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VEHICLE CONCEPT MODEL ABSTRACTIONS FOR INTEGRATED GEOMETRIC, INERTIAL, RIGID BODY, POWERTRAIN, AND FE ANALYSES

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ABSTRACT

Vehicle analysis models of any kind have their basis in some type of physical representation of the design domain. Rather than describing three-dimensional continua of a collection of components as is done in detail-level CAD models, an architecture-level abstraction describes fundamental function and arrangement, while capturing just enough physical detail to be used as the basis for a meaningful design space representation and eventually, analyses that permit architecture assessment. The design information captured by the abstractions is available at the very earliest stages of the vehicle development process, so the model itself can function as a "design space for ideas". In this paper we describe vehicle architecture abstractions appropriate for integrated model extractions suitable for geometric, inertial, rigid body, acceleration, braking, fuel efficiency[1], structural, and NVH assessments. Additionally, we discuss the requisite level of information required for each analysis type.

INTRODUCTION

Often when developing a new vehicle, the only data available is a set of performance and functional requirements. A traditional conceptual design stage typically includes the following steps. Concept sketches are drawn representing critical functional requirements and overall vehicle shape. CAD models representing major architecture features are developed based upon the sketches and inertial properties, compartment volumes, vehicle stability parameters, and acceleration/braking performance are estimated from the CAD model by assuming engine power, gear ratios, and payload requirements. Once the minimal performance requirements are met, detailed CAD and FE models incorporating exact component geometry are developed to perform structural analyses on the components, assemblies, and full vehicle. However, the architecture layout and major features influencing structural performance were established prior to FEA support during the detailed model creation. While invaluable for validating a completed design, these detailed models are difficult to implement for conceptual architecture studies, because the requisite level of geometric detail is simply not available early in the development process and their sheer size inhibits drastic architecture modifications. Forgoing structural analysis during the concept design stage, often results in suboptimal vehicle architecture layout, expensive redesign, longer development times, and even project failures.

By dividing a vehicle structure into connected functional assemblies and assemblies into functional components - beams, surfaces, major compliance joints, and assemblage joints - and modeling those components in a simple, direct fashion, it is possible to develop an attribute-based first-order model for a vehicle. These attribute-based models are smaller than traditional models, straightforward to modify, and because of the division into functional components, simple to interpret. We shall refer to simplified attribute-based models as "concept models[2]," while continuing to describe traditional NVH models

[1] Fuel efficiency shall refer to the total amount of energy used for a given duty cycle of the vehicle, whether the energy is a petroleum based fossil fuel, battery, or pressurized fluid.

[2] The nomenclature "simplified model" has also been applied to attribute-based FEMs. We avoid this terminology because these models, while small in terms of element count, involve modeling decisions critical to the overall accuracy of the results. In fact, the use of specialized elements and joint representations add a level of complexity not present in detailed models.

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as “detailed models.” By including abstractions specific to engines, motors, transmissions, differentials, power split devices, transfer cases, fuel tanks, batteries, and brakes, concept models can accurately predict the inertial properties, compartment volumes, clearances, top speed, maximum acceleration, minimum braking distance, fuel efficiency, payload capacity, structural integrity, and NVH characteristics of a vehicle architecture without requiring a comprehensive geometric description. They can be used to optimize the architecture layout of a vehicle, conduct iterative design studies, or develop reference models based upon a baseline design.

This paper discusses the requisite modeling abstractions for the aforementioned analyses types performed during vehicle conceptual design. The modeling abstractions include geometric and connectivity abstractions to represent load paths within a vehicle based upon load types carried by subcomponents. Additionally, relevant powertrain and brake system abstractions are included based on the data required to establish the energy and power transmission paths. These abstractions are consistent with conceptual design information. They are sufficient to quickly perform vehicle performance evaluations and optimize the vehicle architecture layout based on structural analyses. Once the concept vehicle model meets the minimum requirements, detailed models should be developed for localized optimization and final design validation before prototyping. This serialized optimization process provides critical CAE support for NVH assessment to the designer during the conceptual design stage. A software package with the working title of CMTS (Concept Modeling Tool Suite) was developed at the University of Louisville VARL (Vehicle Architecture Research Laboratory.) When using CMTS, all models required for the analyses, including FEA, are created automatically from the vehicle concept model abstractions. Thus, CMTS could be utilized by vehicle designers with limited knowledge of the modeling procedures.

REVIEW OF PREVIOUS LITERATURE

The earliest vehicle finite element models (FEM) were, in effect, concept models. The theoretical formulations for the beam, shell, and plate elements that comprise the majority of a detailed noise, vibration, and harshness (NVH) model have been available for many decades. Their practical application awaited only computer hardware and software combinations capable of solving the large systems of equations that result when such elements are applied to a complex system such as a vehicle body. In the interim, simple automotive FEMs were constructed by using one-dimensional beam elements to model the vehicle body’s critical load-carrying members. These “stick models” permitted refinement of the vehicle body structure through quantitative assessment of stiffness and modal parameter changes resulting from modifications to the beam geometries and positions. Later, flat panels and very coarse shell arrays were used to connect the beams, and stiffness elements were incorporated into the joints.

