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ABSTRACT

Research is being conducted at the Georgia Tech Research Institute (GTRI) to develop advanced aerodynamic devices to improve the performance, economics, stability, handling and safety of operation of Heavy Vehicles by using previously-developed and flight-tested pneumatic (blown) aircraft technology. Recent wind-tunnel investigations of a generic Heavy Vehicle model with blowing slots on both the leading and trailing edges of the trailer have been conducted under contract to the DOE Office of Heavy Vehicle Technologies. These experimental results show overall aerodynamic drag reductions on the Pneumatic Heavy Vehicle of 50% using only 1 psig blowing pressure in the plenums, and over 80% drag reductions if additional blowing air were available. Additionally, an increase in drag force for braking was confirmed by blowing different slots. Lift coefficient was increased for rolling resistance reduction by blowing only the top slot, while downforce was produced for traction increase by blowing only the bottom. Also, side force and yawing moment were generated on either side of the vehicle, and directional stability was restored by blowing the appropriate side slot. These experimental results and the predicted full-scale payoffs are presented in this paper, as is a discussion of additional applications to conventional commercial autos, buses, motor homes, and Sport Utility Vehicles.

INTRODUCTION

Users of heavy trucks such as tractor/trailer combination vehicles face a number of less than optimum operating conditions. Despite significant reductions in drag coefficients in the latest generation of tractors, these Heavy Vehicles (HVs) remain "draggy" compared to much more streamlined automobiles. This is due in part to practical limitations on: physically providing a long smooth aft surface such as a boat tail to prevent flow separation and turbulence at the rear of the trailer; completely sealing the gap between the tractor and the trailer; and smoothing the underbody of the vehicle. In addition, front radiators have not been optimized from a drag-reduction standpoint. Typical drag coefficient values for a variety of HVs can range from 0.65 to 0.9 (from Reference 1). Figure 1 shows the significant fuel savings that can result if the drag coefficient can be reduced. It has been estimated by engineering personnel of the American Trucking Associations (ATA) that, if applied to today's US Heavy Vehicle fleet operating on level roads, these drag reductions approaching 35% could result in roughly 1.2 billion gallons of fuel saved per year. Extrapolated, a 50% drag reduction could save over 1.7 billion gallons of diesel each year. A further result of aerodynamically "dirty" vehicles is the production of splash and spray, a nuisance to motorists and truck drivers alike, as well as turbulence in the vicinity of large vehicles, which is disturbing to passenger car drivers. These shortcomings are explained further in the ATA Statement of Need for Improved Heavy Truck Aerodynamics, Reference 2.

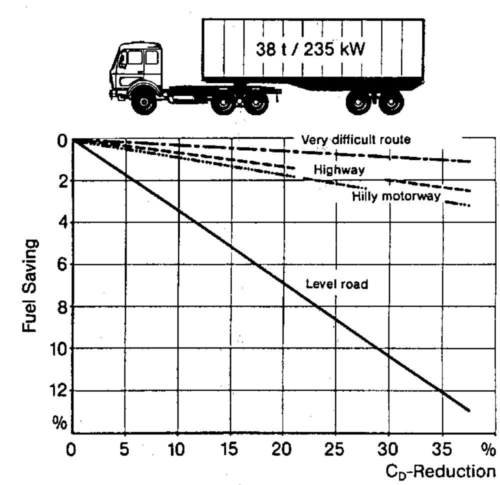


Figure 1 – Effect of Drag Coefficient Reduction on Fuel Consumption (from Ref. 1)

Considerable recent interest has arisen in technology to reduce Heavy Vehicle drag to improve highway operating efficiency, primarily because the drag force rises with the square of the vehicle speed while the required horsepower to overcome that drag increases with the cube of the velocity. With fuel prices rising dramatically recently, drag reduction is thus a vital concern to the trucking industry. However, appreciable additional gains can also be had by careful control of aerodynamic forces and moments other than drag, which for the most part have been ignored in current truck design and operation. For instance, the creation of lift on the vehicle (effective weight reduction) can unload the tires and reduce rolling resistance, while creation of negative lift or downforce can increase "weight" on the wheels and traction, thus increasing braking as well as handling in wet/icy weather. This aerodynamic download can also eliminate hydroplaning. While it has been shown that drag increases greatly due to side wind or yaw angle (Refs. 1 and 3), side wind presence also implies increased side force and yawing moment on the trailer, thus reducing its directional stability and safety. Safety, stability and handling can be enhanced by blowing control of side loads and moments on these Heavy Vehicles if caused by side winds, gusts or other vehicles passing. An aerodynamically-controlled concept may also help to eliminate the jack-knifing problem if resulting from extreme wind side loads on the trailer. Lastly, there are instances where additional drag increase is desirable, such as steep downhill operations in mountains, or sudden need for emergency braking from high speed.

