Application of Model Based System Engineering (MBSE) Principles to an Automotive Driveline Sub-System Architecture

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Discussion Agenda

- Introduction & Project Summary
- Driveline Definitions and Concepts
- Systems Engineering Concepts
- MBSE Concepts
- Driveline Model Structure – *Functional and Logical Decomposition*
- Requirements & Test Case Management
- Requirements Management : Satisfy Relationships
- Parametric Relationships – *Constraint Modeling Applied to Sizing*
- Benefits of Applied MBSE

Introduction & Project Summary

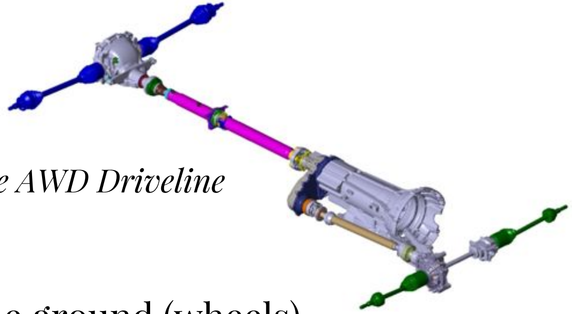
Current State: Today's automotive driveline system engineering process is "document based"

- Complex system requirements and specifications are communicated through large amounts of electronic data
- Often leads to incomplete or conflicting requirements
- Inefficient, redundant, error prone
- Running changes introduce potential problems

Project Summary:

- Obtained and deconstructed existing driveline system methods and sizing tools
- Identified need for improved requirements traceability in driveline systems engineering
- Created detailed driveline system model to apply the concepts of MBSE using SysML
- Added parametric constraints for sizing calculations
- Delivered functional MBSE model as proof of concept

Driveline Definitions and Concepts



Complete AWD Driveline

Architecture:

- A driveline system links the powertrain output to the drive wheels
- Primary function is to transmit drive torque from the powertrain to the ground (wheels)
- Driveline subtypes such as FWD, RWD, AWD are treated as *generalizations* in SysML

Components:

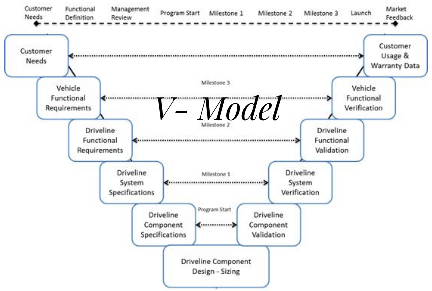
- Driveshaft / half shaft - transmits torque to front/rear or left/right
- Axle - multiplies driveshaft torque and directs to wheels
- Additional - Transfer case, PTU, disconnect device, U-joints, CV-joints, flex coupler

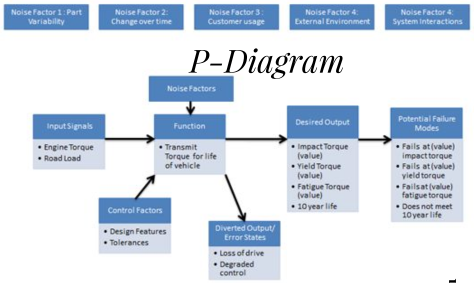
Sizing:

- Design optimization of each component, system and subsystem is the primary objective
- A sizing tool converts input data into torque outputs for all vehicle variations and uses industry standard equations and some correction factors.