The advent of first, supercomputers, and later, high-performance workstations, permitted reasonable solution times for very large FEMs. In the automotive industry, first order models were largely discarded in favor of finely meshed shell element full-body models. However, the advantages of concept models are so compelling that designers, researchers, and analysts are revisiting their use. The advantages of concept models (referred to as “hybrid models”), based upon beams and shell elements, has been described and correlation with experimentally measured parameters was undertaken, with good results [1]. By using concept models and detailed models in support of a passenger car development program, NVH improvements and reduced development time was possible [2]. Shortcomings in detailed FEM such as long modeling time and lack of detailed architectural features required for an accurate model result in critical design decisions being made without CAE support [3]. These investigators used parametric topology/ concept models to conduct stochastic studies that yield an optimized conceptual design, which then serves as a starting point for intermediate and detail design.

Concept modeling methodologies have been integrated with a goal programming optimization algorithm [4]. The very critical issue of representing major body joint compliance in architecture concept models was addressed by a number of works [5-7]. Suitability of using concept models for pickup truck boxes was investigated [8]. Beam-only concept models were used to support the design of a construction vehicle cab [9]. Beam/shell FE concept models have been used to reduce weight and increase stiffness of a light-duty truck floorpan [10]. Simplified concept models have been developed for the investigation of structural adhesive joints [11]. Concept models were also implemented to support passenger car side door development [12].

In addition to NVH considerations, vehicle designers must be concerned about crash performance and dynamic response characteristics in the conceptual design phase. Concept models can support the decision-making processes involved in optimizing performance in these areas. Simplified kinematic models with a “compression-bending” formulation were developed to assess the crash behavior of thin-walled structures [13]. Simplified passenger car model results for crashworthiness analysis were compared to the results obtained from a detailed model, with excellent correlation [14-17]. Element types appropriate for specific portions of a structure were described in the literature [18]. Crash concept models were applied to aluminum front-end structural components [19] and a full-body model for a light-duty body-on-frame utility vehicle [20].

In concept models used for dynamic analysis, particular care must be taken to maintain appropriate representation of inertia and stiffness distributions throughout the model domain. Two methods of creating dynamic concept models, one of which involves condensing the stiffness and mass matrices on the boundary degrees of freedom (DOF) and a second involving shell-to-beam substitutions for closed shapes was described [21]. Concept models were used to predict body-in-white, trimmed body, and full vehicle frequency response functions with good agreement to experimentally measured results [22]. Forced response characteristics of a full vehicle dynamic concept model composed of rigid bodies was compared to an equivalent concept model that included compliant components [23]. They determined that including component compliance dramatically improved the accuracy of the results.

Based upon the existing literature, we can surmise that vehicle concept modeling arose out of necessity in response to computer hardware and software limitations, fell out of favor as large, high-fidelity FEMs became practical, and is beginning to re-emerge as designers recognize the value an attribute-based model can add to conceptual design activities. While some researchers [24] have developed parametric based concept models with automated FE meshing, it has not previously been done at the vehicle level, nor has the additional analysis tools and stages been encompassed into the concept development process. Our work here addresses a number of open issues, including abstractions of concept modeling techniques for various types of vehicle performance and architecture assessment completed during conceptual design.

VEHICLE ARCHITECTURE ABSTRACTIONS

Vehicle architecture abstractions suitable for geometric, inertial, powertrain performance, rigid body dynamics, and FE assessments involve the representation of functional assemblies and their association to one another including structural connectivity and energy/power transmission paths. Each assembly may be categorized as structural, inertial, energy storage, power source, or power transmitting. All assembly types require a position transformation including a vector description of the assembly's coordinate system relative to the vehicle coordinate system, and orientation within the vehicle coordinate system based on a set of three Euler angles. Each assembly type requires structural connectivity information to at least one other assembly within the vehicle architecture and all assemblies within the vehicle must be interconnected in some manner to form a contiguous vehicle. Any energy storage, power source, or power transmitting assembly needs additional paths to represent energy and power flow within the vehicle. Figure 1 depicts a light-duty rear wheel drive four door pickup truck architecture with structural ladder frame, crew cab compartment, and payload assemblies, fuel tank energy storage assembly, V8 SI engine power source assembly, and transmission, differential, and wheel power transmission assemblies.

Structural Assemblies

Assemblies designed to carry the loads in the vehicle are termed structural assemblies. They contain components that may deform significantly relative to the amount of deformation in the assembly connections when external loads are applied to the vehicle. Concept modeling methodologies for structural assemblies begin with a functional division of architectural features based on the internal load distribution, followed by an assessment of how critical the influence of a component's features are on the overall model performance. A structural assembly concept model must represent the architecture layout and connectivity involving primary load carrying structural members (beams), major compliance joints at the beam junctions, panels carrying secondary in-plane loads, inertial items, and assemblage joints connecting components to other components as in Figure 2. These component and connection type abstractions are sufficient for constructing structural assembly concept models.

Figure 1. Pickup truck architecture abstractions.

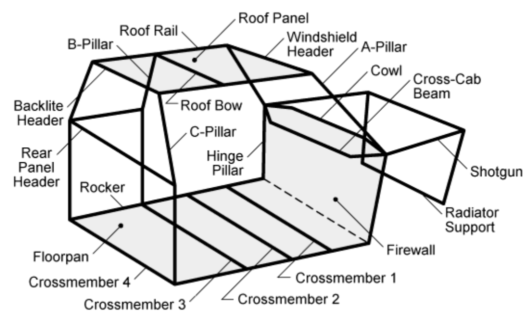

Figure 2. Pickup truck crew cab compartment structural components abstractions.

