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website:- [www.ultrascientist.org](http://www.ultrascientist.org)**Application of Design Structure Matrix to Optimize Various Powertrain Attributes of a vehicle**ATIF AZIZ<sup>1\*</sup> and AMEEN KHAN<sup>2</sup><sup>1</sup>M. Tech Student, All Saints College of Technology, Bhopal India<sup>2</sup>Senior Team Leader TATA Technologies Ltd., Pune, IndiaCorresponding Author Email: [atifaziz82@gmail.com](mailto:atifaziz82@gmail.com)

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**Abstract**

In ever increasing competition in the automotive sector, there is a growing need to reduce the vehicle development time and bring new vehicles to market much faster and first time right with the desired attributes in order to retain the competitive advantage. Powertrain systems engineering is an important area which affects many critical Vehicle attributes perceived by the customer. Most of these powertrain attributes often impose conflicting requirements on the Powertrain design parameters. These conflicts are most often realized at a very late stage of the vehicle development which results in rework and delays as currently there is no Process available to optimize the Powertrain attributes quite early in the program. In this paper, few key Powertrain attributes are shortlisted to demonstrate the new approach for powertrain multi-attribute target development for vehicle integration. A design structure matrix (DSM) provides a simple, compact, and visual representation of a complex system that supports innovative solutions to decomposition and integration problems<sup>11</sup>. A Design Structure Matrix is created for the Powertrain attributes to demonstrate various interactions among powertrain attributes and balance the Targets.

This Research paper aims to develop and demonstrate Powertrain attributes Design Structure Matrix as a new approach for powertrain multi-attribute target development and balancing for vehicle integration.

*Key words* : Powertrain, design structure matrix, design optimization, attributes, vehicle

**Introduction**

Those Automotive organizations which meet the customer expectations better than their competition have dominated the segments where they compete. These leaders recognize that consumer satisfaction goes beyond simply providing superior components assembled into a final vehicle. It is a deeper mind-set and holistic perspective of the customer and the vehicle. An automotive company

must empathetically understand how their Vehicles are used by customers over the life cycle of the vehicle. The customer's view is a collection of categories to evaluate the vehicle, balanced in a manner relevant to the customer. These categories are termed as Vehicle attributes and form a natural functional decomposition of the product, which establishes the context for the consumer.

Therefore, there is a need to focus on the key Vehicle attributes the customer actually appreciates and that

eventually drive his purchase decision. Axiomatic Design is a methodological approach using elementary matrix methods that is used to attain stable system and sub-system concepts and to analyse and optimize the transformation of customer needs into functional requirements, design parameters, and eventually into process variables. According to the principles of axiomatic design, complete vehicle characteristics can be divided into three levels: The first level, the customer domain, is represented by the customer relevant or primary vehicle attributes which directly influence the purchase decision. The functional or secondary vehicle characteristics on the second level, the functional domain, are the vehicle functions and properties that are necessary to realize the first level characteristics. The characteristics of the third level *i.e.* physical domain are physical prerequisites for the characteristics of the functional domain.

Key Primary attributes directly related to the Powertrain system are as follows,

- Powertrain NVH (Noise, Power, and Harshness) & Sound Quality
- Performance & Drivability
- Fuel Economy
- Powertrain Durability

Attribute Descriptions: -By attribute we mean, “Those Vehicle characteristics by which a vehicle is judged by the Customers”.

There are two main sources of excitation for the noise & vibrations in a vehicle.

Following table shows the NVH excitation sources for an automobile

Table 1 –NVH Excitation Sources in a vehicle

NVH Excitation Source	Sub-system Responsible	Phenomenon	Customer perceived NVH Issue
Powertrain	Engine Clutch Gear-box Driveline Axle	Rotating & Reciprocating	Powertrain sound quality
		Imbalance	Perceived vibrations
		Torsional vibrations,	Harshness
		Clutch Rattle Clunk	Clutch pedal vibrations
		Gear Rattle	Take-off shudder
		Driveshaft Imbalance	Noise
		Axle gear mesh variation	Vibrations at GSL knob
			Floor vibrations
			Boom
			Axle whine
Road	Wheel Suspension	Road undulations	Seat Vibrations
		Tire Force variation	Steering wheel Vibrations
		Wheel imbalance	Road noise
		Road undulations	Suspension noise
		Steering geometry	Steering wobble

Powertrain NVH & Sound quality is a complex attribute having interactions with many other vehicle attributes, systems and sub-systems. It is very difficult to model and predict through available CAE tools in early phases of product development. Therefore, in most cases, NVH issues are realized at a very late stage in the vehicle development program which necessitates countermeasures resulting into cost & weight increase, rework & delays, customer dis-satisfaction etc.

