Multi-stage Analysis Approach to Low Speed Vehicle Impacts using the *SENSOR Keywords

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1 Abstract

The low speed impact tests outlined in ECE R42 and FMVSS 581 consist of multiple consecutive impacts on a vehicle bumper to assess vulnerability to damage and repairability. Typical CAE approaches to assessing multi-stage analyses involve running each stage of the analysis individually, inputting deformations, stresses, and strains from the end of the previous analysis. This approach typically requires manual model editing before each analysis, which is time consuming and increases the risk of human error.

*This paper outlines a methodology using the *SENSOR keywords to run multiple low speed impacts sequentially in a single analysis. This includes the use of *SENSOR keywords to initialize each impact in order, slow and restrain the vehicle and terminate the analysis based on the model responses.*

The techniques discussed can be applied to other multi-stage analyses and more widely to terminate analyses at a specific event prior to a specified run time, saving computational time and reducing the number of output files.

2 Introduction

Vehicle bumpers are designed to minimise a vehicle's vulnerability to damage and reduce repair costs resulting from low speed front and rear collisions, such as a 5mph impact from a vehicle of the same weight while parked. The impact resistances of the front and rear bumpers are evaluated using low speed impact test ECE R42 in Europe and FMVSS 581 in the federal markets. These tests involve subjecting the bumpers to multiple consecutive impacts from single and double ridged pendulums with equal mass to the vehicle. Drawings of the pendulums and the impact test rig are shown in Fig.1: and Fig.2:. The repairability of the vehicle is assessed after a series of two corner impacts and two longitudinal impacts on the front and rear bumpers. The more rigorous FMVSS 581 test also includes an additional impact against a fixed collision barrier or a flat wall after the pendulum impacts, and this particular test will serve as the basis for the paper's research.

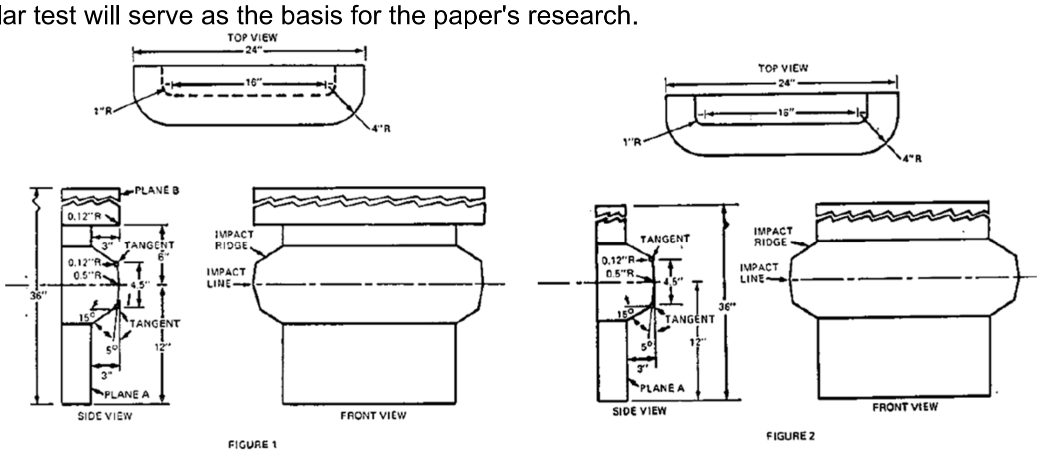


Fig.1: FMVSS 581 (a) double ridged pendulum with upper plane B and (b) single ridge pendulum drawings without upper plane B [1]

Fig.2: Impactor test rig [2]

What makes the federal bumper assessments quite unusual is that the sequential impacts are carried out on the same vehicle with at least 30minutes between each impact. The bumper and supporting structure cannot be replaced or repaired between impacts.

Analysing the sequential impacts poses a challenge in CAE. Typically, each impact analysis is run individually with deformations, residual stresses and strains and damage transferred to the next impact. A common approach to achieve this is to use **`*INTERFACE_SPRINGBACK`** in combination with **`*CONTROL_STAGED_CONSTRUCTION`**. This creates a "dynain" file that can be read into the next analysis, providing the necessary information to begin a new analysis from the same state, including deformed node coordinates, stress and history variables for every element. The workflow for these dependent analyses is shown in Fig.3:. This method is workable but has limitations with file size, file management and intermediate pre and post processing steps between impacts that can be improved upon.

The disk space taken up for each run can become a complication as a large "dynain" file often needs to be written out to encompass the various assemblies beyond just the front and rear bumpers that may observe damage. Furthermore, keywords that are present in the 'dynain' file (e.g. **`*NODE, *ELEMENT`** and **`*INITIAL`**) need to be removed from the existing includes to avoid duplicate definitions. This creates temporary versions of includes and models that also takes up additional space and presents secondary file management difficulties as updates to the temporary files cannot be directly used for other loadcases.

In addition to removing the duplicate keyword definitions before the analysis, further intermediate model modification steps are required to correctly position the impactors before the next analysis. For all pendulum impacts the vehicle is in idle with the brakes off, therefore post-processing is required to find the displacement of the vehicle after the impact and apply a **`*INCLUDE_TRANSFORM`** in pre-processing to shift the vehicle or impactor nodes to the correct position. These modifications require greater input from the analysing engineer, increasing the time taken to set up and run models and risk of introducing human errors.

