THE UNIVERSITY OF MELBOURNE

Major Project

Department of Mechanical and Manufacturing Engineering

Final Report

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Project Title: Evaluation of various compounds for use in the Drip Gutter Weather Strip

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Thank you all for putting up with us during this project.

Contents

1. Executive Summary

The relationship between the two customer metrics, interior loudness and door closing effect (DCE), for the tertiary door seal was established. This was done by evaluating the current Drip Gutter Weather Strip (DGWS) compound against a softer compound. Both seals featured the same profile. At the conclusion, it was found that there was significant benefit in introducing the softer DGWS in terms of reducing DCE by 52% with a corresponding 3% increase in wind noise.

In order to arrive at this conclusion, a number of different tests were conducted to evaluate the impact of a softer DGWS on both metrics. For interior loudness, open road wind noise drives where conducted as well wind tunnel measurements. The latter seeks to validate the former by removing extra noise generated by other sources such as from the engine and tyres. For DCE, tests were conducted using a spring-load cell set up known as the force gauge. In all these testing situations, various vehicle setups were employed to gain a more complete picture of the difference between the current DGWS and the softer DGWS. For each of the different tests, validation procedures in the form of a Gauge Repeatability and Reliability were conducted. This ensured that the measurements were useable and not distorted by bias or inconsistent procedures.

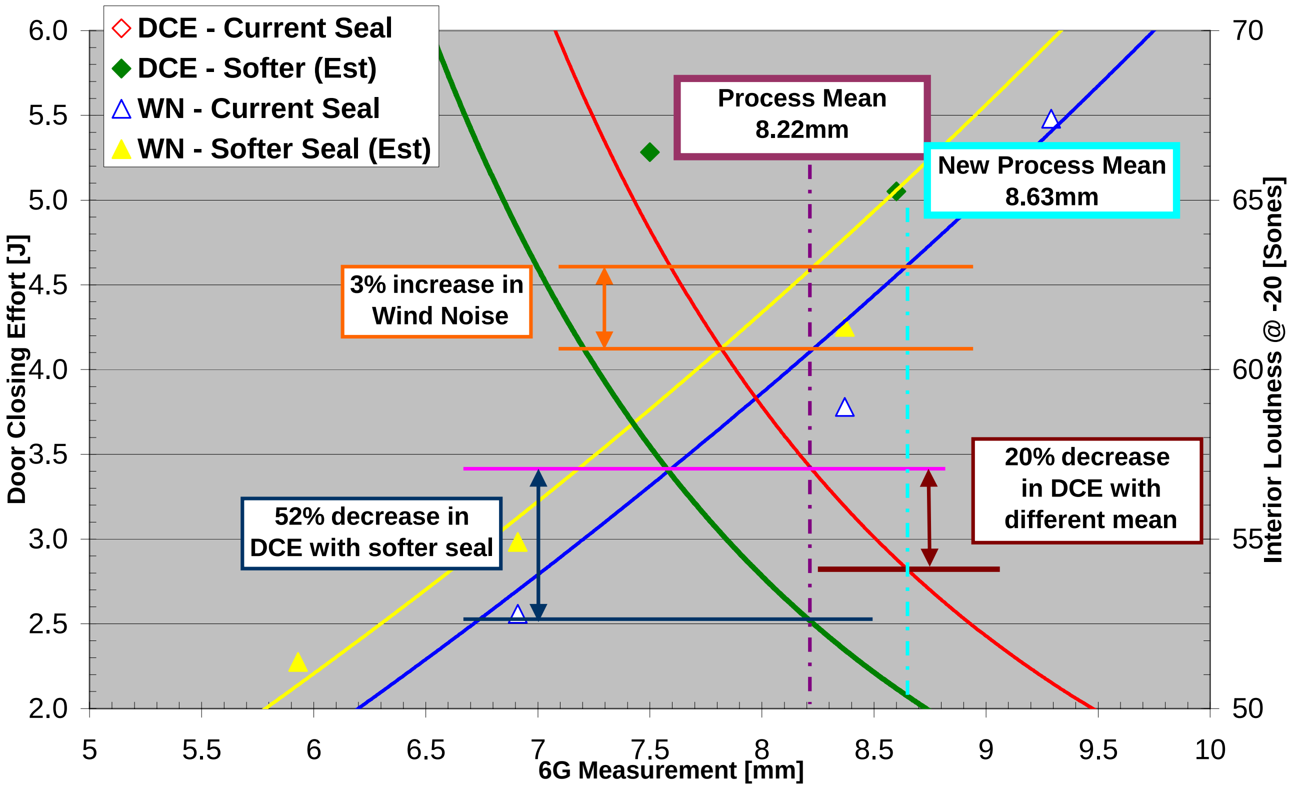


Figure 1. DCE vs. 6G vs. Interior Loudness: Region of Interest

At the completion of the analysis of results from the tests conducted over the duration of this project, it is quite obvious that the transition to a softer seal should be made. Even though the data used was of a limited sample size, the authors are confident that further testing would not generate values far removed from these educated estimates. Figure 1 highlights this variation. Even if the supplier is able to manufacture the DGWS from a compound that is not quite as soft as the one which was investigated for this project, there would still be a large enough decrease in DCE for only a marginal increase in interior loudness. If this course of action was taken, a more comprehensive testing regime involving interior loudness, DCE and measurement of door gaps should be undertaken to properly determine the relationship demonstrated in Figure 1.

Since any option to implement a different DGWS into production can be ruled out in the short term, another solution has been investigated. This alternative requires a slight variation in the process mean, but only delivers a 20% reduction in DCE. However, it achieves this with the same increase in interior loudness (3%) experienced with the softer DGWS. It also continues use of the current DGWS part which would be cheaper than introducing a new part. The problem with this scenario is that during the course of the project the authors were made aware of the difficulty in controlling door sets on the production line. This hurdle may rule this option out, or at the very least make this an impractical idea.

Considering the two solutions suggested it may be cheaper to improve the process, ensuring tighter control over process mean and spread, than to research and re-test a softer DGWS compound. The Client will need to make this decision, in light of the supplier's constraints and their own ever changing customer expectations.

2. Introduction

In today's increasingly competitive automotive market, improvements are sought wherever possible. One of the main drivers for advancement is meeting customer expectations and reducing negative feedback from them. Extensive market research is conducted before new and updated models are launched, to ensure that the car that is delivered is a car which customers actually want. Nearly all facets of the design and manufacture of a car are related to customer expectations.

One of the most noticeable elements of the driving experience is the sound level within the cabin. There are many factors that contribute to the cabin interior loudness. Some sources of noise are from the engine, tyres, brakes, road, wind, aspiration, squeaks, rattles and the power train. One of the major paths of noise transmission is through the door assembly, in particular, the sealing system. Family vehicles can have up to three door seals, which are designed to prevent this transmission path being established. As well as preventing the passage of noise, door seals have to maintain the comfort of the cabin environment by sealing out dust, moisture (rain, sleet, snow, ice) and insulate the cabin from temperature differentials.

The presence of seals also impacts on the amount of energy required to close the door. This is another important facet of customer satisfaction, especially for family cars. Door closing effort is related to seal size and stiffness, as is the transmission of noise and environmental sealing characteristics. The two elements, interior loudness and door closing effort, are at loggerheads since improvements in one will affect the other detrimentally. This leads to a trade-off between these two competing requirements.

The purpose of this report is to investigate the interaction of these tradeoffs. This will be achieved through numerous tests and experiments. It is expected that at the completion of this report the effects of these interactions on important customer metrics can be easily defined. The report will focus on the impact a change in the rubber compound of the tertiary door seal has on these metrics. This impact is to be assessed over the course of the tests and experiments, with the final outcome being a critical appraisal of the proposed change.

3. Literature Review

Automotive door seals were first used to accommodate variations in the construction of the body and door sets. More recently the design was oriented to better isolate passengers and the compartment from dust, moisture and air leakage. Today however, the general trend in seal design is for the isolation of the passenger compartment from noise and vibration. Previously dominant noise sources (such as the engine and tyres) have become less of an issue due to improved insulation in other areas of the car, to the point that wind noise has become more noticeable and hence escalated as an area of interest [1].

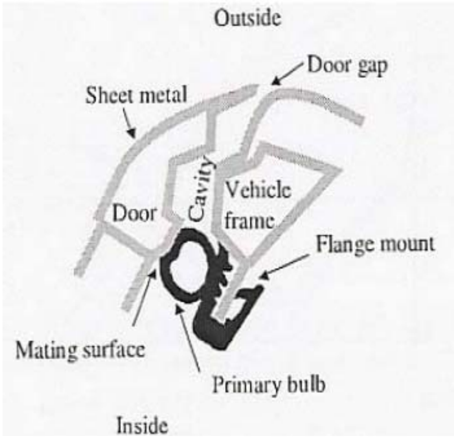


Figure 2 – Installed seal cross-section

Automotive weather seals are typically extruded bulbs of sponge and dense rubber that are attached to the door or the car body in order to seal the passenger compartment. The seals can be held in place by several means, for instance using intermittent clips or continuous carriers, and have a vast variety of shapes as evidenced by numerous patents for different profiles.

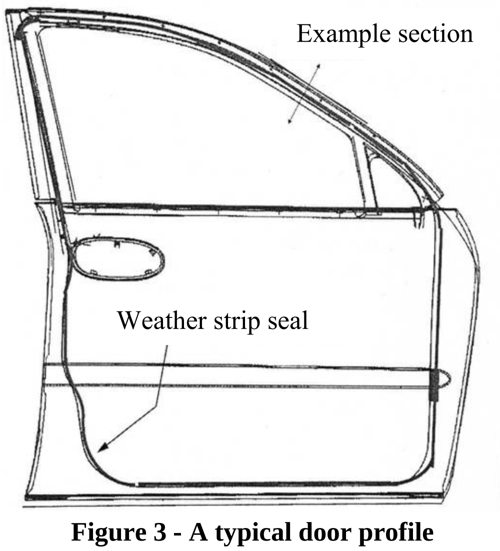


Figure 3 - A typical door profile

In a vehicle door, the seal typically runs around the perimeter of the door. When the door is closed onto the door opening panel, it remains in contact with the vehicle body through the hinges at the front, the latch mechanism at the rear and through the seal all around the perimeter of the door. The seal has some stiffness and contributes to the door closing effort as well as playing a role in the way exterior noise and vibration is transmitted to the interior of the vehicle. For automotive applications, other aspects of the material properties, such as resilience, weather resistance (including ultraviolet

radiation effects), bonding strength, tear abrasion, resistance, etc. also need to be considered when designing optimal weather seals.

In references [2,3] specific aspects are outlined that need to be taken into consideration when designing an optimal vehicle door weather seal. Factors that characterise the seal static and dynamic performance are defined, namely: the compression load deflection behaviour (CLD), the shape of the seal during compression, the contact pressure distribution, the aspiration condition and the sound transmission loss (STL) characteristic of the seal.

When closing a vehicle door on the door opening panel, energy is spent to overcome the resistance latch mechanism at the rear of the door and to compress the seal that runs around the perimeter of the door. The CLD curve gives information on the amount of energy spent to compress the seal, which can represent up to 50% of the total energy needed to close the door [2]. It is influenced mainly by the seal material characteristics and by seal shape. The change of contact pressure distribution during compression gives information on the likelihood of air and water leakage through the seal [2]. The deformed shape during compression gives information on the stress distribution in the seal [2].

Aspiration is a condition which is defined as the loss of contact between the seal and the facing metal surface of the door. In certain driving conditions, the pressure difference between the interior and the exterior of the car pushes the seal outward. If the resultant pressure is higher than the frictional force at the contact area, separation occurs. Thus separation is influenced by the compression rate and the friction coefficient of the rubber-metal contact area.

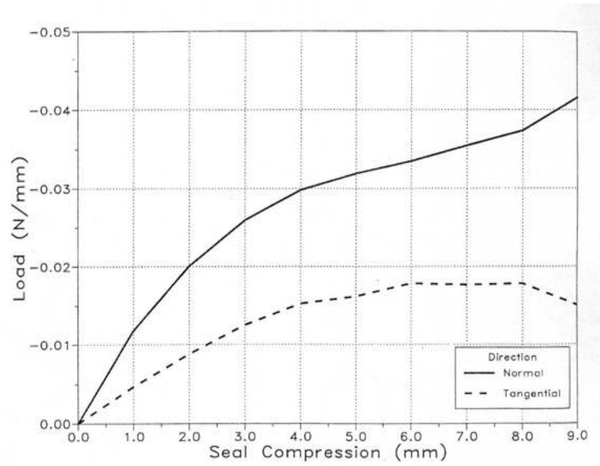


Figure 4 – Standard Weather Strip CLD Curve [2]

When aspiration occurs, a channel is created for noise, which generates turbulence at the door edge. This turbulence is due to the interaction between escaping air vortices from the passenger compartment, with vortices outside the car [2]. The airborne noise generated outside the car is mainly due to wind noise, exhaust noise, engine noise and tyre noise [3, 4]. Wind noise is generated mainly on the side glass windows of the doors by the turbulent flow of air around the A-pillar (the front pillar between windscreen and door) structures and other recesses and projections in the body surface. The noise is transmitted into the vehicle interior through body panels, side window glass and the seal gap between the door and the door opening panel. In reference [5] it is emphasised that the side glass windows and the car door seals are the two main mechanisms of sound transmission from the exterior to the interior of the passenger cabin. Seals are usually considered acoustically transparent, i.e. zero STL. The noise entering the passenger compartment through the door seals is then comparable in level to the noise generated by window panel vibrations.

4. Project Conceptualisation

4.1 Existing Technology

Weather strips have many uses and are not restricted to only automotive applications. There are many other rubber seals which constitute weather strips and some of the other applications of these are in shower screens, external doors and windows. They all act to perform the same basic functions, namely to seal a gap against transmission of wind, moisture (in all its forms i.e. rain, sleet, snow, ice), dust, noise and temperature. As would be expected from such versatile operating parameters, there has been considerable research into various facets of weather strip design and manufacture. While most automotive companies and their suppliers regard this information as closely guarded trade secrets, there are some that have patented different functions and characteristics of various weather strips. A few of these will be examined below.

Firstly, the method of attachment will be discussed. US Patent number 6,247,271 submitted by Ford Global Technologies examined weather strips and their interaction with the flange they are connected to (Figure 5) [9]. Most weather strips in use in automotive applications, including the DGWS examined in this report, attach to the body of the vehicle via a metal flange. In the case of the DGWS, this flange runs from the base of the A-Pillar to the bottom of the C-Pillar. Its shape is maintained constantly along the whole path. Ideally the weather strip should attach easily onto this flange, allowing quick and effortless installation on the production line, yet be difficult to remove to maintain good sealing characteristics during the seal's lifetime. There are instances where the seal has to seal around tight corners. An example of this would be the C-Pillar/Roof Line intersection of a wagon. In these situations, in order to maintain the low insertion/high extraction force and good sealing characteristics, expensive moulds are used. This patent proposed a number of important changes to the basic weather strip design to allow both variable width flanges to be used and also to remove the

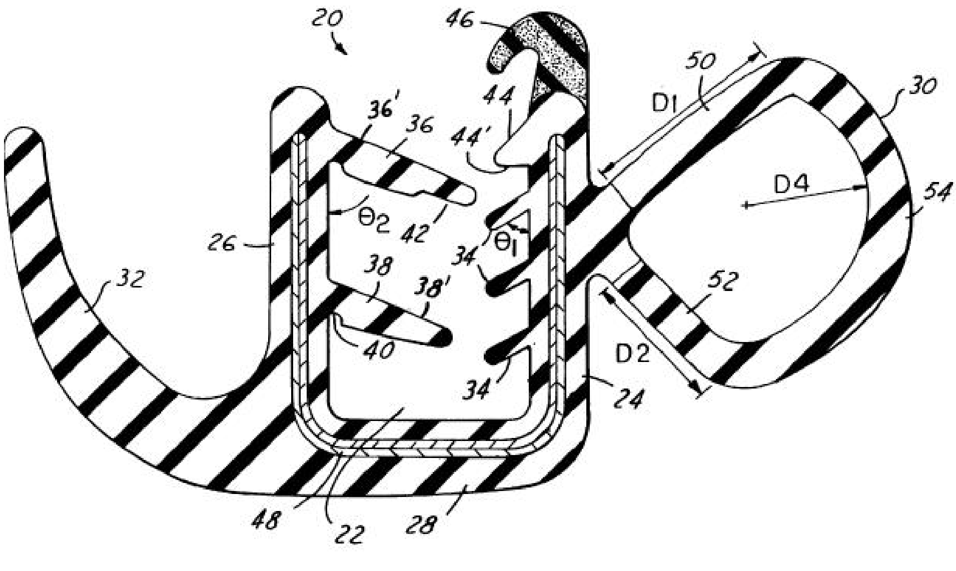


Figure 5. U.S. Patent 6,247,271 - Variable Flange Width Weather Strip

need for expensive moulds on tight corners. The fingers numbered 34, 36, and 38 grab the flange when inserted and through friction provide the necessary high extraction force. The angles these fingers extend at, θ_1 and θ_2, can be set to vary the insertion/extraction force required. At the base of fingers 36 and 38, where they attach to side 26, the small indentation allows for easy bending to accommodate the various width flanges. Further to this, the finger 36 has a bevelled tip section which allows further bending in the case of wider flanges being inserted. This also has the double effect to

further increase the surface area that the fingers grab at the flange, thus increasing the friction required to remove the flange. In order to accommodate the tight corners the weather strip is required to seal around, the bulb section is of two different arm lengths (50 and 52). This reduces the tendency of normal bulbs, with arms of the same length, to rotate upwards and unseal.

U.S. Patent 5,423,147 (Figure 6) discusses an alternative method of attaching the weather strip to the flange [10]. This patent is not entirely suited to the DGWS under examination in this project however, the technology may be adapted to suit. In many weather seal applications, the carrier (12) includes wire or metal reinforcement in order to enhance the grip the carrier has on the flange (22). However, such setups increase cost and complexity when fabricating the seal. They can also hamper

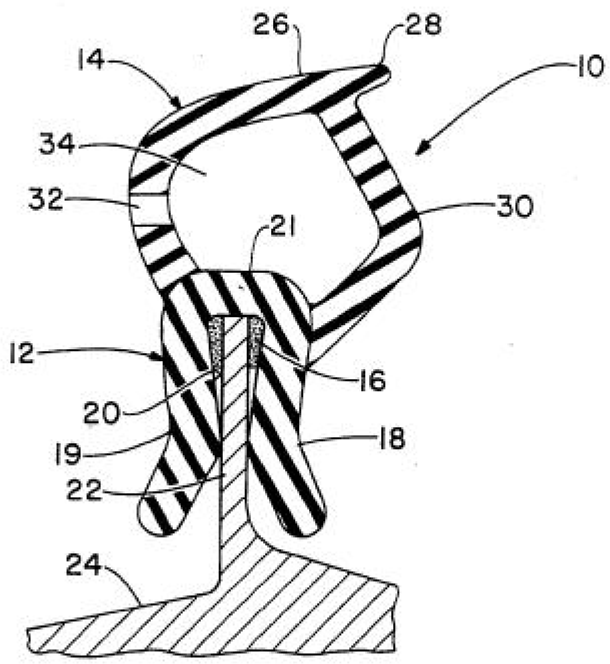
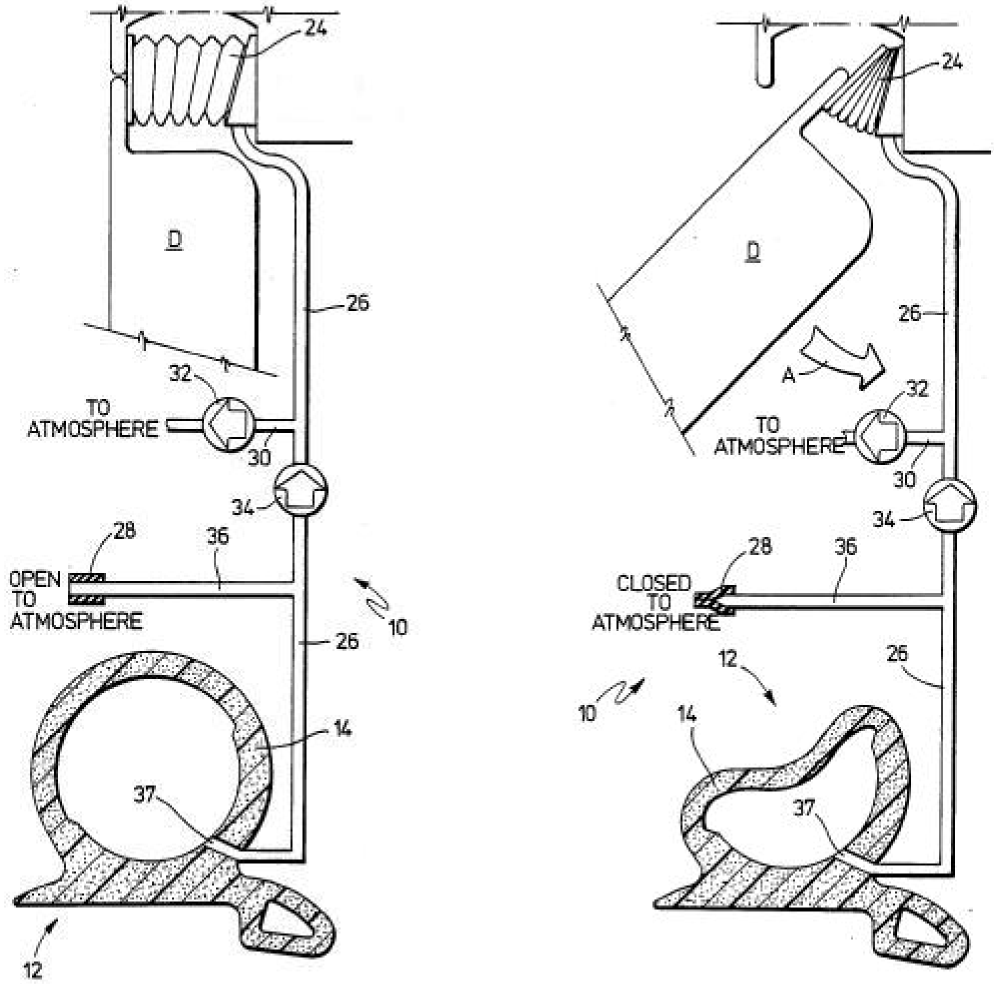


Figure 6. U.S. Patent 5,423,147 - Hot Melt Adhesive Carrier

seal performance on tight corners, if the wire/steel reinforcing is not sufficiently flexible laterally. An alternative to the use of wire carrier inserts, is to use a hot-melt adhesive (16) in the carrier cavity (20) which bonds with the flange. This hot-melt is proposed to be inserted into the carrier cavity during the extrusion of the weather strip. Approximately 10% to 30% of this cavity is filled the adhesive. The adhesive is also suggested to be foamed by the introduction of an inert gas (e.g. nitrogen) which reduces the amount and hence the cost of adhesive as well as increasing the volume/weight ratio. This foaming occurs simultaneously with the insertion of the hot-melt carrier, just after the seal has been extruded. Because the carrier does not contain any wire/metal insert, the rubber compound used in this section does not have to be any denser than that of the bulb section (10). The outcome of this is a better compression load deflection (CLD) characteristic, a criterion important for customer satisfaction levels as it directly relates to door closing effort.

Another U.S Patent, 4,791,917, focuses on an ingenious means to reduce door closing effort and improve sealing characteristics [11]. This approach aims to make the bulb of the weather strip inflatable. It describes a mechanism that deflates the bulb when the door is open and reinflates it when shut. Thus, this reduces the energy required to close the door as it is closed against a deflated seal. It also provides a better seal against the closed door when inflated. This better seal is achieved because bulb height is not compromised by the need to design for a particular level of door closing energy. To

deflate the seal, negative pressure is supplied via a bellow (24). The patent also describes other methods of providing this negative pressure but these are not presented here. The seal is inflated to atmospheric pressure, thus even upon failure of the bellows the pressure in the bulb of the seal will still be preserved, maintaining a good seal between the body of the vehicle and the door.



(a) (b)

Figure 7. U.S. Patent 4791917 - Deflateable Weather Strip. (a) Door Closed, (b) Door Open

Figure 7 describes the operation of such a mechanism when the door is both open and closed. When the door is open, the bellows (24) compress the air in the system (10) and as the door is shut, the bellows expand recreating its vacuum. When the door is shut, the pinch valve (28) is opened to the atmosphere, inflating the bulb. However, then the door is shut, valve 28 is shut and pressurised air is vented from the bellows forcing the deflation of the bulb (14).

There are numerous other patents that apply to the DGWS under examination, some of which are only slightly related. Some of these patents discuss slip-coats, a coating that is either sprayed on the seal or extruded as part of the seal, which acts to reduce the friction of the seal against surfaces [12]. U.S. Patent 6,602,589 examined a weather strip which has a variable bulb shape, depending on the section of the body. This was a design ideology our Client moved away from in their latest design iteration of the DGWS. They did this due to the higher cost of maintaining multiple dies and due to having to join different sections of seal. Patents also exist that relate to possible different rubber compounds, which have low compression-set properties, useful in seals used as weather strips [13]. A German

patent [14] examines a method for having overlapping flaps from both the primary and secondary door seals, accommodating a greater variability in door build. These have not been examined in detail as they are not directly related to the functions of the DGWS under investigation in this report.

4.2 Supplier Site Visit

An important part of the project conceptualisation involved getting a basic understanding of the manufacturing process of the DGWS. This was achieved through a site visit to the suppliers manufacturing plant in Bendigo. Unfortunately on the day of the site visit the DGWS was not being produced, but a similar seal for another one of the Client's vehicles was being manufactured. The extrusion process was observed, however, mixing of the rubber compound occurred in a different plant that we did not visit. The extrusion for the DGWS is complicated, as there are two different rubber compounds (labelled 1 and 2 in Figure 8) as well as the wire (material 3 in Figure 8) which is used in the carrier section (the section which attaches to the body flange).

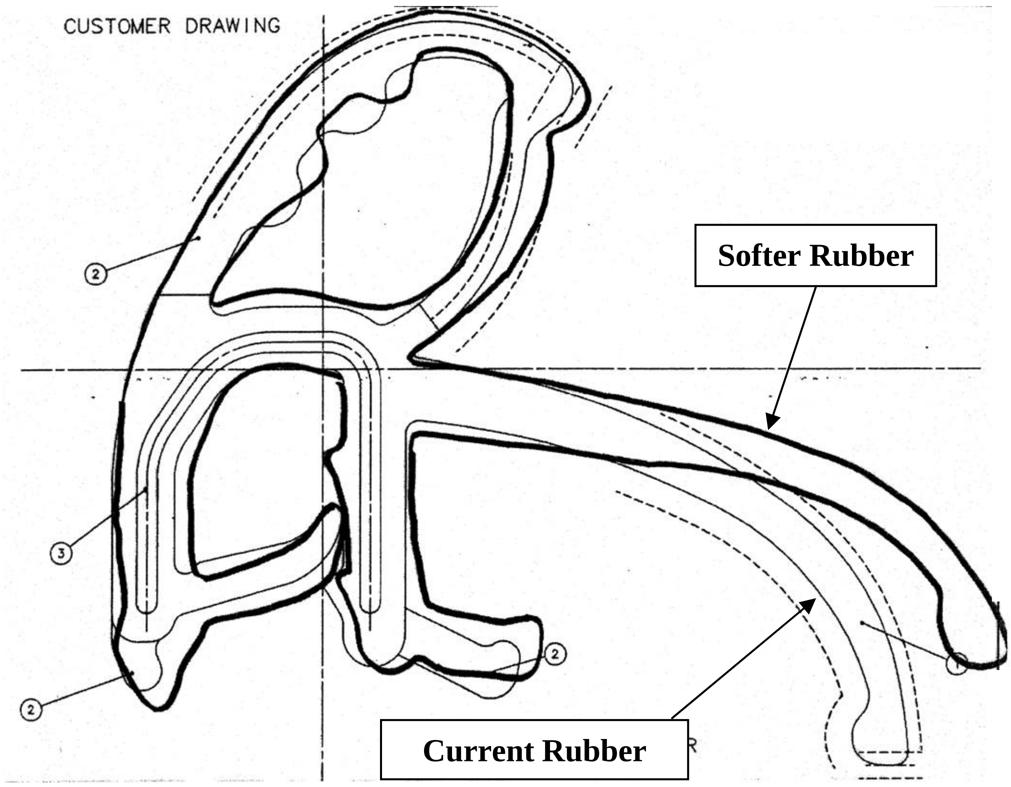


Figure 8. DGWS Profile. Softer in dark, Current in light

The seal is extruded because this is cheaper than other forms of manufacture. The process also allows for a continuos seal to be produced and allows easy minor modifications to be made to the seal quickly. This is crucial to the process, as slight variations in the compound will affect seal shape and properties. At the commencement of a run, several samples are cut which are compared against benchmarks for shape and compression-deflection behaviour. This allows the line operators to tweak settings to meet the Client's specifications. Shape is checked by comparing a section of the seal, under magnification, against a part drawing. The compression-deflection behaviour is tested in a compression testing machine, by fitting a section of the DGWS onto a fixture that represents the attachment location on the vehicle body, and is compressed by a cut out piece of the door assembly.

