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Advanced Experimental Methods for the Analysis and Aerodynamic Design of Heavy Vehicles

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ABSTRACT

An experimental investigation of the aerodynamic impact of rotating wheels on both simplified and detailed truck models is presented. For this study, wind tunnel measurement of aerodynamic forces and surface pressures are used in both stationary road and rolling road conditions.

The following research revealed that the effects of rotating wheels on aerodynamic forces, as compared to stationary wheels, are dependent on the interaction of the flow around the rotating wheels and the base wake of the trailer as well as the changes in flow separation points between the stationary versus rotating wheels. These results emphasize that wind tunnel testing with rotating wheels is indispensable during the aerodynamic development process to design an aerodynamically optimal truck.

INTRODUCTION

Since the first oil crisis in the 70's, truck aerodynamic efficiency has been a focus of scientific investigation using generic truck models. As a result, a significant number of possible aerodynamic solutions have been suggested. However, many of these designs have failed to see mass acceptance within the trucking industry. Two of the main reasons for this lack of acceptance are:

- Overall tractor-trailer design is limited by federal regulations as well as the current infrastructure in which they have to operate (loading platforms etc.)
- Tractor shape is designed to meet the sometimes conflicting requirements of aerodynamic performance and styling which are driven by customer desires.

However, it is increasingly obvious that fuel efficiency will continue to play a paramount role in the transportation industry. Therefore it is imperative that aerodynamic solutions are found which can be adopted by the majority of the trucking industry. Previous research has shown that rotating wheels play a major role in the overall aerodynamic development of a passenger car [1]. This study shows that the same is true of semi-trucks. Therefore truck design should include rolling road wind tunnel testing early on in the product's development cycle.

Experience at the Auto Research Center with various vehicles ranging from passenger cars to open wheel racecars has shown that rotating wheels play a key role in aerodynamic performance. In many tests at the ARC it has been found that changes made to a vehicle may show a drag decrease in a fixed floor tunnel test, yet show an increase when the wheels are rotated. It must also be said that the opposite effect has also been witnessed. This highly nonlinear interaction of rotating wheels with the overall airflow around the vehicle must be considered carefully when designing aerodynamically optimal vehicles. This study confirms that this is also the case for tests conducted with rotating wheels on both standard production vehicles and class 8 trucks. Each evaluation yields similar dependency trends, which emphasizes drag reductions found with fixed non-rotating wheels are at times drag increases once the wheels are rotated and vice versa.

In this paper we investigate the influence of rotating wheels on semi-truck aerodynamics. The baseline configuration was based on the generic simplified truck previously studied by NASA [2]. This model was further refined to include rotating wheels as well as additional details to study flows in the engine compartment and the underbody of the tractor and trailer. Further comprehensive testing with rotating the wheels on semi-trucks while utilizing several underbody flow devices was conducted utilizing two base models, the NASA generic model and a more representative truck model. The testing included parts which are meant to highlight the interaction of the rotating wheels with the airflow and not necessarily practical for implementation on real world trucks.

TRACTOR TRAILER MODELS

For the investigation of the influence of rotating wheels on the aerodynamics of heavy vehicles, two base models were used. It is paramount to measure the influence of rotating wheels on a realistic tractor-trailer truck, because real world effects are the point of interest for the truck manufacturer aerodynamicist. The airflow around the truck has to be managed for the real road conditions of a real truck. Therefore one of the truck models is representative of a normal production truck with attention to detail given towards the undercarriage, or underbody, and engine compartment.

Nevertheless the effects of rotating wheels can be studied and quantified more easily, if the truck body is a streamlined shape. By omitting complex geometries, internal flows, interference effects of the cooling airflow as well as of the underbody flow spillage, correlation can be made between ARC tests and previous tests conducted by NASA Ames [2,3,4]. Therefore the basic studies have been conducted with a simplified truck model (Generic Conventional Model) in a scale of 1:8. In addition the GCM has one more advantage, having been tested by NASA, data is already available for the non-rotating wheels case. For this reason, validation of ARC experiments became simplified for the non-rotating wheels configuration.

THE GCM MODEL

Figure 1 (right) and Figure 2 shows the GCM model as built by ARC. It is a replica of the GCM run by NASA in earlier research (figure 1 left). The GCM is a simplified representation of a generic class-8 tractor-trailer developed initially for CFD validation. It has no detailing, no engine compartment flow and the underbody is smooth. Detailed 3D geometry of the NASA GCM was obtained from Bruce Storms at NASA [2] and is summarized in figure 3. The only differences between the ARC GCM and the GCM used by NASA are the tire areas and trailer dual wheels geometry. Such modifications were necessary in order to have the ability to compare results between fixed floor and rolling road tests using the same model

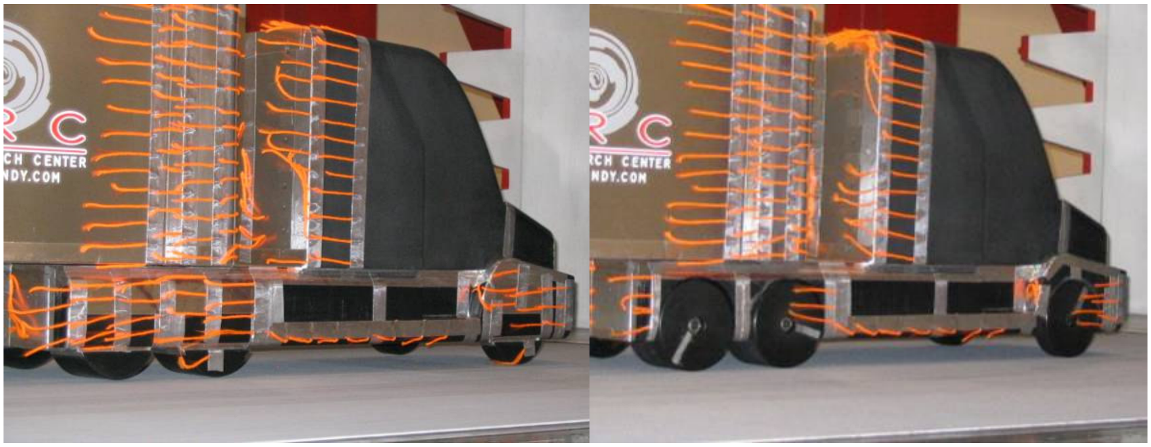


Figure 1 – NASA GCM (left) and ARC rolling wheel version (right)