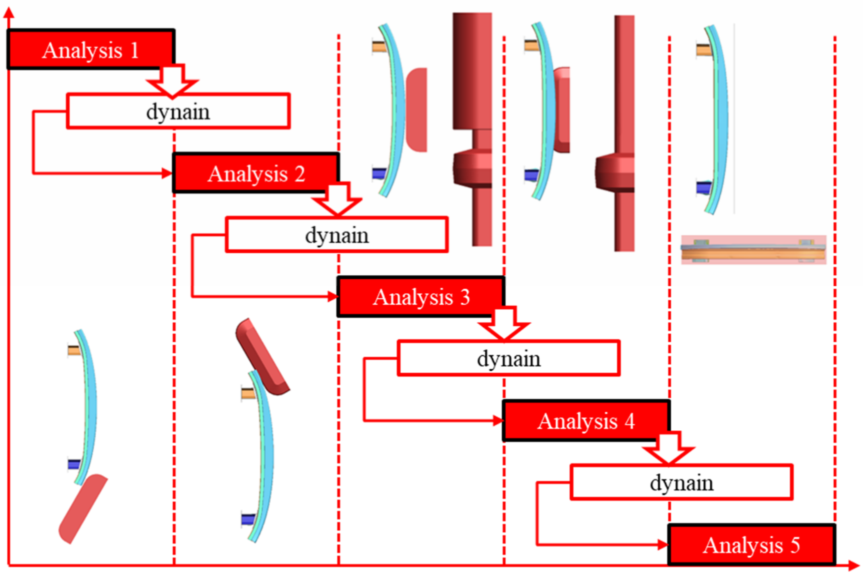


Fig.3: Common approach to assessing low speed impact performance

The modifications to the existing model and the transform could be automated using scripts, however for the analysis to be fully streamlined the following steps would need to be automated:

- Remove duplicated keywords present in 'dynain' file from input model and write out temporary includes and model referencing them.
- Detect when a single impact ends and run intermediate set-up scripts.
- Extract displacement of vehicle from results and transform includes to position the vehicle relative to the impactors.
- Save transformed model in new folder with updated impactor, impact velocity and vehicle restraint depending on the impact.
- Run subsequent analysis.

These scripts require significant set up, will be bespoke to this analysis and does not avoid the large dynain files output for each analysis.

This paper provides an alternative methodology using the **`*SENSOR`** keywords to combine the sequential impacts into a single analysis. These sensors can be used to detect when one impact is over, slow the vehicle down and bring it to a full stop before initiating the next impact in the sequence. This approach also effectively uses **`*SENSOR`** keywords to position the impactors and terminate the analysis once all impacts have taken place.

3 *SENSOR keywords

Before introducing the alternative methodology, it is important to understand the concept of sensors in both the real world and LS-DYNA.

Physical sensors are devices that respond to a physical input and transmit a resulting output. In an airplane there are numerous sensors measuring inputs such as height and speed; these are processed by a computer, which could subsequently send a signal to the engine to increase speed or to the control surfaces to provide greater lift.

In LS-DYNA, **`*SENSOR`** keywords can be *defined* to monitor model responses instead of physical inputs, such as contact forces and nodal velocities. At particular values of the responses, they can toggle *switches* that *control* other LS-DYNA keywords in the model, for instance SPCs and Boundary Prescribed Motions. This ability to effectively turn on/off different entities and restraints in an LS-DYNA model means that **`*SENSORS`** are particularly powerful in multistage analyses such as the problem outlined.

Three definitions or building blocks are required to define and utilise a sensor:

- ***SENSOR_DEFINE** – defines the monitored model response that will initiate the switching ON or switching OFF of model entities.
- ***SENSOR_SWITCH** – compares the value from the response being monitored by ***SENSOR_DEFINE** with a threshold to see if a switching condition is met. These switches can be combined using boolean logic with ***SENSOR_SWITCH_CALC-LOGIC**.
- ***SENSOR_CONTROL** – Determines how and what to control based on the logic value of ***SENSOR_SWITCH**.

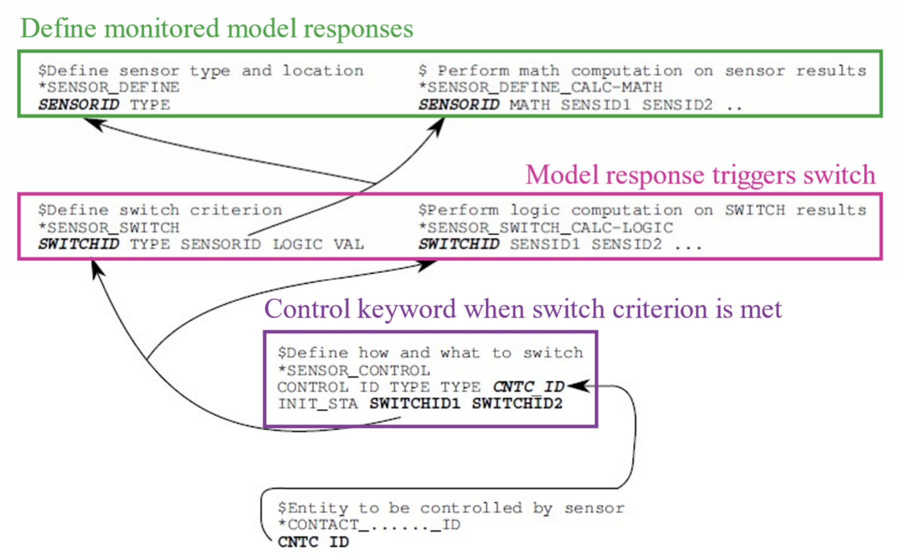


Fig.4: Relationship between sensor keyword definitions [3]

The LS-DYNA Manual [3] also provides explanations of these components and a useful figure on how they are linked together (annotated in Fig.4:).

***SENSOR_SWITCH** can also be used to terminate analyses at a specific event before the specified end time in ***CONTROL_TERMINATION** using ***TERMINATION_SENSOR**, saving computational time and reducing the number of output files.

Much of the functionality of ***SENSOR** keywords have been developed and improved in more recent versions of LS-DYNA and therefore it is recommended that analysis using these keywords be run in versions R12 or later.

3.1 Triggering Switches

Often the most difficult aspect of using sensors is ensuring the switches that feed into ***SENSOR_CONTROL** or ***TERMINATION_SENSOR** trigger at the right time (or at all).