System Engineering Concepts

- V-Model:
  - Top level requirements are decomposed to the subsystem and component levels, each with a specific validation plan flowing down the left side of the V and back up the right side.
- Context Diagram:
  - Represents system interactions to an external environment
  - Interacting systems are defined as “black boxes”
- P-Diagram:
  - Expands and refines context for more detailed black boxes
  - Includes detail on input signals, control factors, noise factors, outputs, and potential failure modes
- ***MBSE***
  - Modeling Language (SysML, UML etc)
  - Modeling Method
  - Modeling Tool (Magicdraw, IBM Rational Rhapsody etc)





Model Based System Engineering Concepts: *System Requirements*

- Requirements define customer and stakeholder needs in technical terms
- In SysML, system requirement statements are defined as *objects*
- Each *object* contains the requirement text & a unique identifier
- The requirement *type* defines the features a requirement can be associated with
- *Generalizations* manage and allocate requirements through inheritance relationships
- Requirements must be verified by *test cases*
- *Test cases* are checkpoints, such as design reviews or physical tests

Requirement Type	General Description	Example
Functional Requirement	Specifies a behavior of the system	Must transmit torque from transmission to wheels.
Performance Requirement	Specification, a quantifiable measurement of performance	Operational at vehicle top speed of 120 mph.
Interface Requirement	Specification for how system components connect	Must mount to transmission output flange PN FRZ102345.
Design Constraint	Design rule, or constraint on implementation	Threaded fastners must use common metric threads and standard hex sizes.
Physical Requirement	Physical constraints on the system	Must fit within underbody package envelope.
Usability Requirement	Constraint on usage by physical actors	Must allow clearance for 95th% hand to access control lever.
Business Requirement	Constraint related to business processes	System must be back compatible with existing service axle lubricants.

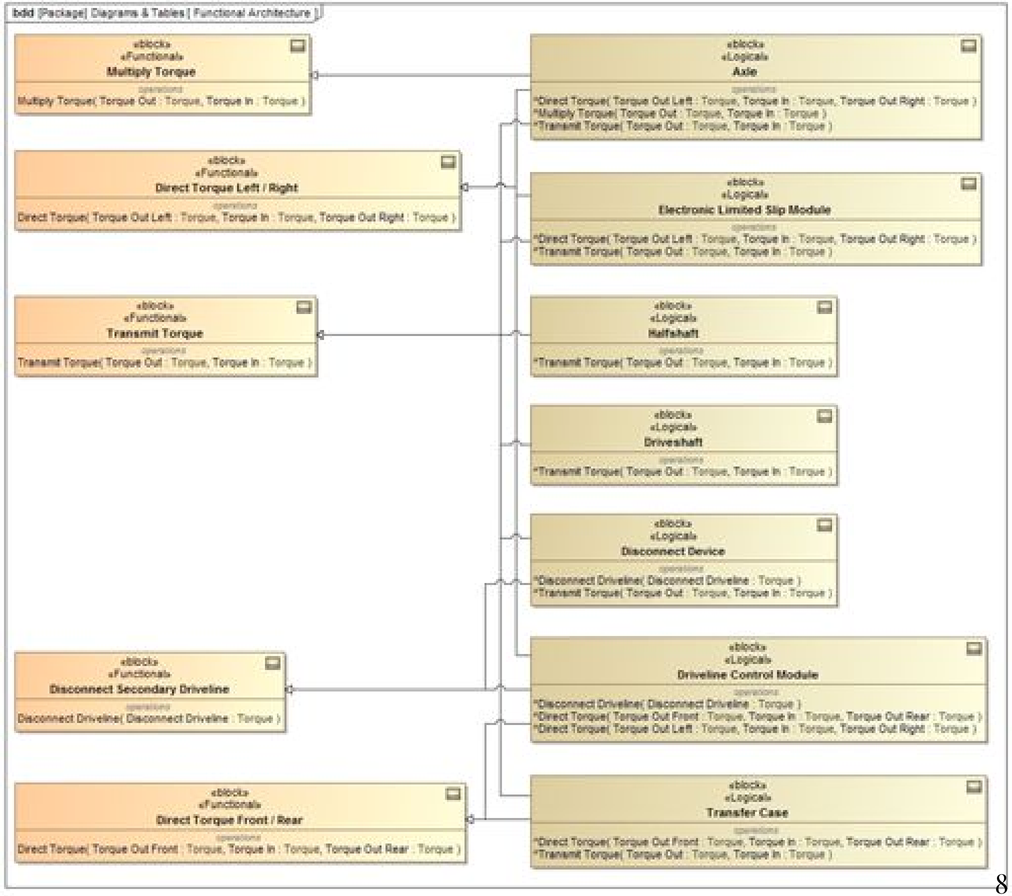
Standard type requirements within SysML are used to provide rigor and clarity when defining the system