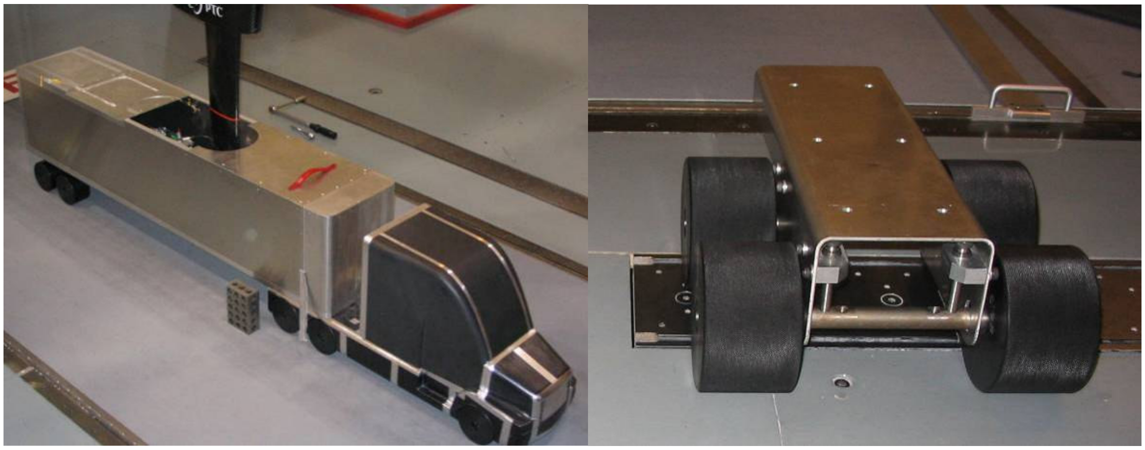


Figure 2 – ARC rolling wheel version of the NASA GCM 1/8th scale truck

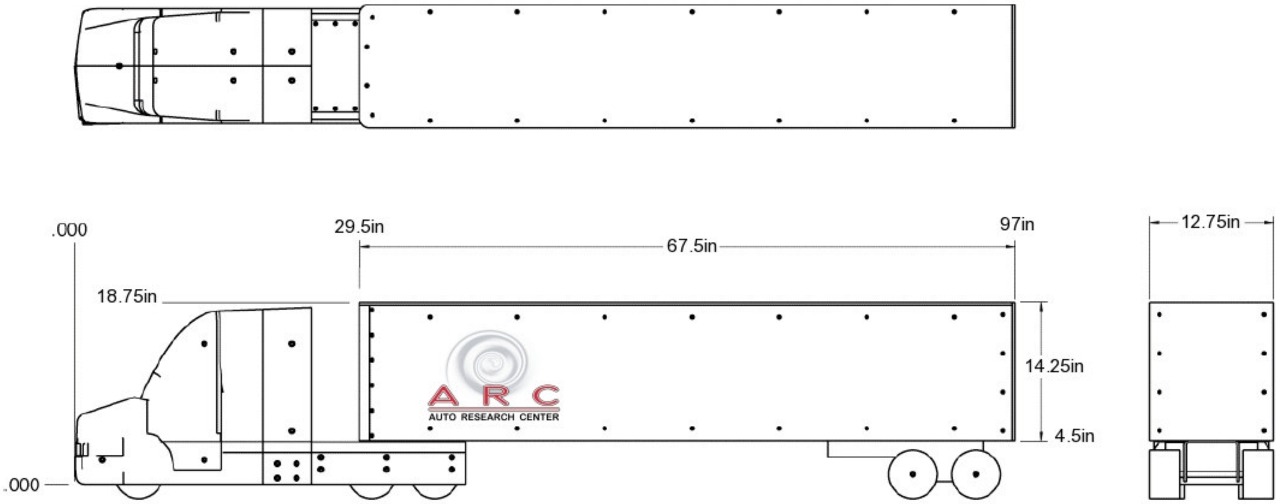


Figure 3 – Dimensions of the ARC / NASA GCM 1/8th scale truck

THE ARC MODEL

A model more representative of a production truck was developed based on the GCM design. While keeping the upper body identical, implementation of the detailing of the undercarriage and engine areas was implemented. Figure 4 shows the implemented tractor and trailer suspensions as well as engine compartment.

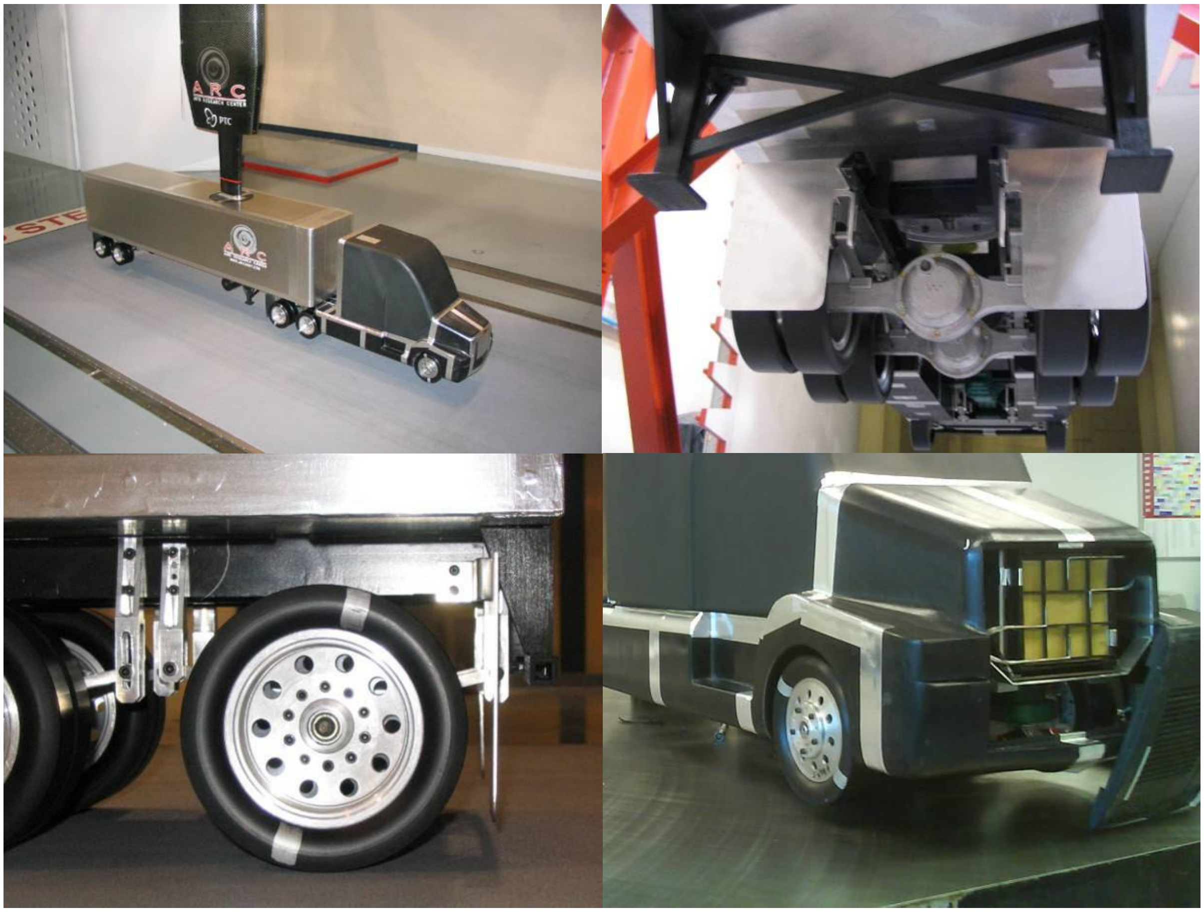


Figure 4 – ARC detailed undercarriage featuring accurate rolling wheels and internal radiator/engine flows

EXPERIMENTAL SET UP

Measurements were conducted by the Auto Research Center in their own closed circuit single return ¾ open jet wind tunnel. The ARC wind tunnel utilizes a contraction ratio of 4.8 to 1, rolling road matching air test speeds to +/- 0.1 m/s in a temperature controlled environment of +/- 0.2 degrees Celsius. Tests were conducted at a maximum wind and road speed of 50m/s, (constant dynamic pressure). The turbulence intensity is 0.11% and flow angularity is within 0.2°. Boundary layer thickness measures 99.8% free stream at 1 mm above the moving belt in the center of the test section. The moving ground plane size is 3.4m long by 1.66m wide. Models were located at a position 0.5 m from the leading edge of the rolling road and 1.2 m downstream of the ground plane leading edge. Both models were suspended via an overhead support strut in the test section at a ride height of 152.4 mm, with their center of rotation identical to the NASA experiment, located 1.38 m aft of the tractor front bumper.