For the low speed impact assessment, after an impactor loses contact with the vehicle, entities will be switched ON to slow and stop the vehicle before proceeding with the next impact. A ***SENSOR_SWITCH** detecting a zero contact force is insufficient on its own to trigger this switch at the correct time as the switching criteria is first met at the start of the analysis. Therefore, the process to slow the vehicle will be switched on earlier than required.

Three key methods are detailed in this paper to manage this issue, which can be used individually or in combination:

- Activating switches after the condition has been met for a duration of time specified by the TIMWIN parameter on the ***SENSOR_SWITCH** keyword.
- Combining switches with AND/OR gates using ***SENSOR_SWITCH_CALC_LOGIC**
- Ordering of switches within the ***SENSOR_CONTROL** definition

4 Impact Substages

When approaching a complex analysis, especially ones that require a series of **`*SENSORS`**, it is necessary to break down the problem into a series of more manageable substages. Each impact in the test can be split into substages whose active entities are initiated and terminated by a switching event from a specific model response.

Each impact can be broken down into the substages shown in Fig.5:.
1. Accelerate Impactor
2. Low Speed Impact
3. Slow Vehicle
4. Stop Vehicle
5. Accelerate Next Impactor

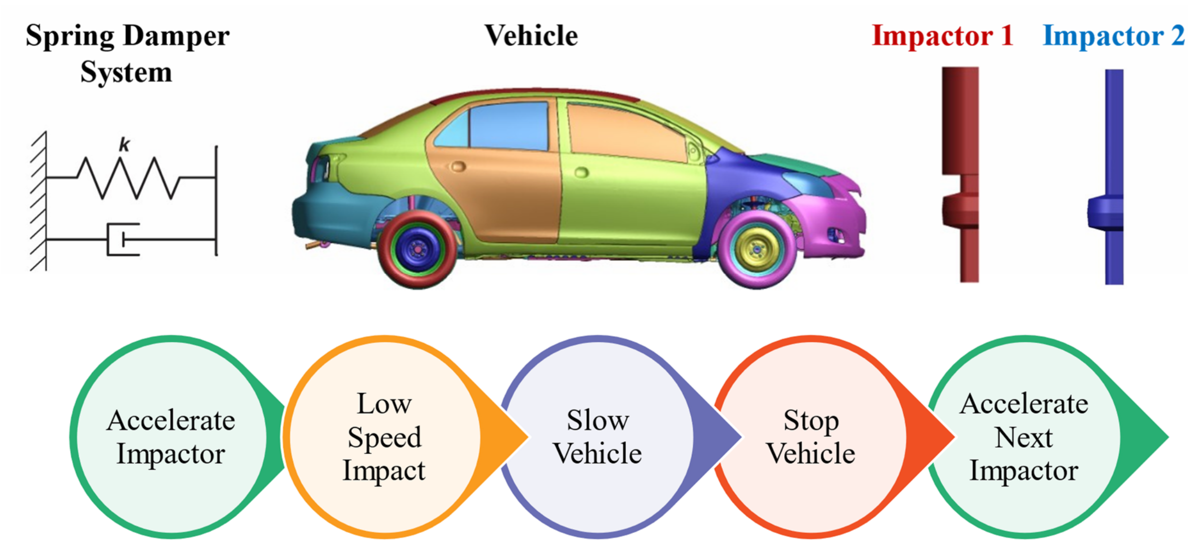
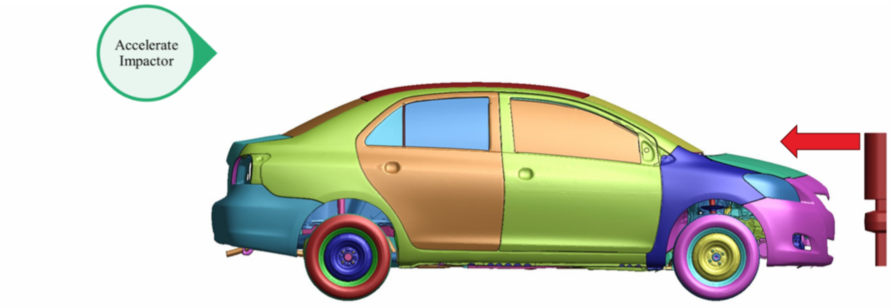


Fig.5: Substages for each low speed impact

Each substage is discussed as it was approached in developing the methodology. First the objective of the substage is understood before exploring compatible keywords with **`*SENSOR_CONTROL`** that could be implemented to achieve the objective in LS-DYNA and the specific event that will initiate the next substage. Finally, sensor definitions are developed: toggling ON the entities needed to achieve the objective in **`*SENSOR_CONTROL`**, defining monitored model responses in **`*SENSOR_DEFINE`** to initiate the next substage when the **`*SENSOR_SWITCH`** switching criteria is met. The sensor definitions in each substages were subsequently brought together and visualised using a flowchart, as shown in Appendix A.

4.1 Substage 1: Accelerate Impactors



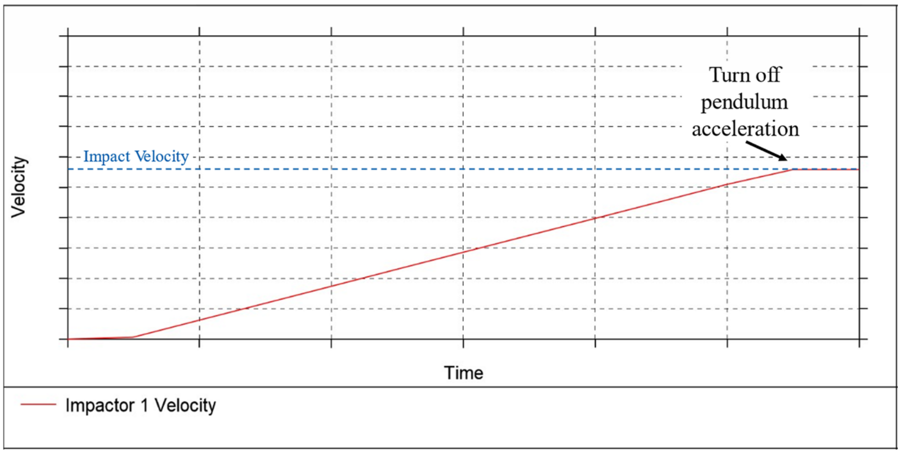


Fig.6: Accelerating first impactor up to speed

In the physical tests the longitudinal impactors impact the vehicle at 2.5mph, while the corner impactors impact at 1.5mph but need to be positioned at 30 degrees to the vehicle midline.