Model Based System Engineering Concepts: *Functional & Logical Architecture*

- Functions define what actions / activities must be accomplished or completed to achieve a desired outcome
- An *operation* is a property of a *block*
- A *block* is an abstract representation of any part of a system, like physical hardware or a signal
- Functions are linked through logical relationships to the various subsystems and components
- The *logical architecture* describes how a system will be implemented
- It abstractly defines a technical solution based on the system's required sub-systems, components and their relationships
- A logical architecture should only be created after the system's functions and requirements are clearly defined
- It does not define any *particular* system implementation, but rather the general guidelines so as to remain *solution-neutral*

Methods of Modeling: *Functional Decomposition*

- Five basic operations of the driveline systems were identified from the P-diagram
- The system needs to
  - Transmit torque
  - Direct torque left / right
  - Direct torque fore / aft
  - Multiply torque
  - Disconnect the secondary driveline
- Each function is associated, or mapped, to at least one logical block
- The function, or operation, is then inherited through generalizations

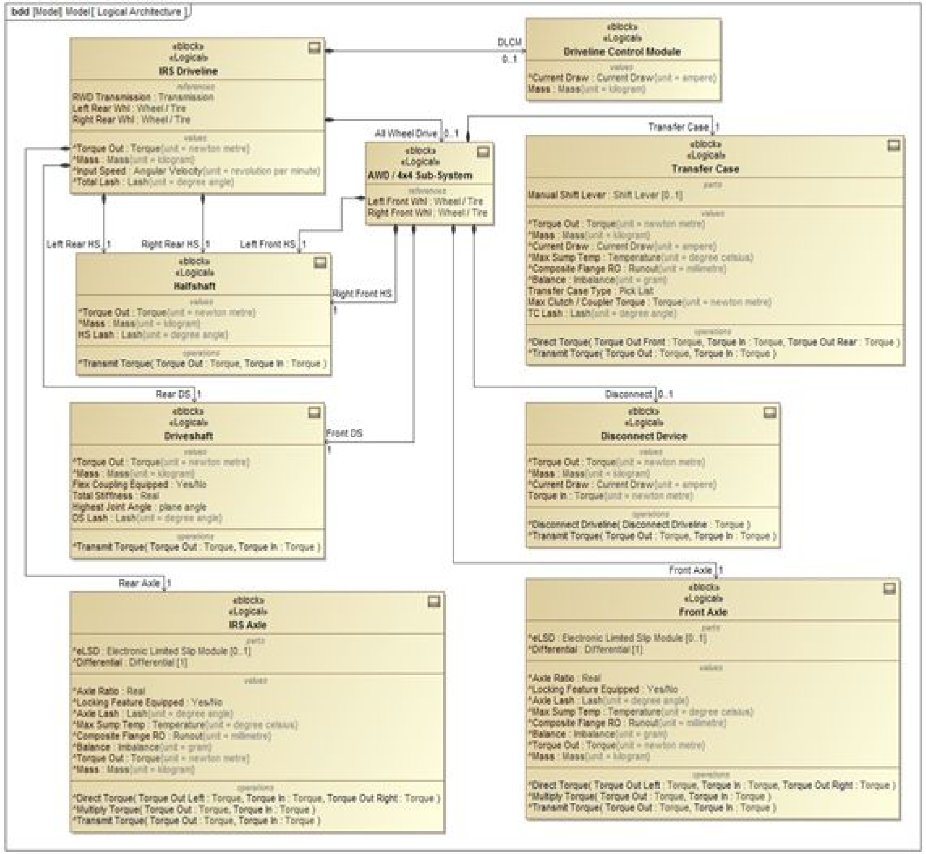


Methods of Modeling: *Functional Decomposition*

- Transmission of propulsion force from the powertrain to the wheels is the most basic, and most obvious, driveline function
- At the functional level of abstraction the degree or amount of torque transferred is not necessarily relevant – all that matters is that all drivelines transmit torque