Beams - Many of the primary structural members in most vehicle body assemblies are beam-like structures. These beam components are characterized by a length much greater than the width and depth of the cross section. Their cross section geometry can be classified as thin-walled or thick-walled, opened or closed, and welded or unwelded. Beam components are capable of carrying various combinations of axial forces, bending moments, and torsional moments that are analogous to beam elements. The beam components are characterized by the path formed by the locus of cross sectional centroids along the length of the member (drag path), cross section shape defined by the median line of the sheet metal in the cross section, and sheet metal gauge at various locations within the cross section as shown in Figure 3. The drag path of a beam may be simple for a straight member with constant section, or quite complex for a curved member with multiple section changes.

Beam geometry can be defined in terms of a drag path curve type, geometric control points (GCP) defining the drag path shape, and cross sectional shapes along the drag path, Figure 3. Curvature type determines the quantity of GCPs required to define the drag path shape. The drag path is represented by a set of three parametric equations, one for each of the Cartesian axes, with polynomial degree defined by the curvature type and coefficients determined from the GCPs. By representing the drag path with a parametric equation, a hierarchal relationship in terms of the parametric coordinates of another component may be established for modeling. Additionally, the locations of cross sectional changes can easily be specified in terms of the parametric coordinates. The beam geometry normal to the drag path is represented as a set of piecewise parametric equations, one parametric equation corresponding to each section property of a cross section and one segment of each piecewise parametric equation for each cross section region. Regions between identical cross sections are constant, while regions between dissimilar cross sections are linearly tapered. Geometry for the individual cross sections may be represented as a set of connected points with each connection between two points defining a wall of specified thickness or from more abstract numerical data with sectional area, area and cross product moments of inertia, and torsional constant.

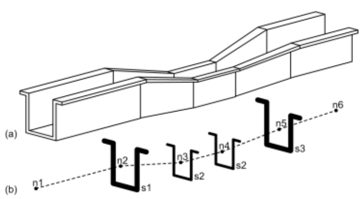

Figure 3. Beam abstraction including 6 GCPs, a piece-wise linear drag path, and 5 cross section regions (3 constant and 2 tapered.)

Major Compliance Joints - Junctions of two or more load-carrying beam-like members in a vehicle body structure can be modeled as major compliance joints (MCJ), Figure 4. These joint types are often quite flexible in at least one direction, and their compliance permits relative rotation among the intersecting beam branches. The magnitude of this compliance is large enough that such joints have a significant effect upon all aspects of a vehicle body's static and dynamic response. Furthermore, MCJ characteristics are strongly influenced by local topology, sheet metal gauge, and assemblage joint details, and thus are a target of design optimization efforts.

The best method for modeling MCJs involves sets of elastic parameters for the individual beam branches [25]. The elastic parameters for each leg includes one parameter for angular deflection about the legs centroidal path and two additional parameters related to orthogonal angular deflections along the leg's path. One disadvantage of these elastic parameters is that they require a level of design detail that may be unavailable early in the design process, where concept models should be most useful. Finally, it may not be obvious how joint model iterations applied to a concept model may be implemented in a physical joint. However, by using a superelement model with element parameters that maintain a specific physical interpretation can minimize all of these limitations.

The elasticity model implemented for structural analyses utilizes effective stiffness beam elements based on elastic constants. This method correlates to detailed model results with less than 1% difference for NVH assessment of passenger car bodies [26]. The elastic parameter abstractions for each leg of an MCJ involves identifying the cross sectional properties at the leg beam interface and scaling the area moments of inertia and torsional constant for each leg's cross section interface with the beam component by a constant pertaining to the stiffness parameter being scaled. Thus, three constants per leg of an MCJ are required to define the MCJ elasticity. These constants determine the localized elasticity of the MCJ's legs and corresponding relative deformations among the legs for the MCJ. By adding a bulk head into the MCJ region the scaling factor may exceed unity, otherwise the scaling factors are normally less than unity.

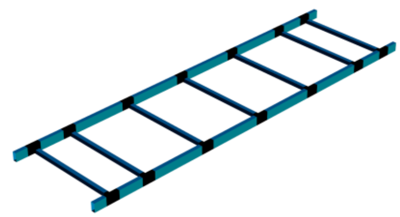

Figure 4. Ladder frame depicting MCJs (dark regions) at the beam intersections.

Panels - Most auto body architectures contain secondary shell-like members with large flat or slightly curved surface areas and very thin wall thicknesses. These panel components are capable of carrying in-plane loads through strain energy storage and are analogous to shell elements. Panel geometry is characterized by a surface boundary, prominent interior features, and wall thickness as in Figure 5. The surface boundary may be simple for a flat rectangular panel or quite complex for a curved surface with cut-outs, stamp-in beads, and a highly curved boundary. The surface boundary may be represented by a set of paths, characterized by the type of curvature and corresponding set of GCPs that connect end to end forming a closed loop. Surface curvature away from the surface boundary is defined by additional internal GCPs. Panel geometry is also represented parametrically based on the bounding curves and interior GCPs using sets of B-spline basis functions. The panel thickness is the only remaining property required to fully specify the physical geometry of the panel. Cutouts as shown in the right surface in Figure 5 are defined by parametric dependencies on the same surface without a cutout.

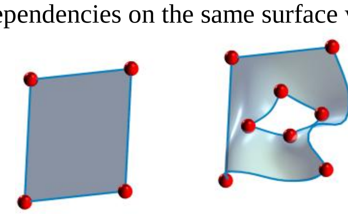

Figure 5. Panel component abstraction.