To replicate this in CAE, keywords should be defined to accelerate the impactor up to the specified speed before releasing the impactor to allow it to collide with the vehicle unrestrained without inputting additional forces.

For single stage impacts, ***INITIAL_VELOCITY** is often used to define the impact velocity, however this is not suitable for multiple impacts where subsequent impacts start at later unknown times, additionally the keyword is not supported by ***SENSOR_CONTROL** (as of R13). Therefore, an alternative approach can be adopting using ***BOUNDARY_PRESCRIBED_MOTION** with a linear velocity curve up to the impact velocity.

4.1.1 Sensor Definitions

A ***BOUNDARY_PRESCRIBED_MOTION** accelerates the impactor at the beginning of the analysis with a linear velocity curve. A ***SENSOR_DEFINE** monitors the impactor velocity and a ***SENSOR_CONTROL** toggles OFF the ***BOUNDARY_PRESCRIBED_MOTION** once the ***SENSOR_SWITCH** criterion is met – impactor velocity equals the specified impact velocity (see Fig.6:).

4.2 Substage 2: Low Speed Impact

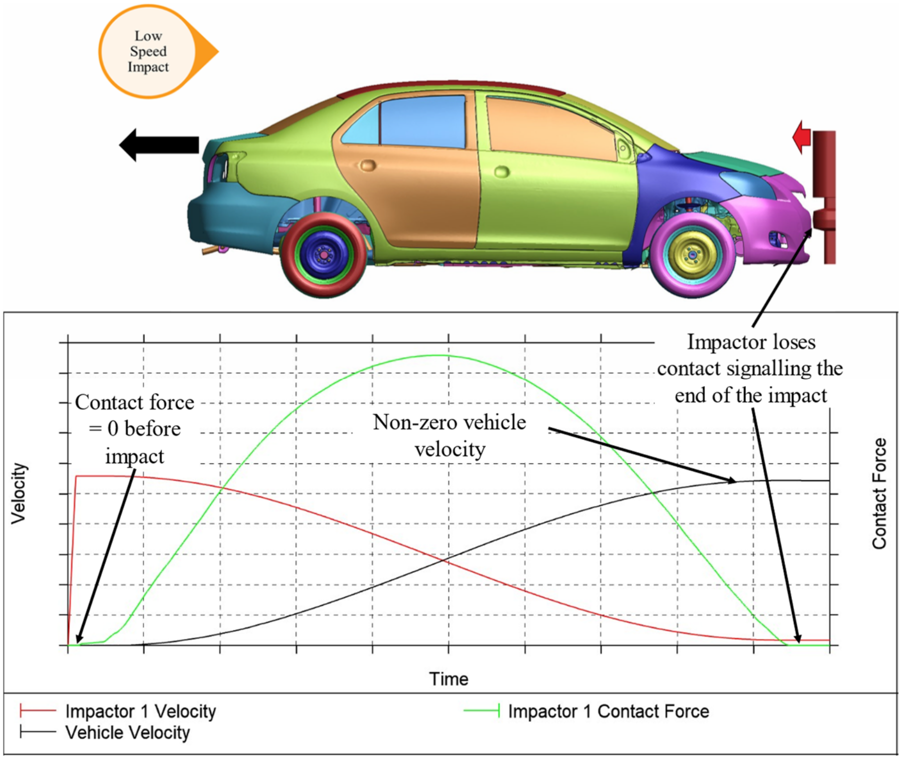


Fig.7: Low speed impact with vehicle

Once at speed, the pendulum impacts the vehicle at idle and with the brakes disengaged as specified in FMVSS 581 (except for the flat barrier impact). During the impact, the kinetic energy of the impactor is converted into internal energy through damage to the bumper and supporting structure and into vehicle kinetic energy.

The contact force can be monitored to establish when the impactor loses contact with the vehicle to indicate the end of the impact. As discussed in Section 3.1, losing contact is insufficient to establish the end of the impact as the condition is also true before the impactor contacts the vehicle (see Fig.7:). The switching event should be unique where possible to ensure the next substage is initiated at the correct time – the impactor losing contact AND a non-zero vehicle velocity.

At this point a single impact has been completed and a switch could terminate the analysis. However, to allow subsequent impacts to take place a substage to slow the vehicle should be switched on.

4.2.1 Sensor Definitions

`*SENSOR_DEFINE`s monitor the contact force between the impactor and vehicle and the vehicle velocity. A **`*SENSOR_SWITCH_CALC_LOGIC`** determines when the contact force is zero AND vehicle velocity is greater than zero, signalling the end of the impact and initiating the next substage.