MODEL AND WIND TUNNEL INSTRUMENTATION

The models were equipped with a six-component internal balance (manufactured by Aerotech) measuring the overall models' loads inside the trailer. The balance is of one-piece construction and each strain gauge bridge is dedicated to the measurement of one aerodynamic component alone. The manufacturer specified accuracies are given in Appendix A. Both models were implemented with 120 pressure taps respectively, 60 on the tractor and 60 on the trailer. The surface pressure was measured via an electronically scanned pressure system (ESP Pressure Scanner transducer and an electronic pressure scanner calibrator PCM100). Raw forces, moment and pressure data were recorded respectively by MISTRAL and PiAero software.

TEST PROCEDURE

A wind speed of 50 m/s, constant dynamic, was used for these investigations. A Reynolds number of $Re=10^6$ results from the models width (0.3239m) as characteristic length matching closely to the NASA experiment [3]. Both models were tested with the rolling road on and off. The GCM model was yawed through a range of angles between 0^o and -10^o by increments of 2^o. The ARC model was tested only at 0^o yaw angle. Underbody development items were only tested on the ARC model.

DIFFERENCES TO NASA TEST

As expected, there were some differences in the setup between the stationary road GCM model tested in ARC's tunnel compared to the GCM tested in the NASA tunnels. Notable differences between the two tests are listed below:

1. Model Mounting: four posts were used to suspend the model by NASA. These were not required for ARC testing due to the overhead sting mounting method.
2. Solid Blockage: NASA tests were conducted in closed jet wind tunnels. This will generate small variation in the streamlines around the same model configuration. The ARC wind tunnel is a closed circuit single return ¾ open jet type.
3. Test Section Boundary Layer: to compensate for the boundary layer thickness NASA had to mount the model above the wind tunnel floor.
4. Model Geometry: Rotating wheels requirement for the model run by ARC yield to an alteration of the initial GCM design. The use of flexures to connect the tractor and trailer by NASA lead to an inclination of the tractor.
5. Body axis force and moment calculation: NASA measurements were made by the facility scale system in the wind axis coordinate system, sensitive to errors in yaw angle. [5]

RESULTS AND DISCUSSION

As the purpose for these tests is to show the differences between rolling road and non-rolling road testing of semi-trucks, it was important to initially draw a comparison between previous NASA testing in other tunnels. Since all other testing was completed in a non-rolling road environment, ARC completed a large amount of non-rolling road comparison testing in its rolling road capable open jet tunnel. The wind tunnel at ARC has the capability of running with the rolling road in motion or stationary, therefore it was simple to compare results to those previously published by NASA with the ARC GCM simply by running with the road stationary.

The ARC GCM model had two base configurations: The first baseline configuration utilized wheels that were not capable of rotating and matched the previous NASA GCM model tested in other tunnels. The second baseline configuration included a wheel system capable of rotating the wheels on the same GCM model.

Ensuring consistency, the first baseline GCM (non-rotating wheels), was initially run through multiple yaw angles in one yawing direction (driver's left direction). This model was run through a beta sweep of 0^{o} to -10^{o} in 2^{o} increments. Since the previous NASA work ran this condition with its model raised just above the boundary layer, the same was done by ARC. This caused the model to be above the belt and even though this first baseline model did not have rotating wheels, its raised height allowed ARC to rotate the belt beneath the raised model. Therefore, two sets of yaw data were collected, the first set with the belt stationary and the second set with the belt rotating 50 m/s. For both conditions, the airspeed was maintained at 50 m/s.

The analysis of results will be limited to drag forces and pressures in order to simplify the discussion. Details of specific moment measurements were recorded, but not utilized for the purpose of this paper. Comparing the C_ds measured between NASA and their GCM model versus ARC and its GCM model, both without a rotating floor, reveal close correlation (see figure 5). The slight differences in absolute values can be explained by the differences previously discussed. For some yaw angles the data directly over lays prior NASA measured data. There is an area where a slight difference is seen at the smaller beta angles. In the smaller beta angle region, (beta = 0^{o} to -4^{o}), the data shows a small cross over difference between prior NASA data and ARC data for the GCM model. This can be accounted for between different error values between measurement systems and hardware as well as the previously discussed differences between the two models.

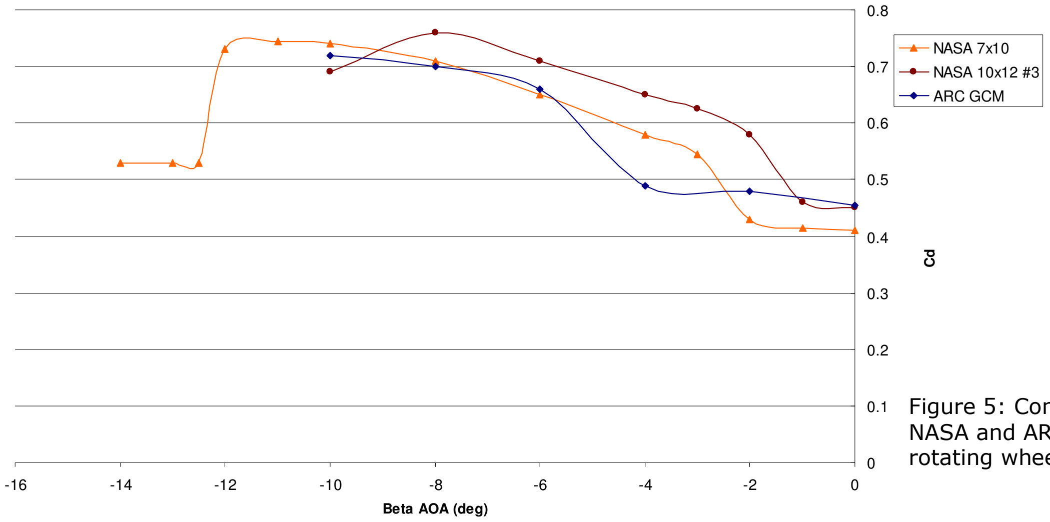
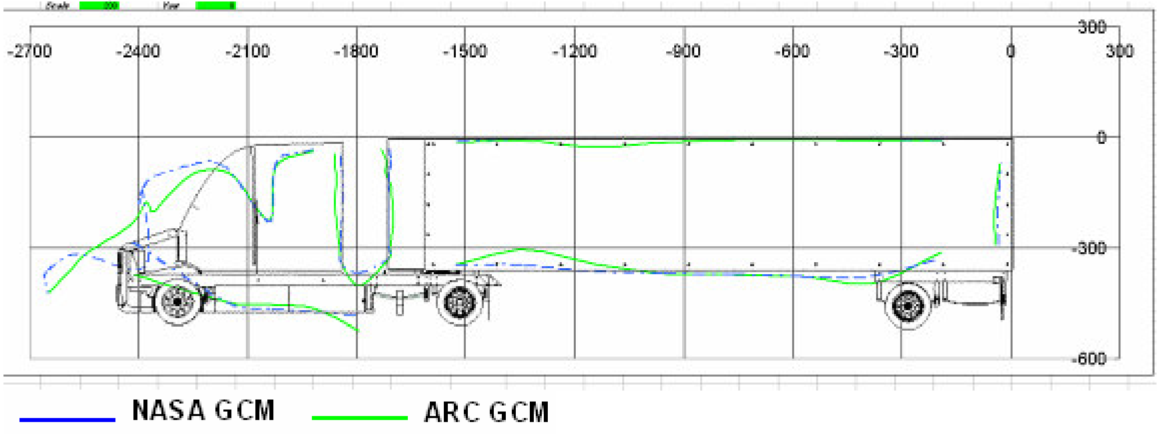