Based on the above considerations, it should be quite desirable to develop aerodynamic devices that could achieve at least two or more of these potential gains while requiring little mechanical restriction or impact on vehicle operation. Recent aerodynamic research (Reference 3) at GTRI's Aerospace, Transportation and Advanced Systems Lab has identified significant reductions and/or augmentations of vehicle forces and moments which can be achieved on automotive vehicles by the use of tangential injection of pressurized air into the vehicle's aft region, strongly modifying the aerodynamic flowfield around that vehicle. Since momentum injection can affect the vehicle's lift, drag, and side force as well as aerodynamic moments, the impact of blowing on the performance, safety, economics and stability appears to offer significant improvements in Heavy Vehicle operation. These potential gains have led to a current research program being conducted at GTRI for the DOE Office of Heavy Vehicle Technologies (Reference 4). A description of this program and the novel aerodynamic technology being employed is provided in Reference 5. Since that paper was presented in June, 2000, two series of wind-tunnel evaluations have been conducted at GTRI to confirm aerodynamic improvements yielded first by novel unblown geometry changes, and second by the addition of blowing to various portions of a Heavy Vehicle model. The objectives of these tests were to verify the blown concept's capabilities to: reduce aerodynamic drag for efficiency or increase drag for braking; increase lift to reduce tire rolling resistance or reduce lift to increase traction and braking; and provide increased lateral/directional stability and safety, all without use of external moving aerodynamic components. The present paper first describes the basis of pneumatic aerodynamics and its application to Heavy Vehicles, and then provides details of the two wind-tunnel programs, their results, and possible future applications.

PNEUMATIC AERODYNAMICS

GTRI researchers have been involved for a number of years in the development of pneumatic (pressurized air blowing) concepts to yield efficient yet mechanically simple means to control and augment or reduce the aerodynamic forces and moments acting on aircraft. This was detailed in References 5, 6, 7, and 8, but will be summarized briefly here to familiarize the reader with the technology. Figure 2 shows the basic pneumatic concept, which has become known as Circulation Control (CC) aerodynamics. Here, an airfoil's conventional mechanical trailing edge device has been replaced with a fixed curved surface and a tangential slot ejecting a jet sheet over that surface. That jet remains attached to the curved surface by a balance between sub-ambient static pressure on the surface and centrifugal force (the so-called Coanda Effect, Reference 8). This greatly entrains the external flowfield to follow the jet, and thus enhances the circulation around the airfoil and the aerodynamic forces produced by it. The governing parameter is not angle of attack, but rather the blowing momentum coefficient:

$$C_\mu = m\, V_j / (q\, S)$$

where m is the jet mass flow, V_j the isentropic jet velocity, S is a reference wing area (or frontal area A for a vehicle configuration) and q is the freestream dynamic pressure, $0.5\ \rho\ V^2$, with ρ being the free-stream density, not the jet's density. At lower blowing coefficient (C_μ) values, augmentation of the aerodynamic lift by a factor of $\Delta C_l / C_\mu = 80$ has been recorded (Ref. 8), representing an 8000% return on the invested momentum (which in a physical sense is also equal to the jet thrust). Familiarity with blown

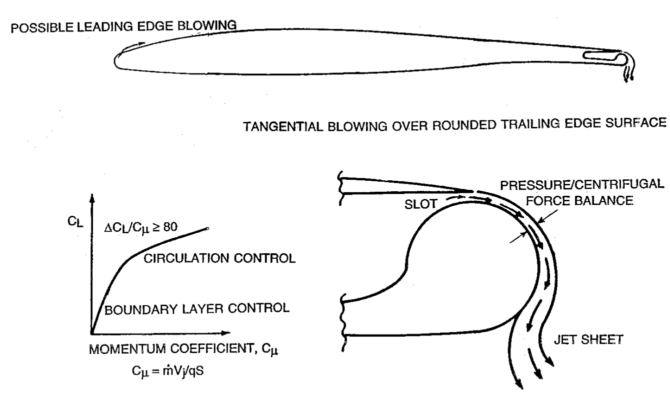


Figure 2 – Basics of Circulation Control Aerodynamics on a Simple 2-D Airfoil

aerodynamic systems will remind the reader that this is quite extraordinary: thrust-deflecting Vertical Take-Off and Landing (VTOL) aircraft are fortunate if they recover anything near 100% of the engine thrust expended for vertical lift. It is because of this high return, or conversely, because of very low required blowing input and associated power required to achieve a desired lift, that Circulation Control airfoils appear very promising for a number of applications. The A-6/CC Wing Short Take Off & Landing (STOL) flight demonstrator aircraft (Figure 3 and Reference 6) showed the STOL performance listed, but also suggested capabilities very useful to ground vehicles: during short takeoff, it demonstrated very high lift and reduced drag, while in the approach/landing mode, high lift with high drag was shown.