Inertial Components - Nearly all assemblies contain components that are not designed to carry structural loads in the assembly, such as entertainment system components, climate control components, powered window motors, seats, and other trim items. However, these inertial items have an influence on the inertial properties and dynamic response of the assembly and overall vehicle. The critical parameters describing the inertial components contributions to the assembly are the inertial parameters and their attachment locations.

Inertial parameters include the mass of the item, centroid, and mass moments of inertia. These inertial parameters can be specified directly or determined from the geometric abstraction representing the component. Options for the geometric representation include path with cross sectional area, surface with thickness, and enclosed volume with specified inertial parameters. When specifying a volume, all inertial properties for the component must be specified since the internal material distribution is still unknown in nearly all cases except the trivial solid homogeneous part. Enclosures are represented by parametric equations as well and they are defined by a closed set of bounding surfaces.

Attachment locations for the inertial component are defined in terms of parametric coordinates to maintain consistency with the underlying vehicle hierarchy. The quantity of parametric coordinates required is dependent on the geometric representation of the rigid component, paths have one, surfaces have two, and volumes have three. The inertial components implementing volumetric representations permit the connections to fall within the volume or on the surface allowing for geometric modeling inconsistencies with the physical domain.

Assemblage Joints - The majority of the spot welds, adhesive bonds, or fasteners in a vehicle body structure can be modeled as assemblage type joints. These assemblage joints occur between beams, panels, and inertial components and are accurately modeled by a set of rigid connections at the corresponding physical fastener parametric locations relative to the component. There are three assemblage joint classifications; point, path, and surface based connections with each one defined by the geometric relationship between two components, Figure 6.

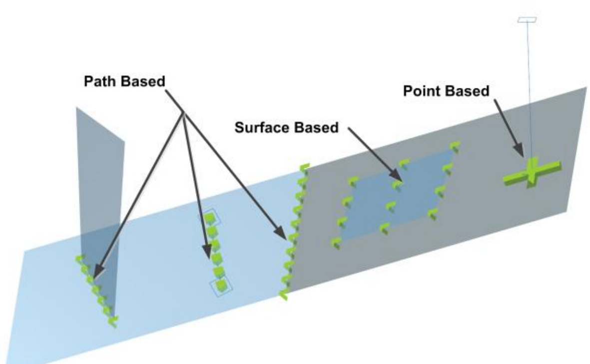

Figure 6. Assemblage joint classifications.

Point based connections occur between a beam component intersecting a panel component and rigid components connecting to other rigid components at a joint. Point based connections involving panels are modeled by a single multi-point connection that fixes the beam centroid to a set of corresponding connection locations on the panel. These multi-point connections implemented in beam to panel component assemblage joints help evenly distribute the large out of plane loads that may be transferred to the panel by the beam. The only data abstraction required for point based panel component connections are the quantity of attachment points to the panel and the radius of the attachment points. Point based rigid to rigid component connection abstractions require specification of the joint's DOF if any exist.

Path based connections occur between beam components tangential to panel components and two panel components sharing an edge dependency. Data abstractions for path based component connections include weld pitch spacing and parametric range along the connection path. This level of information is sufficient to define component discretization points parametrically.

Surface based connections occur between two panel components partially sharing a surface and panel component to enclosure component connections. They simply extend the path based connection to a second dimension by adding an additional weld pitch spacing and parametric range in the orthogonal parametric coordinate. Similar to path based connections, component discretization is done parametrically based on the connection data.

Inertial Assembly Abstraction

Any assembly that does not specifically provide structural support for the vehicle architecture can be modeled as an inertial assembly. The critical features of these inertial assemblies are the inertial properties and the connectivity to the other assemblies in the vehicle. Mass and mass moments of inertia for the assembly are the only abstractions required to define the concept model. However, specialized abstractions are required for critical functional assemblies influencing powertrain performance such as acceleration, braking, and fuel efficiency. These powertrain assemblies can be classified into three functional groups; energy storage, power source, and power transmission assemblies.

Energy Storage Assemblies - Fuel tanks, batteries packs, and hydraulic accumulators in a vehicle are examples of energy storage assemblies, Figure 7. Each energy storage type provides a unique form of energy for a specific type a power source assembly. Thus, correct energy flow paths required for the vehicle can automatically be determined based on the energy storage and power source assembly abstractions. Similarly, it is possible to algorithmically validate that the energy flow paths are correct for a given vehicle configuration.

Fuel tank abstractions must be appropriate to determine the quantity of energy available for an IC engine based on tank volume and type of stored fuel. Property abstractions for a rectangular prismatic fuel tank with rounded edges are length, width, height, thickness, fillet radius, and stored fuel type. Fuel types include common fuels such as regular and premium gasoline, light, medium, heavy, and bio diesels, and normal cetane. The properties required for the available energy are determined from the volume of the tank and the fuel's heating value and ratio of specific heats.

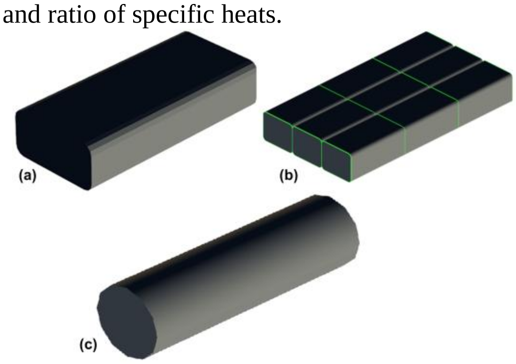

Figure 7. Energy storage assembly abstractions (a) fuel tank, (b) battery pack, and (c) hydraulic accumulator.