Once the seal has been shaped and cooled, various levels of slip coat are applied to certain surfaces. These act to reduce friction, preventing paint abrasion and squeak. For the DGWS, slip coat is applied to the top of the flap and the surface of the bulb which seals against the door. The slip coat on top of the flap is to ensure smooth flow of water off the roof, and the coating on the bulb is to reduce friction for door closing/opening and to prevent squeak. Once these have been applied the seal is 'cured', a process which stabilises the molecular structure of the rubber compound.

The final operation carried is attaching the various moulds that make up the corner/end pieces. This is achieved by compression moulding. There is a special mould where the DGWS fits to the bottom of the A-Pillar, and another special mould where the roof line and the C-Pillar meet on the station wagon variant. This second mould is due to a sudden change in direction, required by the different shape of the doors on the wagon. These moulds are quite complex and costly due to the complicated tooling required. A sample set up can be seen in Figure 9. The mould is created by injecting the compound into a cavity, with also contains the two separate seal lengths that are to be joined. The compression moulding operation the supplier uses generates a slight material excess, called the 'flash', which the operator must remove. This is the most time and labour intensive parts of the DGWS manufacture.

Figure 9. Compression Mould Press in open position

4.3 Client Standards Review

4.3.1 Wind Noise

The Client's internal documentation set out standards which sub-systems and components must comply with. These standards apply to all of the Client's divisions worldwide. There are numerous wind noise standards relevant to the testing to be carried out during this project. The most detail in the Client's Attribute Requirements List (ARL) for Noise, Vibration and Harshness (NVH) is given for wind noise tests conducted in a wind tunnel. These requirements are expected to be met for cars launched in model year 2006 onwards, and subsequent to this a 0.3 sone decrease in loudness is expected per year. In 2006, baseline wind tunnel targets for a passenger sedan at an angle of attack/yaw of 0° is 23.9 sones at 130 km/h and 36.4 sones at 160 km/h. This data is shown in Table 1.

Table 1. Requirements for Wind Noise in Wind Tunnel Testing [15]

Yaw [Degrees]	Loudness [Sones]	
	130 km/h	160 km/h
-20° (leeward)	31.9	49.9
-10° (leeward)	25.9	39.9
0°	23.9	36.4
10° (windward)	24.4	37.4
20° (windward)	27.9	42.4

Thus, whilst not explicitly stated, the 2005 wind noise requirement for a sedan with 0° at 160km/h would be 36.1 sones (assuming a 0.3 sone deduction from 2006 standards to reach 2005).
Requirements also exist for more realistic tests. These tests fall into 3 broad categories: smooth, coarse and rough road. These tests, however, are virtual CAE (Computer Aided Engineering) tests. The tools required to undertake these tests are beyond the scope of this project. However, it is worth noting that the levels these tests are required to meet are determined by 'measuring competitive vehicle sound levels during high speed (130 km/h to 160 km/h) cruise on a smooth/coarse/rough road' [16]. At these speeds, wind noise dominates the interior loudness. At speeds below this (50 km/h – 100 km/h) tyre noise dominates, hence the greater speed the test is conducted at above 130 km/h the more isolated the source of noise will be (i.e. the less influence tyre noise and engine noise will have on interior wind noise). Figure 10 describes this graphically.

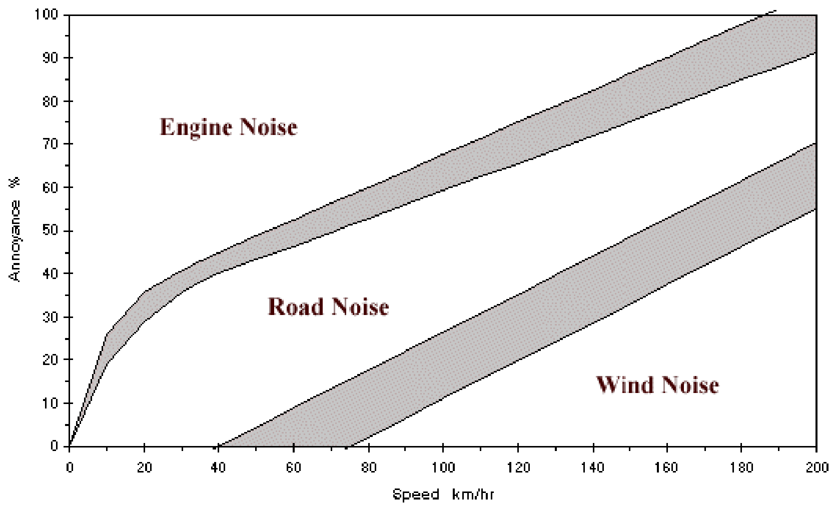


Figure 10. Levels of Annoyance at Increasing Speeds

The two standards mentioned are design standards. Hence, vehicles already in production are not required to meet them. For the vehicle under consideration in this report, the following production standards also apply: Interior loudness of 38 sones for 0° yaw at 160 km/h in a wind tunnel. The target interior loudness for 130 km/h on a smooth road is currently set at 29.5 sones. These are higher than the 2006 levels set out in the ARL, and take into consideration local issues and manufacturing limitations.

4.3.2 Door Closing Effort

The Client's SDS specifies that dynamic door closing efforts must not be any greater than 8.0 J of energy which correlates to 86.7N spring force as tested on a completely trimmed door on a vehicle at ambient conditions. This applies to the vehicle as received by the customer, which represents a sealing system that has reached the aged (72 hours) condition. The closing effort must not exceed 12 J of energy or 104.5 N spring force at -29°C. Recommended targets are 5.0 ± 1.5 J at ambient conditions and the efforts on any one vehicle cannot vary more than 1.5 J door to door [17].

It is important to understand the major factors that could contribute to high DCE. These include:

- Weather-strip CLD (Compression Load Deflection)
    - The Primary seal contributes up to 25% of the effort required to close the door
    - Secondary and auxiliary seals contribute an additional 10 percent of the effort to close the door
- Weather-strip height
    - Distance from top of bulb to carrier
    - Taller weather-strips will increase DCE although CLD may be held constant
- Air compression
    - Contributes up to 40% of the DCE required
    - High pressure spikes (air compression) contribute to DCE
    - Air extractors with adequate size and a good path through the trim to exit point can improve door closing efforts
    - Air pressure between primary seal and secondary seal

Table 2. Summary of DCE contributing factors

	Contribution to DCE
Air Pressure	3.0 J max
Weather strip (W/S) Compression	3.0 J max
Door Potential Energy	-1.5 J from the 25 degree open position
Hinge Friction	1.5J max from the 25 degree open position
Striker/latch H/L alignment	1.25 J max
Latch engagement	1.0J max
Check Contribution	0.5J max
Over slam bumper compression	0.25J max
Weather strip Vent Hole Losses	TBD (small)
Latch over travel	Included in weather strip target
Door cheat	TBD (small)
Air between Seal Compression	TBD (small)
Air drag on door	TBD (small)

The negative energy value in the table represents a 'door assist' component if designed correctly.

5. Evaluation and Testing

5.1 Wind Noise

5.1.1 Proving Ground

An integral component of the testing regime the Client undertakes on new parts is the wind noise drive. The basis behind this is that is a low cost method to quickly assess the impact proposed part changes have on interior loudness. At speeds greater than 130 km/h, wind noise dominates interior loudness. The major sources of wind noise effecting interior loudness are;

- Aerodynamic turbulence,
- Cavity resonance, and
- Aspiration leaks [18].

Measurement of wind noise is conducted using a device called an AACHEN Head. This was installed in the front passenger side of the vehicle. The AACHEN Head mimics the shape of a human torso and head, with two highly sensitive microphones situated in the ears. This allows high-fidelity sound recording that simulates human hearing. The AACHEN Head is attached to a laptop, which functions as the recording device. The laptop is controlled by an operator who sits in the back seat. Data is recorded from each ear/channel, which allows complicated analysis of cabin noise and specifically interior noise, especially noise transmitted through the door assembly (by selecting only a single channel for analysis).

Figure 11. The AACHEN Head set-up

The AACHEN Head Analysis Software outputs its data as a dB(A) vs. frequency, a more valuable form is when the results are presented in Sones. Sones are an acoustic measure of loudness. As loudness is a subjective property, the sones scale is calibrated such that doubling the number of sones equates to an increase of 10dB. Using this output allows a quick and easy method of comparing cabin noise between different tests.

As stated previously, the drives are conducted at 130 km/h, operating both north to south and south to north. Operating in both directions gives a clear indication of the effect the wind direction and strength has on interior loudness, and promotes a deeper understanding of the results. Further to this, each separate test is repeated four times, two in the northern direction and two in the southern direction. The final result is an average of each north-south pair of runs. This removes the systematic errors that creep into the results due to the different wind direction/strengths and other minor variations that occur over the course of a few hours.

Figure 12. Door Gaps Taped

The vehicle speed is controlled by cruise control, of which the set point of 130km/h is set whilst on the constant velocity track (CVT). The CVT is an oval circuit with banked corners that allows a car to travel at a constant velocity without the driver needing to touch the steering wheel. Thus, whilst performing the wind noise drive, the driver accelerates to just below 130km/h then activates the cruise control to reach 130km/h. This results in a constant speed during the 10 second duration of the test.

The purpose of this test is to determine if the softer compound used in the proposed DGWS has an effect on the interior loudness. In order to determine this, the new softer compound DGWS was tested against a range of other DGWS options. These options where:

- Green Current DGWS
- Aged Current DGWS (repeated as well)
- No DGWS Fitted
- Door Gaps Taped

As the DGWS is an EPDM, it continues to set for a period after it is manufactured. This represents a softening of the DGWS, which decreases the door closing effort whilst not having a noticeable impact on interior loudness. A seal that has completed its setting period is called aged. Internal documentation states that after 72 hours the bulk of the seal aging has completed [19]. Two tests were

conducted with an aged current seal on the test car, so an indication of the variability of the process can be determined. A test was also conducted with all door gaps taped (see Figure 12), to give an indication of the best possible interior loudness. This is due to the fact that no noise can enter the cabin through the door seal system and cavity resonances are not generated around the door. Thus, it is impossible to get better results than this by simply changing the door seal. This also provides an ultimate target to work towards. The opposite of this situation is the test with no DGWS fitted. Here, instead of having 3 door seals the vehicle only has 2 seals insulating it from wind noise. As the area between the door and body, exposed to the outer atmosphere, is increased so too is the generation of cavity resonances caused by the flow of air over the door/roof area. This is the worst case scenario.

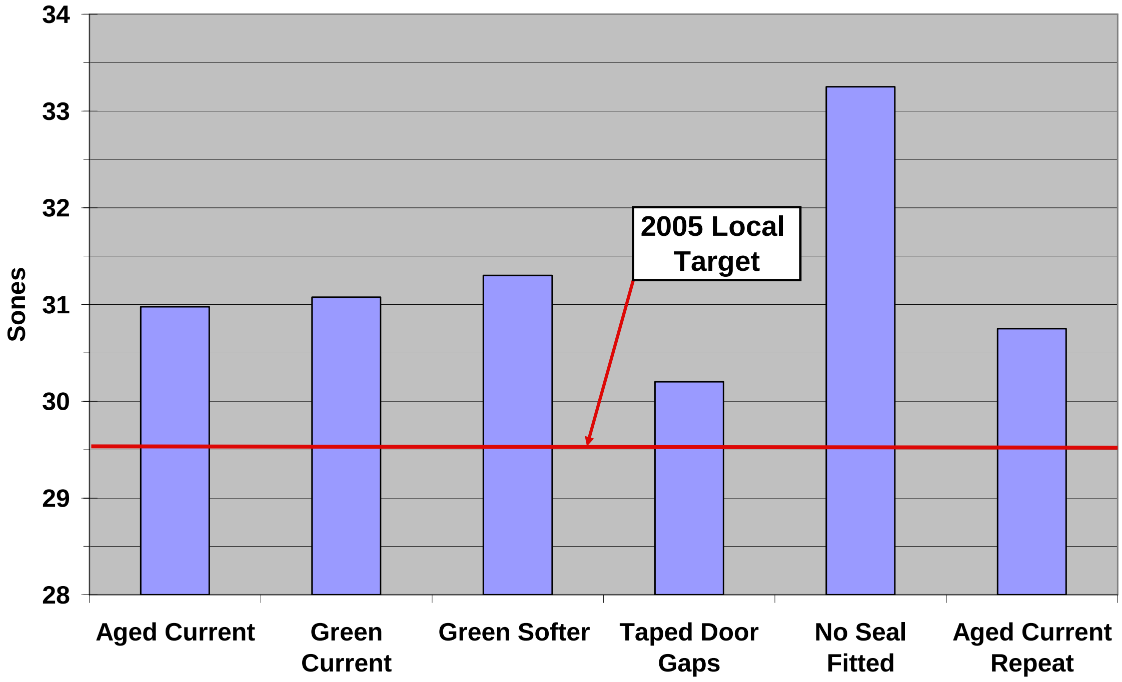


Figure 13. Average Wind Noise: Wind Noise Drives (LH Ear)

The results in Figure 13 show that the softer DGWS is slightly worse than both the green current and aged current seals, however it is within the variability and tolerance of the process. This variability can be seen in the difference between the two tests on the aged current seal. As such, the green softer seal does not represent a problem in wind noise terms. From the figure above, it is also possible to assess the impact on interior loudness due to the softening of the DGWS due to the compression setting. This difference is also within the variability of the process, yet is extremely small, indicating little effect on interior loudness.

A further analysis of the variability and tolerance can be seen in Figure 14. Here the whole spectra can be seen for the two aged current tests. The units here are dB(A). The variability can be seen to be quite small and located only at certain frequencies.

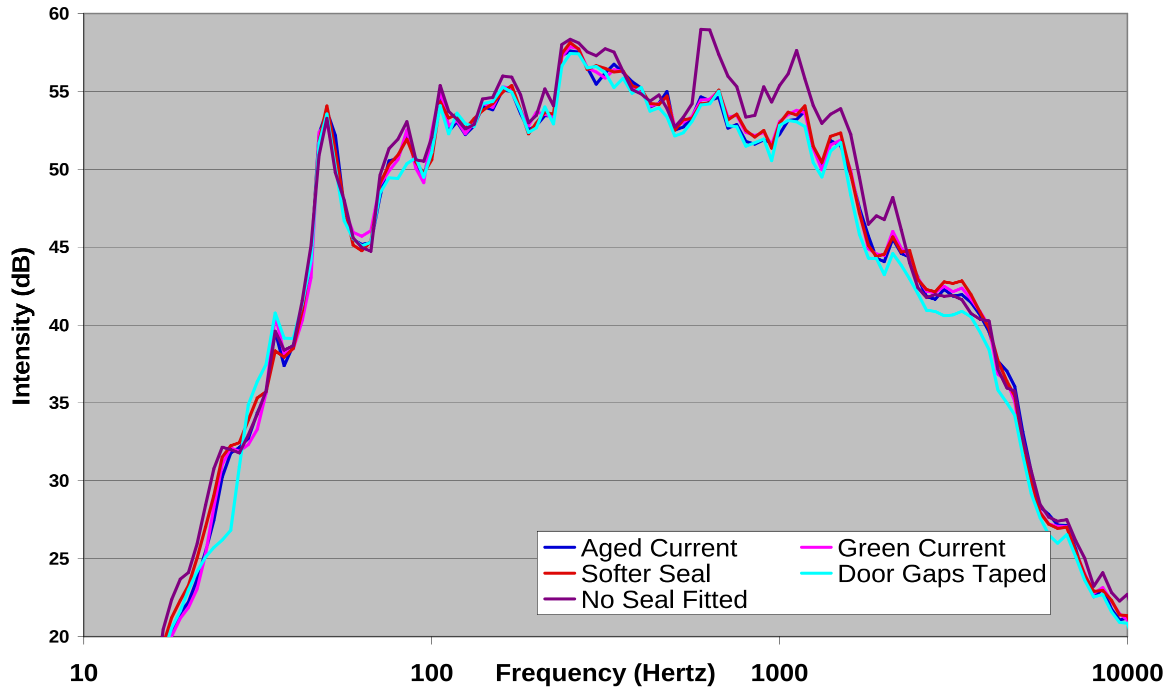


Figure 14. Wind Noise Spectra: Wind Noise Drives (LH Ear)

Both Figure 13 and Figure 14 use values taken from the left ear of the AACHEN Head bust. The reason for this is that this is the ear closest to the door and hence 'hears' the most wind noise. A comparison of the interior loudness between the right and left ear is shown in Figure 15. This figure shows that interior loudness meets the 2005 Target only on the right ear, the quieter ear. It is clear from Table 3 that the left ear registers a consistently higher loudness than the right, of the order of $15\% \pm 1.5$.

Table 3. Percentage Difference between Ears

Seal	Ear [Sones]		Percentage Difference
	Left	Right	
Aged Current	30.975	26.925	15.04%
Green Current	31.075	27.375	13.52%
Green Softer	31.3	27.475	13.92%
Taped Door Gaps	30.2	25.975	16.27%
Aged Current Repeat	33.25	28.975	14.75%
No Seal Fitted	30.75	26.75	14.95%

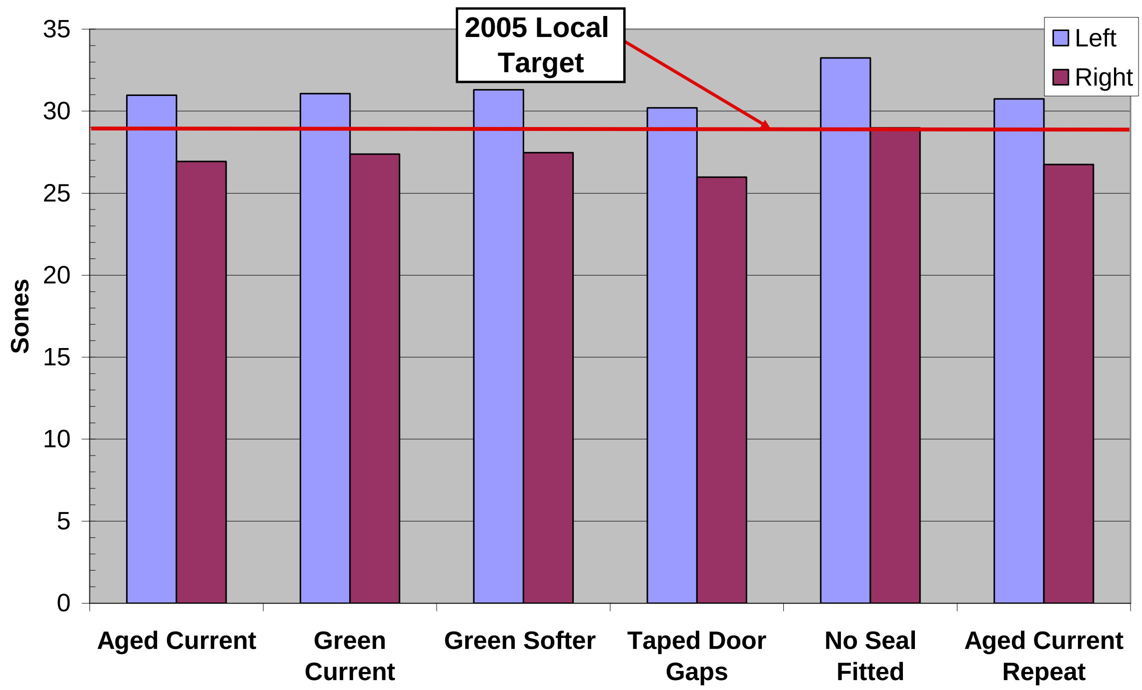


Figure 15. Average Wind Noise: Passenger Ear

On the day testing was carried out, the ambient wind speed was slightly higher than optimal. At the beginning of testing, wind noise was measured at 22 km/h, whereas optimal conditions are considered less than 15 km/h. Due to ambient wind strength and direction some tests are run with the wind and some against, so as not to allow bias in the results. It is expected that the ambient wind strength and direction impacts the test data. The differences in the results obtained in each direction are shown in Figure 16. Whilst the magnitude of the interior loudness changes with the runs in each direction, the important thing to note is that the variation between test types, i.e. the types of seals, approximately stays the same, especially considering the variably of the process evident in the difference between the repeat test. This is summarised in Table 4.

Table 4. Percentage Diffence due to Test Direction

Seal	Percentage difference due to direction	
	Left Ear	Right Ear
Aged Current	17.37%	13.69%
Aged Current - Repeat	10.26%	7.77%
Green Current	17.69%	13.45%
Green Softer	15.86%	12.57%
Taped Door Gaps	16.10%	15.56%
No Seals Fitted	18.03%	8.83%

Figure 16 also highlights the importance of wind direction on interior loudness. The north runs achieved the 2005 local target for interior loudness, yet the south based runs did not. Thus, even though this target appears not to have been reached it is important to remember that the ambient wind strength was not ideal on the day testing was carried out. In fact, the optimal testing target of 15 km/h was chosen because it is the mean 3pm Wind Speed for Melbourne [20]. As can be seen in Table 5, this value for Melbourne is one of the higher, with the national average at 13.39 km/h. Thus, in the majority, conditions experienced are not sufficient to induce high levels of interior loudness.

Table 5. Average Wind Speeds for Australian Capital Cities [20]

City	Mean 3pm Wind Speed [km/h]
Melbourne	15.0
Sydney	16.6
Adelaide	11.1
Perth	17.3
Brisbane	12.6
Darwin	9.6
Canberra	11.5
Australian Capital City Average	13.39

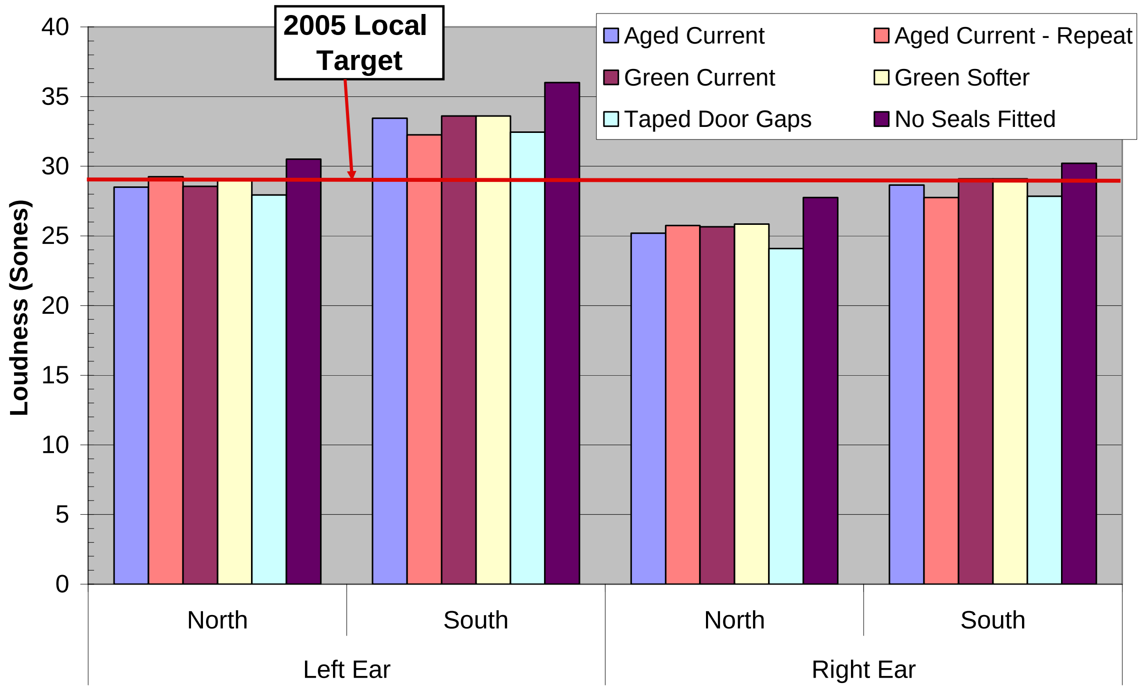


Figure 16. Wind Noise: Effect of Measurement Direction

5.1.2 Wind Tunnel

As the wind noise drives were deemed a success, time was booked during the Clients' next wind tunnel testing period. The facility the Client uses is the Monash University 1.5Mw wind tunnel, which is large enough to allow a full sized car to be tested. These tests differ from the wind noise drives as the noise measured in the car by the AACHEN Head is only due to the flow of air over the surface of the car. Whilst interior loudness at speeds over 130km/h is dominated by wind noise, there remains a contribution from other factors such as road and engine noise. The wind tunnel testing allows for the wind velocity to be regulated, something not achievable in a wind noise drive. The wind speed used in all tests was 160km/h.

Due to a constrained testing schedule and the increased length of these types of tests, only four different setups were tested. The no seals fitted and taped door gaps tests were not repeated from the wind noise drives. However, enough time had elapsed since the manufacture of the softer DGWS that an aged sample was able to be tested. Thus an indication of the behaviour of the new compound once set was able to be investigated.

Table 6. Wind Tunnel 1: Percentage Difference at Zero Yaw

Seal	Ear [Sones]		Percentage Difference
	Left	Right	
Aged Current	31.8	37.7	18.55%
Aged Softer	32.3	37.6	16.41%
Green Current	32.2	37.5	16.46%
Green Softer	32.4	37.9	16.98%

Compared to the proving ground noise drives, the AACHEN Head was situated in the driver's seat; hence the right ear was closest to the door and the source of the largest measured loudness (Figure 17). The percentage difference, as seen in Table 6, between the two ears on the AACHEN Head is slightly greater in these tests than in the wind noise drives which can be explained by the lack of road noise and engine noise and the higher experimental speed. These two sources of noise would be more apparent in the ear closest to the centre of the car.

