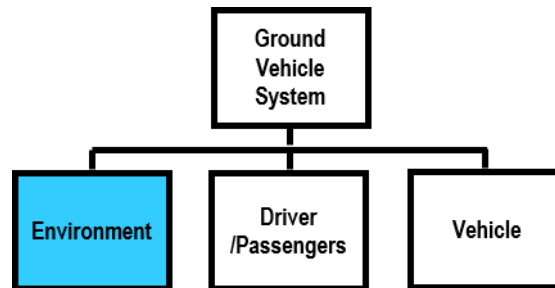


Figure 6-3 - Environment Subsystem hierarchical architecture location

6.2.1.1 Purpose and Functional Description

The Environment Subsystem defines the physical state of the exterior space surrounding the vehicle and driver that affects operation and performance of the ground vehicle system and subsystems. The surrounding physical state of the vehicle is described in terms of the conditions of the atmosphere, road/terrain, and traffic/surroundings of the vehicle. And, for remotely operated vehicles, where the driver is not located within the vehicle, a Remote Human-Machine Interface (HMI) Subsystem describes the surroundings of the driver, which is used by a remotely located driver to control and monitor the Ground Vehicle System through teleoperation.

6.2.1.2 Subsystem Interface Summary

A specification of the subsystem interfaces is provided by the interface table listed below in Table 1, and the primary connections depicting functional operation and power transfer mechanisms are shown in the connectivity diagram of Figure 6-4.

Table 1 - Environment Subsystem interface connections

<u>No.</u>	<u>Connected Subsystem</u>	<u>Connection Interface Port Type</u>	<u>Purpose of Connection Port</u>	<u>Checked</u>
1	Driver /Passengers	Atmospheric Conditions	For the Atmospheric Subsystem (of the Environment Subsystem) to provide atmospheric conditions at the requested coordinate locations of the driver, remote driver, and passengers, as needed.	
2		Thermal Power	For a set of heat transfer connections between the Atmospheric Subsystem (of the Environment Subsystem) and the Driver/Passengers Subsystem at the coordinate locations of the driver, remote driver, and passengers where needed at the coupling and/or contact points, as needed. This interface could be used for solar radiation and/or convection heat transfer to support thermal modeling of driver/passengers for human comfort studies.	
3		Road/Terrain Conditions	For the Road/Terrain Subsystem (of the Environment Subsystem) to provide road/terrain conditions to the Driver/Passengers Subsystem at the requested coordinate locations of the driver and passengers, as needed.	
4		Traffic Conditions	For the Traffic/Surroundings Subsystem (of the Environment Subsystem) to provide traffic conditions to the Driver/Passengers Subsystem at the requested coordinate locations of the driver and passengers, as needed.	