Battery pack abstractions required to calculate the available energy for an electric motor includes cell type, maximum state of charge (SOC), minimum SOC, minimum activation SOC, nominal voltage, and battery size. The battery pack is assumed to be a rectangular prism and thus is described by length, width, and height parameters. Additionally, cell type must be specified in order to determine the battery capacity. Lead acid, nickel cadmium, nickel iron, and nickel zinc are some common cell types used in automotive battery packs. Regardless of cell type the critical performance parameters for battery cells are specific energy and energy density of the cell.

Hydraulic accumulators used in conjunction with hydraulic motors have available energy abstractions based on the accumulator cylinder volume derived from a length and diameter, maximum pressure, current pressure, and percent of usable accumulator volume. These abstractions are sufficient to determine the energy stored in the accumulator.

Power Source Assemblies – Internal combustion engines, electric motors/generator, hydraulic motors/pumps, and brakes are examples of power source assemblies within a vehicle, Figure 8. Brakes are considered as power source assemblies if they are implemented as regenerative assemblies for either electric or hydraulic vehicles. If not, they are power drain assemblies. These assemblies convert stored energy into work to propel the vehicle or generate energy for some electric/hydraulic hybrid systems. Energy consumption or production rates, torque outputs, and inertial properties must be captured by the abstractions of these assemblies. Estimates of inertial properties are obtained for each classification based on abstractions defining the characteristic shape but they could be supplied by a knowledgeable designer or existing manufacturer's data.

Internal combustion engines including SI and CI types, require specification of three torque outputs corresponding to idle, peak, and redline engine speeds, minimum, idle, and redline brake specific fuel consumptions (bsfc) at ¼, ½, and full throttle settings, and speed at minimum bsfc to determine fuel efficiency and acceleration performance. Inertial properties, shape, and size can be estimated based on bank configuration, bank angle, number of cylinders, cylinder bore, cylinder spacing, slant angle, crank radius, and piston height parameters.

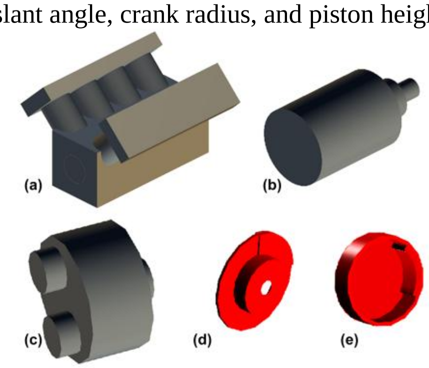

Figure 8. Power source assembly abstractions (a) V8 IC engine, (b) electric motor/generator, and (c) hydraulic motor/pump, (d) disc brake, and (e) drum brake.

Performance assessment requires parameter abstractions to determine battery consumption rates and torque output at a given throttle setting and motor speed for electric motors. Base speed, peak speed, and power output are sufficient parameters to develop an electric motor torque speed curve that can be used to determine torque output and energy consumption rate. Shape and size of electric motors is represented by three progressively smaller cylinders placed end to end. The geometric properties required are the large diameter, overall length, two diameter ratios, and two length ratios.

Hydraulic motor performance criteria abstractions include base speed, top speed, rated pressure, and rated flow rate. The size and inertial property estimates are based on a set of cylinders representing fluid input/output, hydraulic to mechanical power converter, and shaft output. Overall diameter and length of the motor along with fluid input/output diameter and length ratios are used to describe the necessary geometry for inertial property calculations.

Critical performance parameters relevant to powertrain analysis for brakes include the braking torque and whether or not it is controlled by an antilock brake system (ABS). Brake torque for both disc and drum brakes can be determined based on the brake pad contact area, effective radius to the center of contact area, maximum shoe pressure, application percentage, and shoe material friction coefficient. Additional disc brake abstractions including rotor diameter, width, thickness, and venting option, and shoe width, thickness, and arc angle are required to estimate the inertial contributions of disc brakes to the vehicle inertia and establish frictional surface area. Drum brake abstractions include drum diameter, width, and thickness, and shoe thickness and arc angle parameters to estimate inertia and maximum potential brake torque.

Power Transmitting Assembly – Power split devices, transmissions, differentials, and wheels are a few examples of power transmitting assemblies, Figure 9. These assemblies transmit power from one assembly to the next assembly connected by a power transmission path or, in the case of the wheel; power at a driven wheel is transferred to the ground. In addition to spatial and inertial parameters, speed/torque ratios are the critical abstractions for powertrain performance assessment.

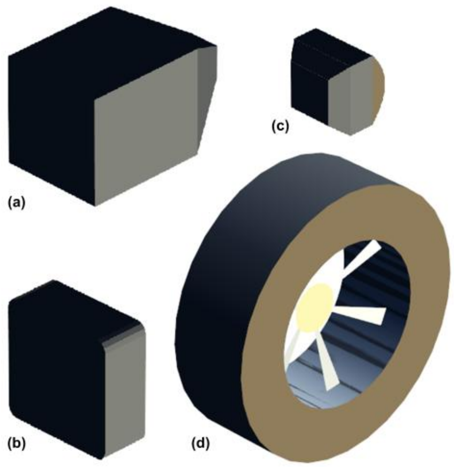

Figure 9. Power transmitting assembly abstractions (a) transmission, (b) power split device, (c) differential, and (d) wheel.