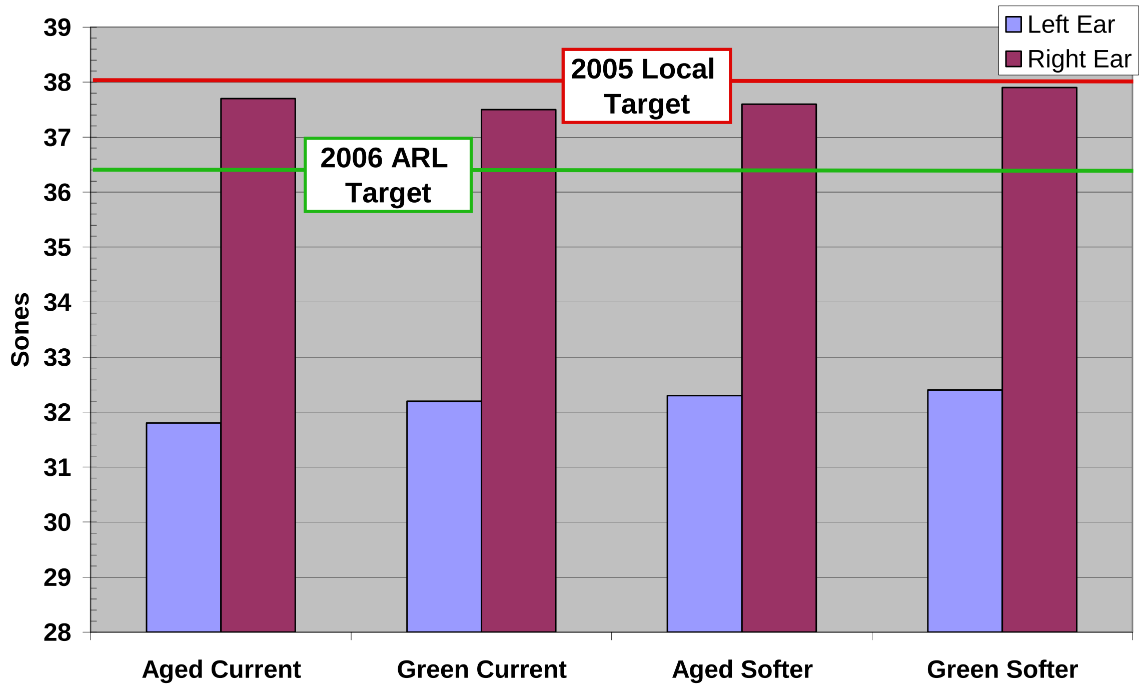


Figure 17. Wind Tunnel 1: Zero Yaw Condition

It can also be seen from Figure 17 that the softer DGWS complies with the 2005 local interior loudness target. Yet, there is still a ways to come until compliance with the 2006 ARL target is achieved. Thus, the next generation of vehicles will have a sizeable improvement in interior loudness levels if compliance is achieved.

As well as conducting tests mimicking the wind noise drives, the wind tunnel facility is equipped with a rotating floor which allows the car to be presented at different angles of attack to the oncoming air flow. The results from this yaw variation can be seen in Figure 20. The ability to change the yaw of the car allows a fairly good representation of the variability of wind conditions experienced whilst driving. Positive yaw represents the case, where the drivers side (the side the AACHEN Head is on) is windward and negative yaw is when the drivers side is leeward (Figure 18). When the yaw is positive, the door is forced in towards the body of the car by the air flow. This prevents the DGWS from unsealing from the door. The condition when the DGWS unseals from the door is known as

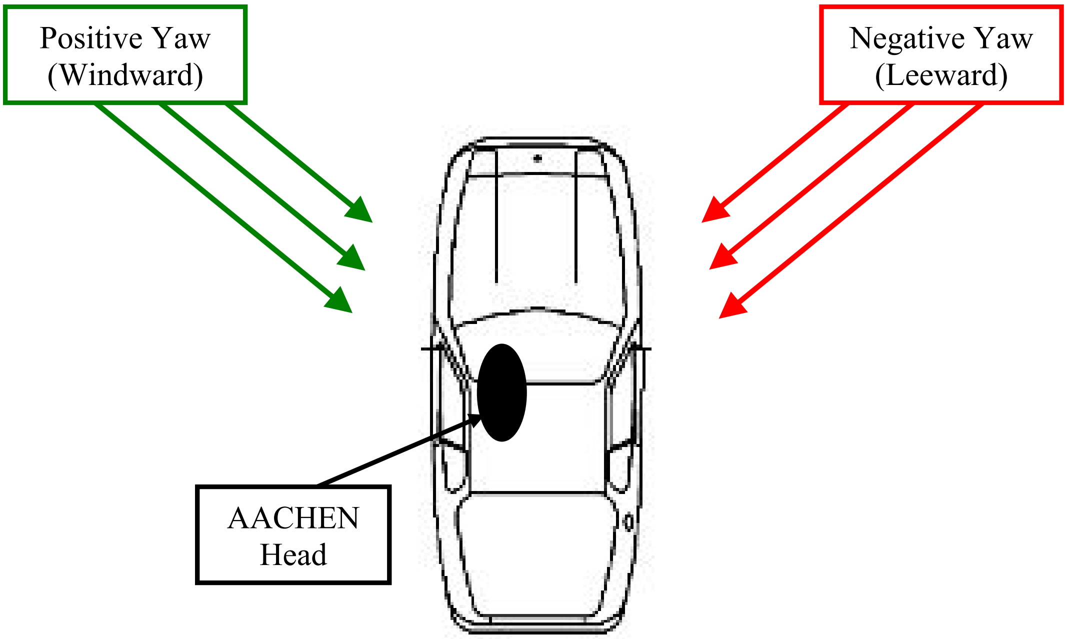


Figure 18. Explanation of Positive/Negative Yaw

aspiration. In normal driving conditions, aspiration occurs due to the pressure differential between the two sides of the DGWS bulb. When the car is rotated into the negative yaw condition, aspiration plays some part in the increase in cabin noise. However, in these positions, the flow of air over the roof of the car is catching the top edge of the door and forcing it away from the body. Hence loudness due to aspiration cannot be easily determined from these tests as it is not the only mechanism introducing a direct sound transmission path between the outside of the car and the door cavity. The results taken over the whole yaw sweep from -20° to 20° are displayed in Figure 20.

Figure 19. Monash University 1.5Mw Wind Tunnel

An interesting feature of these results is the position of the minimum cabin noise. Instead of being situated at 0° as would be expected, it is at 5°. At 0°, the windscreen acts as a large deflector to the flow. At 5° yaw the A-Pillar acts to split the flow, so some is deflected by the windscreen and some is deflected by the car. Whilst this may not be the most aerodynamic profile of the car, the combination of the aerodynamic profile and the size of the cross section result in the best condition for cabin noise. From this position to the worst position when the car is at -20° yaw, there is over 40% increase in cabin noise.

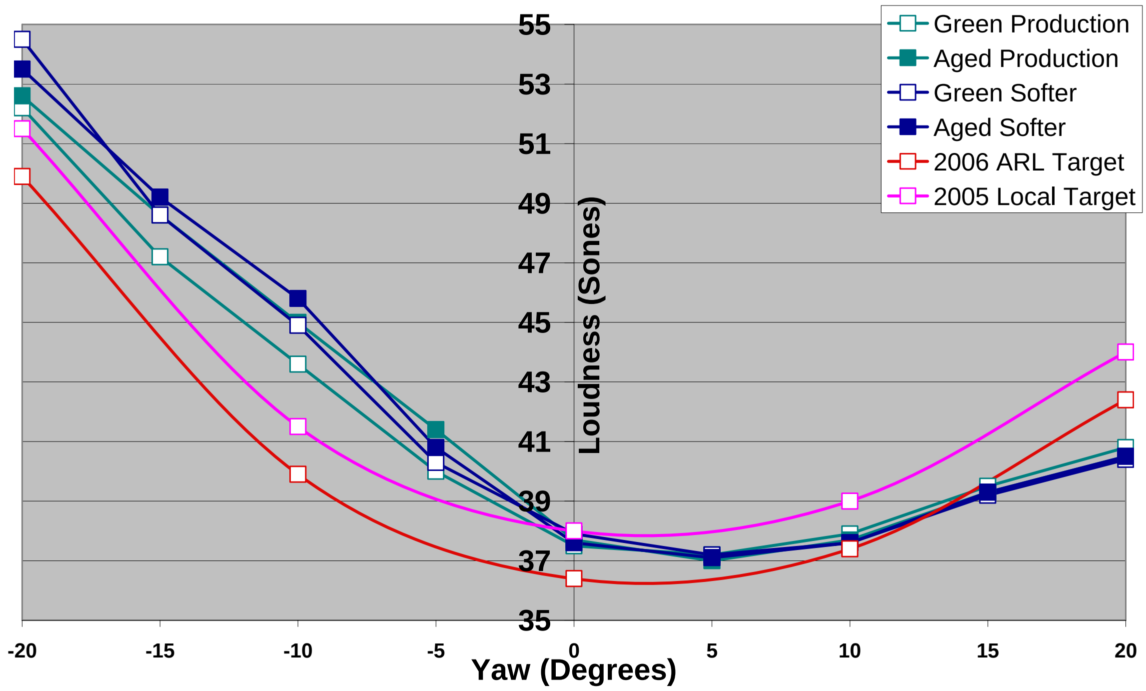


Figure 20. Wind Tunnel 1: Wind Noise Sweeps (RH Ear)

Figure 20 also highlights that none of the tests conducted achieved the 2005 interior loudness target when the AACHEN Head is in the leeward/negative yaw position. Yet for windward/positive yaw both seals met the 2005 target but only reached levels satisfying the 2006 target when at 15° yaw or larger.

Table 7. Wind Tunnel 1: Loudness due to Variation in Yaw

Seal	RH Ear [Sones]		Percentage Difference
	-20° Yaw	5° Yaw	
Aged Current	52.6	37	42.16%
Aged Softer	53.5	37.1	44.20%
Green Current	52.2	37.2	40.32%
Green Softer	54.5	37.2	46.51%

All these results indicate that both the green and aged DGWS are of equivalent standard to the current DGWS compound used in production. The extra time for the DGWS compound to set increase the loudness in the cabin by 0.4 sones for the current compound compared with 1 sone with the newer compound. This difference, whilst small, is most likely due to the extra deformation the bulb undergoes due to the complex forces generated between the door and body of the car by air circulation in this cavity. However, this is an area that would need to be studied if interior loudness targets are to be met for the leeward/negative yaw position. If the softer DGWS was implemented into production a

lower zero yaw interior loudness would have to be targeted, so as to accommodate this extra deterioration in loudness as the seal sets.

A second series of tests were also conducted at the Monash University wind tunnel facility. The purpose of this series of tests was to conduct wind noise sweeps at varying wind speed and in varying vehicles, as all data collected so far had been from the same vehicle. In these tests, 5 different vehicles were used and tests were conducted with wind speeds set at 100km/h, 130km/h and 160km/h. Yet again, as with the last set of wind tunnel tests, there were constraints which restricted the number of parts that could be tested. Thus, only two variations on the DGWS were tested, the current and softer, both of the aged variety. This aged softer seal had been on a car stored outside since the proving ground test several weeks earlier.

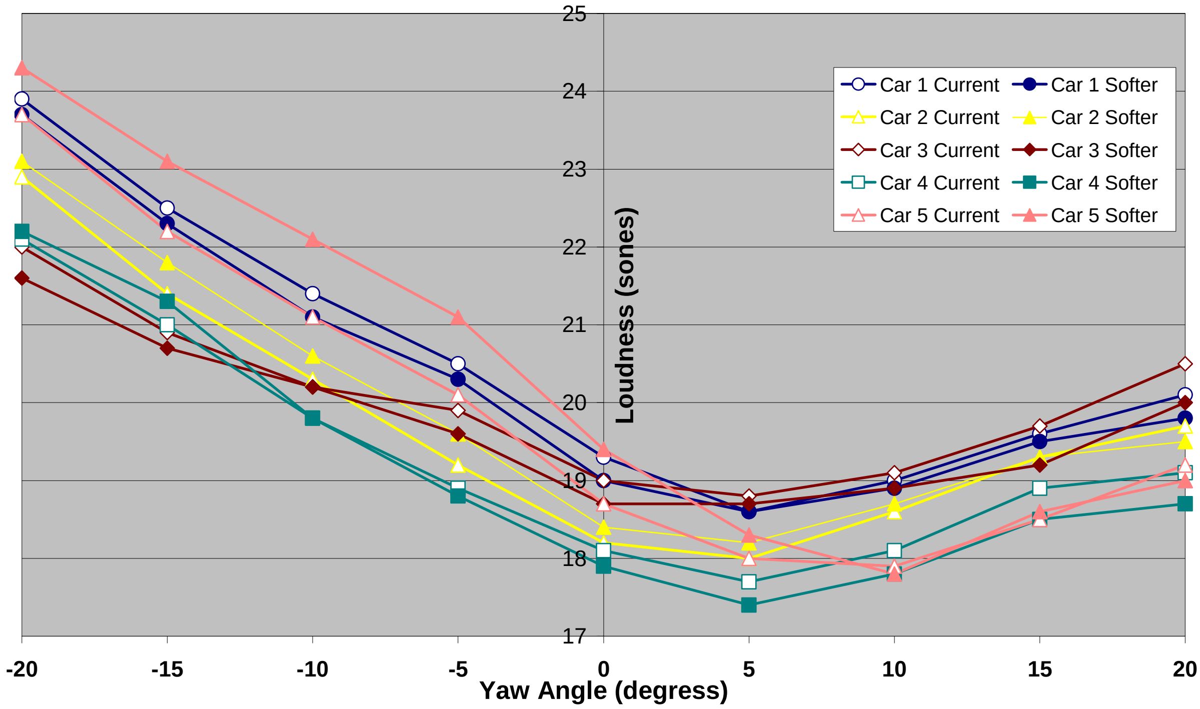


Figure 21. Wind Tunnel 2: 100 km/h Wind Noise Sweep

Looking at Figure 21, Figure 22 and Figure 23 the variability in the process can once again be seen. Ideally, the loudness for each car should be about the same. The body of the car is not different from model to model. However, there can be aerodynamic package differences between models. An example of this would be a sportier model with front bumper spoiler and side skirts. Also, a luxury model should have better tolerance for wind noise. At slower speeds, the variability is difficult to observe whereas at 160 km/h it is quite obvious. It is also easy to spot the variability in the process as opposed to the method of measurement, as values at each yaw angle for the softer and current seal are always close (within 1 sone for most tests). The variability can also be put down to the range of cars used and hence the range of 6G and 7G values that would exist. Difference in these values affect door closing effort, and this will be examined in more depth later in this section.

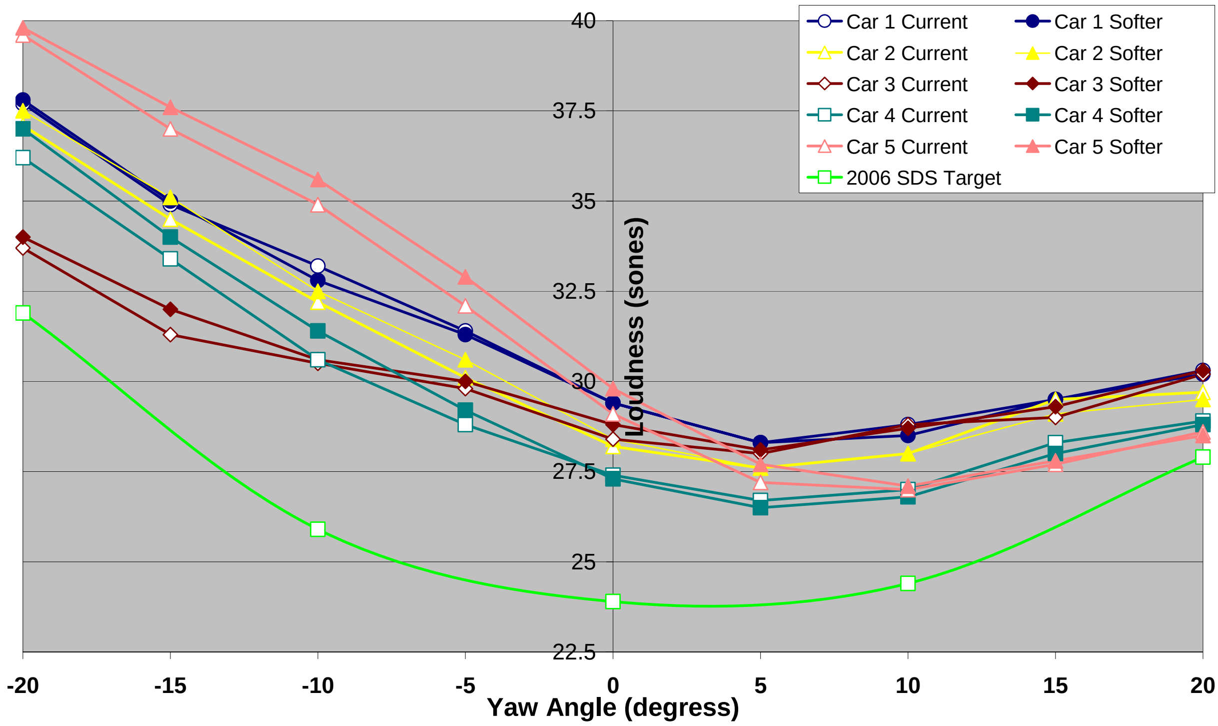


Figure 22. Wind Tunnel 2: 130 km/h Wind Noise Sweep

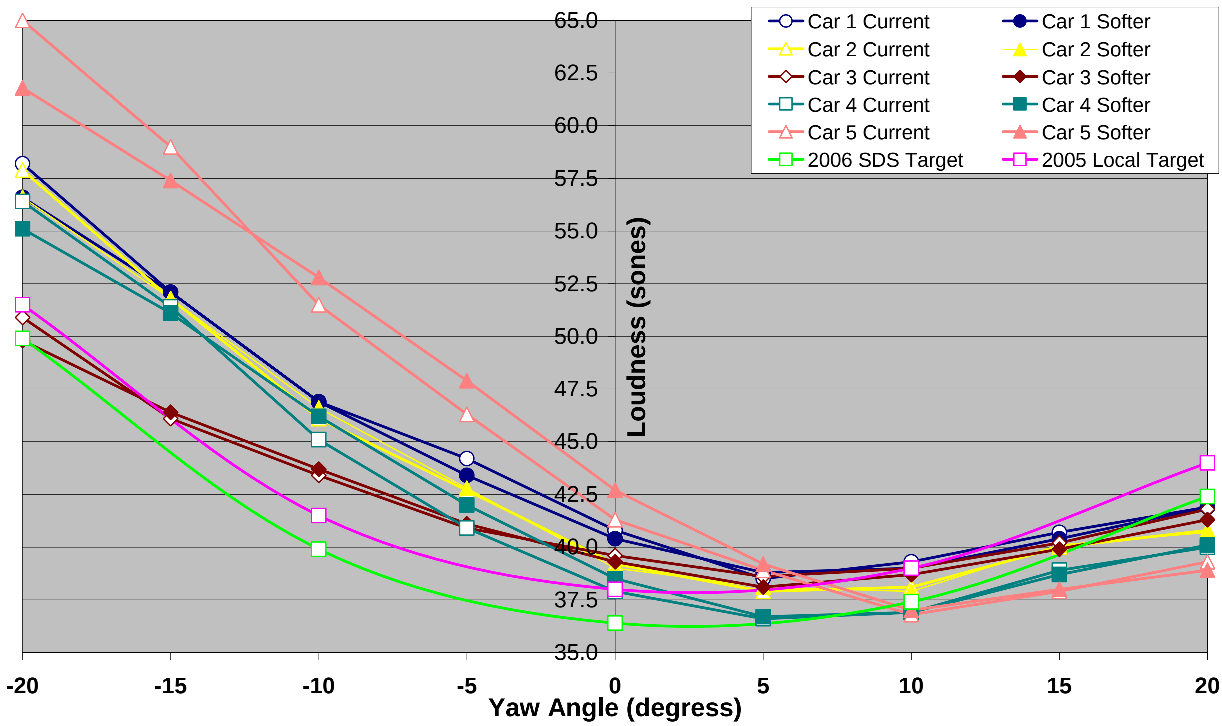


Figure 23. Wind Tunnel 2: 160 km/h Wind Noise Sweep

Once again, when comparing values in Figure 22 and Figure 23 to the targeted values, it is possible to determine that the interior loudness spread is closer to the 2006 target at the 160 km/h tests compared with the 130 km/h tests. The reason behind this is unknown, and would require a more detailed analysis of the frequency response for these tests. At 160 km/h and in the windward/positive yaw

position the results show a better performance against both the 2005 and 2006 targets than in the leeward/negative yaw position. This is consistent with results seen in the first wind tunnel test (Figure 20).

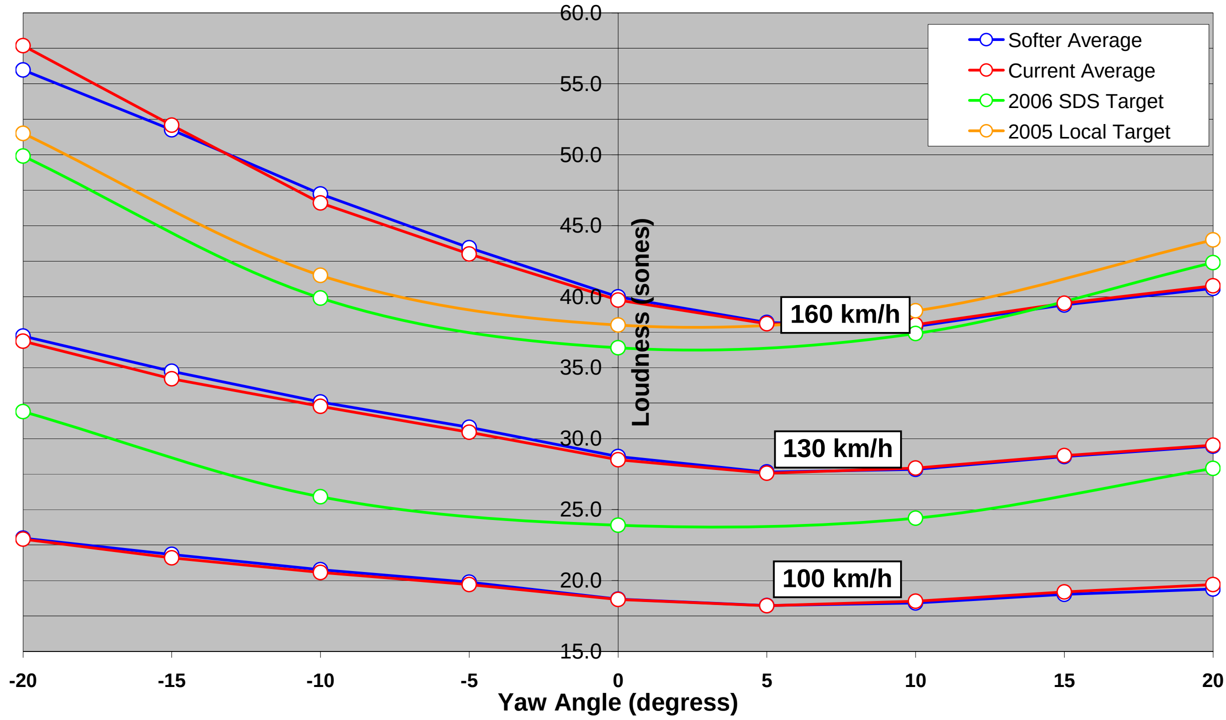


Figure 24. Wind Tunnel 2: Average Wind Noise Sweep

Overall, the performance of the softer DGWS was acceptable, if not identical (in the case of 100 km/h). This can be seen in Figure 24. Keeping in mind that the loudness scale with sones is not logarithmic like the decimals scale, a 2~3 sone difference would be almost indiscernible by the human ear. This is even more obvious when you consider the effect vehicle speed has on cabin noise. As can be seen in Table 8, an increase of approximately 30% in speed increases the cabin noise by over 50%. These values are at the minimum range of the actual values, as the vehicle in the wind tunnel is not producing any road or engine noise. These two extra noise sources would definitely contribute to cabin noise. Hence, an extra 2 or 3 sones due to a different DGWS is not an issue. Looking at Table 8, it is interesting to note that increasing the car's speed by 60% will result in an increase in cabin noise of approximately 150%. Once again, this is neglecting the increase in noise that would occur due to road and engine noise, which would be significant in cabin noise measurements.

From the perspective of the 2006 ARL target, a move to a softer DGWS would move the interior loudness further away from desired levels. Since relaxation is expected when the softer seal undergoes compression setting, interior loudness would be expected to worsen even more.

Table 8. Wind Tunnel 2: Percentage Comparison at Different Speeds at Maximum Yaw

Seal	100km/h to 130 km/h Percentage Difference	130km/h to 160 km/h Percentage Difference	100km/h to 160 km/h Percentage Difference
Aged Current	60.82%	56.48%	151.66%
Aged Softer	61.97%	50.40%	143.60%

Table 9 shows that the difference between the two different seals from the quietest yaw angle to the loudest is within the variability of the process. At worst, the softer seal was 4.77% worse than the current seal, a value deemed acceptable by the Client.

Table 9. Wind Tunnel 2: Loudness due to Variation in Yaw

Speed	Seal	-20° Yaw	5° Yaw	Percentage Difference
100 km/h	Aged Current	22.92	18.22	25.80%
	Aged Softer	22.98	18.24	25.99%
130 km/h	Aged Current	36.86	27.56	33.74%
	Aged Softer	37.22	27.64	34.66%
160 km/h	Aged Current	57.68	38.1	51.39%
	Aged Softer	55.98	38.18	46.62%

5.2 Door Closing Effort

Door closing effort (DCE) is one of the quality issues that are of concern to both vehicle designers and customers. Door closing effort is a very closely monitored parameter at assembly plants. If a closing effort issue is identified, plant personnel usually would immediately set the door outboard to reduce the effect. This action would be detrimental to other attributes such as wind noise and water leakage. The objective is to keep the energy required to close the car door to less than 8.0J which correlates to 86.7N spring force [17]. DCE is determined by how much energy is required such that the door reaches the latch position and just closes and can be described by the transfer function:

Door Closing effort (energy) = *f* (Air pressure + primary/secondary/tertiary weather strips compression (seal stiffness and compression amount/seal gap) + weather strips vent hole losses + air between seal compression + air drag on door + hinge friction + check friction + check forces + door potential energy (mgh) + latch engagement + latch over travel (additional weather strip compression) + striker/latch misalignment (energy to bend/lift door) + door cheat + wiring harness friction + over slam bumper compression) [19].

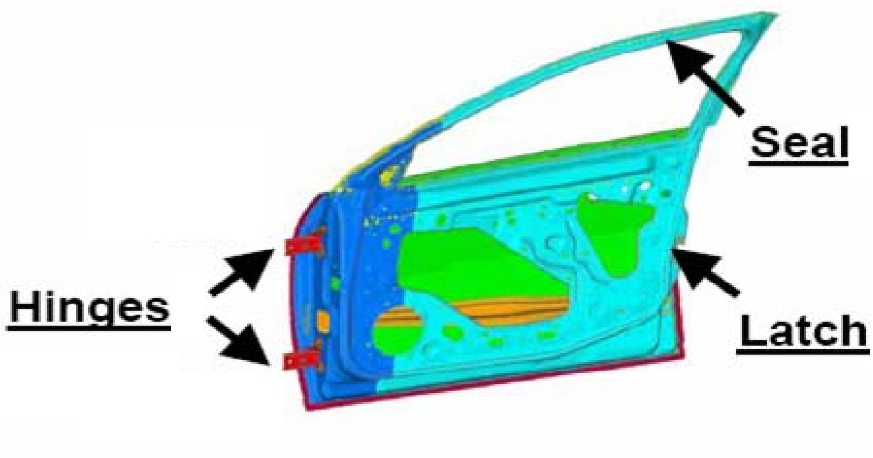


Figure 25. Door showing major features [22]

It is clear from the transfer function that DCE is affected by several factors, however, most of these are beyond the scope of this project. The weather strip factors affecting DCE from the transfer function above are the: weather strip compression, vent-hole losses and compression of air between the seal. The major *weather strip compression* contributors are due to weather strip CLD, the amount of compression (seal gap environment) and sliding friction of the weather strip over the sealing surface. *Weather strip vent-hole losses* are affected by the speed of the door just prior to closing, the amount of air inside the weather strip bulb that must escape, vent-hole size and vent-hole spacing. The *air between seal compression* is a function of the speed of the door just prior to closing, the amount of air trapped in the seal bulb and the venting between seals. However the contribution of these last two factors is very small. The energy contribution of each of these is shown in Table 10.