These advantages led to the application of this pneumatic concept to improve the aerodynamics of an already streamlined car (Reference 3). The resulting large jet turning angle and the curved rear of the vehicle are shown in Figure 4. Significant but distinctly different trends were observed depending upon which portion of the tangential slot was blown. Blowing the full slot produced the large jet turning in Figure 4, and drag increases of greater than 70%, showing potential for pneumatic aerodynamic braking. Blowing only the outside corner of the slot weakened the corner vortex rollup, lessened aft suction, and reduced drag by as much as 35% (refer back to Figure 1 for representative fuel savings). Blowing the aft slot also yielded a lift increase of 170%. One can envision a similar slot applied to the lower rear surface that could yield negative lift or positive down force instead. This concept has been patented by GTRI and verified by a similar installation on a model of a European Formula 1 race car (Reference 5).

Flight Test Results:140% Increase in Usable Lift Coefficient, C_L
30-35% Reduction in Takeoff & Approach Flight Speeds
60-65% Reduction in Takeoff & Landing Ground Rolls
75% Increase in Liftable Takeoff Payload
Confirmation of Full-Scale Blown CCW Operation

Figure 3 – A-6/CCW STOL Flight Tests Confirming Pneumatic Devices for Aerodynamic Force Augmentation or Reduction

Figure 4 - Experimental Confirmation of Pneumatic Technology on a Streamlined Car; Aft View showing Blown Jet Turning

DOE PNEUMATIC HEAVY VEHICLE PROGRAM TEST RESULTS

Based on the above results, a research program was initiated at GTRI for the Department of Energy's Office of Heavy Vehicle Technologies (Reference 4). The goal was to apply this pneumatic technology to tractor-trailer configurations to develop an experimental proof-of-concept evaluation that would hopefully lead to an on-the-road demonstration on an operating blown Pneumatic Heavy Vehicle (PHV). Portions of that effort, including a preliminary feasibility study, Computational Fluid Dynamics (CFD) pneumatic analyses, and design of baseline and pneumatic wind-tunnel configurations, have been completed and were reported in Reference 5. Figure 5 shows a possible schematic of a generic Pneumatic Heavy Vehicle with tangential blowing slots on each of the trailer's aft edges as well as blowing on the rounded upper leading edge of the trailer.

PHASE I WIND-TUNNEL EVALUATIONS OF BASELINE UNBLOWN HV-

To serve as a reference and to investigate initial non-blown aerodynamic improvements, a Phase I baseline wind-tunnel test was conducted. For this, a baseline model was needed to act as a standard prior to the planned blowing tests, and as a basis upon which to install the pneumatic model configuration. A team of current researchers working for DOE on the HV aerodynamic drag problem had determined that an existing generic Heavy Vehicle configuration, the Ground Transportation Systems (GTS) vehicle of Reference 9, was quite appropriate. It is sketched in Figure 6, and is actually representative of a faired cab-over-engine vehicle based on the Penske racing team's car carrier, before the blowing modifications shown were installed. As such, it is relatively generic and independent of the numerous and varying cab roof fairings employed on a number of current Heavy Vehicles.

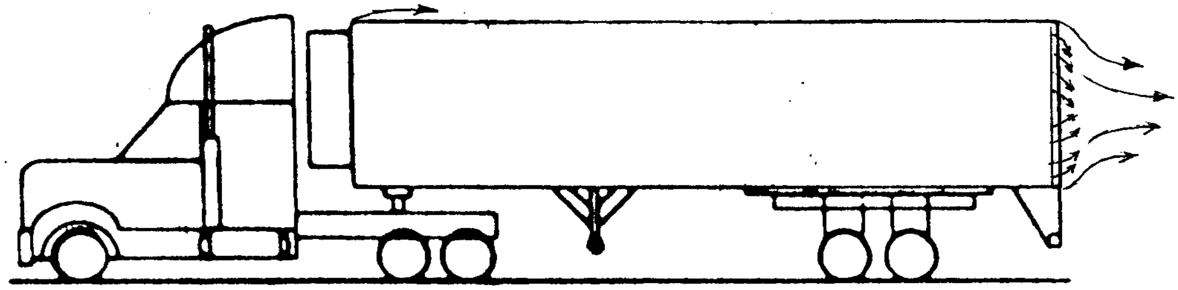


Figure 5 – Schematic of Application of GTRI Pneumatic Aerodynamic Technology to Heavy Vehicle Trailer, Showing 4 Aft Blowing Slots and Upper Leading-Edge Blowing Slot