Power split device assemblies are planetary gear sets used to split power from an IC engine to the driveshaft and an electric generator or hydraulic pump for parallel hybrid powertrains. They are represented as a rectangular prism with rounded longitudinal edges and require length, width, height, fillet radius, and wall thickness parameters. Sun to planet gear ratio is the sole performance parameter required to determine the relationship of input speed and torque to the output speeds and torques.

Transmission assemblies are represented by a rectangular prism with a truncated pyramid on the output side. The geometric properties include input width/height, input length, output/input section width/height ratio, output pyramid length, and wall thickness. Performance parameters required are dependent on the transmission types; manual, automatic, and continuously variable (CVT) transmissions. Both manual and automatic transmissions have a set of forward and reverse gear ratios and efficiency defined for them. CVTs have minimum and maximum gear ratios and efficiency parameters to determine input to output speed and torque relationships.

Differential assembly abstractions have to represent the torque outputs for both of the connected wheels based on the input torque. All differential types are represented by a truncated pyramid input section, followed by a rectangular prism with paraboloid extending away from the input section. Geometric abstraction parameters include input width/height parameter, truncated pyramid length, input/base section width/height ratio, offset of paraboloid curvature, and thickness. Acceleration performance is dependent on the internal mechanics of the differential which determines the potential torque distribution to each connected wheel. The internal mechanics of differentials used to proportion torque to the driven wheels can be classified as normal, limited slip, or locking.

Normal differentials provide equal torque to both wheels, but the magnitude of the torque applied to the wheels is the minimum traction force of the two wheels. Traction force is a function of the frictional coefficient and normal load at the wheel. Thus, if one wheel is lifted off of the ground or on ice no or very little tractive force is generated at the opposite wheel.

Limited slip differentials can provide additional torque to one wheel relative to the other wheel when relative rotation occurs between the two wheels. The amount of additional torque is a function of the internal mechanics but at a high abstraction level only the limited slip torque parameter is of interest. The torque output for the wheel with the larger traction force is the torque at the wheel with less traction force potential plus the additional torque from the limited slip differential preventing relative rotation.

Locking differentials provide equal torques to both wheels regardless of the available traction force at each wheel. However, when the wheels are not free to slip relative to one another, the possibility of driveline windup exist causing undo stress on the powertrain components.

Wheels are represented as a tire and rim combination. The tire abstractions include a diameter, thickness, and tire type used to estimate rolling resistance coefficients and peak traction friction coefficients. The tire is assumed to have the same width as the rim. Rim abstractions include a rim diameter, width, and thickness, hub face diameter, hub face offset, hub rim offset, hub percent open area, and rim material type. An option for dual wheels with an additional wheel spacing parameter is required to represent common rear wheels of medium to heavy duty trucks. This level of wheel abstraction provides the pertinent information for determining size, shape, inertia, connectivity location, and potential propulsive force based on applied torque from the driveline.

Assembly connections

Structural connections among assemblies have a significant impact on the dynamic characteristics of a vehicle's architecture. The critical features of these structural assembly connections involve the geometric locations of the attachment points within the vehicle along with individual connection properties. These connection properties include the DOF, compliance, and damping properties associated with each attachment in the assembly connection. An assembly connection is represented as a set of connections between two assemblies contained in a vehicle concept model.

Geometric location of the attachment points within assembly connections are defined in terms of the vehicle hierarchy. Each end of the assembly connection connects to one of the two specified assemblies. Thus, for a given attachment point of a connection within an assembly connection, the geometric location is described by identifying the assembly, the component on the assembly, and the parametric location on that component. By maintaining this hierarchal definition, automated extraction of the various analysis models required for the aforementioned analyses is possible.

Connection model types include the standard mechanical joints; fixed, hinge (rotation about one axis), ball-joint (rotations about all axes), slider (translation along one axis), spring, damper, and permutations of these combined together.

Energy and Power Transmission Paths

These connections are normally insignificant in terms of the structural loads supported by the vehicle architecture itself, especially the energy transmission paths such as fuel, electric, and hydraulic fluid lines. The loads carried by shafts to transmit torque between the aforementioned power source and power transmitting assemblies have a significant impact on the shaft design but they can readily be designed in isolation of the vehicle architecture. The primary purpose of these path abstraction types for the vehicle architecture are the relationships of energy consumption by power source assemblies from connected energy storage assemblies and speed/torque changes that occur as power passes through power transmitting assemblies. Figure 10 depicts energy flow (yellow for fuel and green for electric currents) and power transmission (red) for a conventional and parallel electric hybrid powertrain.

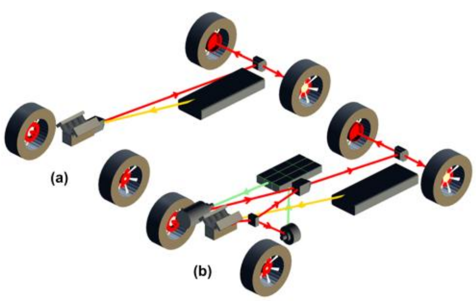

Figure 10. Vehicle energy and power transmission path abstractions for (a) conventional IC engine and (b) parallel electric hybrid rear wheel drive powertrains.