Table 10. Energy Contributions of various weather strip attributes [23]

	Contribution	% of Target
Weather strip Contributions		
- Primary Seal Compression	2.0 J	25 %
- Other Seal Compression (incl. DGWS – Tertiary seal)	0.85 J	~ 10 %
- Vent hole losses	0.1 J	~ 1.25 %
- Air between seal compression	0.1 J	~ 1.25 %
Total Weather strip Contribution	3.0 J	37.5 %
Total DCE Target	8.0 J	100 %

5.2.1 Force Gauge

The first set of trials was conducted using the energy method on various DGWS samples at the Proving grounds. The ‘energy method’ setup consists of a spring force-gauge (of known spring constant k) connected in series to a load cell with a digital display. This is then attached to the inside of either the front or rear opposing doors. This method measures DCE in Joules, i.e. as energy and is shown in Figure 26. The test vehicle proved to be a good specimen due to the variation in door ‘set’ between the driver’s-side door and the front passenger-side door. The driver’s side (RHS) was an example of good door set, whilst the passenger side door (LHS) was poorly set.

Figure 26. DCE ‘Energy Method’ Setup

DCE was measured for four major DGWS conditions: 'Green' seals are straight from the supplier, whereas 'Aged' seals have been allowed to set for over 72 hours which represents the minimum time before a customer takes delivery of a car. During this time the features of the seals change as compression-setting occurs in the seal material and DCE decrease. The 'No Seal' condition is assumed to be the best-case scenario, in the sense that there is no seal contribution to DCE. See A. Appendix A: DCE Sample Calculation for a sample DCE calculation from force measurements. The results are displayed in Figure 27 for the front and Figure 28 for the rear doors.

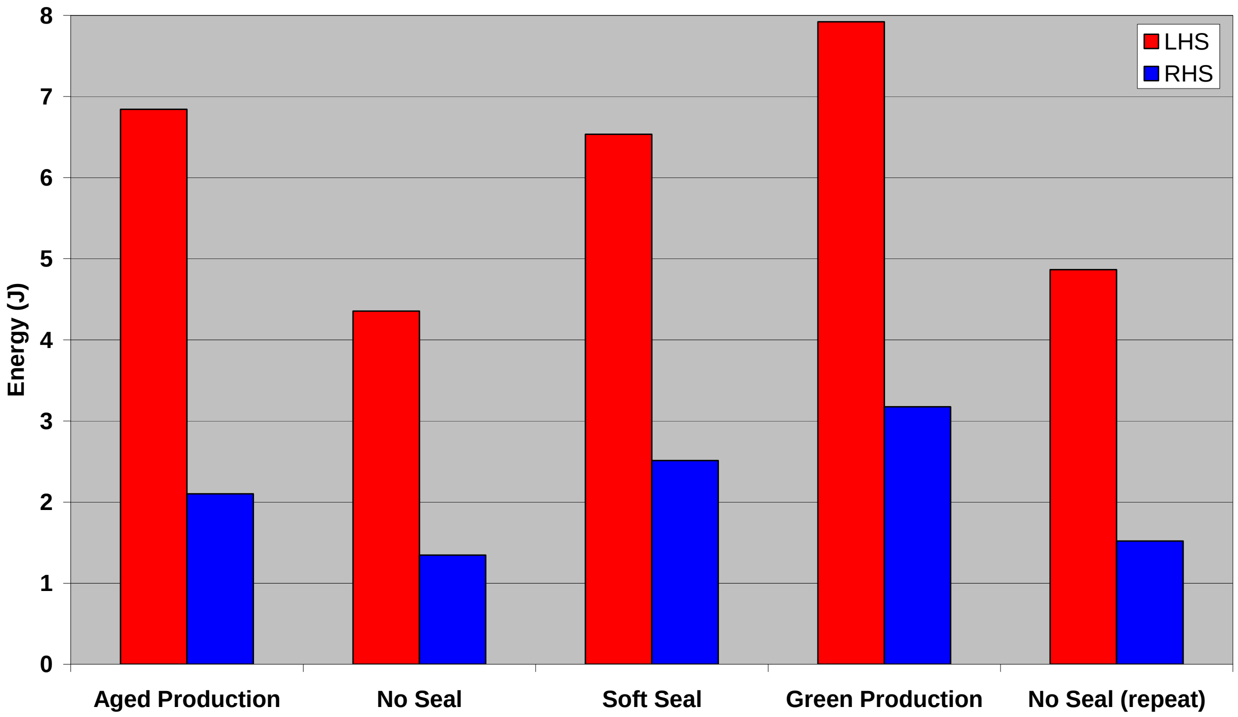


Figure 27. Door Closing Efforts for Front Door

Overall we see that the DCE is less than the 8J. According to our Client's Design Standards, the efforts on any one vehicle cannot vary more than 1.5J door to door. Clearly the front doors of this vehicle do not meet this criterion. The green soft seal requires less energy to close doors when excluding the nil seal and aged conditions. The effort required is definitely less than the green production DGWS, which is the appropriate seal to make a direct comparison with. Taking into account the fact that aged seals have lower DCE, it can be inferred that the soft seal would have an even lower DCE once it had aged. A comparison between the aged production and the soft seal for the LHS door yields the observation that the softer DGWS is also more forgiving on a poor door set. There is less than 0.5J variability in this test when comparing the no DGWS conditions.

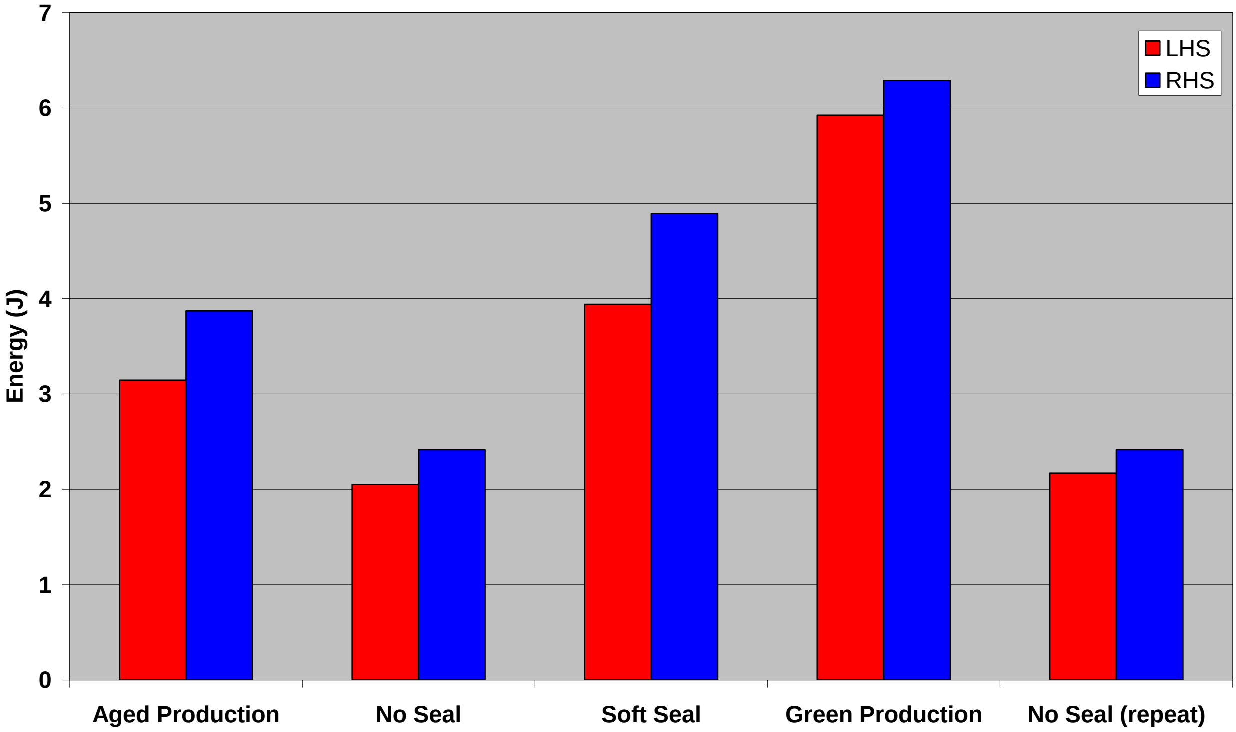


Figure 28. Door Closing Efforts for Rear Door

There is much less variation between LHS and RHS DCE for the rear doors (Figure 28). However it should be noted that door gaps were not measured for the rear doors. Again it is quite clear that the softer green seal has a lower DCE than the production green seal. Considering the 2J reduction in DCE for aged production versus green production seals, we can infer that an aged softer seal would have an even lower DCE. There is less than 0.2J variability in this test when comparing the no DGWS conditions.

5.2.2 Velocity Meter

DCE can be measured by using a velocity measurement system. The relationship between closing energy measured by the energy method and the velocity method are different for different vehicle models. A conversion formula is established once a vehicle is in production. The Client uses a 'velocity meter' (Figure 29) in conjunction with a conversion table to determine DCE in the production situation. The velocity measurement system is better suited to a production environment, as it is quick to setup, collect readings and easy to find the corresponding DCE value in tables.

Figure 29. Velocity meter being used to measure DCE [24]

5.3 Gauge Repeatability and Reproducibility

A Gauge Repeatability and Reproducibility (R&R) experiment aims to measure the individual impact a process has on measurement results, as well as assess the impact different operators have on the process results. In effect, it aims to highlight wether bias in the results are from the process or the equipment used. Repeatability is considered the variation that occurs when the same object is measured by different operators. Reproducibility is the variation arising from using the same measurement process among different instruments and operators. Ideally, there should be no impact on results due to different operators (indicating a sound process) and only small a small impact due to measurement error.

5.3.1 Force Gauge & Velocity method

This R&R was conducted such that there were 2 operators and 5 'vehicles'. In this instance a 'vehicle' was considered to be a single car door, so 2 cars were used to complete the testing regime. The operator and vehicle order was randomly generated to eliminate bias. At each instance the door closing energy, measured with the force gauge, was obtained at the same time as the door closing velocity was measured.

The results of the Gauge R&R are shown in Figure 30 and Figure 31. The Total Gauge R&R for the Energy method was found to be 7.37 % which is good, however for the velocity method it was found to be 27.2 %, which is not an acceptable value. For reference, Six Sigma literature classifies 10% or less as green (good), less than 30% study variation as orange (acceptable) and anything over 30% as red (unacceptable).

It is clear that the components of variation are much larger for the velocity measurement method. The number of distinct categories determined for DCE was five, whereas only two could be determined for the velocity method. Distinct categories should correlate to the number of items being measured. There is also greater variability in the readings for each velocity method when comparing by vehicle or by operator. The operator-vehicle interaction graphs show that the energy method is repeatable by different operators due to the closeness of the two lines, whereas the lines for the velocity method are not close at all.

The energy method was found to be far superior in terms of repeatability and reproducibility. However, the velocity meter will continue to be used in plant because of ease of use and the lack of a viable alternative at this time. The energy method has been shown to be more suitable for the product development stage.

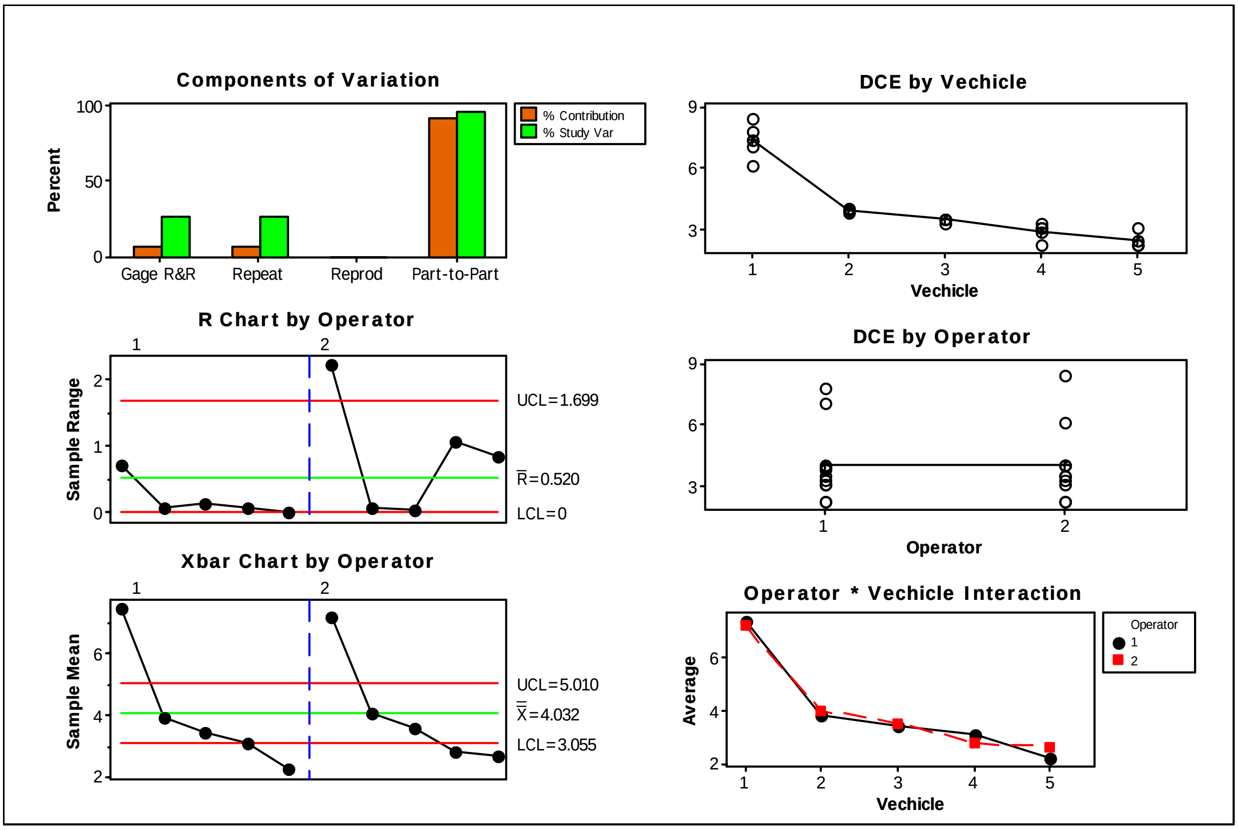


Figure 30 - Gauge R&R for Force-Gauge Sensor

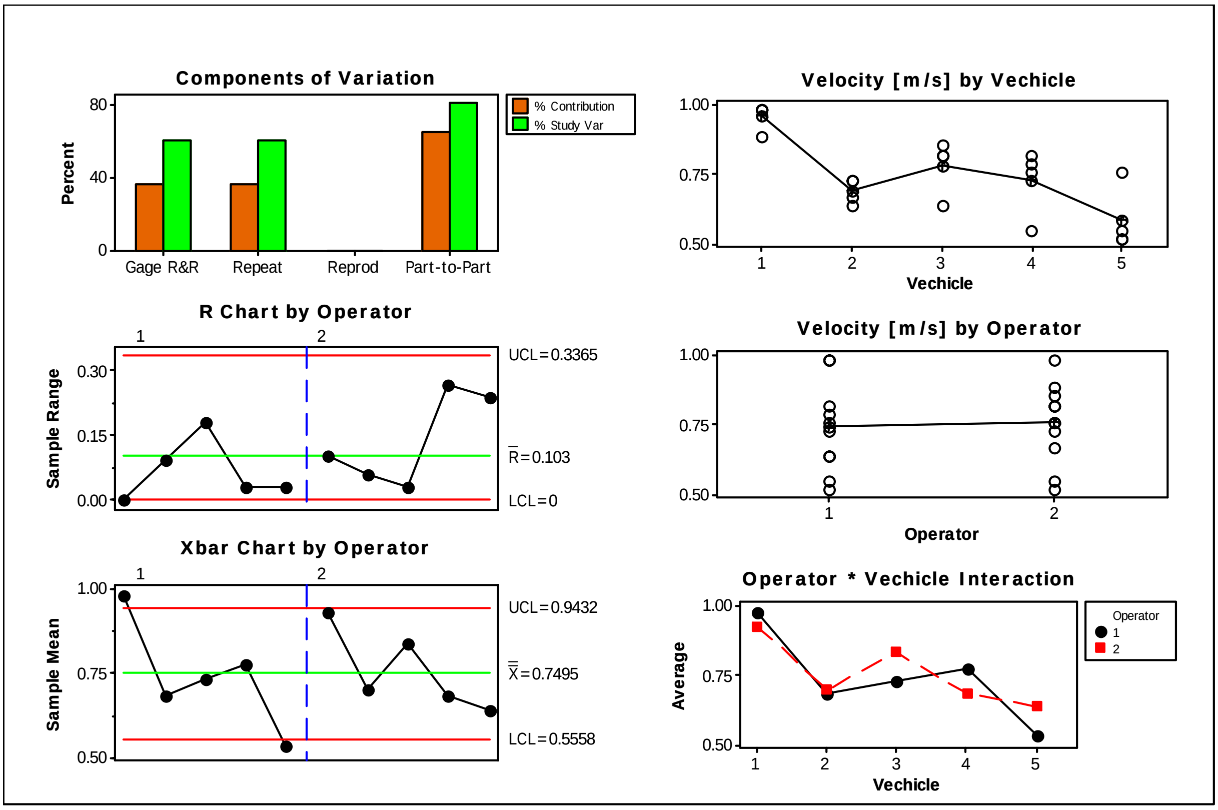


Figure 31 - Gauge R&R for Velocity Meter

5.3.2 AACHEN Head

Our Client was able to supply us with the AACHEN Head R&R. This study was conducted in 2003 and it also suggested improvements to increase accuracy. However, for the purpose of this project the R&R results are all that are of significance.

Firstly, wind tunnel testing was conducted on a Toyota Harrier and a BMW X5 using the AACHEN Head. In order to increase part to part variation, measurements were taken at 0 and 20 degrees yaw. Thus both vehicle measurements were taken at two different operational setups to give the extremes of operation. A total of 4 runs were conducted at each combination of operational setup and yaw angle, giving 16 runs in total for each car. On the X5, the first set of 8 runs were made late in the day and the next 8 runs the following day. On the Harrier the two sets of 8 runs were made 30 minutes apart. Recordings were made on the AACHEN Head DAT tape and analysed by engineers at the Proving Ground.

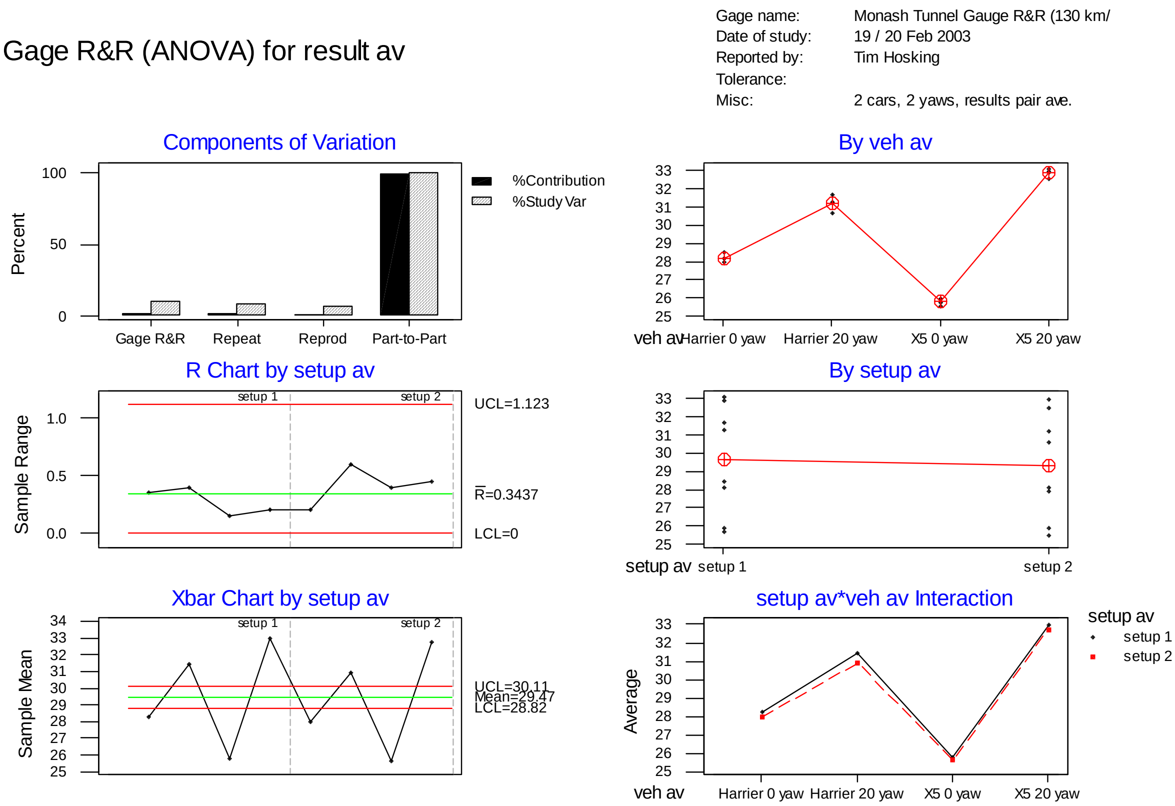


Figure 32– Tunnel Gauge R&R for on paired, averaged results (Sones).

Paired averaging was used in Figure 32 to ensure there was less variation between successive paired measurements than there were between other measurements of the same setup. The number of distinct categories was determined to be 14, which is pretty close to the 16 runs conducted. It should be noted that measuring the same property 8 times in the tunnel gave results ranging approximately ± 0.3 to ± 0.6 sones about the mean (similar results for both cars at both yaws). This observation and the gauge R&R study show the tunnel can show differences of 0.5 to 1.0 sones between vehicles. There also seems to be more variance at 20 degrees yaw than at 0 yaw.

As well as tests completed in the wind tunnel, an experiment was also conducted at the proving ground. In this instance, tests were performed using two BA Falcons, an AU III Falcon and a 2000 BMW 528i using the AACHEN head. The spread of cars from best in class to previous production

gave a significant part to part variance. On all vehicles, measurements were taken at 2 different operational setups to give extremes of operation. A total of 8 runs were conducted for each combination of setup, giving 16 runs total for each car. Runs were paired North-South on the same track and then averaged. The runs were completed at the proving ground at 130km/h in the centre of the NVH track, early in the morning to ensure calm wind conditions (typically 1.5 – 3.5 km/h). . Recordings were made on the AACHEN head DAT tape and analysed engineers at the Proving Ground.

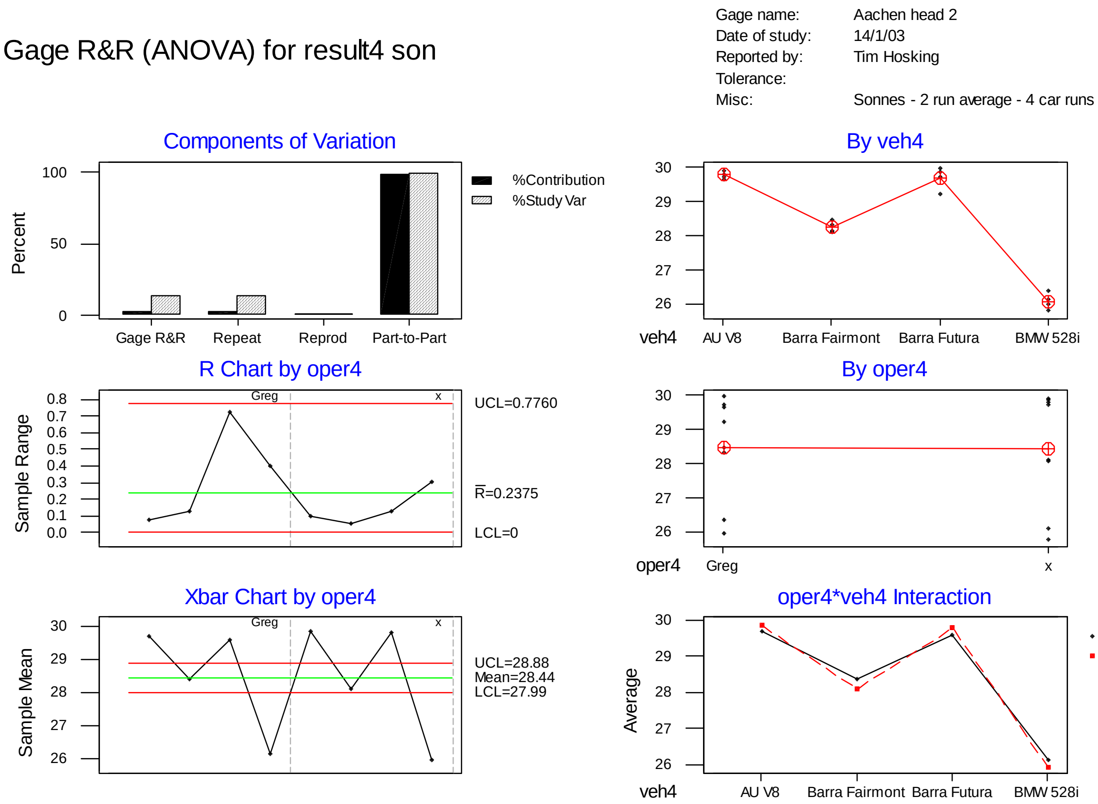


Figure 33. Gauge R&R Results for Track Testing: North - South.

Each North-South run was averaged with the repeat North-South run. The number of distinct categories found was 10, which is reasonably good compared to the 16 runs performed. The results are shown in Figure 33. Gauge R&R was 19.6 %, which is an acceptable (orange) gauge R&R.

In conclusion, the study found that the gauge R&R for the Monash Wind Tunnel was 9.7% to measure pure wind noise in the wind tunnel, indicating a very good level of repeatability and reproducibility. Work on the track found the Gauge R&R to be 13.3%, also indicating a good level of repeatability and reproducibility for in vehicle noise measurements. It is important to note that pure wind noise can not be measured on the track, rather total interior loudness (including engine, tyre/road, vibration and driveline noise) at speed is measured. For this reason the tunnel has both a better R&R result and gives a more meaningful metric for measuring pure wind noise. The tunnel allows the user to measure the dominant wind noise on the car, with the only other noise source being the tunnel operation noise transmitted into the car.

5.4 Door Gaps

The door sets were measured, after the force-gauge was setup, by finding the horizontal gap between the door and body 50mm back from the A-Pillar (6G location) and 50mm forwards of the B-Pillar (7G location) respectively. The door sets were measured using a vernier as in Figure 34 (a), however, they are usually checked at the Client's production facility using a gauge as shown in Figure 34 (b).

(a) (b)

Figure 34. Measurement of 6G and 7G

Non-constant seal gaps are a major cause of wind noise sensitivity to door position. The relationship between door-set and wind noise is discussed in section 5.5 Wind Noise vs. Door Gaps. Seal gap variability must be minimised to reduce DCE and minimise the trade off between wind noise and DCE targets. One half of this relationship can be seen in Figure 38. This requires dimensional coordination between the door and the body shell.