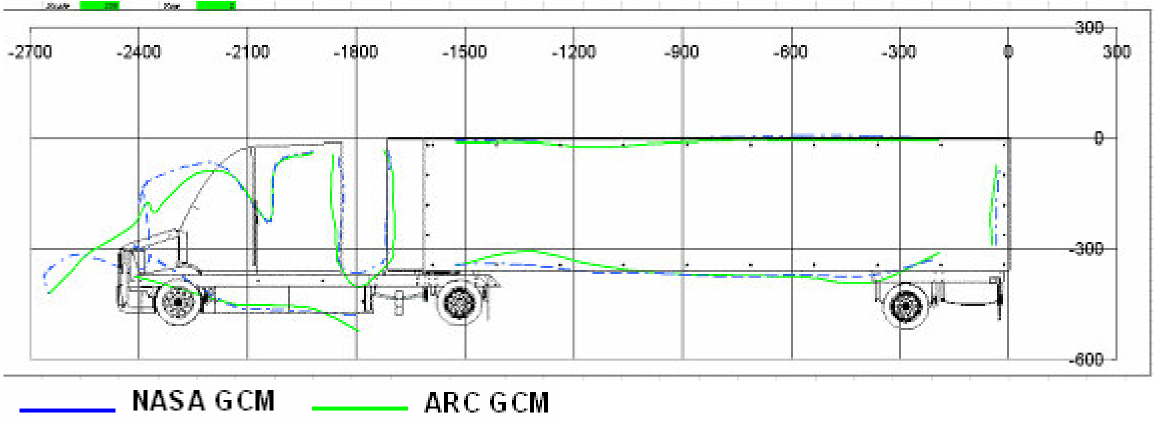
Figure 5: Comparison of NASA and ARC GCM Cd non-rotating wheels.

Below is a static pressure comparison between NASA's and ARC's GCM non-rotating wheel models from 0° yaw through -10° yaw. Figure 6 shows this series of pressure data graphs.

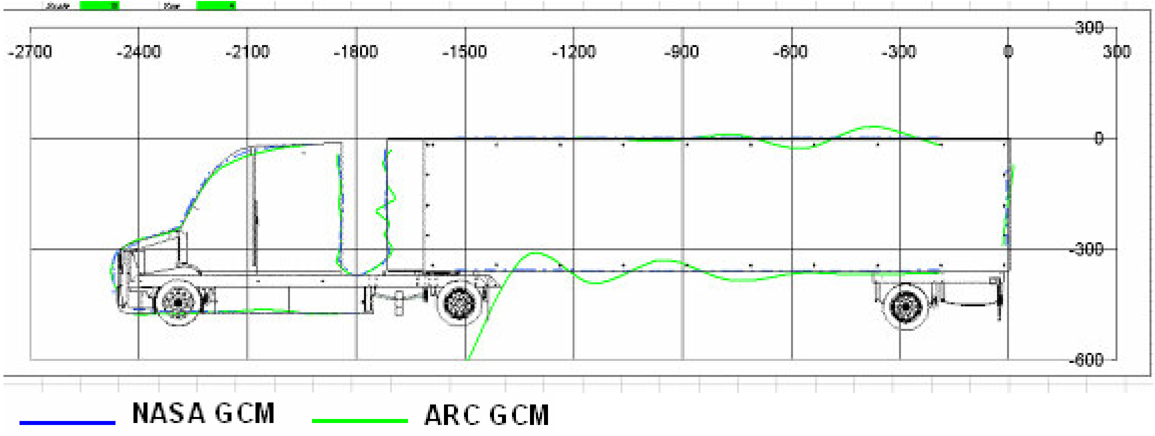
0° beta / road off:



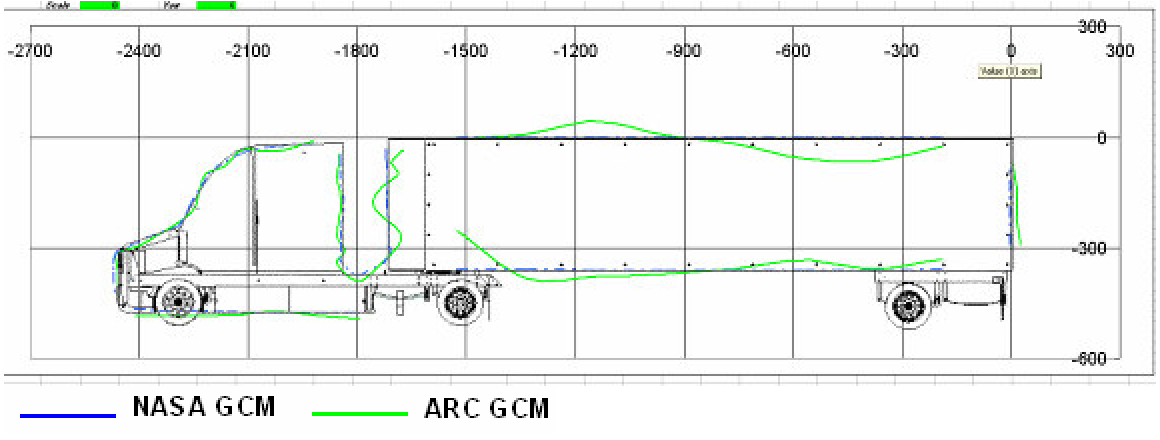
-2° beta / road off:



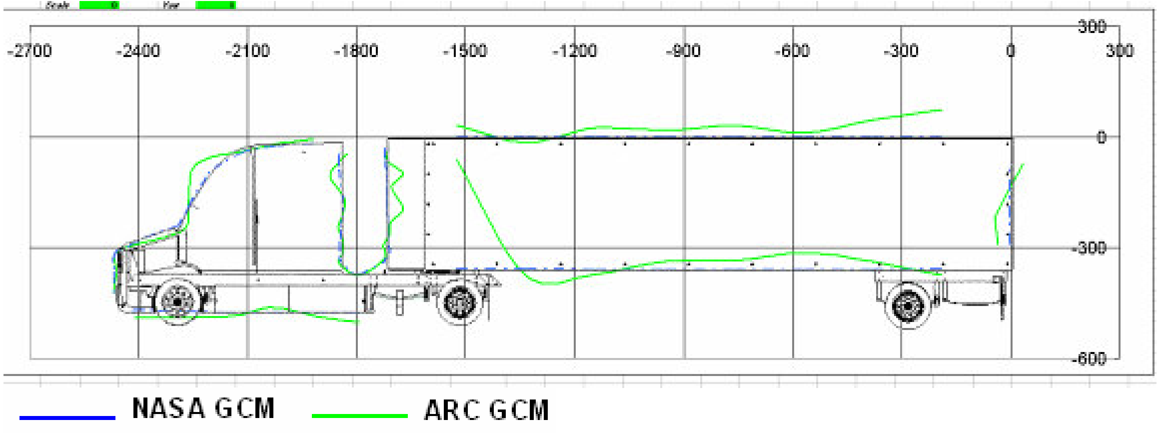
-4° beta / road off:



-6° beta / road off:



-8° beta / road off:



-10° beta / road off:

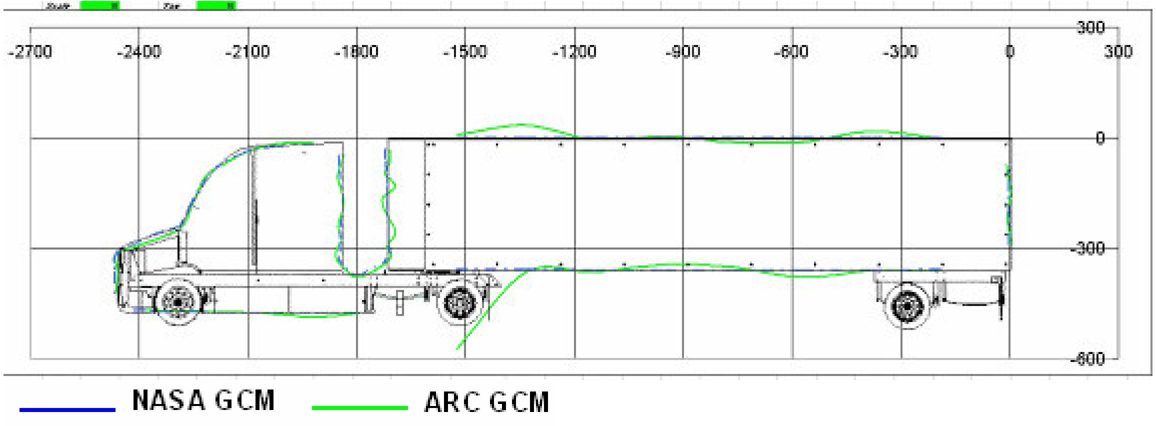


Figure 6: Comparison of NASA and ARC GCM pressure data for beta angles 0° - -10°.

At most of the beta angles, good pressure data correlation was found. There were some discrepancies at -2° and -4° yaw angles. These differences match the force data differences recorded at these smaller beta angles. Other than these slight variances, ARC measured pressure data correlated quite well.

After correlating to NASA's previous testing of their GCM, ARC ran the rolling road for the ARC GCM without rotating wheels as well as ARC's GCM with rotating wheels capability. To close the loop, ARC also ran its GCM with rotating wheels capability with the road stationary through all of the same beta sweeps. The complete drag comparison between ARC's two configurations of the GCM both with and without the rotating road can be seen in Figure 7.

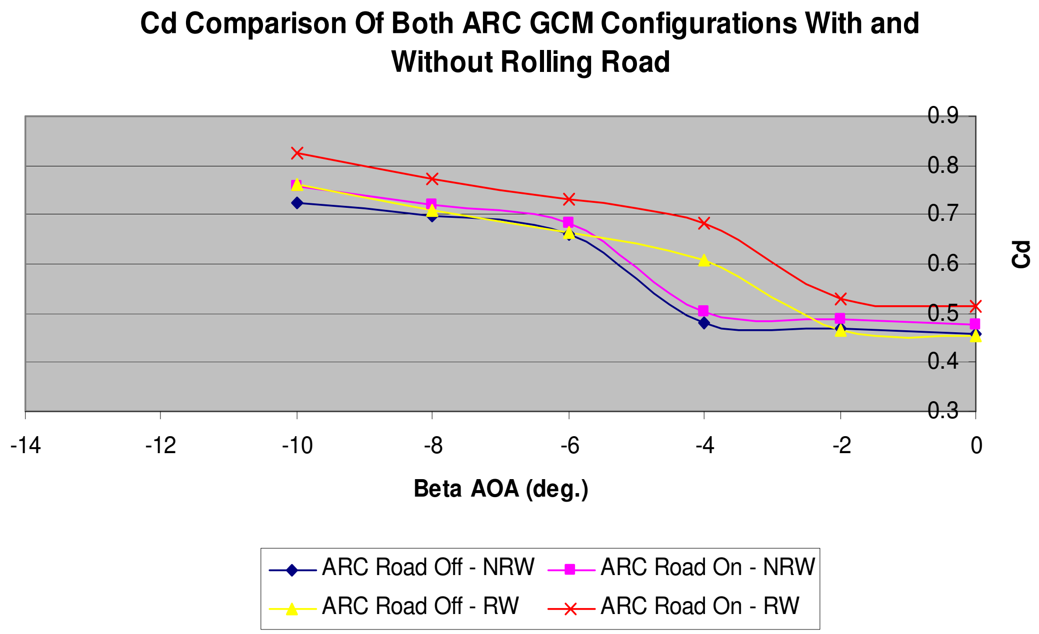


Figure 7: C_d comparison of both ARC GCM configurations with and without rotating wheels.

The comparison in Figure 7 shows some interesting trends. First, the difference between the two configurations NRW (non-rotating wheel) and RW (rotating wheel) is a small 2 mm gap between the wheels that rotate and the rest of the wheel housing. Running the RW configuration through beta sweeps shows a trend change for the lower beta angles that is similar to the previously measured NASA data. Another interesting trend is that each time the belt is rotated for either configuration, an increase in drag was measured. It was also worthy to note that the increase in drag measured for the RW configuration is nearly three times that measured for the NRW configuration. This is explainable because the RW configuration has the added effect of wheels actually rotating which create the common "pumping" effect seen with rotating wheels. The absence of this "pumping" effect (as seen with the NRW configuration) demonstrates the effects of the belt entrainment only. For the NRW configuration, rotating the road without the capacity of the wheels to rotate, increases the drag measured by 4.6%. For the RW configuration, rotating the road with the wheels rotating on the road, increases the drag measured by 12.4%. Therefore, the air entrainment caused by the belt alone is approximately 4.6% of the increase, while the additional wheel rotation effects are responsible for another 7.8%. These results show how improvement in the general underbody of the truck will show an improvement in general, but improvements around the wheels will give a much bigger benefit.

Figures 8 and 9 show the differences in static pressure between the two different run conditions for the two different baselines, NRW and RW.