ANALYSIS MODEL ABSTRACTIONS

During the course of developing a vehicle concept model, different analyses models may be abstracted from the concept model based on the current level of specification for the concept model. Geometric assessment may commence as soon as points specifying the spatial envelop of an individual assembly are defined by the designer. Inertial analysis of an assembly or vehicle may begin once geometric features such as paths, surfaces, and volumes are marked as beam, panel, and inertial components, respectively. By specifying the powertrain energy storage, power source, and power transmission assemblies and the energy and power transmission connectivity for the vehicle, acceleration, braking, and fuel efficiency performance assessment may be performed by the analyst. Finally, once the assembly connectivity of the assemblies is defined in terms of the connection compliance and DOF, rigid body, structural, and NVH assessments may also be investigated by the analyst.

Geometric (Spatial)

Calculation of gross dimensions for an assembly only requires the points identifying the spatial envelop of the assembly to be defined by the designer. By specifying the paths between the points, bounding paths for surfaces, surfaces for enclosures, assembly compartment volumes such as the engine or crew cab compartment may be determined from the concept model. If additional assemblies are added to a vehicle and the location and orientation of each assembly relative to the vehicle coordinate system are specified, then vehicle level parameters such as overall size, wheel base, track width, and ground clearances are obtainable based on the vehicle assembly abstractions. For instance, wheels included in the vehicle are identified based on their classification type and the maximum longitudinal distance between any two wheels can be calculated to determine the geometric wheelbase of the vehicle.

Inertial

Once the points, paths, surfaces, and enclosure have been defined for an assembly, the designer must identify which paths, surfaces, and enclosures are physical beams, panels, and inertial components. Each component's abstraction properties must be specified accordingly by the designer, before proceeding to inertial analysis of the assembly. Inertial properties for individual component are determined by discretizing the component into smaller elements and summing the contribution of each element to the inertial property of the component. Similarly, by adding additional assemblies to the vehicle and identifying their location and orientation relative to the vehicle's coordinate system, the designer may obtain estimates for vehicle inertial properties derived from the inertial properties of each assembly in the vehicle.

Powertrain Performance

Powertrain assessment includes minimum braking distance, maximum acceleration, and fuel efficiency for a vehicle. These analyses implement a lumped mass model for the vehicle to determine normal force at the wheels based on the external loads such as inertial, aerodynamic drag, and road grade applied to the vehicle. Reasonable estimates of vehicle inertia are required to obtain good powertrain analysis results, but assembly models do not requisite the same level of detail as the FEM. Thus, assemblies could be represented as rigid bodies with specified inertial properties and location and orientation of the assembly within the vehicle coordinate system. If structural analysis will be performed later anyhow, then by specifying the appropriate component abstractions the inertial properties could be determined algorithmically.

Minimum braking distance assessment requires the specification of the vehicle brake and wheel abstractions in addition to the previously described inertial model abstractions for a vehicle. Additionally, the power transmission paths to the wheels for each brake must be specified by the designer in order to obtain brake torques at the braked wheels. This level of model data is sufficient to determine braking performance for systems without antilock brakes. When antilock brakes are included in the vehicle, ABS controls requisite additional abstractions involving valve cycling time, pressure application/release rates, and minimum/maximum allowable wheel slip. Then braking performance for a specified vehicle speed, road grade, and friction coefficient related to road finish can be determined from the vehicle abstraction.

Maximum acceleration calculations require powertrain component specifications beginning with the power source and ending at the driven wheels via the power transmission paths and assemblies. Torque output of the power source assembly is multiplied by the appropriate gear ratios and corresponding gear efficiencies as it enters and leaves a power transmission assembly. If the power limit at a wheel exceeds the traction limit, then depending on the type of differential placed on the axle, adjustment of the torque output to the opposite wheel may be required to obtain the correct solution. Thus, available torque at the drive wheels is a function of the overall powertrain configuration. Maximum acceleration for defined road grade and road surface friction is calculated from the powertrain assembly and power transmission path abstractions for the vehicle.

Fuel efficiency assessment mandates comprehensive powertrain specification including energy storage, power source, and power transmitting assemblies and the energy and power transmission paths. Energy transmission paths are used to balance the energy to power conversions and vice versa, while the power transmission paths are used to determine power output to the ground for vehicle propulsion. Based on these vehicle abstractions, it is possible to obtain fuel consumption while operating the vehicle at a given speed for a specified length of time.

Rigid Body Analysis

Extraction of the rigid body model assumes that all beam and panel components within a structural assembly are treated as rigid components. When two assumed rigid components within a structural assembly are connected by a rigidly connected assemblage joint, the two components can be lumped together forming a single rigid body. By traversing the connectivity of a structural assembly and identifying the flexible connections, an assembly of components can be extracted into a set of interconnected rigid bodies with known connectivity properties. These connectivity properties include the relative location, DOF, spring stiffness, and damping coefficients necessary for multi-body dynamic solutions. Suspension abstractions for the vehicle are an example of the multi-rigid body assemblies within a vehicle. Internal deformations of suspension component are normally insignificant relative to the large compliance element deflections of the assembly connections and thus are treated as rigid components. The inertial properties for each rigid body are derived in the same manner as the inertial analysis section. Locations, DOF, stiffness, and damping coefficients of the various connections between rigid bodies within the vehicle are obtained from the relevant assembly connections or assemblage joint abstractions. By specifying a terrain profile that each wheel in contact with the ground will traverse, it is possible to determine the resulting vehicle dynamics based on the derived rigid body model extracted from the vehicle model abstractions.