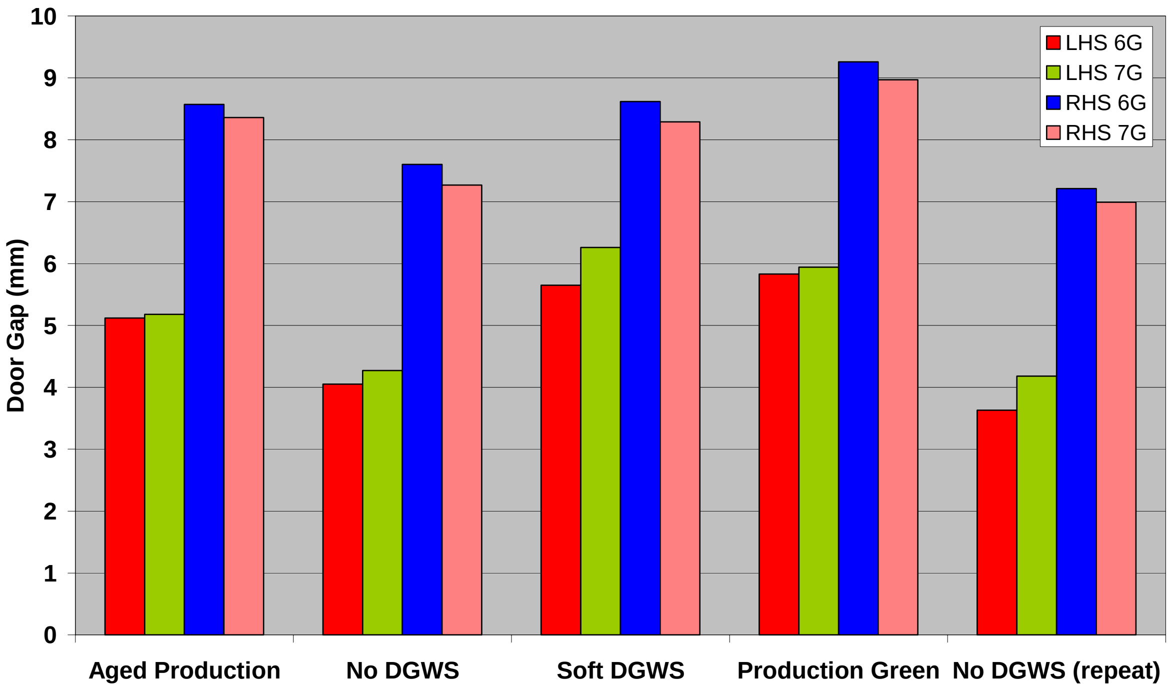


Figure 35. Measurement of 6G and 7G at the Proving Grounds

Figure 35 highlights a marked difference between the 6G and 7G measurements for the LHS compared to the RHS. The cause of this difference is the variation in door set from the left hand side to the right It is also evident that the soft DGWS has smaller door gaps (excepting LHS 7G) than the

green production seal. By comparing these two measurements with no DGWS fitted, the variability of the process can determined to be almost 5.8%. However, the average difference between the production seal and the softer seal is only 3.43%. Thus, it is difficult to know if this is due to measurement variability or seal characteristics. It is also important to realise that the difference between the production seal and the aged seal is that the aged condition has a smaller door gap. This is due to the compression setting phenomenon.

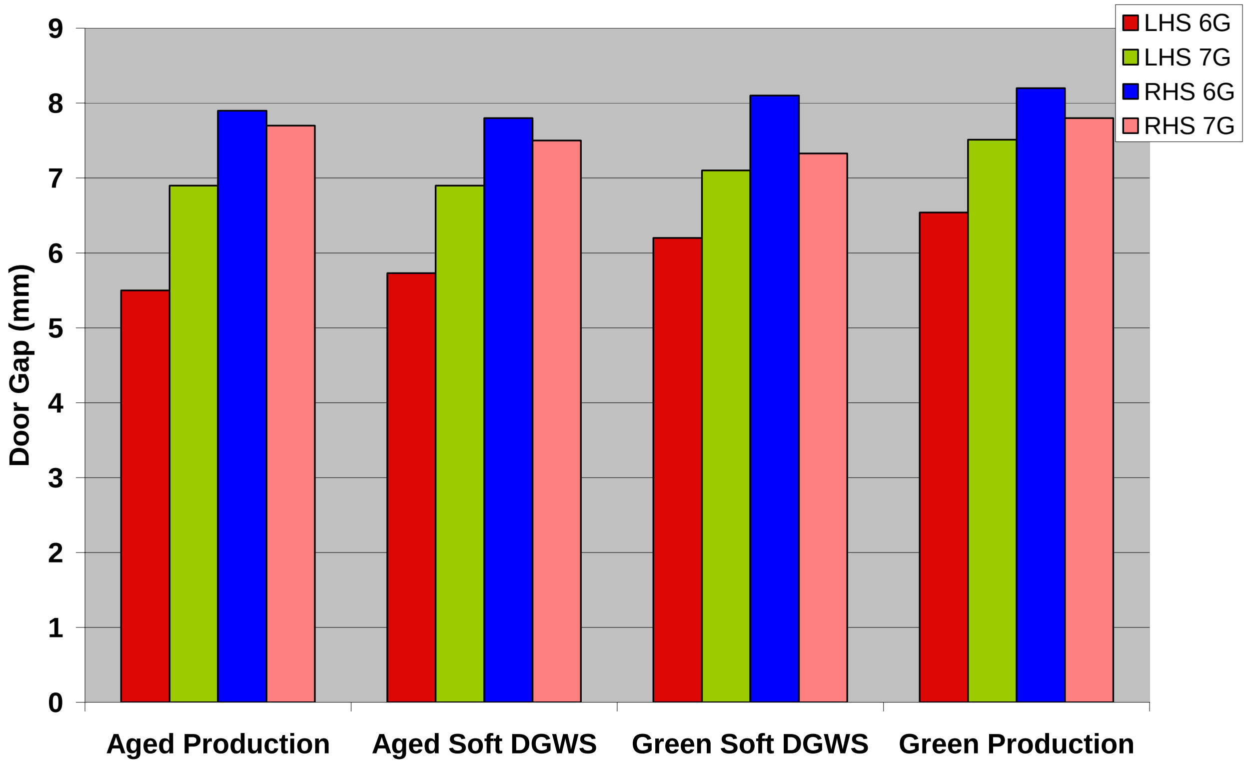


Figure 36. Measurement of 6G and 7G at the Monash Wind Tunnel

As explained in the Wind Noise summary of the Wind Tunnel Tests, sufficient time had elapsed by this stage to classify one of the softer seals as aged. Figure 36 shows that the overall difference between the production and soft seal, whilst taking into consideration both the aged production to aged softer difference as well as the green production to green softer difference, is 2.35%. These results are consistent with that observed in Figure 35, however there is no repeat measurement available to compare this value obtained against the process variability.

5.5 Wind Noise vs. Door Gaps

Whilst at the wind tunnel for a second series of tests, a different comparison was conducted. This test did not involve the new DGWS, but looked at how door set affects wind noise. In this test, two different door sets were used, one typical of normal production standards - labelled original and one which had had its properties adjusted so it was representative of a perfect door. On both of these doors, the door gap at the 6G spot (50mm aft of the top of the A-Pillar) was adjusted to various settings and a wind noise sweep was conducted for each alteration. The results are presented in Figure 37 and Table 11.

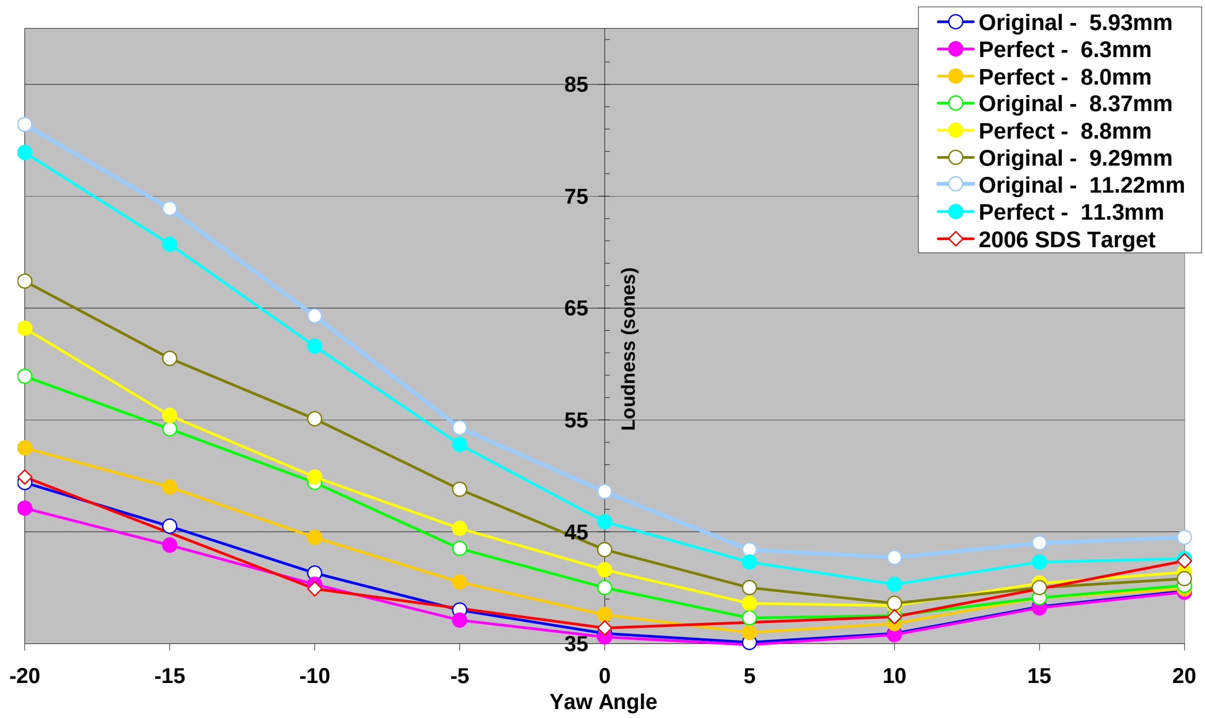


Figure 37. Wind Tunnel 2: 6G vs. Wind Noise @ 160 km/h

The most obvious result from Figure 37 is that the loudness decreases for a decreasing 6G measurement. This trend exists for both perfect and original door sets. Table 11 shows that the relationship between decreasing 6G measurement and decreasing wind noise is not linear, indicating that there are ever more complex factors involved as well. Achieving a better wind noise response requires decreased interior loudness and reducing the 6G is one way to achieve this. This would not require making any changes to the current seal design or compound.

Table 11. 6G vs. Wind Noise @ 160 km/h and -20° Yaw

Type	6G [mm]	% Difference	Loudness [sones]	% Difference
Original Door	5.93	6.24%	49.4	4.88%
Perfect Door	6.30		47.1	
Perfect Door	8.00	4.62%	52.5	12.19%
Original Door	8.37		58.9	
Perfect Door	8.80	5.57%	63.2	6.65%
Original Door	9.29		67.4	
Original Door	11.20	0.89%	81.4	3.17%
Perfect Door	11.30		78.9	

We can see from the Door Gaps section that both the green and aged softer DGWS give 6G measurements of equal to or smaller values compared with the current DGWS. Thus, any increase in interior loudness detected, when comparing a current and a softer DGWS, cannot come from the difference in 6G due to the different seals. Thus varying the yaw from 5° to -20° would be expected to show a similar response, with respect to increasing loudness between both the current and softer seal. The fact that the results are slightly divergent indicates the increase in likelihood for aspiration to occur due to the softer seal compound. However, the conditions required to induce this difference are unlikely to be encountered in normal driving conditions. These conditions would only be induced when the vehicle is driving at speeds over 80 km/h whilst in wind speeds greater than gale force (over 34 knots [21]]).

5.6 DCE vs. Door Gaps

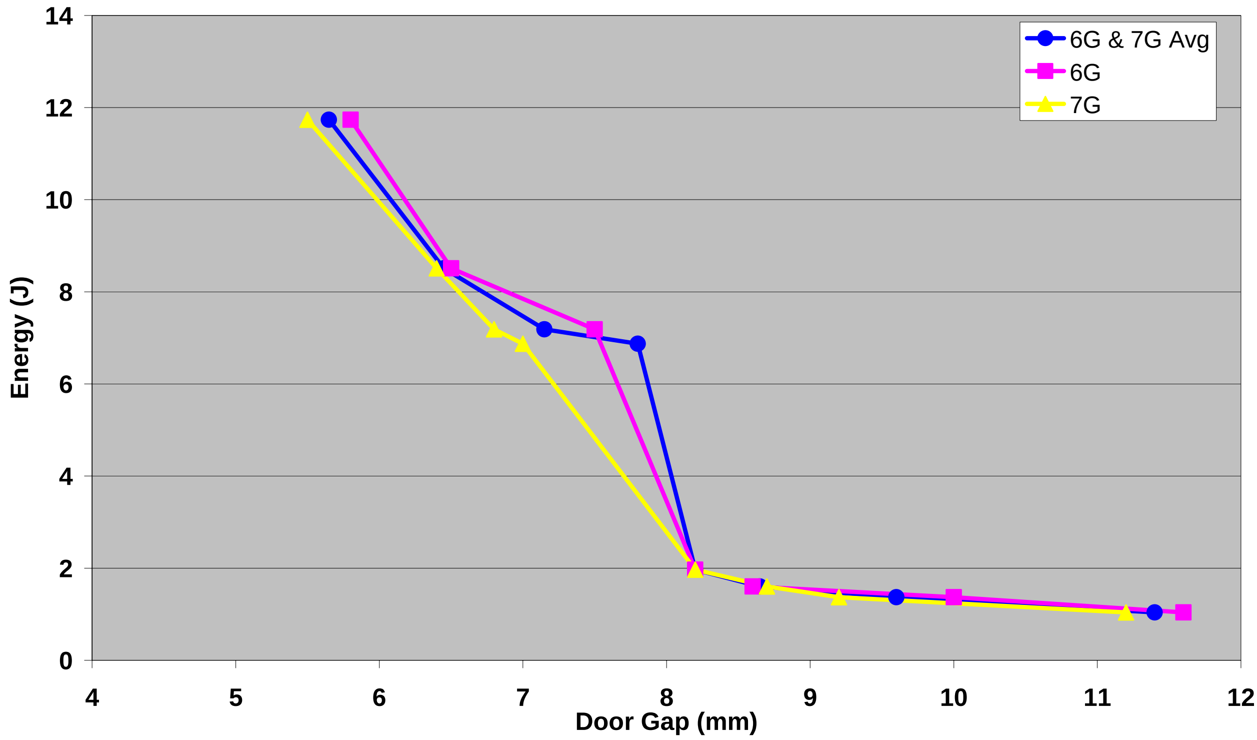


Figure 38. Average Door Gap versus DCE from second wind tunnel test

When comparing the door gaps against DCE, Figure 38 shows that as the average door gap decreases below 8mm, DCE increases steadily. However, for gaps between approximately 8mm and 12mm, the DCE does not change significantly. If the target for the mean door gap was to set to minimise DCE, ignoring other factors influenced by the change in door gap, this target would be no less than 8.22 mm which coincides with the Client's process mean. Due to a lack of sufficient data collection, the authors were unable to compare Door gaps and DCE for the proving ground test or the first wind tunnel test.

5.7 Durability

Durability of the seal refers to the sealing system performance compared with the desired function, examined over a period of 10 years and 240,000 km for the 90th percentile customer. This is determined by completing the side door slam closed test. Side door slam closed cycles are started from the door fully open position. The door must be completely assembled with all trim attached, hardware, glass mechanisms, weather strips, mirrors, ornamentation, etc. fully installed and the vehicle body must include the instrument panel structure. The requirement is that there should be no functional failures for conventional front and rear side doors after 84,000 slam cycles each with a slam energy of 14J. After completion of the test, the door must also still pass the Fit & Finish, Opening Effort, Closing Effort, Squeak & Rattle and the Door Closing Sound Quality Requirements. This is the ultimate test of the door system in that it fully includes all system interactions.

The purpose of the test was to determine if the revised DGWS would offer improved resistance to wear/damage compared to the current production part, when subjected to door slam closed durability cycles. The softer seal was developed in an attempt to improve DCE. For the Client's previous

model, DGWS durability was a problem. To combat this, the seal was made harder until durability was acceptable.

The durability rig comprises of ‘door-slam’ cylinders capable of simulating the opening and closing vehicle doors repeatedly. It is setup to test different parts simultaneously to allow direct comparisons. A current seal was installed on one door and the softer seal on the other. The softer seals are marked with the sticker as in Figure 39 below with L or R indicating the left or right seal respectively. Each seal type was tested on both right and left hand sides of the vehicle. The seals were only subjected to 35,000 door slams before significant damage occurred in all cases.

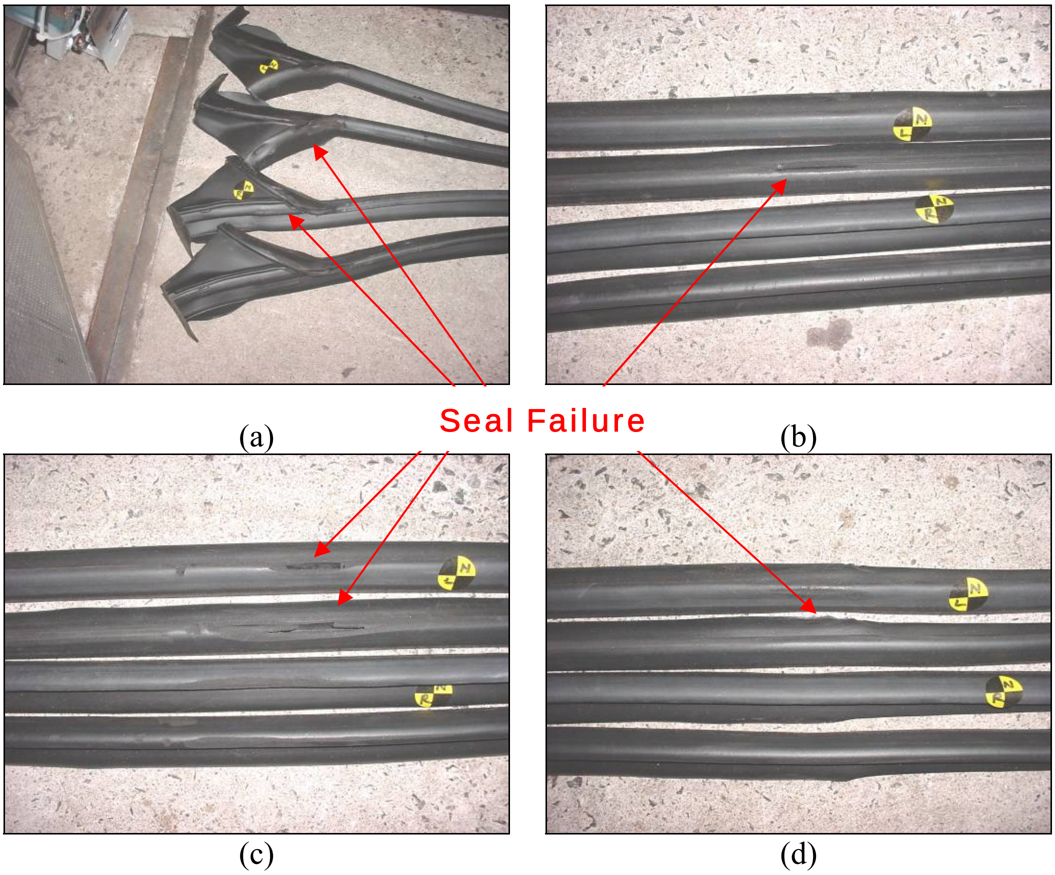


Figure 39. DGWS after 35,000 cycles

The results were as follows: For the 1st run, the current part failed first, whereas for the 2nd run, the softer part failed first. Visible inspection at the end of the test indicated that the overall wear on the softer seals was no worse than the wear observed on the current seal. Both current and softer seals suffered excess damage and perforation as a result of the door slams. Therefore both seals are deemed to be equivalent in direct comparison.

Severe wear was evident at the mould which attaches at the bottom of the A-Pillar, as seen in Figure 39 (a). There was also severe wear at the top of the B-pillar (Figure 39 (c)) due to contact with the top inner corner of the rear doors. Damage to the seals was significantly worse on the LHS of the vehicle. Door settings relative to the vehicle body, and the condition of door sheet metal contacting door seals, are both critical in influencing the degree of seal wear resulting from door slam inputs. The supplied test vehicle was an old used vehicle of questionable quality. No better vehicle was available for use in the test.

5.8 Experimental Analysis

In an attempt to provide the Client with raw data that they are not currently privy to, the authors conducted an experiment to find the CLD characteristics of each seal material. This experiment was also intended as validation of the computer-based models of DGWS that were being developed. Compression tests determine the behaviour of the DGWS under load. The specimen is compressed and deformation at various loads is recorded. Compressive stress and strain are calculated and plotted as a stress-strain diagram which is used to determine the elastic limit, proportional limit, yield point, yield strength and compressive strength which are values that can be used directly by SolidWorks for the CAE model.

The final experimental setup is shown in Figure 40. As a result of several emails and discussions between University of Melbourne Mechanical Engineering personnel in the Stress Analysis, Technical Services and Material Sciences areas, a machine that was capable of applying loads in compression was finally located onsite – the Instron 1000. The machine had not been in use since the end of the Materials Sciences degree, so there were some doubts as to its accuracy. These fears were compounded by the fact that the manufacturer had stopped supporting the instrument five years ago and the last time it was in regular use was about a decade ago!

Figure 40. Experimental Setup with Instron 1000

Since there were no manuals readily available, familiarisation with the operating controls of the Instron had to occur by trial and error. During this initial testing it became clear that the load cell sensitivity differed along its surface. It was found that the load cell was the most sensitive in the very centre. As a result attachments were modified to ensure the force application was directed to the centre of the load cell as shown in Figure 41.

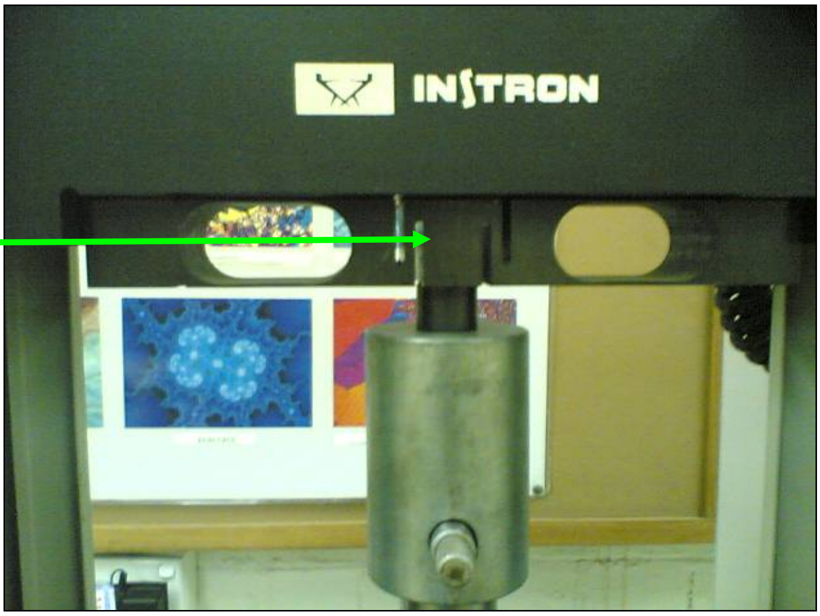


Figure 41. Attachment to transmit forces to load cell centre

The next issue was that the loads applied by the Instron did not seem to be linear. To check this, a calibration was performed by incrementally applying loads measured using digital scales (Figure 42) and marking the corresponding displacement on a chart recorder graph. This also allowed the development of the scale (Force in the y-direction for the charts) for each of the seals. The calibration showed that the scale of the chart recorder graph was in fact linear (as shown in Figure 44), even if it did not seem so at the time!

Figure 42. Digital scale setup used for force calibration

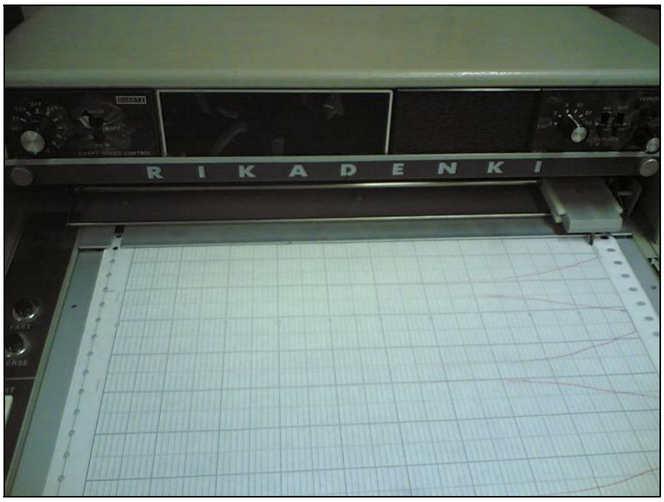


Figure 43. Chart recorder

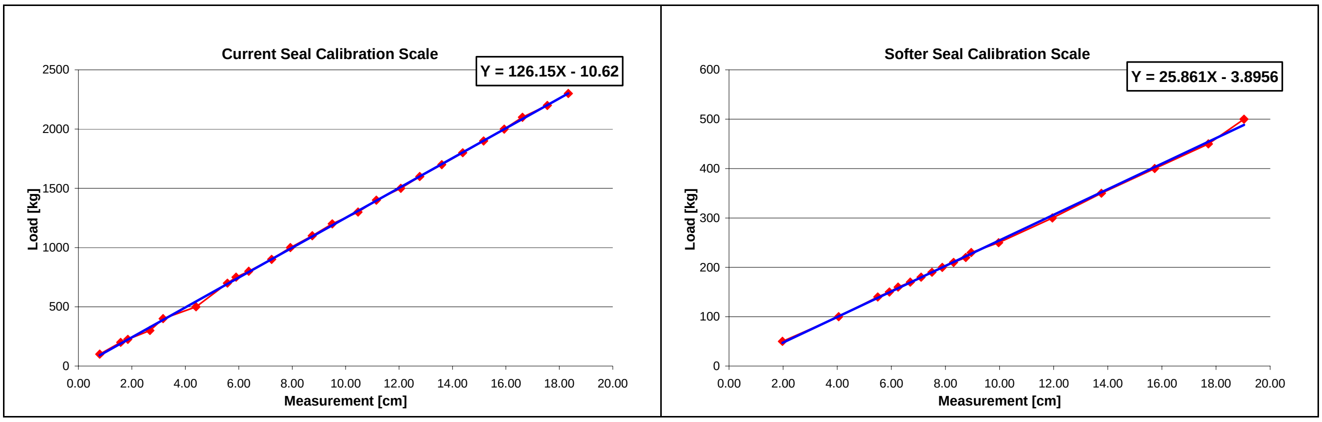
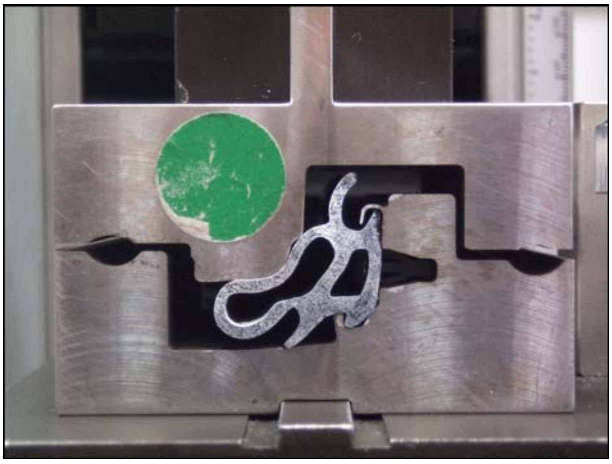


Figure 44. Conversion of Linear Force (in mm) into Force (in N)

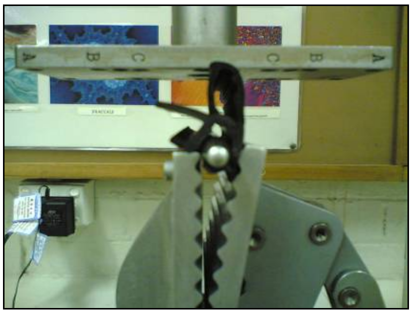


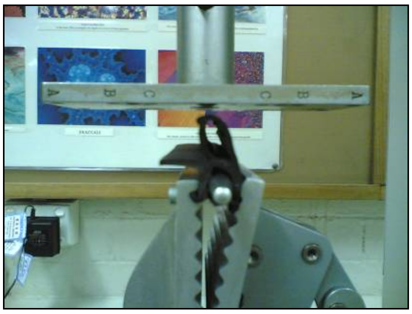
(a)

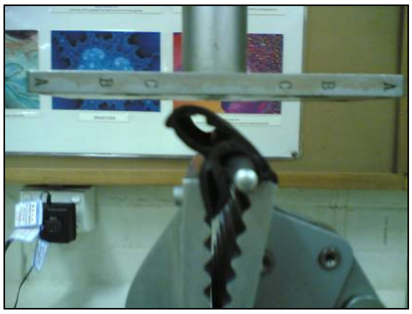
(b)

Figure 45. Holding sample the sample for testing

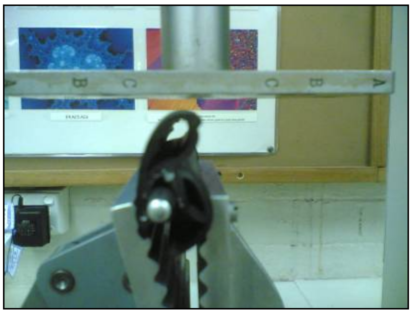
Another significant issue was to find a way to hold the DGWS during testing, be able to easily change DGWS position and to replicate these positions for both seals and multiple experiments. Given more time, one of the available grips would have been modified to suit the specific purpose. However, as a compromise, a camera phone was used to take photos, compare positions by visual inspection and make the adjustments on a standard grip as shown in Figure 45 (b). The positions used for each DGWS experiment are shown in Figure 46. The Client's supplier uses specially designed fixtures, as shown in Figure 45 (a), to simulate the swing of the closing door and the attachment of the seal in the real world. The purpose of the CLD test is to accurately represent the environment in which the seal will function.