4.3 Substage 3: Slow Vehicle

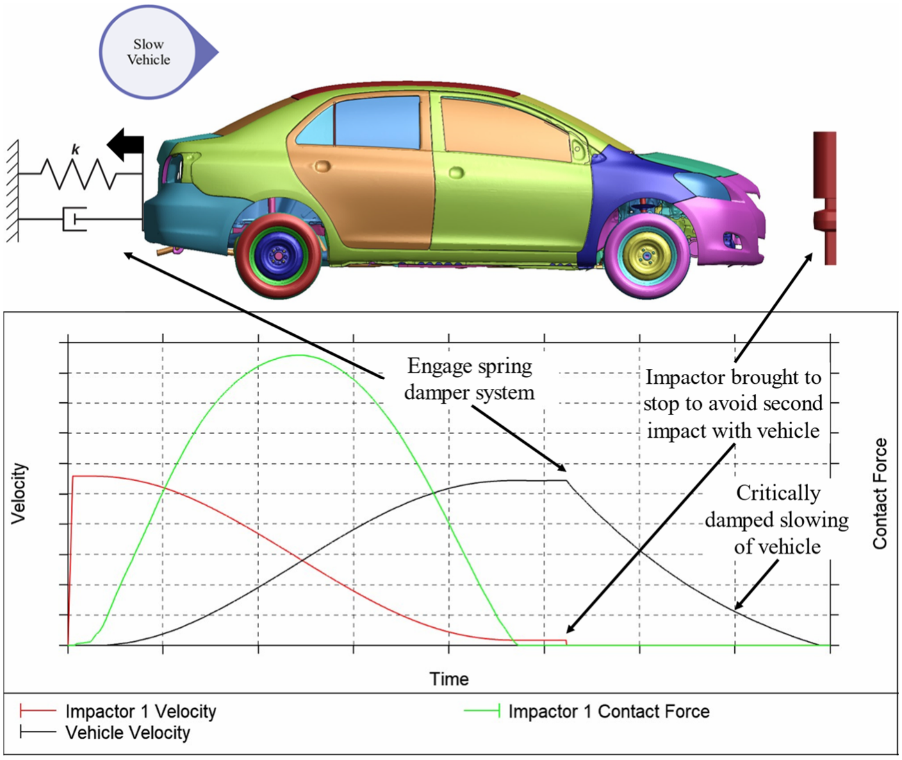


Fig.8: Slowing the vehicle using a spring damper system

All impact tests are performed on a stationary vehicle, therefore after each impact the vehicle needs to be slowed and subsequently brought a complete stop before the next impact can be initiated. When slowing the vehicle, care should be taken to avoid introducing high inertia forces from decelerating the vehicle too quickly.

A critically damped spring damper system with a tuned stiffness is used to efficiently slow the vehicle in a controlled manner, which can be observed in the gentle vehicle velocity curve in Fig.8:. The stiffness of the system should be as high as possible to slow the vehicle quickly, without introducing damage in the vehicle through inertia forces.

Elements cannot be toggled on and off again using sensor definitions, therefore ***JOINT_STIFFNESS** is used to model the spring and damper in parallel.

While the vehicle is being slowed and brought to a stop, the impactor may still have forward momentum. To avoid the impactor impacting the vehicle for a second time, it is brought to a stop and the contact switched off.

The vehicle and impactor velocity reaching zero will subsequently switch on the next substage to bring the vehicle to a complete stop. This is not a unique event in the impact as the vehicle velocity is zero at the beginning of the analysis, however this is resolved using a combination of switch ordering and combined switches as outlined in Section 4.4.1.

4.3.1 Sensor Definitions

The spring damper system (***JOINT_STIFFNESS**) is turned on and the impactor fixed in place by ***SENSOR_CONTROL**s, while a ***SENSOR_DEFINE** monitors the vehicle velocity and impactor velocity to determine when both are zero to switch ON the next substage.

4.4 Substage 4: Stop Vehicle

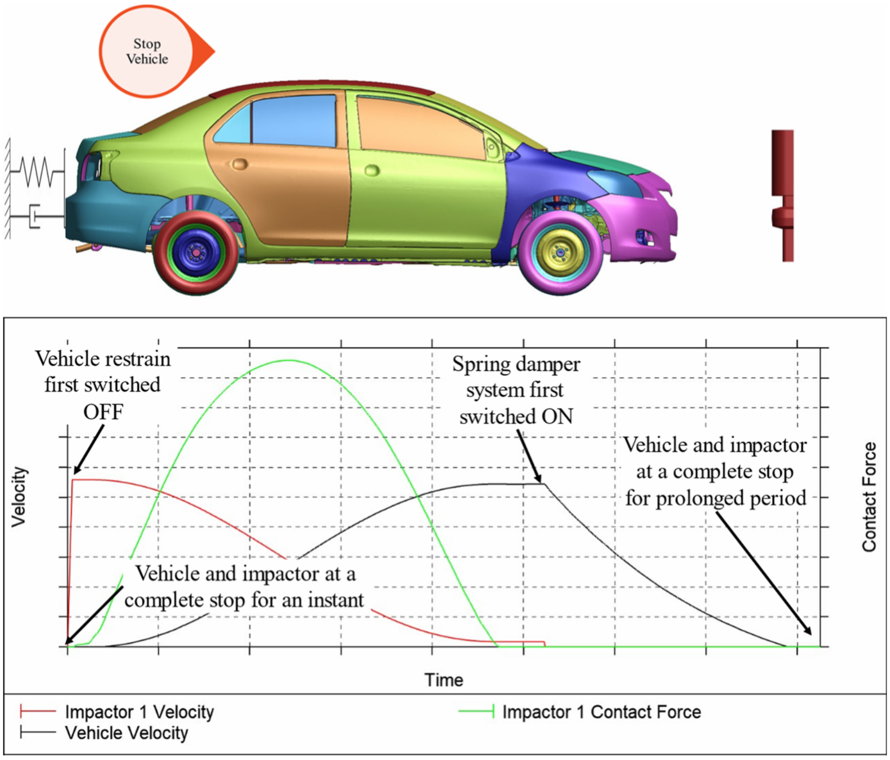


Fig.9: Bringing vehicle to a complete stop

After slowing the vehicle, it needs to be brought to a complete stop before the next impact can proceed. To prevent the vehicle oscillating about zero velocity the spring damper system needs to be turned off and the vehicle motion constrained.

The vehicle can either be restrained using a ***BOUNDARY_PRESCRIBED_MOTION** with zero velocity or ***BOUNDARY_SPC** referencing vehicle nodes, depending on whether the nodes are on a rigid body.