Full Scale Vehicle: W=8.5', H=13.5', $L_{TRAILER}$=48', L_{RIG}=65'; at V=70 mph, $Re_{Trailer}$ =29.3x10^6

Model:

Blockage	W,in.	H.in.	Scale	$L_{TRAILER}$,in.	L_{RIG},in.	$Re_{Trailer}$(V=70 mph)	(q=50 psf)
0.051	6.63	10.53	.0650	37.44	50.70	1.90x10^6	3.90x10^6

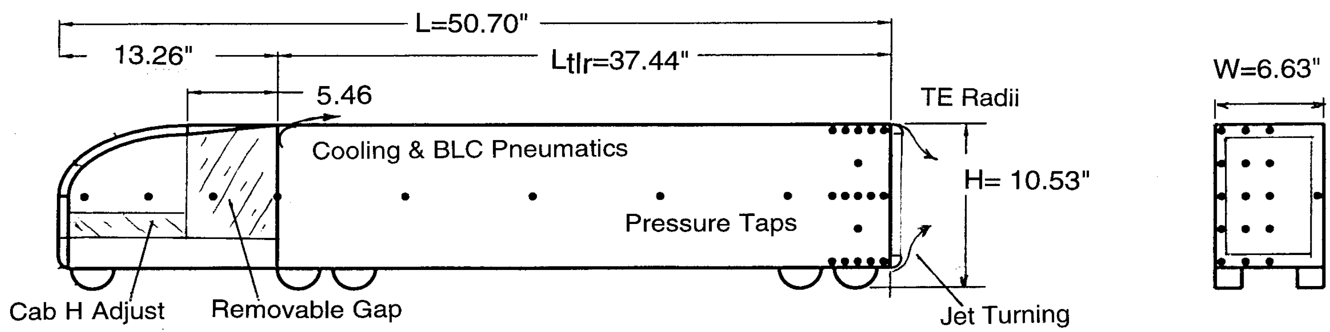


Figure 6 - GTRI 0.065-scale Baseline GTS & PHV Wind-Tunnel Model and Variables

(a) Full-Height Tractor and Yawed Trailer with Rounded Leading Edge and Square Trailing Edge

Figure 7 – Various Configurations of GTRI's Baseline GTS Model, Full Open Gap

(b) Shorter-Height Tractor, Unyawed Trailer

(c) Front Wheels removed

Figure 7 (continued) – Various Configurations of GTRI's Baseline GTS Model, Full Open Gap

Before being fabricated as a valid wind-tunnel model, issues such as model size, wind tunnel blockage and test Reynolds number were important. The test model was scaled to be compatible with the GTRI tunnel test section area of 1290 in^2. Based on Reference 10 criteria, a physical blockage of 5 to 6 percent of tunnel area was desired, as well as a reasonably high Reynolds number. Figure 6 shows that a 0.065-scale model produces a blockage of 5.1% and Reynolds number based on trailer length of 1.90×10^6 at V=70 mph, or 3.90×10^6 at maximum tunnel speed. These factors were incorporated into the Figure 6 design, and fabricated into the model of Figure 7 by prototype shop Novatek Inc. of Smyrna, GA. Here, a number of parameters are variable, including cab/trailer gap, cab height, a removable gap fairing, trailer leading-edge and trailing-edge radii, wheels on/off, vehicle height above the road (floor) and yaw angle between the tractor and trailer. The model was mounted on a single strut, which was hollow and was later used as the blowing air supply duct into the model. This strut was mounted on a six-component floor balance below the tunnel floor, which could be yawed and raised vertically to vary ground clearance height. The test setup will be very similar to that described in Reference 3 for the blown streamlined car test program. Particle-imaging laser velocimeter data were used to quantify the flowfield characteristics aft of the vehicle.