(a) Softer DGWS in position A


(b) Softer DGWS in position B


(c) Softer DGWS in position C


(d) Current DGWS in position A


(e) Current DGWS in position B

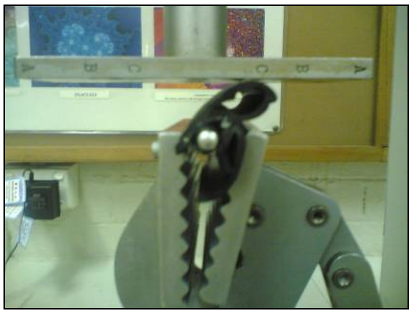

(f) Current DGWS in position C

Figure 46. Two types of DGWS in different positions

Since the crosshead and chart recorder velocities were significant to the calculations to be performed, these values were measured as a further calibration. This was done by simply measuring the time taken for the cross-head and for the chart recorder to move a fixed distance. This enabled the calculation of the actual velocity of each. These values were found to be significantly different from the marked settings on the respective instruments, indicating that they are indeed in need of calibration.

The graphs obtained from the compression tests were then used to find the force required to compress the DGWS in each various position. The equation for the trend lines (in Figure 44 presented earlier) was found and used to convert the reading from a linear measurement to a force in newtons. The original width and length of each sample were measured to allow an estimation of the area that the load was applied over. This was then used to find the stress in compression. The change in length (ΔL) was found using Formula (1):

$$\Delta L = d_{XH} = S_{XH} \times \frac{d_c}{S_c} \qquad (1)$$

This allowed the strain in compression to be found. This in turn was sufficient information to calculate Young's modulus using Formula (2):

$$\text{Young's modulus (E)} = \frac{\text{Stress}}{\text{Strain}} = \frac{\text{Force} \times \text{Area}}{\frac{\Delta L}{L}} \qquad (2)$$

Table 12. Results of compression experiment and calculations

Seal Type	ΔL [mm]	Force [N]	Area [mm^2]	E [N/mm^2]
Current	11.06	19.00	0.09	292.51
	9.50	14.60	0.10	160.34
	10.03	9.53	0.10	78.84
Softer	8.65	22.09	0.11	287.01
	5.74	12.32	0.09	232.92
	8.19	7.97	0.12	76.38

The results were expected to provide distinct values of the Elastic modulus for each of the types of seal. Slight variability was expected, since the positions were chosen by visual inspection as opposed to having fixtures for each position. The significant variation between the elastic modulus values, for positions A, B and C for each seal, indicate that some aspect of the experimental method was flawed (Table 12). The elastic modulus appears to be position dependant and as such varies for each of the seal positions. The values for the elastic modulus also seem to be incorrect by several orders of magnitude.

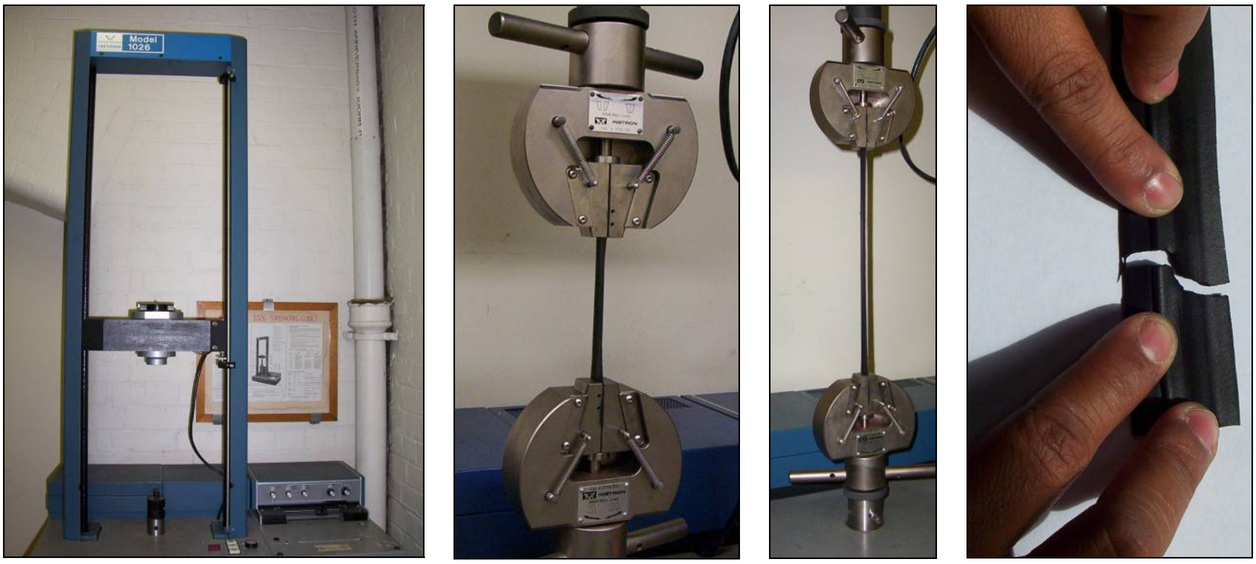


Figure 47. Experiment to determine the Elastic Modulus from tensile testing

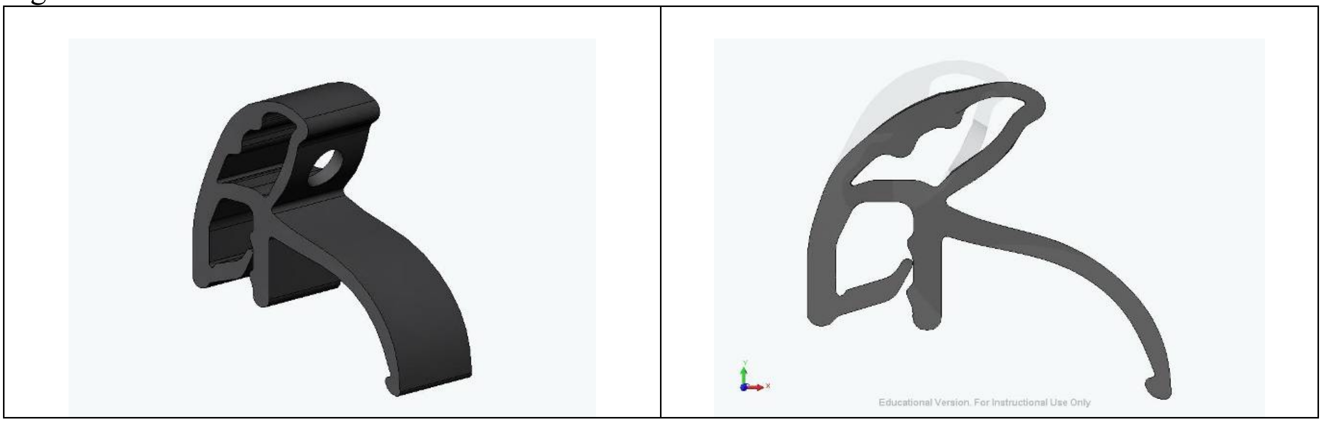
This prompted the author's to reconsider the experimental method. Upon consultation with staff experienced in the area, it was decided that a better test to determine the elastic modulus might be a tension test using the Instron 1026 (Figure 47). Since various features of the seal are made up of different compounds, the weather strip had to be cut into sections to allow testing of the bulb material. This created an additional problem, stress concentrations could occur at points where the strips were not cut smoothly. The seal materials also proved to be difficult to hold in the grips, due to the very

small thickness of the samples. Tests were repeated when the samples slipped out of the grips. The results in Table 13 are more in line with what was expected, however the testing for the softer rubber is not consistent enough to make a determination of its elastic modulus. The values for the elastic modulus still seem to be incorrect by several orders of magnitude. Given more time, further experimentation would have been carried out to improve these results.

Table 13. Results of tensile experiment and calculations

Rubber	ΔL [mm]	Force [N]	Area [mm^2]	E [N/mm^2]
Current	213.33	120	1045.20	0.021
Current	238.67	130	526.40	0.020
Current	212.67	130	1310.74	0.022
Soft	290.00	100	1787.35	0.013
Soft	306.67	50	2057.60	0.006
Soft	365.33	90	178.60	0.030

As mentioned earlier, the reason for undertaking this experiment was to find reasonable values of the elastic modulus for use in the CAE models of current DGWS. The supplier was not able to give the authors this information as they are closely guarded company secrets. Different models based on current common designs were developed using SolidWorks and are shown in Figure 48 through to Figure 51.



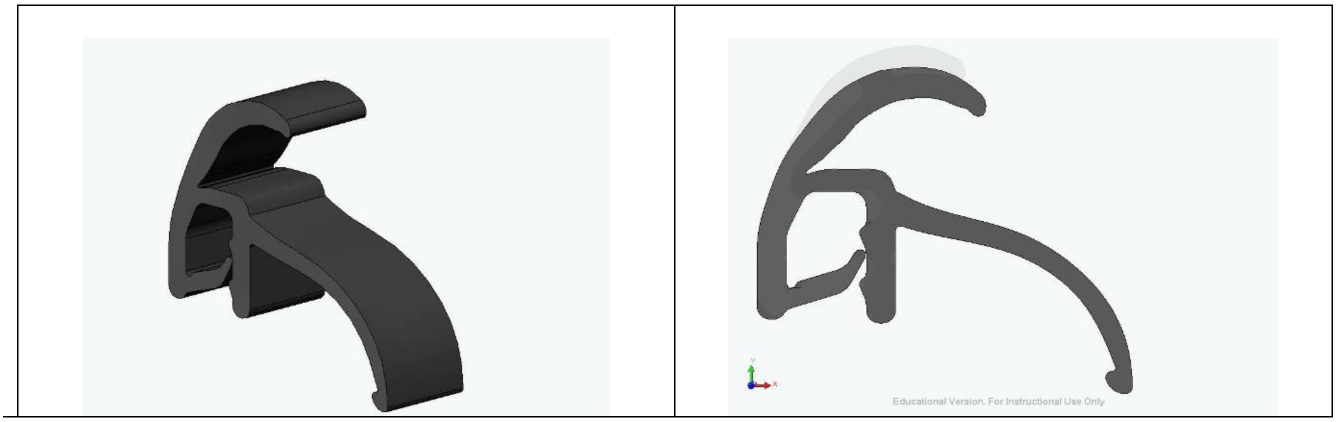
(a) (b)

Figure 48. Current bulb design

(a) (b)

Figure 49. Bulb-in-Bulb DGWS design

The authors intended to compare the current bulb design (Figure 48) to the other variants. A comparison would also have been made between the different material types (i.e. for the different values of elastic modulus). In the figures, (a) is the DGWS in 3D showing the air vent-hole (excepting the cantilever design, which does not have this feature) and (b) is the profile view showing the DGWS when deflected by an applied load (dark grey-coloured profile) and the light grey-coloured profile shows the undeflected DGWS.



(a) (b)

Figure 50. Cantilever DGWS design

(a) (b)

Figure 51. Dual bulb DGWS design

Compression load deflection (CLD) is the most important characteristic for sealing design and is normally reported as the seal resistance force (N) per 100 mm seal length. Ideally, CLD profiles need to be flat in the build variability range. The ideal CLD curves for door seals are shown in Figure 52. The important things to note are:

- The compression set that occurs from part assembly to customer receipt;
- Door stiffness is the difference between build out and blow out;
- Aspiration leaks occur at low compression loads with minimum door stiffness;
- Maximum closing effort is at the latch engagement point;
- The area under the CLD is the closing energy contribution.

The CLD profiles are generated by the Client's supplier by measuring the CLD value at 0.5mm increments over the entire seal gap range of interest. These data points are then plotted. The CLD

curves (both green and aged) for every extrusion of an assembly are used as significant characteristics (that are closely monitored) in production.

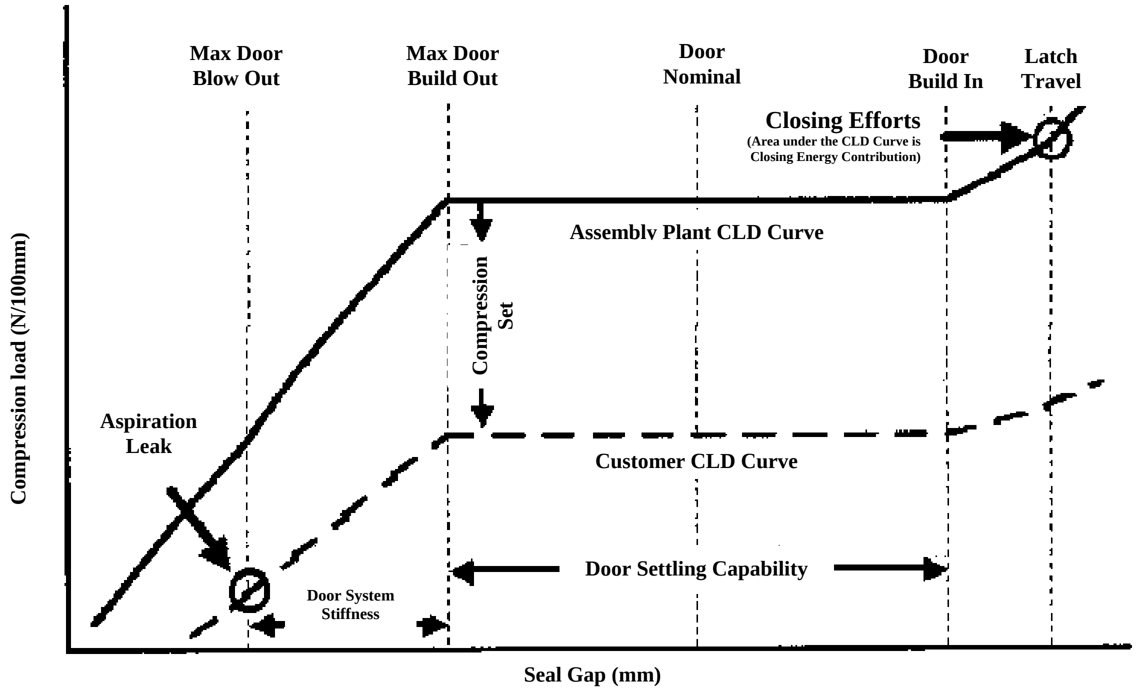


Figure 52. Ideal CLD profile

Figure 53 and Figure 54 are examples of CLD graphs generated by the Client's supplier.

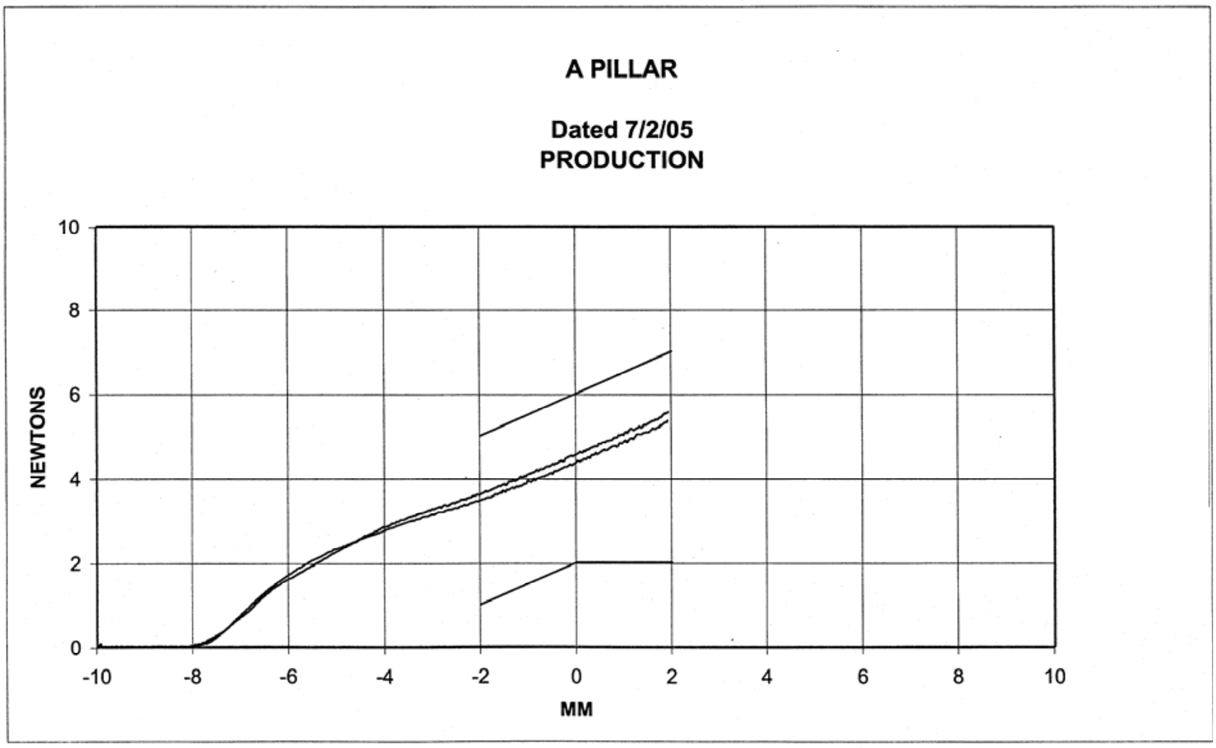


Figure 53. Current DGWS Material

It is clear from these graphs that DCE is lower for negative door sets (larger door gaps) and increases to a maximum at 2mm inboard. The current DGWS is well within the Client's specifications. A comparison of the current and softer DGWS production data shows that the softer variant requires much less energy to close the door. In fact average efforts are below the Client's lower specification limit. This is a good feature in terms of DCE, but the seals ability to perform other functions such as to protect the customer from noise, dust, rain, hail and snow may be detrimentally affected.

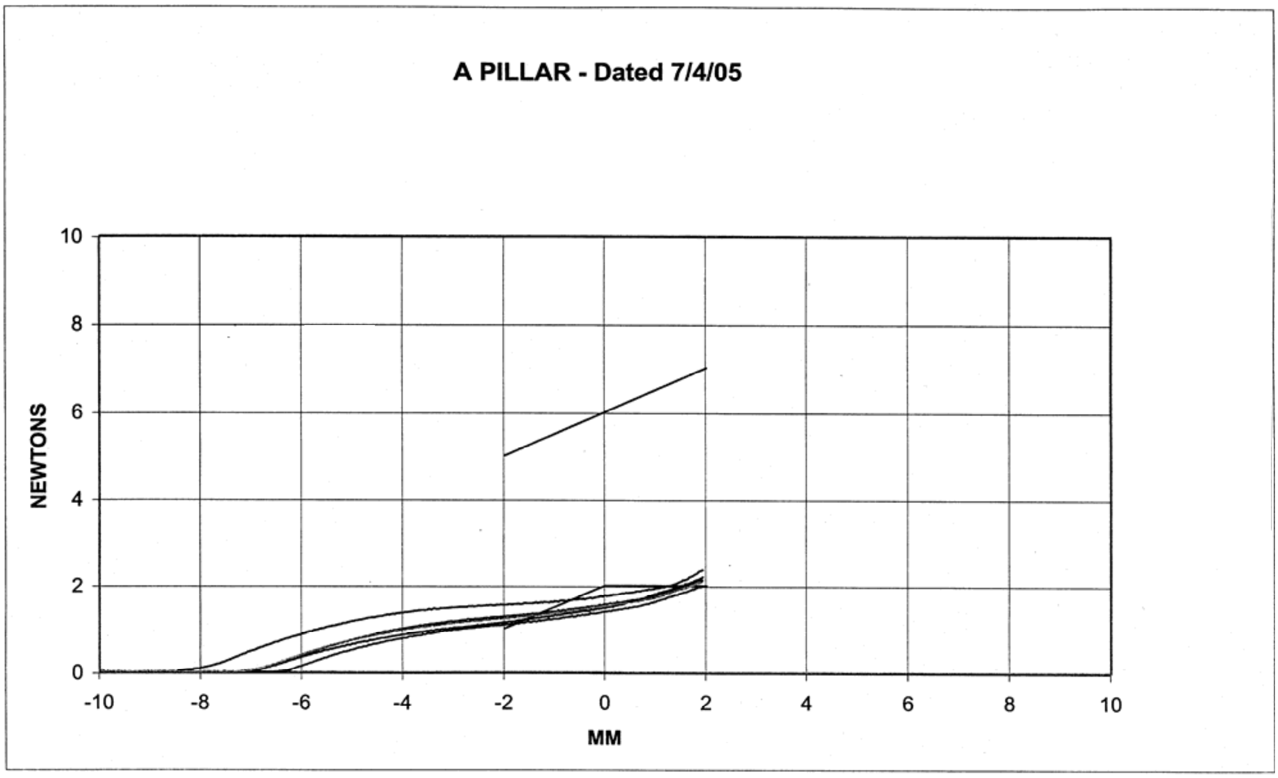


Figure 54. Softer DGWS

6. Implementation

An important stage of the Client's evaluation process involves conducting production line trials. This procedure involves integrating the part under evaluation into production for a trial period. The aim is to uncover any assembly or operator issues arising from introduction of the new part. These would be fully investigated and resolved before implementation into production would be permitted.

'Operator buyoff' is the consultation process between the operator who has to fit the part, the Group Leader of the area and the engineers responsible for the change. This was easily obtained since the assembly procedure did not change in any way.

During the line trial, each vehicle that was fitted with a new DGWS was marked with a special sticker, allowing it to be easily identifiable for later testing.

A craftsmanship audit is completed on the specially marked cars. Craftsmanship, with respect to seals, is defined as the seal having a smooth appearance as well as smooth interfaces to adjoining surfaces. Although craftsmanship has no functional deliverables, it is extremely important because it is one of the first elements that customers visually experience. Weather strips must meet the following visual criteria:

- No puckering, visible flash, wrinkles, bulb rollover, blisters, lumps, ripples, cracks, slits, cuts or visible vent holes
- Uniform colour and gloss of extrusions and moulded details
- Finished extrusion ends (i.e. clean cuts)

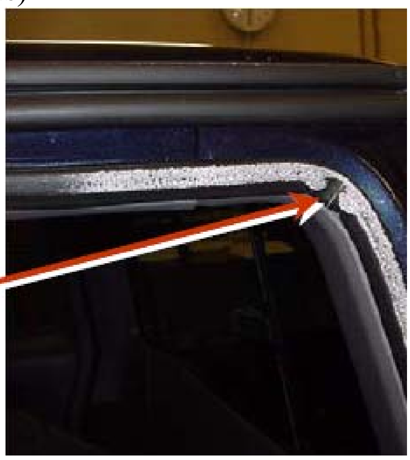


Figure 55. Example of Puckering

Part of the testing conducted on the trial production run involved DCE measurements using the velocity meter method. To date, these results have not been released. However, all indications point to comparable results to those obtained previously. Subjective wind noise tests were also conducted. This test involves a skilled operator, who has an ear for the customer expectations of a 'noisy' car. These types of tests are conducted on a set, open road course, at medium speed (50- 100 km/h) on a smooth road.

Having passed all previous testing, the final stage would have been to implement the DGWS into production. However, at this stage the supplier voiced a concern regarding production issues they were having. As the extrusion process is very difficult to control, the supplier was finding significant variability in their process resulting in excess wastage (due to reject parts). Essentially the supplier was not able to consistently produce extrusions within the Client's specified limits. In conclusion, the entire process has to start again.

7. Discussion

At the completion of all the tests and validation exercises, the complete picture relating to the impact of the softer DGWS should have been established. Unfortunately, due to small sample sizes in all of the tests conducted, it is difficult to identify exact figures for the difference between the softer seal and the current DGWS. The result of this is that there is data which appears counter-intuitive. An example of this is demonstrated in Figure 20 and Figure 24, where the softer seal registers an increase in interior loudness just before the -20° yaw position for the tests conducted at 160 km/h. Another consequence of the small sample size is that there is insufficient data to properly assess the relationship between variation in 6G and interior loudness as well as door closing effort. These shortcomings are to be expected when there are limited parts to test, and the best must be made of the data available. As such, educated estimations are made as to the effect the softer seal has on wind noise and door closing efforts where such data doesn't exist. To give an example, door closing effort tests were not done in the wind tunnel with the softer DGWS fitted. This meant there was no data for door closing efforts and wind noise when at 160 km/h in the tunnel, hence the data from the proving grounds was used as an estimation of this.