- In our model the “transmit torque” function is inherited by all mechanical sub-systems and components
- It is important to note that no one component alone delivers or satisfies the transmit torque function - it is an emergent function of the total system
- The next function is to direct torque left/right which is the operation or behavior of a axle/transaxle differential logical block
- The next function is to direct torque fore-aft which is the behavior of a transfer case and is only present in AWD or 4X4 driveline configuration
- In a driveline system model, the multiply torque function is a behavior of the axle only
- The last function is the disconnect function which is the behavior of a disconnect device

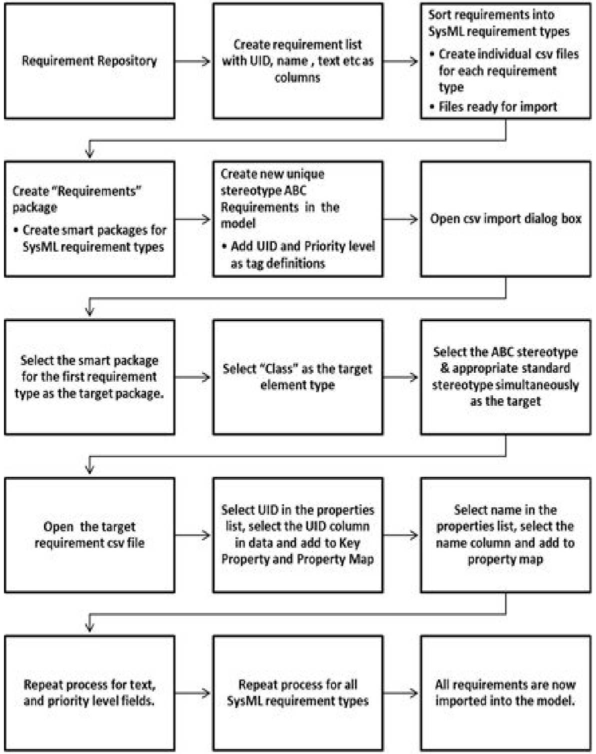
Methods of Modeling: *Logical Decomposition*

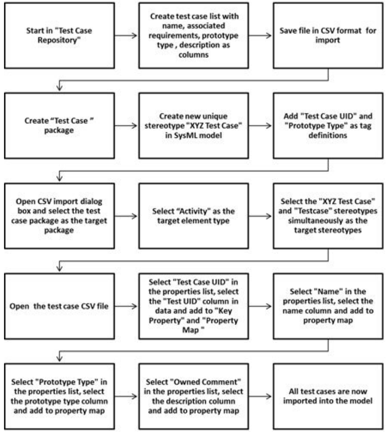
- Logical blocks are constructed after the functional blocks are defined, requiring some experience and engineering judgement
- A good logical decomposition should remain untethered to any specific design concept, since it is unlikely that the first design concept will be the best design concept
- The driveline logical diagram provides the structure required to capture the vehicle inputs required to support parametric equations for calculating driveline impact torques, which is the basis for sizing



Requirements & Test Case Management

- Import the requirements using the import feature in MagicDraw into a requirements package.
- Existing test methods are imported using a method similar to that of importing requirements
- Verify matrices are created and each requirement is verified by one or more test methods.