The vehicle can be considered at a full stop after the vehicle and impactor velocities are zero for a period of time, as shown in Fig.9:, and the next impact can be initiated. The vehicle and impactor velocity is zero at the start of the analysis for an instant before the impactor is accelerated up to speed, therefore the switching criterion needing to be met for a period of time ensures the next impact is initiated at the correct time.

4.4.1 Sensor Definitions

SENSOR_CONTROL**s toggle ON either a ***BOUNDARY_PRESCRIBED_MOTION** or ***BOUNDARY_SPC** to bring it to a stop and toggle off the spring damper system (JOINT_STIFFNESS**).

SENSOR_CONTROL** entities can only be toggled ON/OFF after the first switch referencing them is satisfied, the spring damper system (JOINT_STIFFNESS**) is switched ON in the slow vehicle substage and is therefore turned OFF at the next instance that the vehicle velocity is zero.

A similar approach can be taken for the ***SENSOR_CONTROL** fixing the vehicle in place. If the vehicle restraint is initially ON at the start of the analysis, it can be switched OFF when the low speed impact is initiated (when the impactors reach the impact velocity). The impactor has a non-zero velocity until it is fixed in place during the slow vehicle substage, therefore the ***SENSOR_CONTROL** will only fix the vehicle in place at the next instance that the vehicle velocity and impactor velocity is zero (the next instance the vehicle is zero after the slow vehicle substage).

A ***SENSOR_SWITCH_CALC-LOGIC** initiates the next substage once the vehicle and impactor velocities are zero for a period of time specified by the TIMWIN parameter on the individual ***SENSOR_SWITCH** cards.

4.5 Substage 5: Accelerate Next Impactor

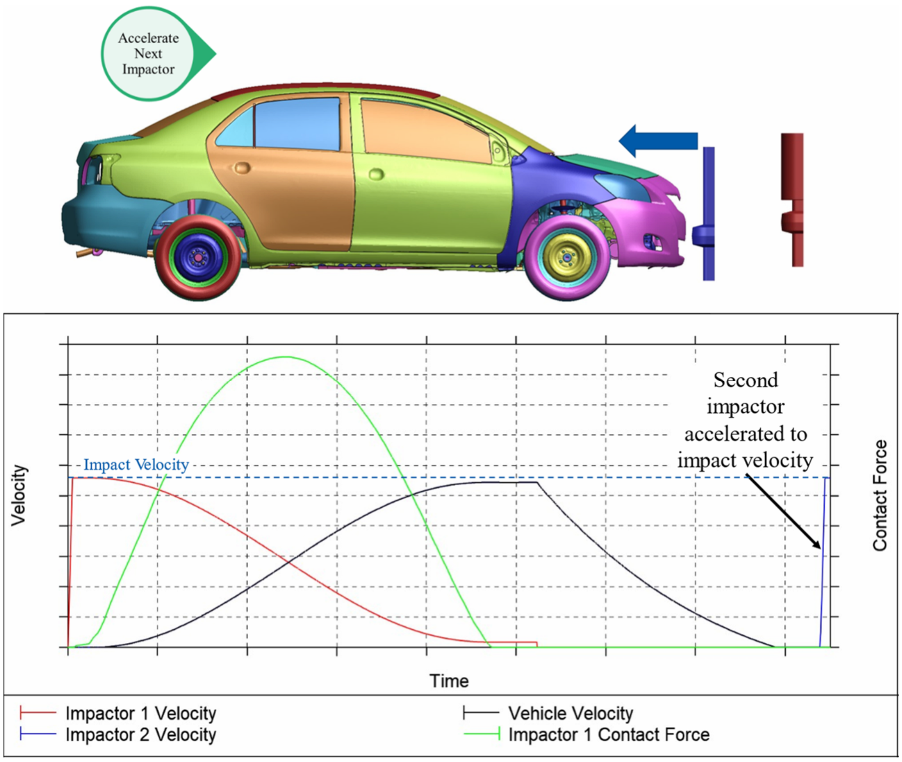


Fig.10: Accelerating second impactor up to speed

Once the vehicle is at a complete stop and the spring damper system disengaged, the next impactor can be accelerated up to speed, thereby beginning the next impact.

The analysis can repeat the substages outlined in Sections 4.1 to 4.5 for each impact until the full suite of impact tests are assessed.

4.5.1 Sensor Definitions

A **`*SENSOR_CONTROL`** switches ON a **`*BOUNDARY_PRESCRIBED_MOTION`** to accelerate the impactor. As outlined in Section 4.1.1, the **`*BOUNDARY_PRESCRIBED_MOTION`** is switched OFF when the impactor velocity equals the specified impact velocity. The **`*SENSOR_SWITCH`** also toggles OFF the entity constraining the vehicle.

5 Initiating Impacts in the Correct Order

The vehicle will be at a complete stop after each of the impacts, and therefore care must be taken in defining a switching condition to ensure that only the impactor in the next impact is initiated rather than all subsequent impacts. Different sensor approaches could be taken to ensure the impacts initiate in the correct order.

In Section 4.4.1 a **`*SENSOR_SWITCH_CALC-LOGIC`** with zero vehicle and impactor velocity for a period of time initiates the next impact. The period could increment with each impact (e.g. 0.1s after the first impact, 0.2s after the second, 0.3s after the third etc.). Therefore, 0.1s after the second impact is initiated all impactor velocities are no longer zero and the switch criterion to initiate the third impactor will not be met.

Alternative methods could monitor the vehicle displacement, time or a non-linear function to specify a unique event.

6 Impactor Positioning

The vehicle moves relative to the initial impactor positions during each impact. Therefore, inactive impactors in subsequent impacts need to be positioned to replicate the physical test before the impact can be initiated. Two methods were developed to position the impactors by “tracking” the vehicle displacement.

The first method used the relative displacement option in ***BOUNDARY_PRESCRIBED_MOTION**. Although the approach successfully positioned the impactor, it can only be applied to rigid bodies (not nodes) and requires aligned reference nodes to provide the direction of travel to track.