FEA

At the conceptual design stage, FEMs still requisite the most comprehensive vehicle architecture descriptions. However, powertrain assemblies and energy and power transmission paths are not required for analysis of the NVH or structural characteristics. They may be represented by simple inertial components with appropriate model connectivity instead to determine the free modal response of powertrain type components, without abstraction parameters related to energy storage, power production, or power transmission. The automated discretization of a vehicle concept model into a FEM involves a complex hierarchal approach in the parametric domain, which will only be briefly discussed in this paper. Vehicle meshing in the parametric domain begins at the vehicle level, then moves to the assembly level one assembly at a time and discretizes each component within an assembly one at a time while tracking coincident nodes and node dependencies due to the connections at the various hierarchal levels.

At the vehicle level, key points such as loads, constraints, and assembly connections to other assemblies must be identified for each component within each assembly. If any component contains multiple key points at the same parametric location, then the points must be merged for the connectivity meshing algorithms to track the nodal dependencies. Similarly, any nodes occupying the same Cartesian coordinates should be merged. These dependencies must be tracked to avoid dependency issues related to the rigid element formulations in FE solvers. Note that for a contiguous vehicle, all assemblies shall have at least one assembly connection to another assembly and thus one component in every assembly will have at least one key point. With the minimal connectivity and key point node set established for the vehicle, propagation of the known dependencies can commence.

Node dependency propagation begins with identifying any assembly connections with rigid DOF and constructing a vehicle level undirected connectivity graph using key points from assembly connections as nodes and edges represented by the rigid assembly connections. Any of these graph nodes that contain dependency information from a specified boundary condition constraint at the same location in the vehicle as the assembly connection may be propagated using the vehicle connectivity graph and rigid element dependency requirements. Once the minimal dependency set at the vehicle level is established, initialization at the assembly level can begin starting with those assemblies with the highest level of dependent node concentrations (ratio of externally forced node dependencies to total number of external nodes) and ending with the assemblies with the least node dependency concentrations. This method implicitly places a higher priority on rigid or nearly rigid assemblies because they have fewer nodes overall compared to the structural assemblies. The priority helps ensure that meshes for rigid components do not have dependency problems and that structural assemblies absorb dependency issues into their beam and panel elements that do not set nodal dependencies. As each assembly resolves internal node dependencies, the vehicle can propagate any new external dependencies to the appropriate mesh and select the next assembly for meshing until all assemblies have been meshed. Assembly connections at the vehicle level are meshed utilizing the predetermined nodal dependencies from the connectivity graphs.

Assembly level meshing is very similar to vehicle level meshing in that key points must be established for each component. However, there will be many more key points at the assembly level for structural assembly types due to the larger number of assemblage joints along the paths of beam and panel components. Once key points and their forced dependencies for all of the components have been established based on the connectivity graph of the assembly, individual components may easily be parametrically meshed based on the previously stated vehicle concept model abstractions. The connectivity graph for structural assemblies may contain hundreds of nodes but the graph is sparse because most nodes are connected to one or two other nodes normally, Figure 11. Since the connectivity graph is sparse, the algorithms quickly determine vehicle nodal dependency.

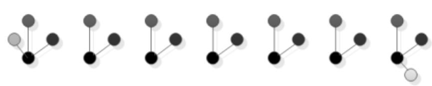

Figure 11. Partial assembly connectivity graph representing merged beam nodes (vertices) connecting to two separate sets of panel nodes (medium and dark grey). Beam end nodes connect to an additional panel component at the corner vertices of a box.

Beam components are meshed with beam elements. The beam component is discretized based on the parametric locations of the key points, critical geometric transition points, and suitable elements sizes for concept modeling. Regions defined by MCJs along the beam component are left unmeshed so that the MCJ abstraction may obtain the appropriate connection nodes and finish meshing their portion of the beam components with suitable stiffness properties.

Panel components are meshed with shell elements and are also discretized based on the parametric locations of the key points, geometric transition points, and suitable element sizes. For meshing relatively simple surfaces without cutouts or highly skewed bounding paths, a rectilinear meshing algorithm is appropriate for the panel. When geometric complexity increases, an advancing front meshing algorithm is more suitable for the panel.

Rigid components have no additional discretization points beyond describing the connection, loading, or constraint points and the center of mass. They are modeled as distributed rigid connections involving careful nodal dependency mapping of the component and ensuring they do not conflict with other assembly or assemblage joint connection dependencies. Thus, they still present a challenge to incorporate their inertial contributions to the overall model due to the node dependency resolution. However, by using a set of undirected graphs at both the vehicle level and individual assembly levels for the entire vehicle, it is possible to establish the appropriate nodal dependencies required for the FEM.

Assemblage and assembly joints within the vehicle are meshed appropriately based on the connection model abstraction implemented in the vehicle concept model. Any rigid portions of a connection are represented as rigid elements while spring and dampers are modeled with appropriate spring and damper elements.

CONCLUSIONS

A hierarchal set of vehicle architecture abstractions suitable for integrated concept model extractions appropriate for geometric, inertial, rigid body, powertrain, and FE analyses has been presented for wheeled vehicles. The required vehicle architecture abstractions include assembly, component, and connectivity classifications and data structures that provide a hierarchal representation of architectural geometry, connectivity, energy flow, and power transmission. Additionally, the relevant vehicle abstractions for each analysis model were presented, so that one may infer the analyses possible at a given development stage within the conceptual design phase. These hierarchal abstractions are also applicable to similar architectures such as aircraft or watercraft with appropriate specialized analysis abstraction models.

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