The powertrain is a vital part of an automobile and is very important to the customer. The powertrain itself is a very complicated system typically controlled by

multiple computers to ensure that all the competing requirements are managed despite ever changing driver inputs. In this paper, we are focusing on how to better develop powertrain NVH & sound quality attribute in order to achieve higher customer satisfaction and develop a process to benefit the engineering development team. This will also help to avoid the rework and delays during the Product development. In most of the vehicle development programs, rework and delays occur because the interactions between various attributes and aggregates is realized much later in the program. Our aim is to predict these interactions quite early in the design stage itself so that these rework &

delays are minimized.

The goal of the authors are to improve the development and management of Powertrain NVH Attribute and sub-attributes through improved understanding of the powertrain NVH attribute/ sub attributes/ sub-system/ components and better understanding of the interactions between them.

#### Literature Review :

The vehicle's powertrain consists of engine, transmission and supporting hardware needed to transmit power to the wheels. About 25%-30% of a vehicle's content by cost and part count is included in the powertrain. The picture in below figure shows a detailed view of the

powertrain sub-systems, which consist of

- Engine
- Transmission
- Powertrain Control Module (PCM)
- Cooling module (Radiator, Fan, coolant container and other cooling components)
- Exhaust System including Catalytic converters
- Air Intake System (AIS)
- Fuel and Vapour Management Systems
- Axles and half shafts
- Driveshaft
- Engine & Transmission Mounts
- Accelerator Controls and Speed Control
- Transmission Shifter and Cables

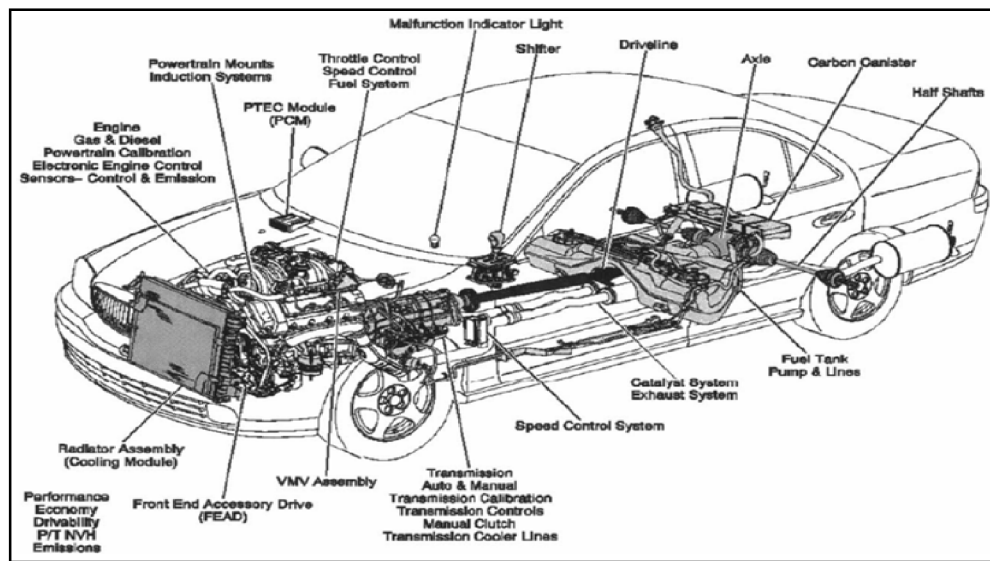


Figure 1 - Powertrain System

Effective Powertrain integration on a vehicle requires proper understanding of each sub-system and various interactions of these sub-systems among them as well as with other vehicle sub-systems like suspension, Body etc. Achievement of desired powertrain NVH & sound quality attribute depends upon proper balancing of these interactions.

#### Powertrain NVH characteristics :

The automotive marketplace has seen a steady increase in customer demands for quiet and more comfortable vehicles. A customer's expectations for Powertrain NVH refinement often contradicts the constraints for lightweight vehicle designs and the need for a powertrain with increased fuel efficiency. The driveline of a vehicle can be a substantial

cause of NVH issues.