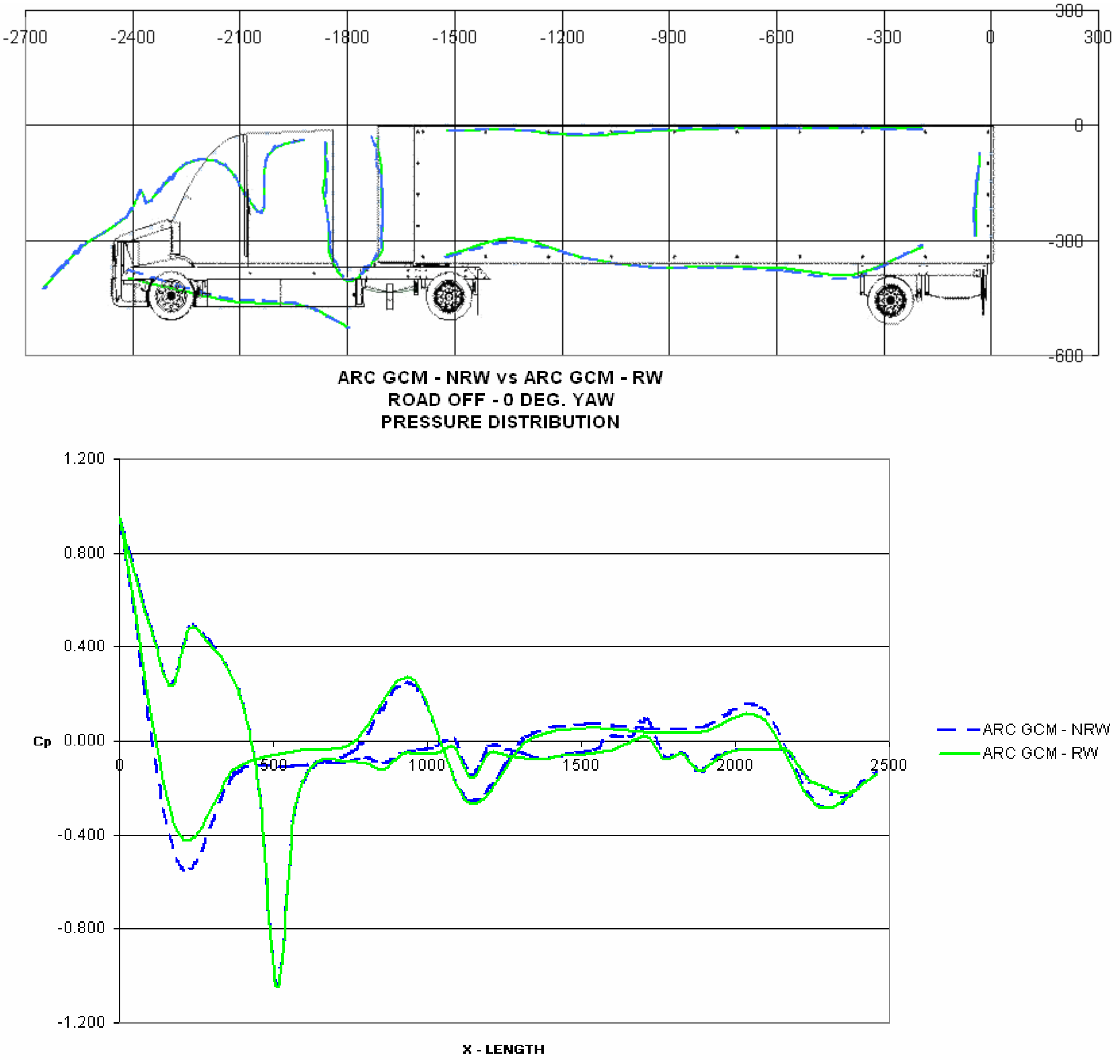


Figure 8: Comparison of ARC's GCM NRW and RW configurations in road off conditions.

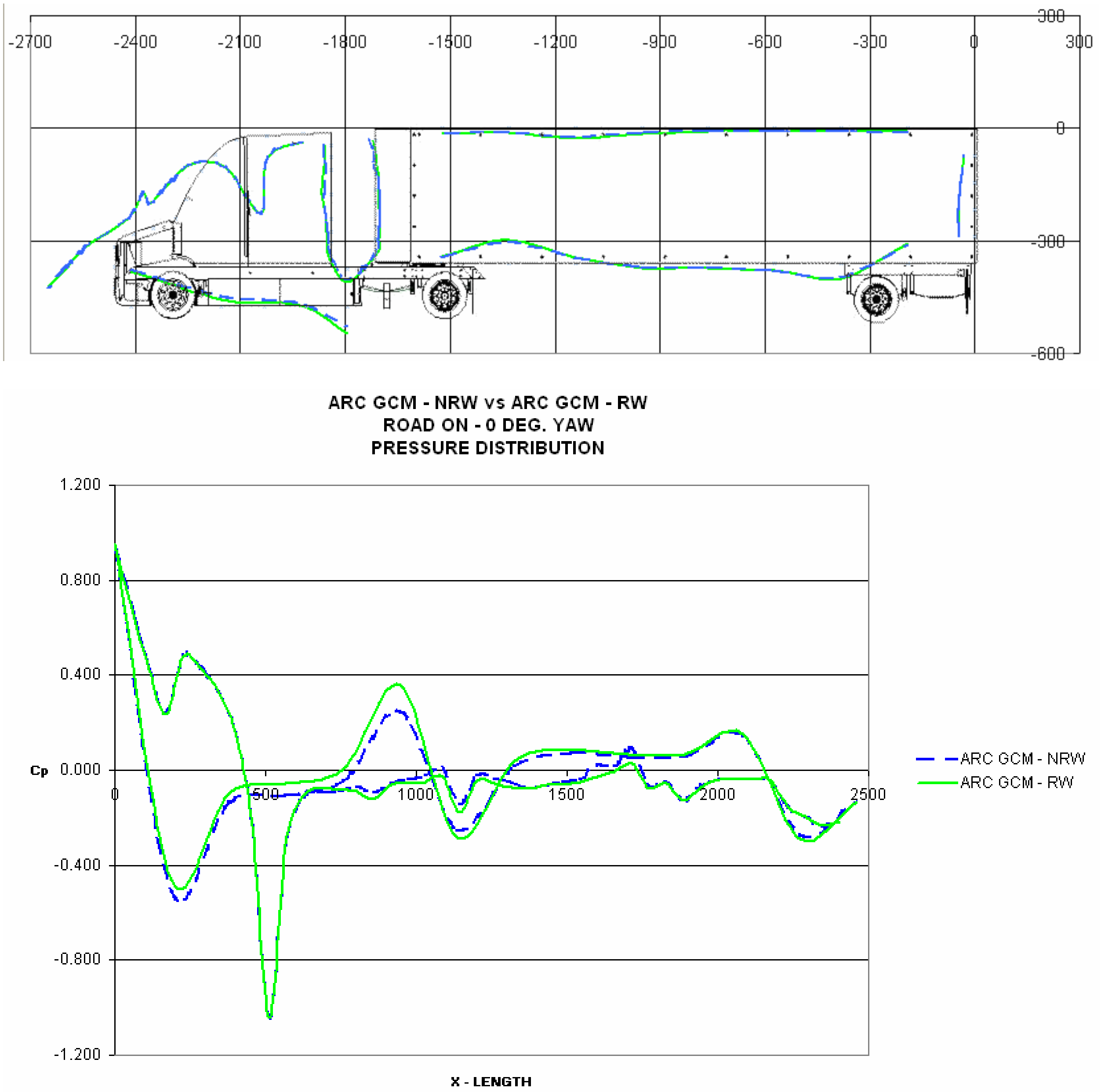


Figure 9: Comparison of ARC's GCM NRW and RW configurations in road on conditions.