The Phase I unblown investigations were intended to determine the effects of various cab/trailer geometries prior to initiation of the blowing tests. Figures 8 and 9 are plots of drag coefficient (based on a model truck projected frontal area of A=0.4542 ft^2, including the wheel projections) versus freestream dynamic pressure, $q = 1/2\ \rho V^2$. Reynolds number (now based on vehicle total length) and several wind speeds in mph are also shown. The uppermost curve of Figure 8 shows a cab height lower than the trailer height, and a rather large gap (0.824 x width) between the cab and trailer. The flow visualization tuft seen in the gap shows significant separation and vorticity there, and the flow unsteadiness is also seen in the data-point scatter for that run. Raising the cab height to a value level with the trailer reduces the drag coefficient by 7% at 70 mph because it shields the sharp square leading edge of the trailer. Then, filling the gap entirely ("Hi Cab, No Gap") reduces C_D by another 20.1%, or 25.7% from the initial configuration. Whereas this solid configuration is not actually possible because of the need for some clearance/movement between the cab and trailer, it does represent an ideal, which might nearly be achieved by flexible connections. Figure 8 also notes the significant drag reduction if the wheels are removed. This also is not a feasible configuration, but identifies the large drag increment which must be added back to model test data or CFD predictions for non-wheeled HV models. Notice in all of these runs that as the regions of separated flow are reduced, so also are the C_D values and the C_D variations with Reynolds number, i.e., the C_D versus q curves become flatter, and the percentage drag reductions become greater. For reference, the full-scale HV at 70 mph would experience a Reynolds number of 40.0×10^6 at sea-level standard-day conditions.

Figure 9 shows additional drag reductions due to further geometry improvement. Run 19 is the "No Gap" configuration from Figure 8. The curve immediately above it shows a drag increase if the no-gap cab is lowered slightly and exposes the square leading (LE) edge of the trailer. This is an actual condition seen on many current faired HVs, where the fairing frequently does not extend high enough to totally shield the trailer's square top LE corner. However, for the same height difference, if the square top LE of the trailer is merely rounded (here a 3/8"radius is sufficient), C_D is reduced by 8.3%. Then, if a 90° arc with 3/4" radius is added to each of the aft edges of the trailer (this represents the unblown pneumatic trailing edge (TE), see Figure 21 of Reference 5), an additional 7.3% drag reduction occurs due to aft flow reattachment and reduced separation. Thus, adding unblown LE and TE rounded corners reduces drag by 15% over the square LE/TE configuration. Significant improvement has been achieved by the pneumatic LE and TE geometries before blowing has even been applied. It should be noted that in both of these figures, and in all the following data, the HV model was situated so that the

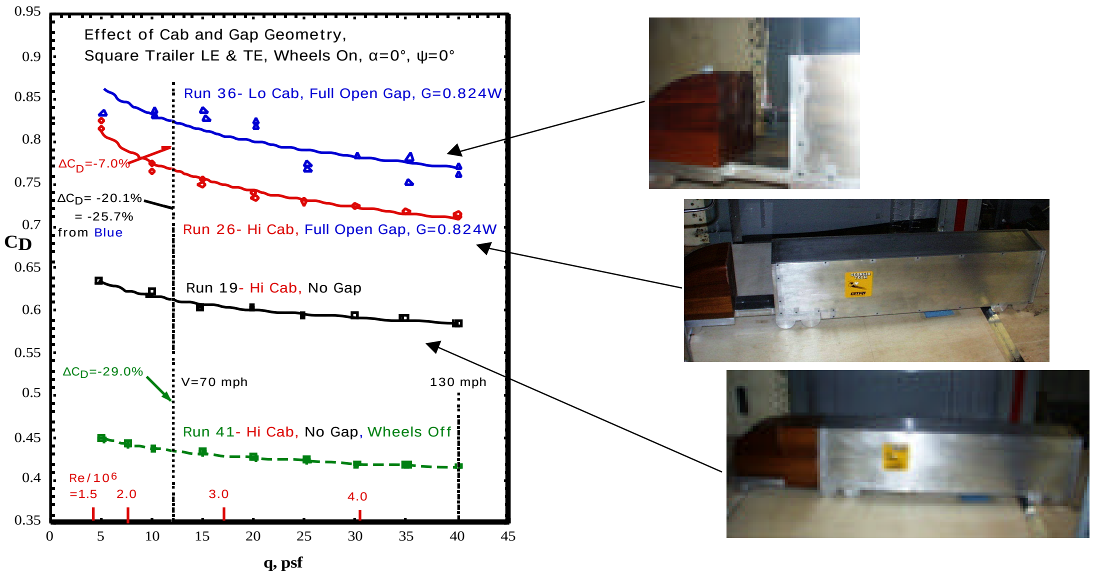


Figure 8 - Phase I Test Results for Unblown Configurations, Showing Effects of Cab Height, Cab/Trailer Gap, Reynolds Number and Wheels