Variants in the driveline architecture (front wheel, rear wheel and four-wheel/all-wheel drive, automatic-, manual-, automatic-shifted manual transmission, etc.) combined with an overall increase in the complexity of the modern driveline systems can make the task of integrating them very challenging. Development of a well refined vehicle requires the understanding and control of several driveline-related noise and vibration problems within different frequency ranges, due to the multitude of driveline components and their potential excitation sources. A key aspect of the driveline integration process is the realization that a design modification can have an impact on numerous NVH phenomena.<sup>5</sup>

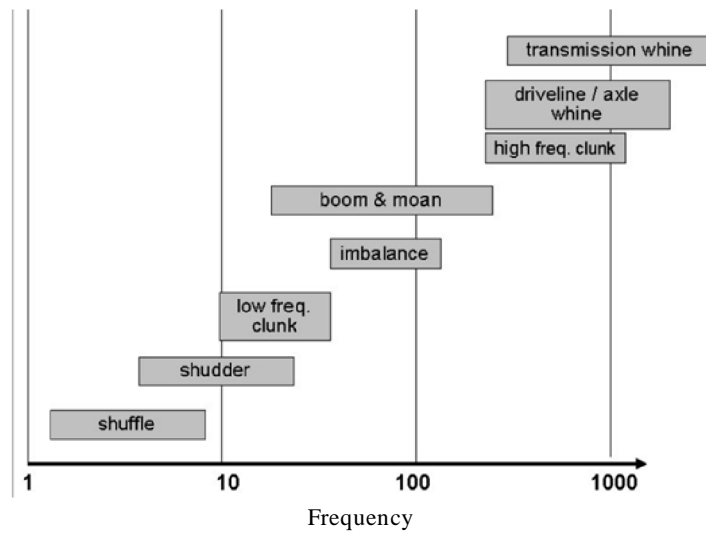


Figure 2. Typical Frequency Range of Various Driveline NVH Issues<sup>5</sup>

The configuration of the driveline can result in a variety of NVH concerns across a broad frequency range. Quick changes in the vehicle’s load (e.g., pedal tip-in/out) can result in an objectionable vehicle shuffle response, which is connected to the first natural frequency of the driveline and is usually in the 2 Hz – 8 Hz frequency range (depending on the selected gear). On the opposite end of the frequency range, driveline dynamics can influence the dynamic mesh forces of a rear axle, resulting in axle whine, which is typically between 300 Hz – 1 kHz, while transmission whine can extend out to the 3 kHz - 4 kHz range. These examples illustrate the wide frequency range and extremely different NVH concerns that have to be considered in the driveline integration process<sup>5</sup>. A list of the most commonly encountered driveline NVH phenomena

and their usual frequency range is shown in above Figure.

The primary cause of these NVH issues can be traced back to various driveline components or subsystems. Driveline related NVH issues and the corresponding primary sources are shown in below Figure. This figure only provides an indication of the primary sources of noise/vibration for the NVH phenomena that is listed. Additional driveline-, engine- and vehicle parameters, which are not specifically shown in the figure, can also have a significant impact on the particular NVH phenomena. Driveline shuffle and clunk, as an example, that occurs during a pedal tip-in maneuver can be influenced by the torque rise rate and can be controlled by the appropriate engine torque management strategies [5].

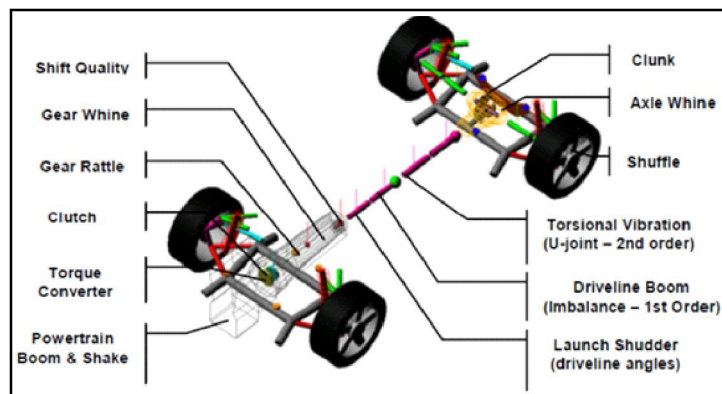


Fig. 3. Typical Driveline NVH Phenomena<sup>5</sup>

Typical excitations of driveline NVH phenomena include:

- Free forces and moments of the combustion engine
- Engine flywheel Torsional vibration
- Driveline imbalance
- Gear meshing forces
- Transient Torsional inputs, such as pedal tip-in

The wide frequency range where driveline-related NVH issues are present combined with the variety of excitations and NVH phenomena illustrate the complex nature of the driveline integration process. Therefore, early in the vehicle development process it is crucial to begin with driveline NVH evaluation, both through CAE and with prototype vehicle testing. During the entire vehicle development process, crucial NVH driveline metrics must be monitored carefully. Currently, the movement towards reduced development time and prototype vehicle availability makes early and increased usage of CAE tools imperative in the vehicle development process<sup>5</sup>.