In the road off condition, both configurations gave similar pressure distributions. However, the road on conditions showed changes throughout the entire vehicle. This is due to the actual rotating wheels of the ARC GCM RW configuration causing the "wheel pumping" effect.

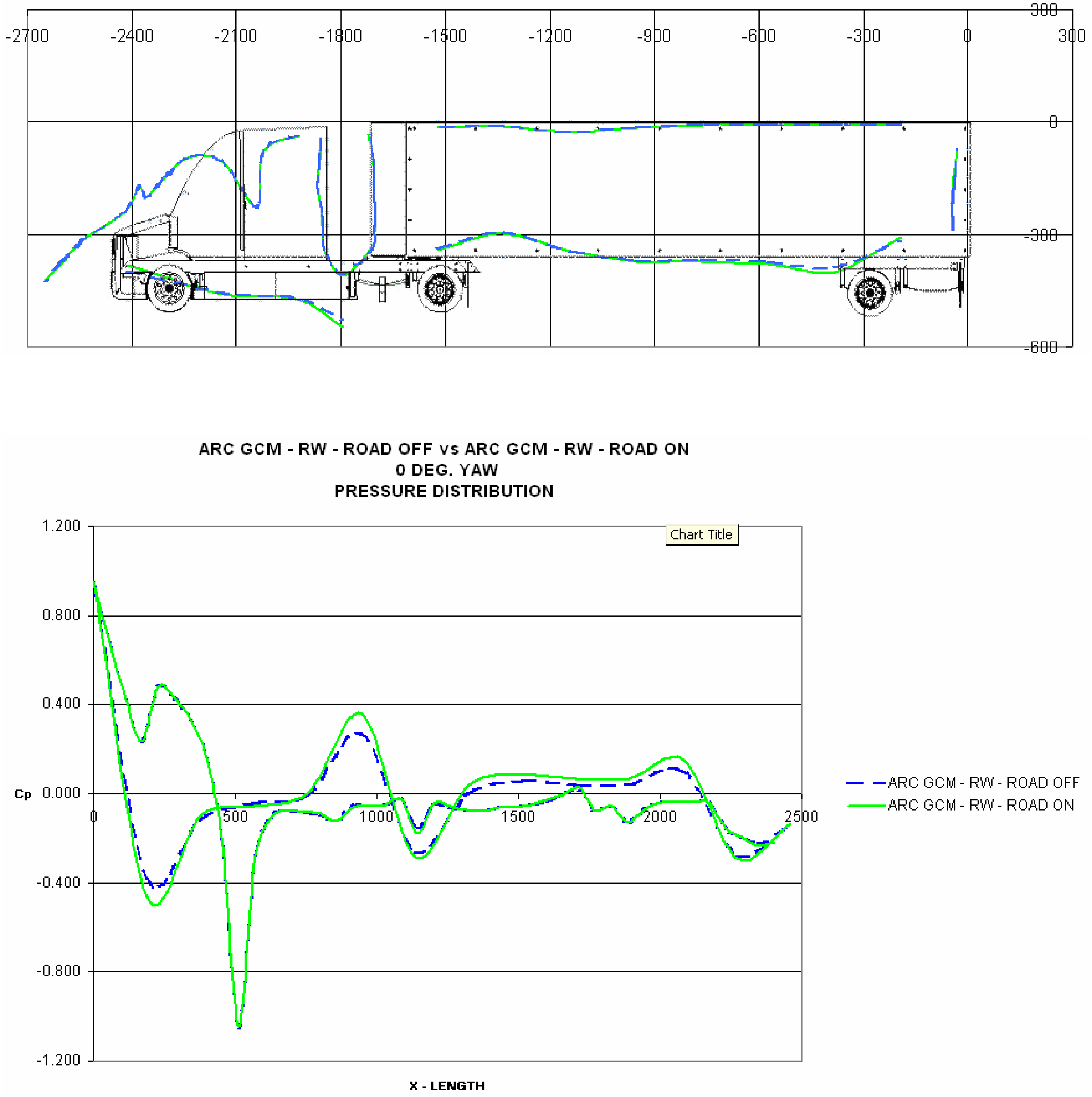


Figure 10: Comparison of ARC's RW configuration in both road off and road on conditions.

In figure 10, the road on condition again shows differences throughout the vehicle length. The larger difference comes from around the wheels and was expected. An interesting observation is the pressure change along the entire trailer. This is caused by the incremental flow field changes from front to back due in part from the rotating wheel's pumping of the air, as well as different flow shedding at different points on the rotating wheels compared to the stationary wheels.

After the initial comparisons with the two different forms of NASA's GCM were concluded and the comparisons showed good correlation to NASA's previous work, ARC changed out models in their tunnel. The next model was a much more detailed semi-truck with particular detailed attention given to the underbody and wheel area. The purpose of an additional model was to validate differences seen between road on versus road off detailed development. All of the changes with this more accurate model were all conducted at a beta angle of 0^o. The reason behind eliminating beta sweeps was to allow for more part changes to be examined between the road on/off conditions.

To begin testing with the more detailed model or MDM, some of the basic elements that would affect the underbody were left off with the idea of adding them on individually to build up to a final realistic configuration. The initial baseline for the MDM began without the landing gear, air tank, spare wheel, rear bumper, chiller unit and the radiator intake completely closed off. Figure 11 shows a table of the results of fitting these standard items in succession in both the road on and road off conditions, respectively.

The measured data with the initial MDM baseline showed an 11.9% increase in drag with the road and wheels rotating compared to the non-rotating measurements, which is consistent with the GCM testing. Adding the landing gear showed the first trend reversal for a model change. With the road not rotating, adding the landing gear showed an increase in drag of 0.64%. With the road rotating, adding the landing gear showed a decrease in drag of 0.38%.

Adding the air tank showed a 1 count drag reduction for both the road off and on conditions or a 0.21% and 0.19% drag reduction respectively. Adding the spare wheel in the road off condition showed no drag change. However, adding the spare wheel in the road on condition showed a 0.38% drag reduction. It is interesting to note that the combined effect of adding the landing gear, air tank and spare wheel in the road off condition results in, there is a drag increase of 0.42% while with the road on it results in a drag reduction of 0.95%. Not only is this a trend reversal, but it offers a variance of approximately 1.4%; this type of trend difference between stationary road and rolling road testing shows the importance of testing with the most realistic conditions possible.

		Road On					**Road Off**			
Comment	**Cd**	**Cl**	**Cs**	**Cym**	**Cpm**	**Cd**	**Cl**	**Cs**	**Cym**	**Cpm**
Baseline MDM	0.527	0.111	-0.019	0.002	-0	0.471	0.091	-0.01	0.006	-0.02
Add Landing Gear	0.525	0.109	-0.026	0.002	0	0.474	0.066	-0.012	0.007	-0.01
Add Air Tank	0.524	0.112	-0.023	0.003	0.001	0.473	0.084	-0.013	0.008	-0.01
Add Spare Wheel	0.522	0.116	-0.022	0.003	0.001	0.473	0.079	-0.009	0.006	-0.01
Add Rear Bumper	0.521	0.097	-0.026	0.003	-0.01	0.469	0.063	-0.018	0.009	-0.01
Add Chiller Unit	0.523	0.093	-0.02	0.004	-0.01	0.472	0.07	-0.012	0.007	-0.01
Add Internal Flow	0.533	0.046	-0.02	0.005	0.035	0.483	0.01	0.002	0.003	0.032

Figure 11: ARC's MDM Data for the addition of standard parts.