Requirement Type	Number of Unique Requirements	Total Number of Test Cases (For Each Rqmt. Type)
Functional Requirements	0	0
Design Constraint Requirements	284	471
Performance Requirements	15	36
Physical Requirements	4	5
Interface Requirements	0	0
Business Requirements	9	11
Usability Requirements	14	18

Requirement Management: *Satisfy Relationships*

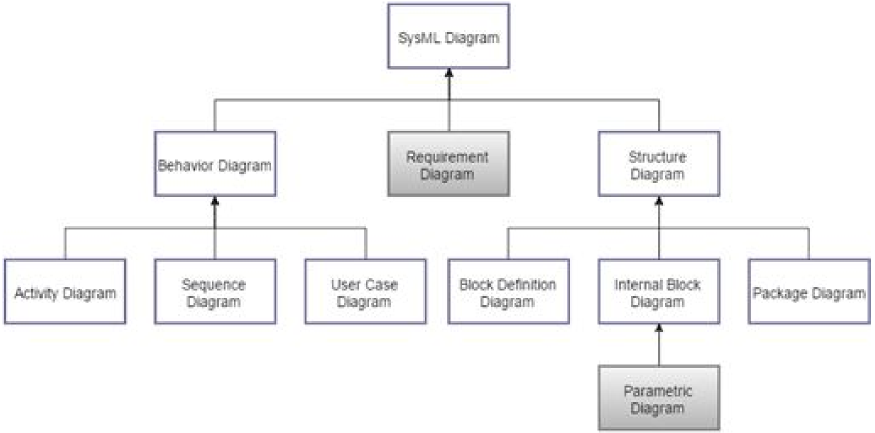
- Requirements are *satisfied* by physical elements
- In MBSE this relationship is created at the logical level of abstraction, prior to any physical parts being designed
- The satisfy matrix indicates that each requirement is mapped to at least one logical block through a satisfy relationship that indicates that the logical block is required to deliver or meet the requirement
- The table shows all the logical elements in the driveline model that satisfy requirements, and the requirements are separated into the seven different SysML requirement types

Logical Elements	No. of Functional Reqmt. Satisfied	No. of Des. Constraint Reqmt. Satisfied	No. of Perf. Reqmt. Satisfied	No. of Physical Reqmt. Satisfied	No. of Interface Reqmt. Satisfied	No. of Business Reqmt. Satisfied	No. of Usability Reqmt. Satisfied
AWD / 4x4 Sub-System		16		1		2	
AWD Sub-System		4		1		2	
Axle		54				2	2
Axle Lash:Value Properties::Lash			2				
Axle Ratio:Real							
Axle / T-Case Inheritance							
Balance:Value Properties::Imbalance			2				
Composite Flange RO:Value Properties::Runout			2				
Max Sump Temp:Value Properties::Temperature			4				
Beam Axle		3		1			
Controls Inheritance Block		1					
Coupling		3					
Disconnect Device		4					
Driveline Control Module		1					
Driveline System		14					1
Total Lash:Value Properties::Lash			1				
Driveshaft		109				1	5
DS Lash:Value Properties::Lash			1				
Electronic Limited Slip		1					
Electronic Locking		1					
Front Axle		11				1	2
Halfshaft		21					1
HS Lash:Value Properties::Lash			1				
IRS Driveline		1				1	
Mechanical Limited Slip		2					
PTU		17		1		1	
PTU Lash:Value Properties::Lash			1				
Shift Lever		5					2
Transfer Case		20		1		1	1
TC Lash:Value Properties::Lash			1				
Transmission		7					
Wheel / Tire		2					

I think I am done for now. Will revise a bit more after Bob and Mike review.