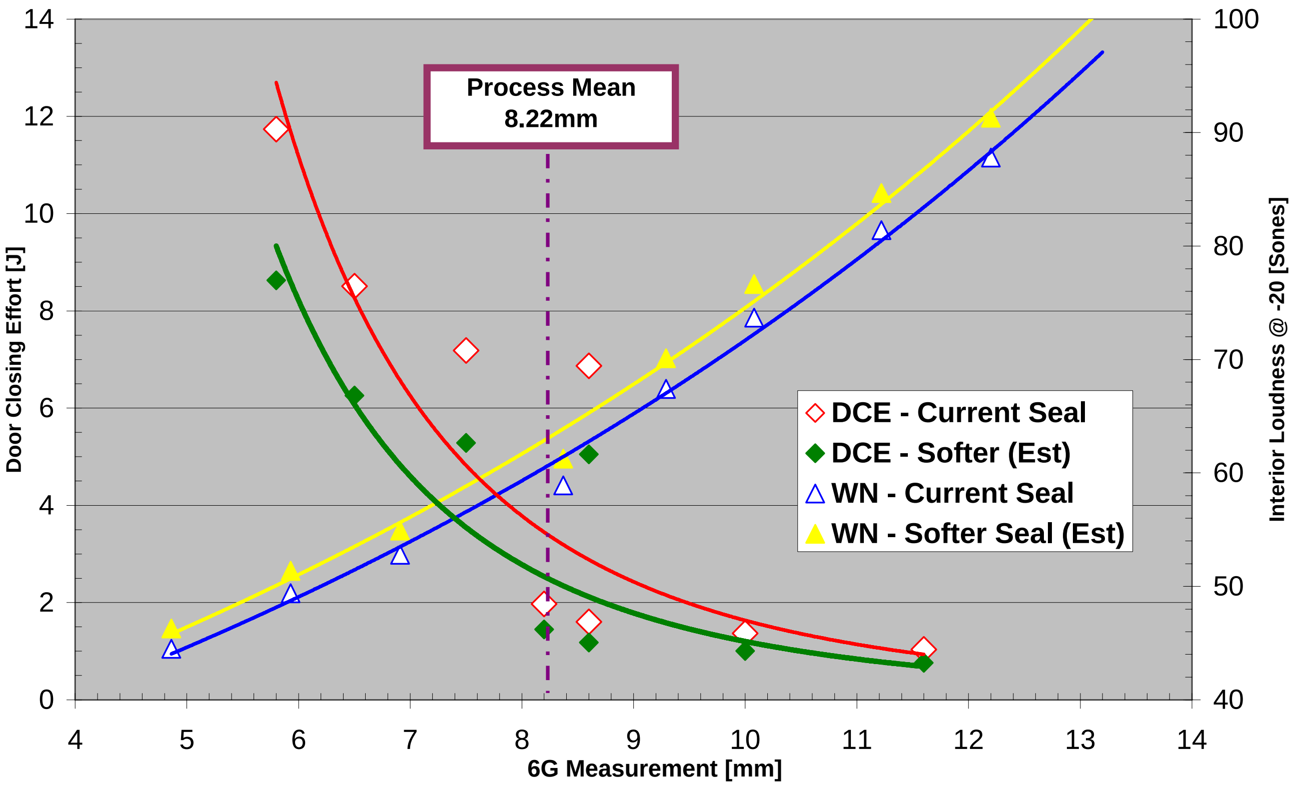


Figure 56. Interior Loudness vs. DCE vs. 6G

In light of this lack of comparable data, the authors have chosen conservative values which aim to take into consideration the variability experienced in the tests conducted. The softer DGWS is thus said to have a 3% increase in interior loudness and a 52% decrease in door closing effort. This can be seen in Figure 56. As mentioned above, since no door closing effort tests where conducted at the wind tunnel, the decease in DCE has been taken from the data collected at the proving grounds.

An alternative can be proposed in an effort to reduce door closing efforts. Assuming that a 3% increase in interior loudness is acceptable, the current seal can be used while still managing to reduce the door closing effort. To realise the 6G process mean could be shifted further outwards. Figure 57

shows a close up view of the region of interest from Figure 56. It shows that if the process mean is moved outwards from 8.22 mm to 8.63mm, for the same 3% increase in wind noise, a 20% reduction in door closing efforts can be realised. This option gives a smaller reduction in door closing effort, yet does not require a part change.

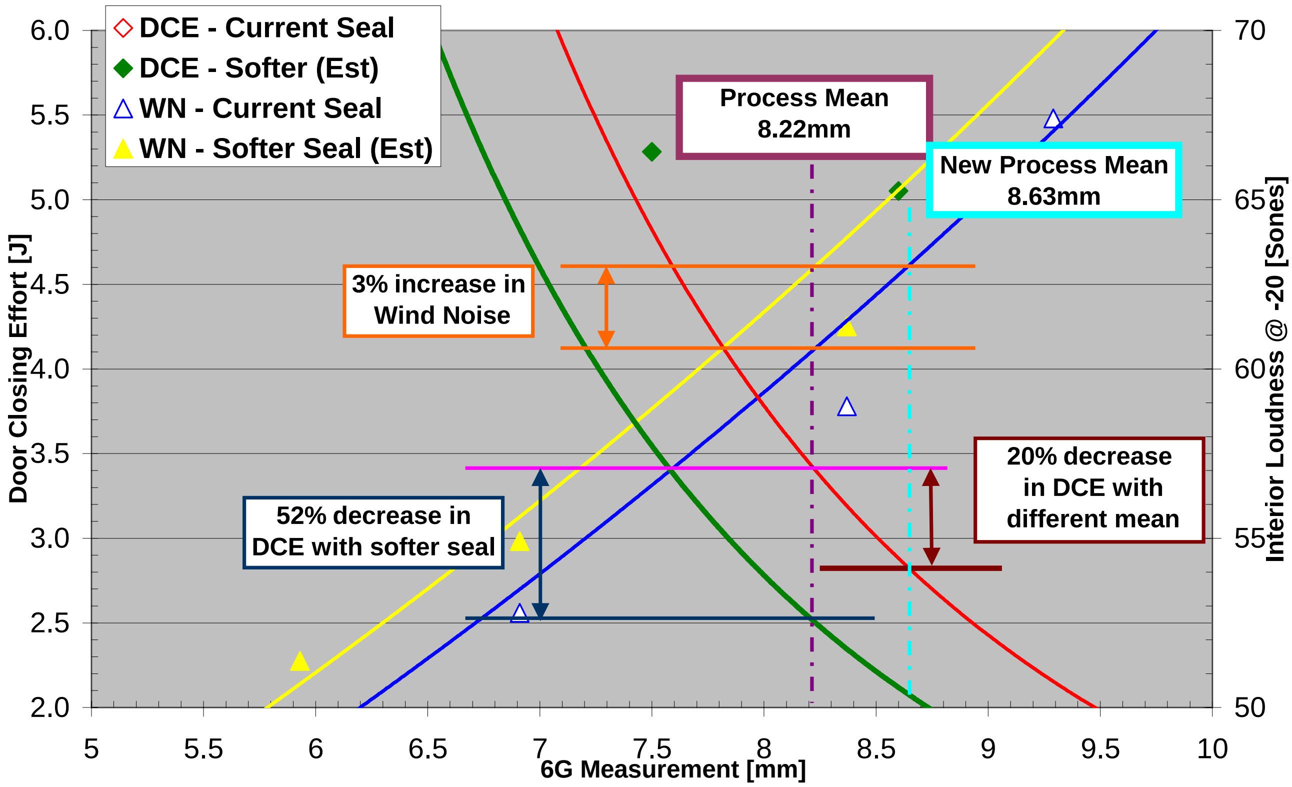


Figure 57. 6G vs. Interior Loudness vs. DCE – Scenario 2

8. Conclusion

As mentioned in the Implementation section, the supplier's feasibility study established that they were not able to manufacture the softer compound to the Client's production requirements. As such, the Client is 'back to square one'. Originally this project was supposed to 'Redesign the DGWS', but the supplier put forward an alternative in the form of the same profile using a softer compound. As such the project was fast-tracked into the testing and validation phase – where it remained over the course of author's involvement.

At the completion of the analysis of results from the tests conducted over the duration of this project, it is quite obvious that the transition to a softer seal should be made. Even through the percentage changes in wind noise and DCE are based upon data with limited sample size, the authors are confident that further testing would not generate values too far removed from these educated estimates. Considering the large decrease in DCE possible, if the supplier is able to manufacture the DGWS from another compound, one not quite as soft as the one investigated for this project, there should still be enough of a reduction in door closing effort to make the transition worthwhile.

Since the option to implement a different DGWS into production immediately can be ruled out, an alternative solution has been investigated. This requires a slight variation in the process mean to deliver a 20% reduction in DCE. However, it achieves this with the same increase in interior loudness that would have occurred with the change to the softer DGWS. The problem with this scenario is that the authors were made aware of the difficulty of controlling door sets throughout the course of the project. Given the sizeable spread of 6G and 7G in current production, the process mean may be difficult to change. The cost of refining the process in-plant to ensure a more controllable spread, hence producing more cars closer to the desired mean, may actually be greater than the cost of developing a softer seal (even with a manufacturing process that results in a lot of waste during its production). The costs and benefits associated with each of these would need to be investigated more rigorously before a fully informed decision can be made.

If the supplier is able to produce a sample batch of a seal that is softer than the current DGWS, another round of testing should be undertaken. This testing should not be embarked upon until the supplier is confident that they can feasibly produce the seal for that given compound. It would be valuable to conduct wind tunnel tests comparing the new compound against the current compound, both for green and aged variants. This gives an indication of the impact on the customer metrics of the compression set of the seal. Whilst conducting these wind tunnel experiments, DCE measurements using the force gauge should also be taken. Ideally, all these tests would be conducted using a number of cars, each with different door sets (that are recorded). This would improve the analyses performed. At the completion of testing, a graph in the form of Figure 56 should be produced in order to properly asses the impact and necessity of a move to the proposed seal compound.

9. Nomenclature

6G	Distance between the door and the roof line measured 50mm aft of the A-Pillar
7G	Distance between the door and the roof line measured 50mm forward of the B-Pillar
A-Pillar	See Figure 58
ARL	Attributes Requirement List
B-Pillar	See Figure 58
CAE	Computer Aided Engineering
CAL	Customer Acceptance Line
CLD	Compression Load Deflection
C-Pillar	See Figure 58
DCE	Door Closing Effort
DGWS	Drip Gutter Weather Strip
EPDM	Ethylene Propylene Diene Monomer
FYP	Final Year Project
Gauge R&R	Gauge Repeatability and Reproducibility
NVH	Noise, Vibration and Harshness
SDS	System Design Specification
STL	Sound Transmissions Loss

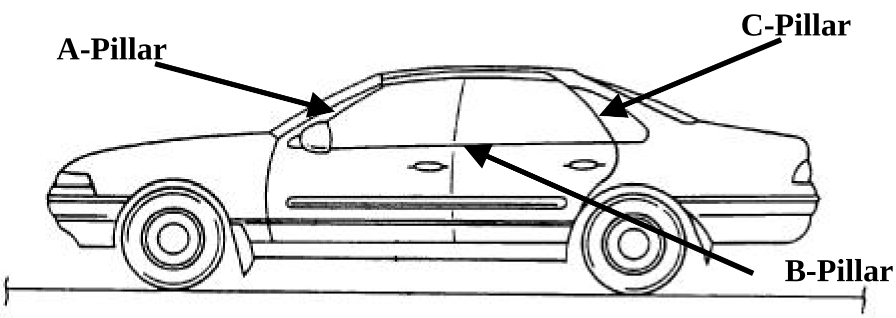


Figure 58. Explanation of A-Pillar, B-Pillar & C-Pillar

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A. Appendix A: DCE Sample Calculation

Table 14. DCE Effort - proving ground tests

	Test Level	Force Closed	Force Open	Closed x	Open x	Closed Energy	Open Energy	DCE
Aged Production	Right	38	57	0.088	0.133	1.681	3.783	2.1 J
	Left	39	86	0.091	0.200	1.771	8.612	6.8 J

The sample calculation is performed for Aged Production seal, RHS which is row 1 in the table above and with spring constant k = 429.4N/m.

The ‘force closed’ is the pre-load on the load cell, whereas the ‘force open’ is the minimum force required to just close the door (read before releasing the door).

Hook’s Law, $F = k \times x$, is used to find the displacement for the open and closed conditions:

$$x = \frac{F}{k} \quad (3)$$

$$x_{closed} = \frac{38}{429.4} = 0.088 \qquad x_{open} = \frac{57}{429.4} = 0.133 \quad (4)$$

Using the kinetic energy equation we can find the energy in the system:

$$E = \frac{1}{2} k \times x^2 \quad (5)$$

$$E_{closed} = \frac{1}{2}(429.4) \times 0.088^2 = 1.66 \qquad E_{open} = \frac{1}{2}(429.4) \times 0.133^2 = 3.79 \quad (6)$$

Therefore DCE is found by finding the difference between the initial and the inertial energy conditions:

$$\text{DCE} = E_{closed} - E_{open} = 2.13\ \text{J} \quad (7)$$

B. Appendix B: Design Diary

THE UNIVERSITY OF MELBOURNE	Major Project Department of Mechanical and Manufacturing Engineering Design Diary March to October, 2005

Project Title: Development and Testing of the Drip Gutter Weather Strip.

Date: September, 2005

Project Team: Sajan James and Robert Spotswood

Identifier: MP–4651

Student workers: Sajan James, 75374
Robert Spotswood, 110169

Academic supervisor: Paul Baker

Version: Final

Date / Time Spent	*Event / Location / Participants*	*Activity description / Tasks Complete*	*Outcomes resulting from the activity/ Tasks Decided Upon*
Mon 17th Jan 1h	**Topic formulation** SJ home SJ	Made initial contact with Industry contacts to find suitable projects.	Initiated project topic search.
Mon 24th Jan 0.5h	**Initial team formation** SJ home SJ & RS	Emailed John Weir details of group. Asked for information re: Project structure, to email to industry contacts.	Members of design team finalised. Started project topic discussion.
Thu 27th Jan 0.25h	**Topic formulation** Union House SJ	Arranged to meet S. Pasricha re: available projects.	Setup meeting for 3rd Feb.
Fri 28th Jan 1h	**Topic formulation** SJ home SJ	Made more initial contact with Industry contacts to find suitable projects. Called A. Selvay about project opportunities. D. Gallo asked how long project is?	Suggested contacting PVT.
Sat 29th Jan 2h	**Topic formulation** Deep Dish SJ & RS	Met to discuss & debate the benefit of doing Industry-based project vs. Academic project. Decide to approach C. Manzie re: Meridian.	Developed rough 'plan of attack' if we were to take on Meridian.
Tue 3rd Feb 1.5h	**Topic formulation** Core Eng - Ford, Campbellfield SJ & RS	Met with S. Pasricha re: available projects. Discussed 'Automatic transfer facility'	Got one potential project.
Thu 10th Feb 3h	**Topic formulation** PVT - Ford SJ & RS	Met with Sandra Geitz, Kevin Brown and Scott Randall (SR) re: potential projects. 1) Understand and develop a transfer function modelling the park brake tension between assembly and dealer delivery 2) Interior Wind noise auditing: Implement an objective sound test to complement the current subjective wind noise auditing procedure.	Got another 2 likely projects.
Fri 11th - 16th Feb 16h	**Initial background research** Eng Club Rooms SJ & RS	Spent the week tossing up between 1) Interior wind noise, 2) Park brake, 3) Meridian, 4) Automatic transfer facility	Team ran though some basic ideas and concepts on whiteboard.
Thu 17th Feb	**Project Administration**	Decided to do "Interior Wind Noise" project.	Completed 100 word description

1h	Eng Club rooms SJ & RS		of project and sent to SR and Colin Burville (CB).
Fri 18th Feb 0.25h	**Project Administration** SJ home SJ	SR corrected description and returned it to us.	Re-sent corrected 100 word description.
Wed 2nd Mar 0.25h	**Project Administration** Eng club rooms SJ	Emailed SR enquiring how best to proceed with the project, which engineers would be involved, how to organise Ford Induction.	
Mon 7th Mar 0.25h	**Project Administration** Eng Club rooms SJ & RS	Reply from SR. Booked Contractor Induction for 18th.	
Wed 9th Mar 0.25h	**Project Administration** ECR Labs SJ	Emailed engineers involved in interior wind noise and requested a meeting on the day of induction. Emailed CB to ask who our supervisor will be.	
Fri 11th Mar 4h	**Literature review commenced** ECR Labs & Eng Lib SJ & RS	Looked for Research papers, journals, text books re: wind noise, auditing, wind noise contributors, noise measurement in automotive industry.	Plenty of reading material.
Mon 14th Mar 1h	**Brainstorming, Scope commenced** Eng Club Rooms SJ & RS	Meeting to discuss what we thought would be involved in the project ahead of meeting with Ford on Friday.	Developed likely task schedule and began work on the scope of works document.
Wed 16th Mar 2h	**Supervisor meeting** 4th Floor Conference Rm SJ, RS & MC	Told by CB that Min Chong (MC) is our supervisor. Arranged to meet MC and explain project brief. MC expressed interest in coming out to Ford. We suggested trying to meet with SR after our induction on Friday.	Resent email to request meeting on Friday. Called SR – away on training.
Thu 17th Mar 0.25h	**Project Administration** ECR Computer lab RS	Emailed MC about not being able to secure meeting for Friday.	
Fri 18th Mar 5h	**Project Administration** PVT - Ford SJ & RS	Impromptu meeting with SR where we presented our initial Scope of Works document. Engineer working on the issue was brought in and Scope was discussed. Apparently all of the items we had on the Scope were spot on…however all of those tasks are already completed. Discussed other projects through conference call with	Completed Induction training. Need to choose another project.

		Start Pretty (SP): 1) Sound transmission through interior roof lining, 2) Redesign of the drip gutter weather strip (DGWS)	
Mon 21st Mar 0.5h	**Project Administration** Eng Club Rooms SJ & RS	Emailed MC & CB about project being already completed. Enquired what academic projects were available as a backup plan in case the projects from Ford fell through again. CB replied with alternative company-based proj. with Integra systems for FEA of press platens.	Received Academic project option. Informed deadline for project decision is 30 June 2005.
Wed 23rd Mar 1h	**Project Administration** ECR Computer lab RS & SJ	Emailed MC about lack of progress, hence no need for weekly meeting. Booked Wed 10.15am for future weekly meetings. MC requests CB to find us an alternative supervisor. CB repeats 30 June deadline and told to keep working with MC until alternate supervisor is found. It is likely to be Paul baker, however this is yet to be confirmed.	
Wed 30th Mar 0.25h	**Topic refinement** ECR Computer lab RS	Received one pager from SR re: DGWS project after numerous phone calls asking for it. Informed that headlining one pager would be sent later.	
Thu 31st Mar 0.5h	**Project Administration** Eng Club rooms SJ & RS	Emailed SR requesting headlining one pager to enable us to make a decision on project topic. MC emailed DGWS proposal and informed that if we didn't hear from Ford by Monday, that we would commence work on DGWS project.	
Mon 4th Apr 0.5h	**Project Administration** After Prof Prac lec SJ & RS	MC emails us suggesting we get a new supervisor. Emailed CB to get a new supervisor and met with CB who strongly advised us to get moving. CB confirmed PB as supervisor and informed no need for PB to go to Ford. Arranged to meet Nat Cucinotta (NC) on 8/04/05 to start on DGWS project. SR on leave until 11/04/05.	Deadline for Project decision was meant to be 30th March not 30th June!! DGWS project selected. Meeting with NC arranged.
Tue 5th Apr 0.25h	**Project Administration** Eng Club Rooms SJ & RS	Called SR & NC to create new 100 word project description.	
Wed 6th Apr 0.5h	**Project Administration** Eng Club Rooms	Emailed 100 word description and engineer contact details to CB & PB.	

	SJ & RS	Emailed CB & PB re: extension for scope given late project start. Emailed PB re: weekly supervisor meeting. Extension approved if PB accepts.	
Thu 7th Apr 0.25h	**Project Administration** Eng Club Rooms SJ & RS	PB replied that extension is ok, but will be unable to review before new due date.	First weekly supervisor meeting set for 3pm Thu 21st April.
Fri 8th Apr 3h	**Topic refinement** Ford NC, SJ & RS	Met with NC. Given overview of the DGWS issue. Did not receive initial developmental work on DGWS due to lack of confidentiality agreement b/w UoM/Ford/Us. Returned to uni and tried to meet with CB - not available. Sent email instead and requested a speedy resolution.	Set up meeting with SP to do some initial testing at Proving Grounds on 11/4 pending signing of confid. agreement.
Mon 11th Apr 0.5h	**Project Administration** ECR Computer lab SJ	Could not go to Proving Grounds due to lack of confid. agreement. Emailed PB, CB, SR and clarified contact list.	
Wed 13th Apr 0.25h	**Project Administration** ECR Computer lab SJ	SR returns from annual leave and expresses confusion re: confid. agreements. CB followed up. SR asks CB to call him.	
Mon 11th-18th Apr 6h	**Literature review continues** ECR Computer lab & Eng Lib SJ & RS	Literature review. Numerous calls to NC & SR to prioritise tasks to be completed and develop scope..	Literature review, formulation of scope and creation of Gantt.
Fri 18th Apr 0.5h	**Project Administration** Eng Club Rooms SJ & RS	Sent Scope and Gantt to SR & NC. Sent Scope and Gantt to PB and requested weekly meeting to be rescheduled due to Grad interviews. Explained still being hindered due to confidentiality issues.	Scope of Works & Gantt chart completed.
Wed 20th Apr 0.25h	**Project Administration** Eng Club Rooms SJ & RS	PB emailed to reschedule meeting for 22/4. PB requested Agenda be brought to meeting each week.	
Thu 21st Apr 4h	**Topic refinement** Ford NC, DB, SJ & RS	Reviewed Gantt chart tasks - made many changes. Met Dave Burn (DB) who gave us relevant SAE paper and expressed interest in our project. Saw SR in passing, who said he was still waiting on HR to review the confid. Agreements.	

		NC suggested a site visit to Empire.	
Fri 22nd Apr 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Introduced project and progress to date. Reviewed and made alterations to Scope. Setup regular and alternative weekly meeting times. Discussed content for Progress Report 1. Email CB re: extension for PR1.	
Sat 23rd Apr 2h	**Existing Product review** ECR Computer lab SJ & RS	Used internet search to find all models of cars that have 'limousine-style' doors to inspect on car yard visit	Generated list of appropriate cars to review.
Mon 25th Apr 1h	**Project Administration** ECR Computer lab SJ & RS	Updated scope of works & Gantt to reflect changes form Ford & PB meeting.	Finalised scope & Gantt chart.
Tue 26th Apr 2h	**Project Administration** ECR Computer lab SJ & RS	Called SR to sort out confidentiality agreement. Agreed to sign 2 page doc on Monday 2/5. Spoke to NC re: Monday meeting, Empire meeting will have to be in Bendigo. Informed that Empire have already developed softer seal that is being run this week.	Gantt chart exported from Excel to MS Project.
Wed 28th Apr 1h	**Literature review continued** ECR Computer lab RS & SJ	Found several SAE papers of interest. Get from Ford, who have a subscription.	
Thu 28th Apr 0.25h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Discussed ongoing confidentiality issue. Clarified confusion over progress report 1 submission date.	
Fri 29th Apr 1h	**Existing Product review** ECR Computer lab SJ	Patent search conducted. Many door seals to use. In-depth review to be completed later.	
Sat 30th Apr 2h	**Existing Product review** Various car yards SJ & RS	Visited car yards and took photos of door seals similar to the DGWS. A small number of cars have similar seals. It was interesting to see the change in seal design from various Ford models.	Gained an understanding of the typical shapes of bulbs.

Mon 2nd May 2h	**Scope clarified** **Ford** NC, SJ & RS	Reviewed latest Scope and made minor corrections. Left Confidentiality for SR to sign & Scope to review. NC informs supplier have trial parts with new rubber compound. Want us to start testing of seals wrt: DCE, wind noise (subjective & Aachen head), water leaks?, Durability testing. postpone meeting with supplier until we need to review any design issues.	Confidentiality agreement ready to be signed. Scope being reviewed by Client. PG testing on Fri 6/05/05 or following Mon?
Wed 4th May 0.25h	**Project Administration** Eng Club Rooms SJ	Called NC re: -Meeting with PB on 13/5 : still unconfirmed. -Proving grounds testing going ahead? -Request SAE papers	Received some SAE papers via email.
Thu 5th May 0.25h	**Project Administration** Eng Club Rooms SJ	Called NC re: -Unable to make Proving Grounds testing on Fri or Mon -Possibility of Wind tunnel Testing on Wednesday	
Thu 5th May 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Demonstrated DGWS section to PB. Returned signed copies of Scope and confid. for PB to sign and submit. Recapped Ford progress to date esp. testing of new rubber part with possibility of tweaking design in response to any issues faced. Possibility of testing at Monash wind tunnel.	
Fri 6th May 0.5h	**Project Administration** Ford SJ	Met with SR who signed confidentiality agreement. Brought back to uni.	Confidentiality agreement signed.
Tue 10th May 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Emailed PB minutes of last meeting. Confusion re: next meeting.	Set weekly meeting & alternate meeting time.
Wed 11th May 5h	**Testing** Lara Proving Grounds SJ & RS	Proving grounds tests: Conducted door gaps, DCE and wind noise testing.	Gathered data for door gaps, DCE and wind noise.
Thu 12th May 2h	**Work on progress report #1 commences** ECR Computer lab	Reviewed data collected thus far. Created graphs of interest.	Graphs for wind noise and DCE generated.

	RS		
Fri 13th May 2h	**Literature review continued** ECR Computer lab SJ	Started collating relevant information relevant to lit review. Create list of references.	
Wed 16th May 2.5h	**Literature review completed** SJ home SJ	Completed literature review.	Lit Review section is reasonably complete.
Tue 17th May 5h	**Testing** Monash Wind Tunnel SJ & RS	Measured door gaps and wind noise at different yaw settings. Missed Weekly Supervisor meeting due to testing.	Gathered data for door gaps and wind noise.
Fri 20th May 1h	**Work on Progress Report #1 continues** ECR Computer lab RS & SJ	Meridian project description completed. Meridian photos taken. Decide which sections to cover. Start experimental write-up.	
Mon 23rd May 1.5h	**Work on Progress Report #1 continues** ECR Computer lab RS & SJ	Create graphs of most recently obtained data.	Graphs for Monash Wind Tunnel.
Wed 25th May 2h	**Work on Progress Report #1 continues** ECR Computer lab RS & SJ	Update Gantt and Scope of Works.	Gantt chart & Progress report finalised. Documents are current.
Fri 27th May 1h	**Progress Report #1** ECR Computer Labs SJ & RS	Completed document merging and proof-reading.	Gantt chart & Progress report submitted by email.
Mon 30th May 0.5h	**Progress Report #1** Eng Club Rooms SJ & RS	Resubmitted Progress Report 1. Informed NC about exams & that we will contact him when they are complete.	Gantt chart & Progress report submitted in hardcopy.
		Exam period	
Fri 8th Jul 2h	**Progress discussed** Ford DB, SJ & RS	Met with DB re: progress. Discussed: - Wind tunnel test 1 results - Wind tunnel test 2 results - Durability results	

		Next step: DC Gauge R&R/calibration Empire site visit	
Thu 14th Jul 0.25h	**Work on progress Report #2 commences** Eng club rooms SJ & RS	Emailed NC re: Empire Site visit and suitable dates.	
Wed 20th Jul 1h	**Progress discussed** Deep Dish SJ & RS	NC postpones site visit for 1 week.	
Mon 25th Jul 2.5h	**Continue progress report #2** Eng Club Rooms SJ & RS	Requested NC to organise site visit, inform when gauges are back to perform R&R & find when durability report is available.	
Tue 26th Jul 1h	**Continue progress report #2** Eng Club Rooms SJ & RS	Force-gauge is repaired and ready for R&R.	Arranged to do testing on Fri 29/06/05
Fri 29th Jul 5h	**Research Continued** SJ & RS	Empire site visit in Bendigo done in preference to Gauge R&R.	Progress Report 2 is due. Gauge R&R to happen on Monday instead.
Mon 1st Aug 3h	**Testing** Ford SJ & RS	Perform Gauge R&R in PVT crib area.	Found energy method has better R&R than Velocity method.
Wed 3rd Aug 0.5h	**Equipment Sourcing** UoM SJ	Called Nick Haritos in Civil Eng & Mike Barry (MB) in Mechanical Eng Technical Services to source experimental equipment to perform compression load deflection test on door seals.	
Thu 4th Aug 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Waiting on feedback from Progress Report 1. PB emailed feedback on Progress Report 1. NC emailed durability photos to us. Asked NC when line trial would take place.	Got feedback on Progress Report 1.
Fri 5th Aug 0.5h	**Continue progress report #2** ERC Computer labs	Emailed PB re: 'variations from progress report 1' and 'progress to start of semester 2' sections in Progress Report 2.	