#### *Design Structure Matrix :*

The design and development of complex engineering products require the efforts and collaboration of hundreds of participants from diverse backgrounds resulting in complex relationships among both people and tasks. Many of the traditional project management tools (PERT, Gantt and CPM methods) do not address problems stemming from this complexity. While these tools allow the modelling of sequential and parallel processes, they fail to address interdependency (feedback and iteration), which is common in complex product development (PD) projects. To address this issue, a matrix-based tool called the Design Structure Matrix (DSM) has evolved. This method differs from traditional project-management tools because it focuses on representing information flows rather than work flows. The DSM method is an information exchange model that allows the representation of complex task (or team) relationships in order to determine a sensible sequence (or grouping) for the tasks (or teams) being modelled<sup>9</sup>.

The Design Structure Matrix (DSM) is a tool that helps to capture the important relationships in a complex system such as that in a design project. The purpose of applying the DSM method to a design project is to understand the information flow and communication in the design process and hence to seek improvements based on better understanding of the system<sup>3</sup>.

The Design Structure Matrix (DSM) is intended to record all the interactions inside a system in a single square matrix. Its principle use is to analytically determine an improved design/development task sequence from these interactions. Different types of interactions can be

modelled in a DSM:

- Interactions between subsystems or elements of the system,
- Between design parameters,
- Tasks to be performed
- Actual people working in the design of the system.

An example of a binary DSM is shown below.

A DSM of two variables A and B. A mark in row A column B means that in order to demonstrate variable A, a value of variable B is first known or assumed but variable B cannot be determined unless the value of variable A is known or assumed. This interdependency between variables makes a circuit. So a guess or estimate has to be made to break these circuits in design iteration process.

	A	B
A	.	X
B	X	.

Fig 4. Sample DSM of variables

Interactions are represented by marks in the matrix. A mark indicates that an item in the column has an impact on the item in the associated row.

On the DSM if the tasks are completed from top to bottom or correspondingly from left to right, the triangle below the diagonal represents feed forwards (information that flows from earlier to later tasks that are sequential in the design process), and the triangle above the diagonal represents feedbacks (information flows that flow in the reverse order of the design process).

A DSM helps project managers to identify these loops, and possibly reorder the tasks or elements of the system in the process so as to minimize the effect of feedbacks.

Use of the DSM method is typically completed using the following 8-step process:

1. Define the system and its boundaries.
2. List all the system elements / process tasks.
3. Study the information flows between the elements or tasks. This is typically done utilizing requirements documents and via interviews with experienced engineers.
4. Build a matrix to represent the information flow.
5. Verify the matrix with engineers.
6. Partition the matrix.
7. Optimize inside cycles using knowledge on the system or process.
8. Consider a reorganization of the process and eventually implement it.

If a system is highly coupled the DSM may not be able to be adequately partitioned. So manual clustering, or manual reordering of the elements in rows and columns, may be the only viable method to achieve a matrix that is close to block triangular form. This is one of the drawbacks of the DSM method.<sup>4</sup>

A DSM has other uses and benefits as well:

- DSMs help one visualize the complexity of a system or process.
- DSMs record system-level knowledge on a single document. This allows information to be made available for less experienced people. This helps them to learn the complexity of a system more easily and quickly.
- DSMs make a very useful project management tool,

since they account for iterative loops. This helps ensure more accurate time and cost planning. DSMs can also help portray the consequences of a modification of one aspect of a system on the development process.

- DSMs allow the design process to be viewed on a task/ information exchange basis rather than on a physical, structural, cultural, historically inherited decomposition or ad hoc basis.
- DSMs remove unnecessary design loops and rework from processes, and identify the causes of unavoidable ones, which is a good starting point for further effective process modification and improvement.”
- DSMs can be updated, if the system is modified

Components		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Front wheels	A	.	2	2	2	1	2					2				2
Transmission	B	2	.	2	2	1	2					2				2
Planetary power splitter	C	2	2	.	2	1	2					2				2
Clutch/brake	D	2	1	1	.	1	2					1				1
Internal Combustion Engine	E	1	1	1	1	.	1					1			2	1
Front motor/Generator	F	2	2	2	2	1	.					2				2
Invertor	G							.								
Battery	H								.							
Rear motor/Generator	I									.	2		2	2		2
Rear Differential	J									2	.		2	2		2
Front axle	K	2	2	2	2	1	2					.				2
Rear axle	L									2	2		.	2		2
Rear wheels	M									2	2		2	.		2
Fuel delivery/storage	N					2										.
Chassis	O	2	2	2	2	1	2			2	2	2	2	2		.