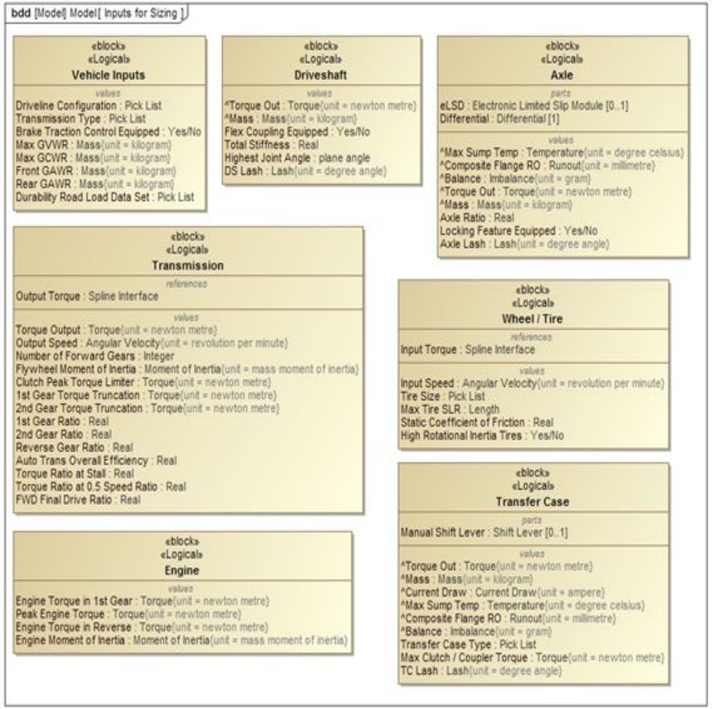
Parametric Relationships

- In systems engineering, design involves making decisions between solution alternatives
- General process is:
  - Generate ideas
  - Evaluate alternatives - engineering analysis
  - Decide between alternatives - interpret results
- SysML provides a language to express and perform mathematical system analysis through parametric diagrams
- Parametric diagrams show mathematical relationships between the blocks of the system model.
- They act as constraints on the system design.



Parametric Relationships: *Sizing Inputs*

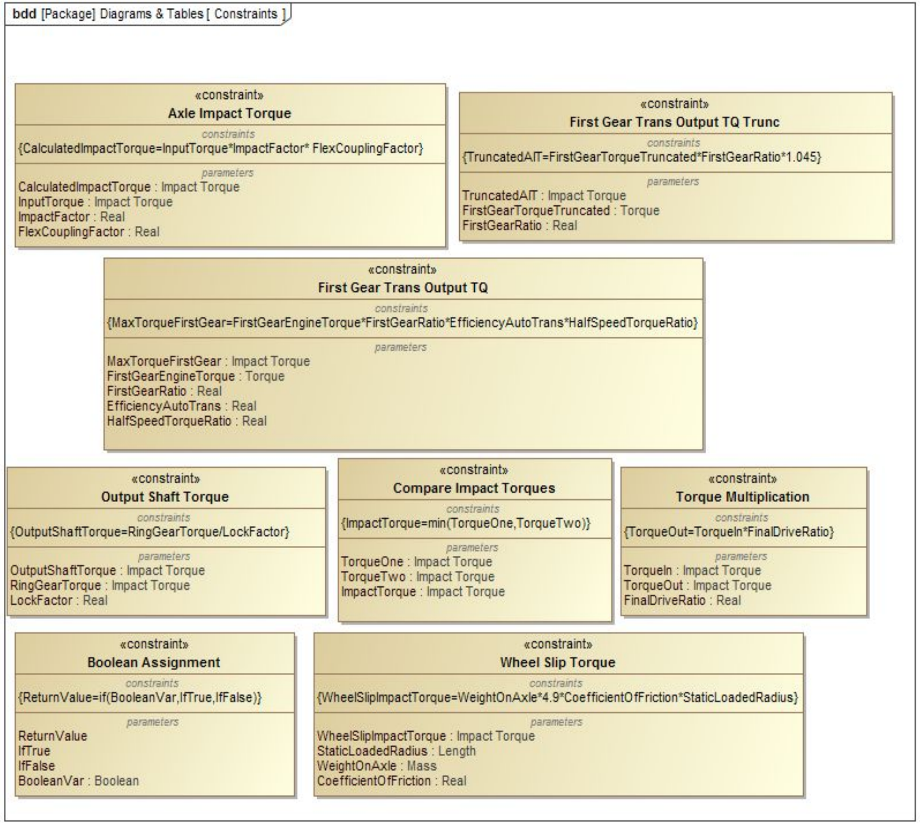
- Parametric input parameters are obtained from industry standard equations for sizing (sizing tool).
- Mapping of parametric inputs as value properties associated with logical blocks based on the property's logical ownership are shown here
- The impact torque sizing inputs are the *value properties* associated with the appropriate logical blocks
- At logical architecture levels, these value properties are *to be defined* variables that are not associated with any specific instance
- Specific instances can be created when required