	SJ & RS		
Sun 7th Aug 2h	**Continue progress report #2** Home SJ & RS	PB emailed back re: query for PR2.	
Mon 8th Aug 0.5h	**Submit Progress Report #2** UoM SJ & RS	Submitted Progress Report 2, however emails bounced. Copied files onto a CD and slipped under PB's door.	Progress Report 2 handed in
Wed 10th Aug 3h	**Solid works models commenced** ECR Computer Labs RS	Created profile. Learnt how to use fillet and radii.	
Thu 11th Aug 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Discussed progress to date.	
Mon 15th Aug 0.5h	**Equipment Sourcing** UoM SJ	Emailed MB and received reply that no equipment suiting our experiment was available. Emailed Prof J. Williams (JFW) re: compression testing.	Arranged meeting for 16/08/05 after 11am.
Tue 16th Aug 0.25h	**Equipment Sourcing** UoM SJ & RS	Missed meeting with JFW, emailed to reschedule.	Emailed apology for missing meeting.
Wed 17th Aug 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Discussed progress to date.	
Thu 18th Aug 1h	**Progress discussed** Eng Club Rooms SJ	Asked NC for estimation of elastic modulus, durability report, sample of rubber. Arrange to meet with NC re: progress & Line trial on 26/08/05.	
Fri 19th Aug 0.5h	**Equipment Sourcing** Eng Club Rooms SJ	JFW replies to contact Saeed, Solids post grad about use of the MTS testing machine. Tried to call Saeed but he was not contactable.	
Mon 22nd Aug	**Equipment Sourcing**	Tried to call Saeed but he was not contactable. Emailed to	

0.25h	UoM SJ	arrange a meeting.	
Wed 24th Aug 0.25h	**Progress discussed** Eng Club Rooms SJ	Confirmation (from NC) of softer DGWS arriving for line trials on Friday.	
Thu 25th Aug 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Discussed progress to date.	
Fri 26th Aug 3.5h	**Line Trial** Ford SJ	Line Trial at Ford to ensure production don't have any issues with the new part.	Got SAE documents and SDS documents.
Mon 29th Aug	**Work on final report** ECR SJ & RS	Divided up tasks for Report write-up.	Workload was shared.
Tue 30th Aug	**Work on final report** ECR SJ & RS	Team met to continue progress on project report.	
Wed 31st Aug 2h	**Compression Experiment** UoM SJ	Met with Saeed briefly, he directed us to Steve Adams (SA) or Dr Graeme Pratt. Emailed JFQ, Dr Pratt & SA re compression testing & incl. picture of seal profile. Tried to call SA. Met with SA in afternoon and was shown Instron 1000.	
Thu 1st Sep 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Dr Pratt replies to speak to SA. JFW says no chance.	
Thu 1st Sep 3h	**Compression Experiment** UoM SJ	Start learning how to use Instron, chart recorder etc with help from SA and Garry from Technical Services.	Familiarisation with equipment.
Fri 2nd Sep 3h	**Compression Experiment** UoM SJ	Compression experiment conducted. Performed experiment for compression of seal in 3 different positions and performed a calibration.	Enough data to generate some material properties, namely E.

Mon 5th Sep 3h	**Solid works models completed**	Complete CAE SolidWorks modelling of seal profile is complete. NC informs us that Empire cannot produce softer seal due to excessive block mould rejects. Process to start from the beginning, options are: - try a harder material, - redesign bulb shape. Emailed Chris Thomas(CT), an engineer at Empire, to ask about possibility of CLD testing in Bendigo.	SolidWorks model is ready for material properties.
Wed 7th Sep 0.25h	**Compression Experiment backup** UoM SJ	CT replied it might be possible to complete testing on or behalf and send back data and video of the test.	
Thu 8th Sep 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Discussed progress to date. Suggest handing in Project report early for review.	
Fri 9th Sep 6h	**Work on final report** ECR SJ & RS	Started writing up recent experiments and analysing the data.	
Mon 12th Sep 5h	**Work on final report** ECR SJ & RS	Submit draft to PB for review.	Draft submitted.
Wed 14th Sep 5h	**Work on final report** ECR SJ & RS	Team met to continue progress on project report.	
Thu 15th Sep 1h	**Weekly Supervisor Meeting** Paul's Office PB, SJ & RS	Retook Photo for Meridian website. Discussed progress. Discussed review before submission.	
Fri 16th Sep 2h	**Tensile Experiment** UoM SJ	Used big Instron to try and find E for seal rubber in tension. Results may not be good.	Difficult to hold samples in grips.
Mon 19th Sep 14h	**Work on final report** ECR SJ & RS	Team met to continue progress on project report.	

Tue 20th Sep 12h	**Work on final report** ECR SJ & RS	Team met to continue progress on project report.	Printing and CD burning to occur.
Wed 21st Sep 12h	**Work on final report** ECR SJ & RS	Team met to continue progress on project report.	Final Report Due today

C. Appendix C: Scope of Works

THE UNIVERSITY OF
MELBOURNE

Major Project

Department of Mechanical and Manufacturing Engineering

Scope of Works

March to October, 2005

Project Title:	Evaluation of various compounds for use in the Drip Gutter Weather Strip
Client Organisation:	Plant Vehicle Team Ford Motor Company of Australia Ltd. 1727 Sydney Road Campbellfield 3061
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Date:	22 September 2005
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Identifier:	MP–4651
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Version: Final

1. Project

Evaluation of various compounds for use in the Drip Gutter Weather Strip

2. Objectives

To investigate the current DGWS in conjunction with a proposed softer DGWS with respect to the customer expectation metrics of interior loudness due to wind noise and door closing effort.

3. Definition of starting point

The DGWS is a tertiary door seal used on all BA model vehicles. It is the outer most seal, which is attached to the body via a flange and seals up against the closed door. It is a continuous strip from the bottom of the A-Pillar to the C-Pillar at the bottom of the rear door. Due to the limousine style-doors used on all BA vehicles, the DGWS acts as a gutter, to collect and channel water from the vehicle roof away from the doors.

Empire Rubber designed the current DGWS as a running-change for the AU model during 1999. Since then, design improvements in other areas have reduced the amount of road noise transmitted into the cabin. Thus, the interior loudness as a result of wind noise generated at speed is more noticeable. This noise, primarily a problem in cross wind situations, is increasingly noticeable as the gap at the 6G location (a point at the intersection of the A-Pillar and the roof) increases. The design of the DGWS is a compromise between the amount of wind noise generated and door closing effort. The door closing effort measured the amount of energy required to close the door. The smaller the measurement at 6G is the greater the door closing effort is.

4. Task descriptions

<u>Part A – Project Conceptualisation</u>

The initial tasks required to understand all the factors and constraints in the DGWS design are listed below.

- Familiarise team with DGWS problem
- Investigate constraints imposed on DGWS by:
    - Door set tolerances ,
    - How Body Assembly set doors, and
    - How seals are installed onto vehicle.
- Literature Review
- Review Existing Technology
- Ford Standards Review
    - Door Closing Effort,
    - Wind Noise, and
    - Durability.

Part B –Virtual Evaluation & Testing

- Empire Rubber site visit
- Physical Evaluation
  - Source Experimental Data
  - Compression Testing
  - Determination of Physical Properties
- Finite Element analysis
  - Preparation of Model
  - Compression Testing
  - Aspiration Testing
- Comparison of FEA with Physical Evaluation

Part C – Ford: Development & Testing

Once a candidate design is chosen which fulfils all the requirements and meets all the constraints developed in the first section of tasks, testing may begin.

- Durability Testing
- Interior Loudness Tests
  - Wind Noise Drives
  - Wind Tunnel (Wind Noise Sweeps)
- Door Closing Effect Tests
  - Green Seals – Softer and Current
  - Aged Seals – Softer and Current
- DCE vs. Wind Noise Analysis
- Conduct Line Trials
  - Raise a deviation
  - Operator/Group Leader buyoff
  - FCPA buyoff
- Conduct craftsmanship evaluation.
- Implement DGWS into production

5. Variation of tasks

Throughout the course of the project, there were major additions and deletions to the agreed tasks to be undertaken. After the submission of Progress Report 1, Ford did not want the design work with Empire Rubber to be completed, as such it was dropped from the project and the focus shifted to the testing of the DGWS. It was also agreed that time should be spent trying to determine the physical characteristics of the DGWS so that a FEA model could be constructed. This would allow different bulb designs to be tested. The original Scope of Works submission is included as a reference to the change in project tasks.

Part A – Project Conceptualisation

The initial tasks required to understand all the factors and constraints in the DGWS design are listed below.

- Review the design choices made in the most recent revision of the DGWS.

- Review Ford design standards and constraints
- Determine the effect the DGWS has on:
    - Door closing effort,
    - Wind noise, and
    - Water drainage.
- Investigate constraints imposed on DGWS by:
    - Door set tolerances (Gather data and obtain Significant Characteristic / Critical Characteristic data),
    - How Body Assembly set doors, and
    - How seals are installed onto vehicle.
- Review initial development work on DGWS effect on door closing effort and wind noise, including,
    - New and aged seals testings,
    - Seal material/compound contribution, and
    - Notching on DGWS effect to 6G

Part B – Empire Rubber - Design and Virtual Evaluation

The next stage of the project involves design of a number of alternative DGWS designs for analysis with an FEA package.

- Brainstorm proposals for refinements/new designs for DGWS within bounds of set constraints, including,
    - Performing trials on alternative materials, and
    - Design concepts.
- Perform FEA analysis on likely designs.
    - Comparison with results from FEA on present DGWS design.

Part C – Ford - Development & Testing

Once a candidate design is chosen which fulfils all the requirements and meets all the constraints developed in the first section of tasks, testing may begin.

- Construct prototype of candidate design for testing.
- Evaluation of candidate design, by;
    - Wind tunnel tests (during Ford's quarterly tests)
    - Wind noise objective/subjective test drives,
    - Door closing effort trials – using green and aged seals,
    - Door closing effort vs. wind noise analysis,
    - Conduct line trials, and
    - Conduct craftsmanship evaluation.

At this stage, it may be required to return to Part B to make modifications to candidate designs to fix problems discovered during the physical evaluation of the candidate DGWS.

Part D – Final Manufacture

- Extrusion Die Development of the DGWS by Empire Rubber
- Launch new DGWS into production.

6. Duration of tasks

See Appendix 1: Gantt chart. Note: These durations are approximations only.

A - PROJECT CONCEPTUALISATION

- Familiarise team with DGWS problem — *16 days*
- Investigate constraints imposed on DGWS by:
  - Door set tolerances , — *18 days*
  - How Body Assembly set doors, and — *3 days*
  - How seals are installed onto vehicle. — *3 days*
- Literature Review — *40 days*
- Review Existing Technology — *10 days*
- Ford Standards Review
  - Door Closing Effort, — *10 days*
  - Wind Noise, and — *10 days*
  - Durability. — *10 days*

B - VIRTUAL EVALUATION & TESTING

- Empire Rubber site visit — *1 days*
- Physical Evaluation
  - Source Experimental Data — *10 days*
  - Compression Testing — *3 days*
  - Determination of Physical Properties — *3 days*
- Finite Element analysis
  - Preparation of Model — *5 days*
  - Compression Testing — *3 days*
  - Aspiration Testing — *3 days*
- Comparison of FEA with Physical Evaluation — *2 days*

C - FORD: DEVELOPMENT & TESTING

- Durability Testing — *2 days*
- Interior Loudness Tests
  - Wind Noise Drives — *1 days*
  - Wind Tunnel (Wind Noise Sweeps) — *4 days*
- Door Closing Effect Tests
  - Green Seals – Softer and Current — *6 days*
  - Aged Seals – Softer and Current — *6 days*
- DCE vs. Wind Noise Analysis — *2 days*
- Conduct Line Trials
  - Raise a deviation — *3 days*
  - Operator/Group Leader buyoff — *5 days*
  - FCPA buyoff — *6 days*
- Conduct craftsmanship evaluation. — *5 days*
- Implement DGWS into production — *11 days*

REPORT

Determine scope	*16 days*
Write up scope	*15 days*
Preparation for Progress Report #1	*11 days*
Write up Progress Report #1	*5 days*
Preparation for Progress Report #2	*11 days*
Write up Progress Report #2	*5 days*
Write up Final Report & Contributions Paper	*22 days*
Preparation for Oral presentation	*7 days*
Preparation for DMME Meridian exhibition	*5 days*

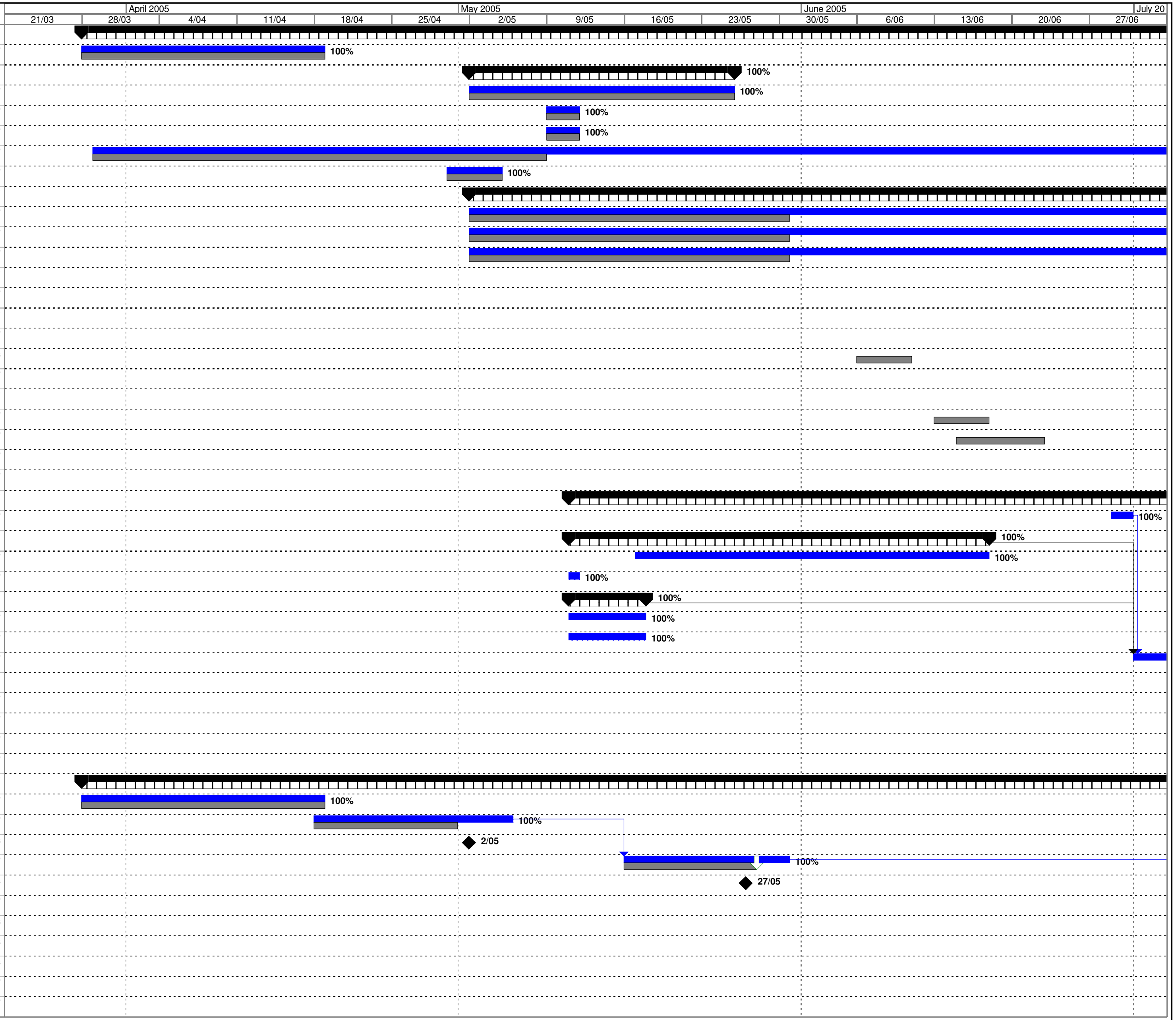
7. End point

The expected outcomes of this project are:

- Determination of the relationship the DGWS has on Door Closing Effort and Wind Noise.
- Virtual model of DGWS verified by physical testing to determine material properties.
- Evaluation of different bulb designs that may reduce door closing effect without having a significant effect on wind noise.

D. Appendix D: Gantt Chart

ID	Task Name	Start	% Complete	Duration
1	**PROJECT CONCEPTUALISATION**	**Mon 28/03/05**	**100%**	**101 days?**
2	Familiarise team with DGWS problem	Mon 28/03/05	100%	16 days?
3	**Investigate constraints:**	**Mon 2/05/05**	**100%**	**18 days?**
4	Door Set Tolerances	Mon 2/05/05	100%	18 days?
5	How Body sets doors	Mon 9/05/05	100%	3 days?
6	How seals are installed	Mon 9/05/05	100%	3 days?
7	Literature review	Tue 29/03/05	100%	93 days?
8	Reviewing existing technology	Sat 30/04/05	100%	4 days?
9	**Ford Standards review:**	**Mon 2/05/05**	**100%**	**75 days?**
10	Door closing effort	Mon 2/05/05	100%	75 days?
11	Wind noise	Mon 2/05/05	100%	75 days?
12	Durability of seals	Mon 2/05/05	100%	75 days?
13	**VIRTUAL EVALUATION & TESTING**	**Fri 29/07/05**	**75%**	**18 days?**
14	Empire Rubber Site Visit	Fri 29/07/05	100%	1 day?
15	**Physical Evaluation:**	**Mon 1/08/05**	**100%**	**15 days?**
16	Source Experimental Equipment	Mon 1/08/05	100%	10 days?
17	Compression Testing	Mon 15/08/05	100%	5 days
18	Determination of Physical Properties	Wed 17/08/05	100%	3 days?
19	**Finite Element Analysis:**	**Mon 8/08/05**	**45%**	**8 days?**
20	Preparation of Model	Mon 8/08/05	100%	5 days?
21	Compression Testing	Mon 15/08/05	0%	3 days?
22	Aspiration Testing	Mon 15/08/05	0%	3 days?
23	Comparison of FEA with Physical Evaluation	Mon 22/08/05	0%	2 days?
24	**FORD: DEVELOPMENT & TESTING**	**Wed 11/05/05**	**83%**	**89 days?**
25	Durability testing	Wed 29/06/05	100%	2 days?
26	**Wind Noise Tests:**	**Wed 11/05/05**	**100%**	**28 days?**
27	Wind Tunnel (Yaw Angle Tests)	Tue 17/05/05	100%	24 days?
28	Wind Noise Drives	Wed 11/05/05	100%	1 day?
29	**Door closing effort trials:**	**Wed 11/05/05**	**100%**	**5 days?**
30	Green seals - New and Old	Wed 11/05/05	100%	5 days?
31	Aged seals - New and Old	Wed 11/05/05	100%	5 days?
32	DCE vs. Wind Noise Analysis	Fri 1/07/05	100%	31 days?
33	**Conduct line trials:**	**Mon 15/08/05**	**100%**	**5 days?**
34	Raise a deviation	Mon 15/08/05	100%	3 days?
35	Operator/Group Leader buyoff	Mon 15/08/05	100%	5 days?
36	Conduct craftsmanship evaluation	Mon 22/08/05	0%	5 days?
37	Implement DGWS into production	Mon 29/08/05	0%	11 days?
38	**REPORT**	**Mon 28/03/05**	**89%**	**141 days?**
39	Determine scope	Mon 28/03/05	100%	16 days?
40	Write up scope	Mon 18/04/05	100%	15 days?
41	Scope of Works Due	Mon 2/05/05	100%	0 days
42	Preparation for progress report #1	Mon 16/05/05	100%	11 days?
43	Progress Report #1 Due	Fri 27/05/05	100%	0 days
44	Preparation for progress report #2	Mon 18/07/05	100%	14 days?
45	Progress Report #2 Due	Fri 29/07/05	100%	0 days
46	Writing up report	Mon 1/08/05	100%	37 days
47	Final Report Due	Thu 22/09/05	100%	0 days
48	Preparation for Oral presentation	Tue 20/09/05	5%	7 days?
49	Preparation for DMME Meridian exhibition	Mon 3/10/05	5%	5 days?

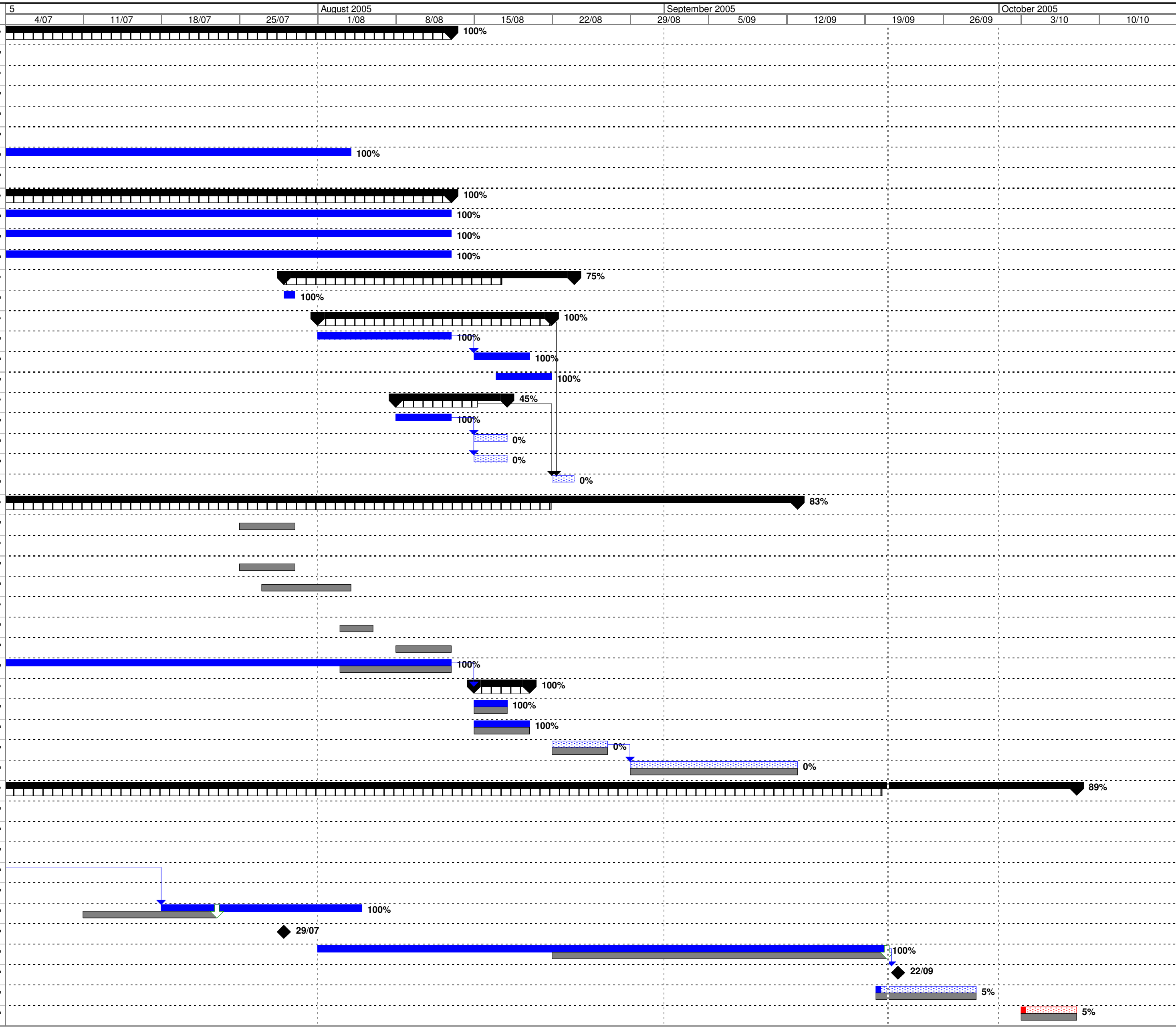


Project: DGWS
Date: Wed 21/09/05

Critical		Task		Baseline		Milestone		Project Summary	
Critical Split		Split		Baseline Split		Summary Progress		External Tasks	
Critical Progress		Task Progress		Baseline Milestone		Summary		External Milestone	

Deadline

ID	Task Name	Start	% Complete
1	**PROJECT CONCEPTUALISATION**	**Mon 28/03/05**	**100%**
2	Familiarise team with DGWS problem	Mon 28/03/05	100%
3	**Investigate constraints:**	**Mon 2/05/05**	**100%**
4	Door Set Tolerances	Mon 2/05/05	100%
5	How Body sets doors	Mon 9/05/05	100%
6	How seals are installed	Mon 9/05/05	100%
7	Literature review	Tue 29/03/05	100%
8	Reviewing existing technology	Sat 30/04/05	100%
9	**Ford Standards review:**	**Mon 2/05/05**	**100%**
10	Door closing effort	Mon 2/05/05	100%
11	Wind noise	Mon 2/05/05	100%
12	Durability of seals	Mon 2/05/05	100%
13	**VIRTUAL EVALUATION & TESTING**	**Fri 29/07/05**	**75%**
14	Empire Rubber Site Visit	Fri 29/07/05	100%
15	**Physical Evaluation:**	**Mon 1/08/05**	**100%**
16	Source Experimental Equipment	Mon 1/08/05	100%
17	Compression Testing	Mon 15/08/05	100%
18	Determination of Physical Properties	Wed 17/08/05	100%
19	**Finite Element Analysis:**	**Mon 8/08/05**	**45%**
20	Preparation of Model	Mon 8/08/05	100%
21	Compression Testing	Mon 15/08/05	0%
22	Aspiration Testing	Mon 15/08/05	0%
23	Comparison of FEA with Physical Evaluation	Mon 22/08/05	0%
24	**FORD: DEVELOPMENT & TESTING**	**Wed 11/05/05**	**83%**
25	Durability testing	Wed 29/06/05	100%
26	**Wind Noise Tests:**	**Wed 11/05/05**	**100%**
27	Wind Tunnel (Yaw Angle Tests)	Tue 17/05/05	100%
28	Wind Noise Drives	Wed 11/05/05	100%
29	**Door closing effort trials:**	**Wed 11/05/05**	**100%**
30	Green seals - New and Old	Wed 11/05/05	100%
31	Aged seals - New and Old	Wed 11/05/05	100%
32	DCE vs. Wind Noise Analysis	Fri 1/07/05	100%
33	**Conduct line trials:**	**Mon 15/08/05**	**100%**
34	Raise a deviation	Mon 15/08/05	100%
35	Operator/Group Leader buyoff	Mon 15/08/05	100%
36	Conduct craftsmanship evaluation	Mon 22/08/05	0%
37	Implement DGWS into production	Mon 29/08/05	0%
38	**REPORT**	**Mon 28/03/05**	**89%**
39	Determine scope	Mon 28/03/05	100%
40	Write up scope	Mon 18/04/05	100%
41	Scope of Works Due	Mon 2/05/05	100%
42	Preparation for progress report #1	Mon 16/05/05	100%
43	Progress Report #1 Due	Fri 27/05/05	100%
44	Preparation for progress report #2	Mon 18/07/05	100%
45	Progress Report #2 Due	Fri 29/07/05	100%
46	Writing up report	Mon 1/08/05	100%
47	Final Report Due	Thu 22/09/05	100%
48	Preparation for Oral presentation	Tue 20/09/05	5%
49	Preparation for DMME Meridian exhibition	Mon 3/10/05	5%



Project: DGWS
Date: Wed 21/09/05

Critical		Task		Baseline		Milestone		Project Summary		Deadline	
Critical Split		Split		Baseline Split		Summary Progress		External Tasks			
Critical Progress		Task Progress		Baseline Milestone		Summary		External Milestone			