Fig. 6. Component- based DSM showing physical interface of vehicle power train interface

Above Fig shows the vehicle power train parts by name in column 1. Each component is given an abbreviation, appearing, in column 2 and row 1. Cells in the body of the DSM show the strength of physical interaction between different components. Components do not ‘interact’ with themselves, so the diagonal is empty. Components that physically interact with another strongly have “2” in the corresponding cell. Other Components that interact more weakly have a “1” in the corresponding cell. Components that do not interact or that interact very weakly have blank cells.

*Partitioning :*

A mathematical algorithm is used to rearrange the

process so as to reduce the effects of feedbacks by getting feedbacks as close to the diagonal as possible without any implicit knowledge on the particular process. More precisely in mathematical terms, it will change the order of the elements in lines and columns so as to reduce the matrix to a block triangular one.

Now consider above Fig. 7. This same as in Fig. 6, but having being properly partitioned. In this figure, there are three small chunks. Chunk 1 design engineers will not exchange information with Chunk 2 design engineers except for component O design engineer because component O design engineer is member of both Chunk 1 and 2. Small chunk arrangements reduce iteration time, in comparison to large chunks.

Similarly chunk 2 design engineers will not exchange information with chunk 3 design engineers, except for component E design engineer because component E design engineer is a member of both chunks 2 and 3. In this way. Fewer design engineers will be involved in the development

process, making the development process simpler, reducing extra communication and negotiation, consuming less time, yielding more productive work, making decisions easier, thereby resulting in a better product with faster development process.

Properly partitioned DSM

Components		G	H	M	L	J	I	O	F	C	B	K	A	D	E	N	
Inverter	G	.															
Battery	H		.														
Rear wheels	M			.	2	2	2	2									
Rear axle	L				2	.	2	2									
Rear differential	J				2	2	.		2								
Rear motor/Generator	I				2	2	2	.	2								
Chassis	O				2	2	2	2	.	2	2	2	2	2	1		
Front motor/Generator	F								2	.	2	2	2	2	1		
Planetary power splitter	C								2	2	.	2	2	2	1		
Transmission	B								2	2	2	.	2	2	1		
Front axle	K								2	2	2	2	.	2	1		
Front wheels	A								2	2	2	2	2	.	1		
Clutch/brake	D								2	2	2	2	2	2	.	1	
Internal Combustion																	
Engine	E								1	1	1	1	1	1	1	.	2
Fuel delivery storage	N															2	.

Fig. 7: Clustering of physical interface in component-based DSM of vehicle powertrain

Fig. 7 shows that components O and E are system interface components. The design engineers of components O and E are systems integration engineers because components O and E design engineers have shared responsibilities. This means that the people required for these positions must have experience in system integration and that their job description ought to include systems. This could mean having professors with systems (or similar) backgrounds supervising student engineers O and E. Other engineers in that figure do not need a system integration background.

The design iteration process of Fig 7 suggests that chunk 2 will perform the iteration cycle first and then freeze the iteration process and will give the result of iteration to chunk 1 and 3 through design engineers O and E. Then chunk 1 and 3 perform their iteration cycles and freeze the iteration cycle and will give the iteration results to chunk 2 through design engineers O and E and repeat the procedure. It might also be possible to synchronize the iteration cycles of the chunks so that they can be parallelized, further shortening the development process time.

## Conclusions

Powertrain attributes are the most important of all attributes to the customer. This research paper is an attempt to develop and demonstrate a new approach for powertrain multi-attribute target development and balancing for vehicle integration. As the Powertrain Attributes are strongly coupled to each other, it is very important to record the interactions among various attributes. Design Structure Matrix tool is used to show these interactions so that they are not missed during early phase of vehicle development.

If a system is highly coupled the DSM may not be able to be adequately partitioned. So manual clustering, or manual reordering of the elements in rows and columns, may be the only viable method to achieve a matrix that is close to block triangular form. This is one of the drawbacks of the DSM method. There may not be enough time to complete a DSM. The DSM process is time consuming, particularly the data gathering process.

### *Recommendations :*

It is recommended to develop an entire vehicle attributes Design Structure Matrix to include the vehicle attributes that are known to cause significant redesigns such as Performance & Drivability, Accommodation & Usage, Vehicle Dynamics and Safety and Powertrain attributes.

As all the attributes are being developed concurrently, a Powertrain Attributes DSM cannot capture the iterations happening in the development of these other attributes. A complete vehicle attributes/design parameter DSM will provide an improved understanding and more accurate view of all potential iterations.

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