Instead, a more flexible and nuanced approach was developed by inputting the vehicle velocity into a ***BOUNDARY_PRESCRIBED_MOTION** controlling the impactor velocity. The vehicle velocity is tracked by a ***SENSOR_DEFINE** and can be converted into an input curve using a ***DEFINE_CURVE_FUNCTION** with the function "SENSORD(X)" where X is the ID of ***SENSOR_DEFINE** monitoring vehicle velocity. A velocity ***BOUNDARY_PRESCRIBED_MOTION** references the curve ID, giving the impactor the same velocity as the vehicle, as shown in **Error! Reference source not found.**. This is effectively a feedback loop, with the model responses being used as model input definitions.

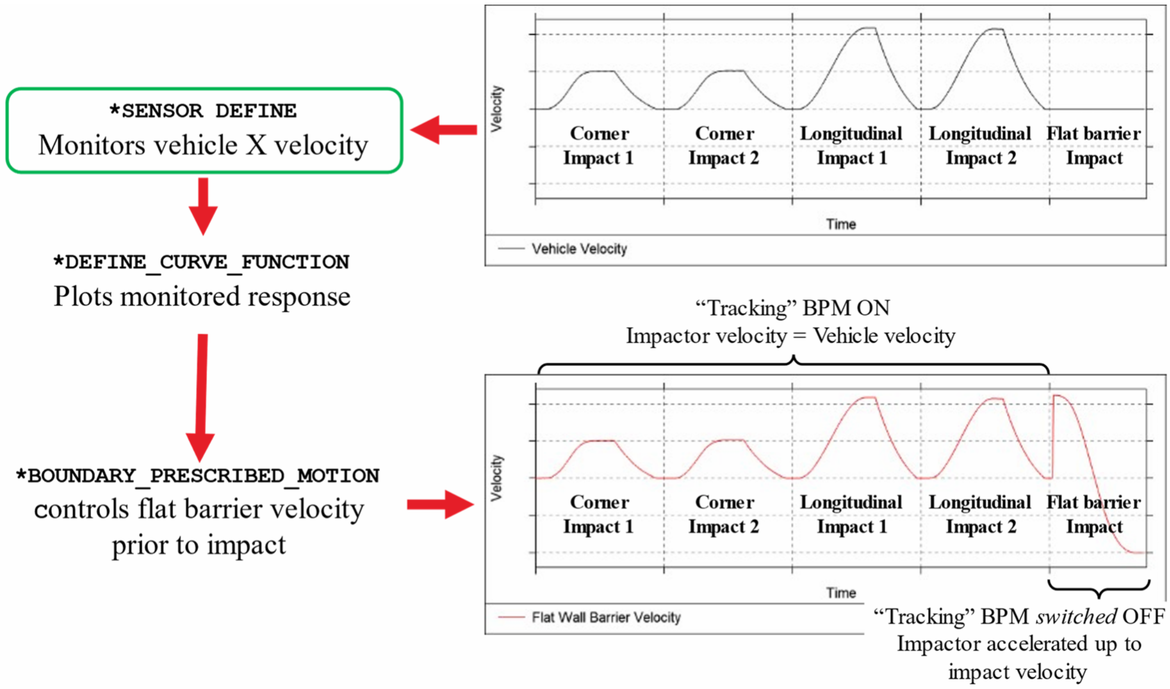


Fig.11: Methodology allowing flat barrier to "track" vehicle velocity

6.1.1 Sensor Definitions

The "tracking" entity is ON at the start of the analysis and switched OFF by the switch that initiates the accelerate next impactor substage (***SENSOR_SWITCH_CALC-LOGIC** with zero vehicle AND impactor velocities.

7 Terminate Analysis

The termination time of the analysis is unknown and will depend on the duration of the impacts and time taken to slow and stop the car. Rather than specifying an unnecessarily long run time, a sensor determines when the final impact has finished and terminates the analysis, saving computational time and reducing the number of output files.

7.1.1 Sensor Definitions

A ***TERMINATION_SENSOR** is defined to terminate the analysis when the conditions for a ***SENSOR_SWITCH_CALC-LOGIC** detecting the end of the final impact (zero vehicle AND impactor velocities for a period of time that ensures the analysis does not terminate after an earlier impact). Again, vehicle displacement, time or a non-linear function could be used instead to ensure the analysis does not terminate earlier than desired.

8 Measuring Success

The methodology for a single impact detailed in the previous sections was repeated for the suite of impact tests on the vehicle, allowing the bumper vulnerability to damage to be assessed in a single analysis. This is a significant improvement on the dependent analysis approach by condensing the run into a single run folder and making the process more user-friendly by removing intermediate post-processing and model modification stages. Although the CPU time may be lower for the dependent analysis approach as it does not include delays and the slowing process, the total runtime may be reduced as analyses can by run overnight or over a weekend without requiring intervention by the CAE engineer after each impact. Furthermore, the model can be refined to reduce the time "lost" bringing the vehicle to the stop quicker and using reduced *SENSOR_SWITCH delays.

Finally the method eliminates large "dynain" files and duplicated includes of assemblies with the data included in the "dynain" file removed.

9 Summary

This paper has outlined an alternative methodology for assessing low speed impact performance of vehicle bumpers using the **`*SENSOR`** keywords to combine sequential impacts into a single analysis.

Each impact was split into more manageable substages: accelerate impactor, low speed impact, slow vehicle, stop vehicle, and accelerate next impactor. These substages have been defined such that they are initiated and terminated by a precise switching event from a specific model response. Sensors were defined to monitor the model responses, define switching conditions, and control the active entities within each substages. The use of switches, delays, and ordering of switches within **`*SENSOR_CONTROL`** allows precise timing for the initiation and termination of these various sub-stages.

A method was developed to allow the inactive impactors to "track" the vehicle, ensuring all impactors were in the correct position for the assessment. This method employed a feedback loop where the input curve for a **`*BOUNDARY_PRESCRIBED_MOTION`** was defined by a sensor monitoring the vehicle velocity.