Parametric Input	Logical Block Ownership	Value Type
Vehicle Assumptions		
Driveline Configuration (Type)	Vehicle Inputs	Pick List
Brake Traction Control Equipped	Vehicle Inputs	Yes / No
Max GVWR	Vehicle Inputs	Kg
Max Front GAWR	Vehicle Inputs	Kg
Max Rear GAWR	Vehicle Inputs	Kg
Max GCWR	Vehicle Inputs	Kg
Durability Road Load Data Set (RLD)	Vehicle Inputs	Pick List
Engine		
Engine Torque in 1st Gear	Engine	N-m
Highest Engine Torque Available	Engine	N-m
Engine Torque in Rev. Gear	Engine	N-m
Engine Moment of Inertia	Engine	MMOI
Transmission		
Transmission Type	Transmission	Pick List
1st Gear Torque Truncation	Transmission	N-m
2nd Gear Torque Truncation	Transmission	N-m
Transmission Efficiency	Transmission	Real #
Torque Converter Ratio @ Stall	Transmission	Real #
Torque Converter Ratio @ 0.5 Speed Ratio	Transmission	Real #
Transaxle FDR	Transmission	Real #
Flywheel Moment of Inertia - Manual Trans	Transmission	MMOI
Clutch Peak Torque Limiter - Manual Trans	Transmission	Real #
Number of Forward Gears	Transmission	Integer
1st Gear Ratio	Transmission	Real #
2nd Gear Ratio	Transmission	Real #
Reverse Gear Ratio	Transmission	Real #
Driveline		
4x4 Transfer case type – Active/On Demand	Transfer Case	Pick List
4x4 Transfer case Max Coupler Torque	Transfer Case	N-m
Flex Coupling Equipped	Driveshaft	Yes / No
Total Driveshaft Stiffness	Driveshaft	N-m/rad
Highest Joint Angle @ Design	Driveshaft	Degrees
Rear Axle Ratio	Axle	Real #
Locking Differential Equipped	Axle	Yes / No
Wheels / Tires		
High Rotational Inertia Tire Equipped	Wheel/Tire	Yes / No
Tire Size	Wheel/Tire	Pick List
Max Tire SLR	Wheel/Tire	Pick List
Tire Coefficient of Static Friction	Wheel/Tire	Real #