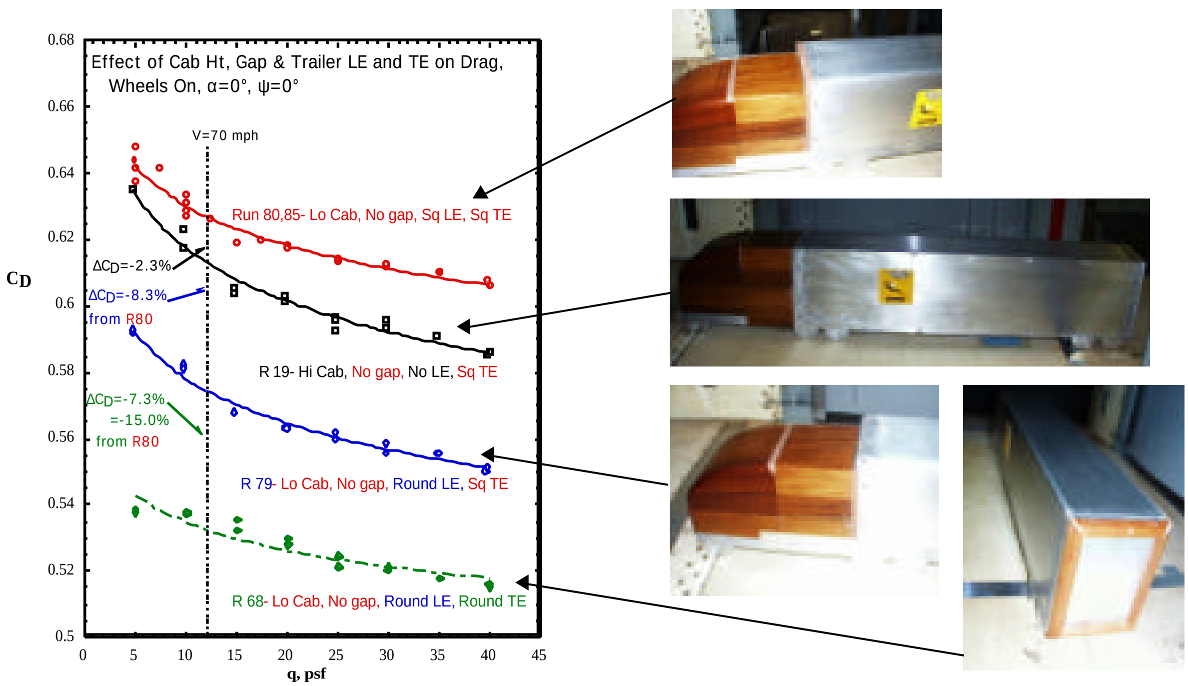


Figure 9 - Phase I Test Results for Unblown Configurations with No Gap, Showing Effects of Cab Height and Trailer Leading– and Trailing- Edge Geometries

wheels were 0.06” above the tunnel floor, and the tunnel boundary layer was eliminated by tangential floor blowing (see Reference 3).

Phase I also investigated the effects of side winds (yaw angle) on the forces, moments and stability of the unblown HV. Figure 10 shows drag variation with side-wind angles up to ±14°. Not only do the open-gap configurations have higher zero-yaw drag values, but they also show dramatic drag increases by a factor of 2 or more with side winds as low as only 5-7° due to higher separation and greater yawed-flow over-pressures on the trailer front face. The “no-gap” models show much lower zero-yaw drag as well as lesser drag increases with yaw because these detrimental gap effects don’t occur. Figure 11 shows resulting side force and yawing moment for these same configurations. Whereas there is little difference in side force (C_Y) for those configurations, the models with a gap show much less yawing moment (C_N) versus yaw angle and thus much less loss in directional stability ($C_{N\psi} = dC_N/d\psi$) than the non-gapped models. Thus the lower-drag “No-Gap” HVs may encounter a problem with directional stability, as implied here.