Moreover, the analysis was terminated automatically once a sensor had detected that the final impact was completed, avoiding unnecessarily long run times and reducing output files.

The traditional approach to assess low speed impact performance of vehicle bumpers involved running separate impact analyses with modifications between impacts, resulting in large "dynain" files, repetitive post-processing, and manual model modifications between runs. By integrating all sequential impacts into a single analysis, sensors provide a more efficient and streamlined approach to assess low speed impact performance of vehicle bumpers – making the process more user-friendly for the CAE engineer.

10 Further Work

Further applications for **`*SENSOR`** keywords should be explored for a range of analysis types within the automotive industry and in other fields.

Where an analysis requires multiple stages to be assessed on the same model, **`*SENSOR`**s or **`*STAGED_CONSTRUCTION`** should be considered to streamline analyses and make them more user friendly.

At the simplest level **`*SENSOR`**s can be widely implemented to terminate analyses when all useful data has been extracted from the run, saving computational time and reducing the number of output files. For the bumper assessment this is when the final impactor loses contact with the vehicle, however **`*TERMINATION_SENSOR`**s can be defined to stop the analysis when it detects the failure of a critical component or erroneous results. In a non-linear time history seismic analysis of an existing building this could be the model failing under gravity, which is a known error as the physical structure is standing. The analysis can be automatically terminated before assessing the typically long and onerous ground motion. Thereby the error can be resolved in the model for reduced computational cost before rerunning and assessing the seismic performance.

11 Literature

[1] U.S. DEPARTMENT OF TRANSPORTATION, Laboratory Test Procedure for Regulation Part 581, Bumper Standard I, 1990

[2] Altran Concept Tech Gmbh, Bumper pendulum (LowSpeedCrashes), 2015

[3] Livermore Software Technology Corporation (LSTC), An ANSYS Company, LS-DYNA Keyword User's Manual, Volume I, 2021

Appendix A Sensor Definition Flow Chart

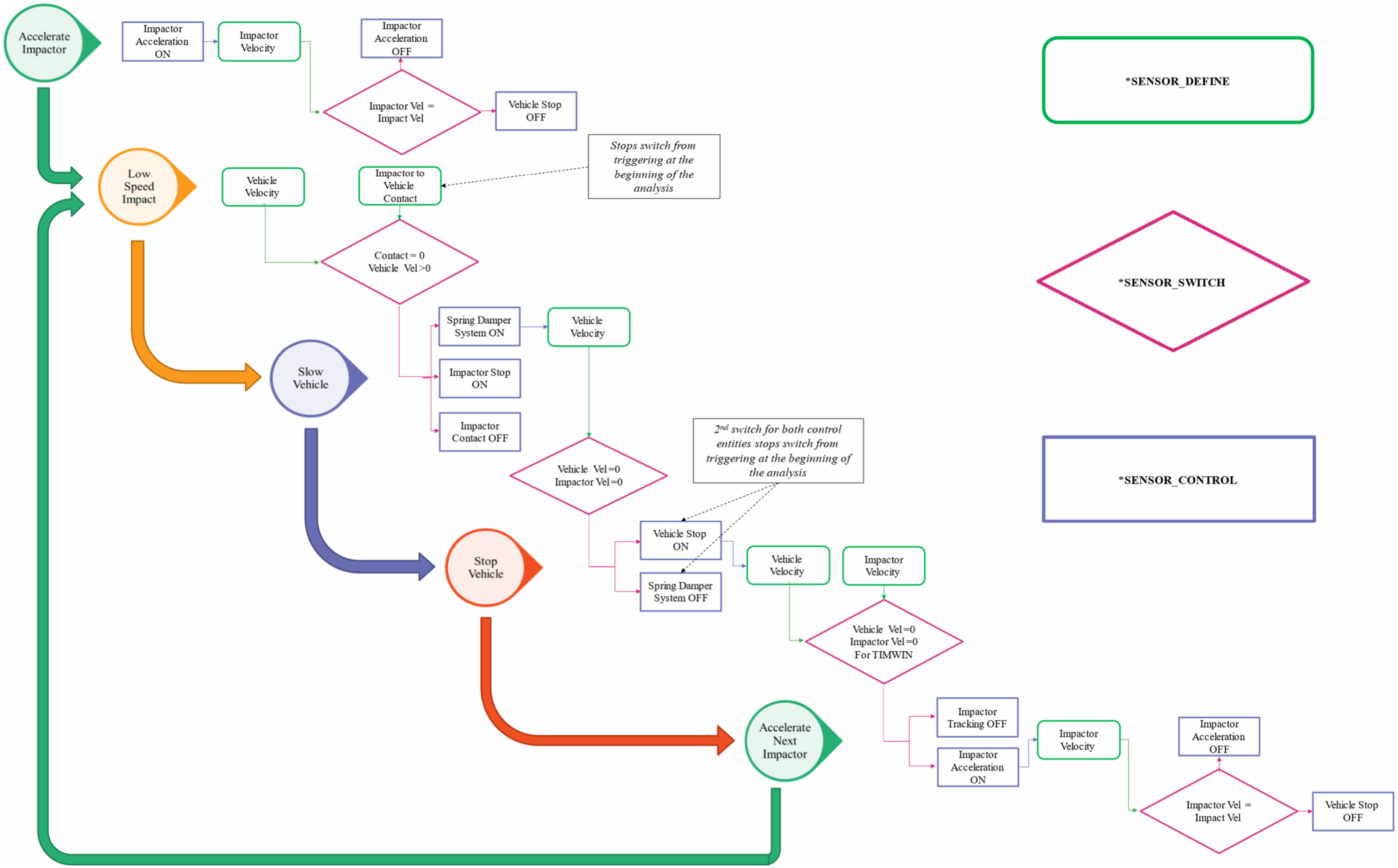


Fig.A1: Flow chart for single impact