As the initial changes to the MDM were to add components that made the MDM even more realistic, the next step was to add some development parts that would alter the flow in critical areas to examine what happens between road on and road off conditions during the development of an improved aerodynamic semi-truck. These parts are not considered to be practical in the sense that they could be employed in current trucks. Instead the parts were developed to highlight the interaction of the underbody flow and rotating wheels and its effect on the overall aerodynamic drag. The types of parts developed, vortex generators and underbody diffusers, are commonly used in race cars to exploit underbody and rotating wheel flow to achieve aerodynamically optimal results To accomplish this, some standard parts had to be removed for certain development parts.

The mud flaps behind the rear wheels of the tractor were removed along with the landing gear. These items were removed to test a simple wheel splitter device. A picture of this rear tractor wheel splitter device can be seen in Figure 12. Figure 13 shows the aerodynamic results of this wheel splitter. Fitting the tractor rear wheel splitter in the road off condition gave a drag increase of 1.04%. Fitting this same splitter in the road on condition gave a 1.52% drag decrease. Again, we see a trend reversal between road on and road off testing.

Figure 12: Development wheel splitter device mounted behind rear truck wheels.

	Road On					Road Off				
Comment	**Cd**	**Cl**	**Cs**	**Cym**	**Cpm**	**Cd**	**Cl**	**Cs**	**Cym**	**Cpm**
Baseline	0.527	0.068	-0.018	0.005	0.042	0.481	0.06	-0.013	0.008	0.044
Rear Wheel Splitter	0.519	0.03	-0.016	0.006	0.037	0.486	0.024	-0.008	0.008	0.043

Figure 13: Comparison of tractor rear wheel splitter on MDM road on/off.

Another development piece tested was a rear trailer diffuser. To test this part, the rear bumper had to be removed. Figure 14 shows a picture of the rear trailer diffuser. Figure 15 shows the table of measured results for the trailer diffuser. Fitting the rear trailer diffuser in the road off condition lost 0.82% of drag. Conversely, fitting this part in the road on condition gave an increase in drag of 0.93%. This part also showed a trend reversal when testing with road off versus road on.

Figure 14: Rear trailer diffuser

		Road On					Road Off			
Comment	**Cd**	**Cl**	**Cs**	**Cym**	**Cpm**	**Cd**	**Cl**	**Cs**	**Cym**	**Cpm**
Baseline	0.536	0.063	-0.017	0.006	0.043	0.486	0.028	-0.005	0.005	0.035
Rear Trailer Diffuser	0.541	0.077	-0.02	0.006	0.049	0.482	0.062	-0.013	0.008	0.058

Figure 15: Effects of rear trailer diffuser on MDM road on/off.

The test conducted by ARC took place over a three day period and testing with the MDM was limited to one day. There were only three development parts tested on the MDM. Two of these three parts resulted in trend reversals. The third and final development item was a set of wheel covers (figure 16). Figure 17 shows the results of fitting this set of wheel covers to the MDM. These wheel covers were fitted while the rear trailer diffuser was still on the MDM. Fitting these wheel covers in the road off condition gave a 3.11% drag reduction. Fitting the same wheel covers in the road on condition gave a 4.44% drag reduction. This test part was the only one out of the three parts to show the same trend, although still a much stronger result in the road on condition. The fact that this change showed the same trend in both road on/off conditions is extremely interesting knowing that the rear trailer diffuser was left on, because the rear trailer diffuser was already identified as having created two distinctively different flow fields around the trailer for each of the road on/off conditions.

Figure 16: Tractor / Trailer Wheel Covers

		Road On					Road Off			
Comment	**Cd**	**Cl**	**Cs**	**Cym**	**Cpm**	**Cd**	**Cl**	**Cs**	**Cym**	**Cpm**
Baseline	0.541	0.077	-0.02	0.006	0.049	0.482	0.062	-0.013	0.008	0.058
Fit Wheel Covers	0.517	0.06	-0.025	0.006	0.047	0.467	0.034	-0.011	0.007	0.046

Figure 17: Effects of fitting wheel covers to the MDM road on/off.

SUMMARY

ARC built a copy of NASA's GCM semi-truck model and tested it in ARC's rolling road capable wind tunnel. Comparison tests between ARC's GCM and NASA's GCM showed good correlation between force and pressure data for the non-rolling road condition through various beta sweeps. Additional comparison runs between ARC's GCM both with non-rotating wheels (NRW) and rotating wheels (RW) were completed. These tests highlighted the importance of understanding and managing the overall flow field resulting from the rolling road effects. For both model configurations, NRW and RW, the road off conditions gave closely matching results. However, the road on condition revealed quantitative differences between the road off conditions with respect towards each model configuration as well as differences between these configurations themselves while tested in the road on condition.

A change in the flow field due to the belt entrainment was separated out from the change in flow fields caused by the rotating wheel "pumping" and rotational wheel shedding. The results concluded that the belt entrainment accounted for 1/3 of the differential, while the wheel pumping and differences in rotational flow shedding accounted for 2/3 of the differential. The individual pressures showed that larger localized differences in the flow field were contained around the wheels themselves, while a consistent growth differential followed the length of the trailer in the rotating wheel, road on measurements.

The ARC detailed model tested in the tunnel represented a more "real world" class 8 truck. Multiple pieces to this model were systematically fitted to build it to a final more accurate specification as individual test runs. While fitting these basic parts, several of them caused a reversal of force trends between the road off and road on conditions. A combination of three of these basic parts, (landing gear, air tank, spare wheel), actually recorded a 0.42% drag increase in the road off condition, while recording a 0.95% drag decrease in the road on condition representing a 1.4% variance.

Three development items were chosen to represent underbody changes that would be influenced by rotating wheels as well as a rotating ground plane. The test items were a tractor rear wheel deflector, a rear trailer diffuser and a set of wheel covers. Two of these three development items showed a trend reversal of the forces. The tractor rear wheel deflector gave a 1.04% drag increase in the road off condition, while giving a 1.52% drag decrease in the road on condition representing a total variance of 2.56%. The rear trailer diffuser gave a 0.82% drag decrease in the road off condition, while giving a 0.93% drag increase for the road on condition representing a variance of 1.75%. Although the wheel covers gave the same force trend for both the road on/off conditions, this change was much larger in the road on condition (1.33% greater change in road on).

During initial testing of ARC's first rolling road scale model semi-truck, it was very quickly discovered that without rolling road testing, semi-truck development could be misleading given the trucking industry's current testing methodologies.

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APPENDIX A

Component		Design Load Range		Calibration Load
Fx	Drag	600N	60Kg	132 Lbs
Fy	Side Force	500N	50Kg	110 Lbs
Fz	Down Force	2000N	200Kg	441 Lbs
Mx	Roll Moment	80Nm	8Kgm	57Ftlbs
My	Pitch Moment	400Nm	40Kgm	289Ftlbs
Mz	Yaw Moment	150Nm	16Kgm	115Ftlbs