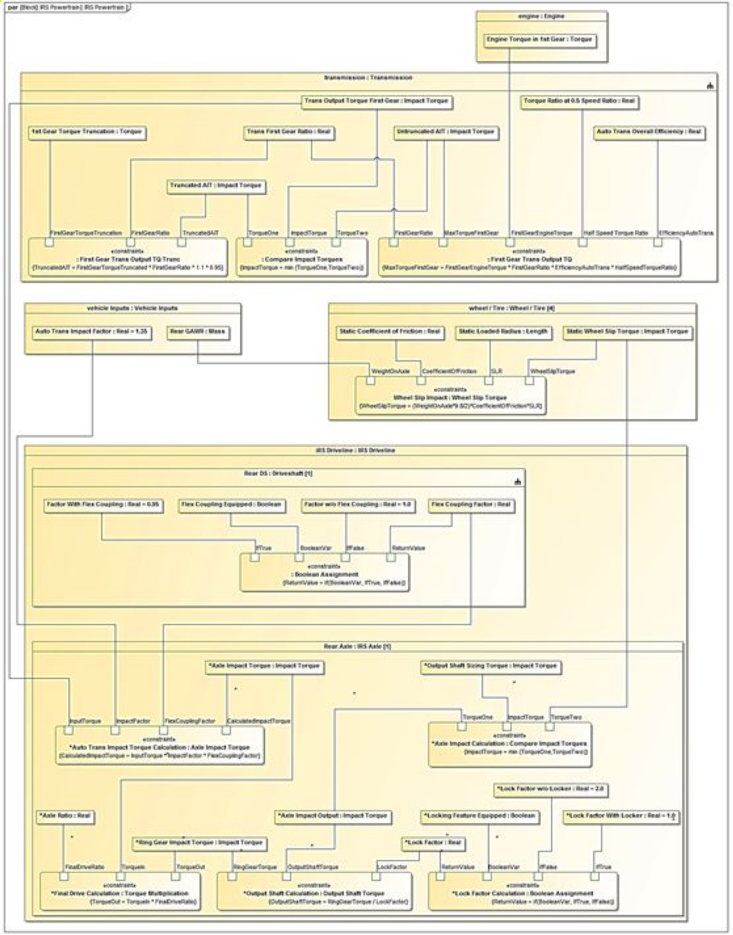
Parametric Relationships: *Constraint modeling*

- Parametric constraints specify equivalence relationships between logical blocks
- Defined in a similar manner to IBDs, but they use internal relationships with constraint parameters instead of part parameters
- Restricted to connecting only through binding connectors, typically with a parametric constraint at one end of the connection
- The key element is the constraint block, which is used to constrain the properties of one or more other blocks
- Constraint blocks consist of constraint expressions $\{\tau = F * d\}$ and constraint parameters (such as τ, F and d)



Parametric Relationships: *Driveline Sizing*

- Goal : Show proof of concept for the calculation of sizing torques
- A total of eight different constraint blocks used to model impact torque, consisting of torque flow equations, logic flow and Boolean assignments
- Instances need to be created with specific inputs to complete parametric analysis for driveline sizing
- Parametric calculations for impact torque were completed for a proposed vehicle program, and compared to the values obtained from existing analytical tools
- Successful proof of concept, however, requires more time and work to reliably replace existing analytical tool



Benefits of Applied MBSE

- Object oriented modeling can be equally applicable to a fully mechanical system
- MBSE improves engineering productivity and efficiency
- System models are more flexible, consistent and scalable across all sub-systems
- Streamlined communication of requirements by making all key input and output parameters available to all model users
- Better traceability and linkages between requirements and their methods of verification
- The reduction of requirement redundancies and automatic validation of test case verification could result in the elimination of entire tracking departments
- The ability to continuously update and manage component design inputs through parametric relationships with vehicle level inputs
- Every individual with access to the model can not only see and verify his or her subsystem, but also view all of the interactions of their subsystem with other parts of the entire system minimizing cross functional issues and miscommunication

Benefits of Applied MBSE

- We emphasized careful categorization of existing requirements and during the import process eliminated redundancies, reduced 500+ to ``~300
- Through our integration efforts into SysML categories, we discovered a clear need and benefit of improved elicitation and partitioning of existing requirements
- Requirements and test cases can be added to the model fairly easily, and can be easily linked with the entire driveline system.
- A new requirement with the document based approach will require a lot of cross referencing with other requirements, and redundancies and total misses are quite possible

Benefits of Applied MBSE: *Parametric Input Cascade and Control*

- Through parametric relationships, top level assumption changes are immediately cascaded down and can be verified against existing component variable properties
  - For example, If engine torque in first gear goes up, it will immediately be calculated into transmission output torque and compared against the axle maximum input torque limit. These are SysML numbers calculated, used as an alert, but details need to also exist to define past systems level. Not too deep and complex. You lose sight of big picture.
  - Changes in tire properties can be linked to and compared against halfshaft joint design limits automatically
- If the input assumptions exceed design limits the model shows an output error alerting engineering to act