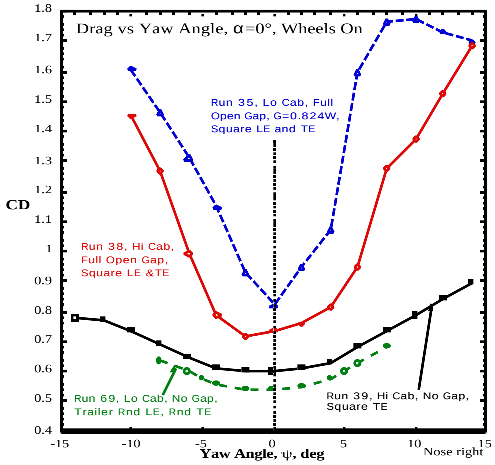
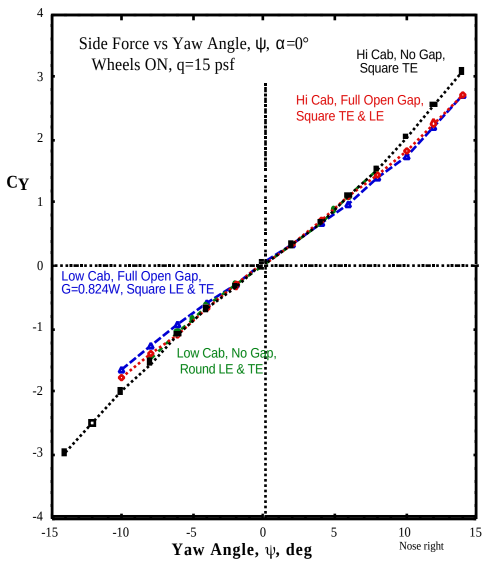
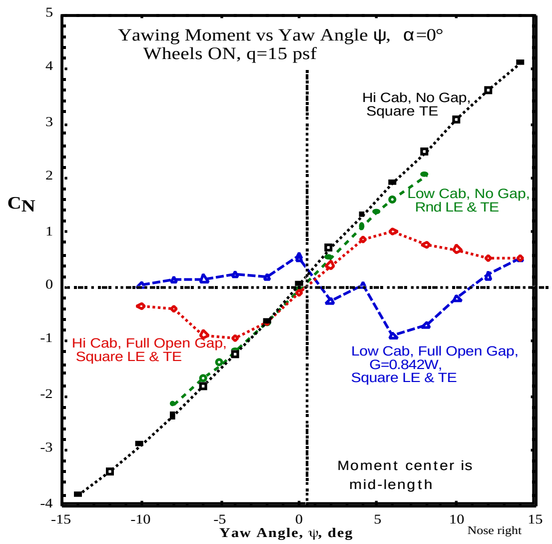


Figure 10 - Effects of Side Winds on Drag for Various Unblown HV Model Configurations



(a.) Side Force



(b.) Yawing Moment about Mid-Length

Figure 11 – Effects of Side Winds on Stability (Positive $dC_N/d\Psi$ is Directionally Unstable)

PHASE II WIND-TUNNEL EVALUATIONS OF BLOWN HV CONFIGURATIONS-

Based on the lower-drag configurations of Phase I, Phase II was intended to evaluate the additional aerodynamic improvements resulting from various blown configurations. Phase II consisted of 99 wind tunnel runs evaluating a range of pneumatic configurations and parameters, including:

- Blown trailer trailing-edge (TE) radius, jet turning angle, jet slot height, blown slot combinations and TE geometry modifications
- Blown trailer leading-edge (LE) radius and blown slot combinations
- Blowing pressure, jet velocity, mass flow, and momentum coefficient, C_μ
- Tunnel dynamic pressures from 5 to 40 psf, wind speeds from 45.9 to 129.8 mph and Reynolds number (based on tractor/trailer total length) from 1.61×10^6 to 4.61×10^6
- Trailer wheel configuration
- Gap between cab and trailer, plus gap side plates
- Yaw (side wind) angle

Details of these investigations are presented in the following sections and emphasize near-term aerodynamic improvements generated by these pneumatic devices. Unless otherwise noted, the blowing variations were run at tunnel (vehicle) wind speeds of approximately 70-71 mph (q=11.86 psf) and blowing slot heights set at h= 0.01”, if not closed.

Drag Reductions (Fuel Economy) or Increases (Braking & Stability)- The slot heights at each aft edge of the trailer could be tested either unblown or blown in any combination of the 4, or later, with the leading edge slots on the trailer front face also blown. Flow visualization tufts in Figure 12 show jet turning of 90° on all four sides, even the bottom slot blowing upwards. This is the 0.75” radius TE configuration. Figure 13 shows even greater turning for the smaller radius (0.375”R) TE surfaces. This smaller radius on the 0.065-scale model represents a full-sized turning radius of only 5.77”. Figure 14 shows the results of this jet turning on reducing or increasing aerodynamic drag by blowing various combinations of these aft slots. In order to represent meaningful values of the jet velocity/free stream velocity ratio, these data were run at blockage-corrected tunnel speeds of approximately 70-71 mph, dynamic pressure of 11.86 psf and $Re=2.51 \times 10^6$ based on tractor/trailer length. The combination of all 4 slots at the same slot height blowing together yielded the greatest drag reduction, more effective than blowing individual slots. Compared to the typical unblown baseline configuration from Phase I (full gap between cab and trailer, square trailer LE and TE, and cab fairing slightly lower than the trailer front) which produced a C_D =0.824 at this Reynolds number, the blown configuration reduced drag coefficient to 0.459 at C_μ = 0.065. This is a 44% C_D reduction, and the internal plenum blowing pressure required was only 0.5 psig. A second blown configuration (labeled 90°/30° TE) used less jet turning on the upper and lower surfaces to generate even greater drag reduction: at 0.5 psig, C_D was reduced by 47%, and at 1.0 psig (C_μ=0.13), C_D was reduced by 50%.

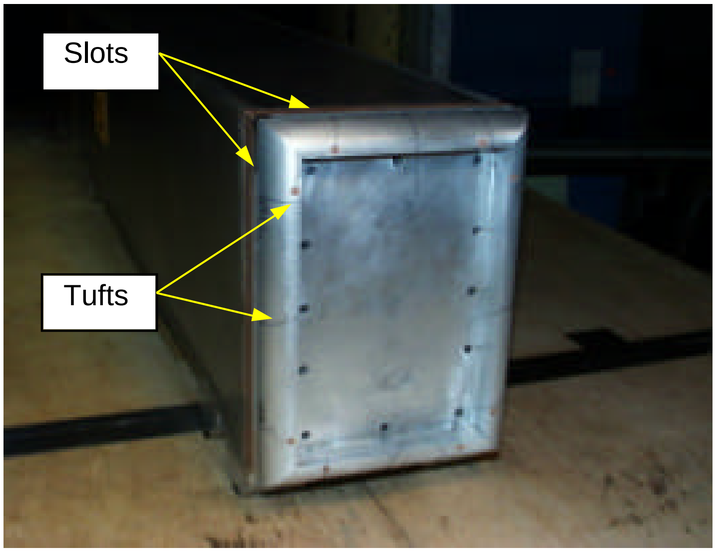


Figure 12–Jet Turning on all 4 Sides of Blown TE, 0.75"R

Figure 13 – Jet Turning on Smaller 0.375"R, 90°/30°Blown Trailer TE with 1/2" plates

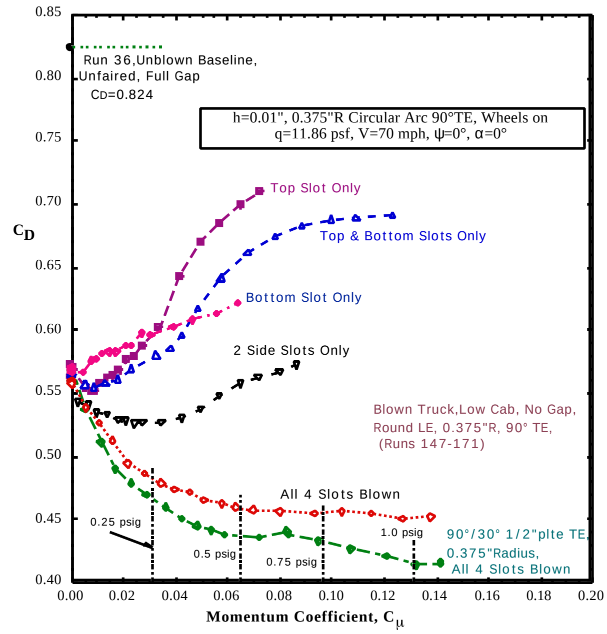


Figure 14 - Drag Reduction or Augmentation on Blown Trailer with 0.375"R Turning Surfaces

When only the top slot, the bottom slot, or both of these slots were blown in the absence of the side jets, drag initially reduced slightly, but then significantly increased with the addition of blowing. This represents an excellent aerodynamic braking capability to supplement the hydraulic brakes. Blowing efficiency is plotted in Figure 15, where ΔC_D is an increment from the blowing-off value (negative ΔC_D is reduced drag). Absolute values of $\Delta C_D/C_\mu$ greater than 1.0 represent greater than 100% return on the input blowing C_μ = (total mass flow x jet velocity) / (tunnel dynamic pressure x frontal area). It is seen that the 4-slotted configuration generates values as high as -5.50, representing 550% of the input blowing momentum recovered as drag reduction. The figure also shows the opposite trend as well, with up to 200% of the blowing momentum from top/bottom slots recovered as increased drag for braking. When $\Delta C_D/C_\mu$ is less than ±1.0, the blowing efficiency diminishes.

However, should additional air be available from an onboard source such as an existing turbocharger or an electric blower, additional drag reduction is possible, as shown in Figure 16. The drag on the previous "worst unblown baseline configuration" with a large open cab/trailer gap is reduced 30% by the blown configuration. Drag coefficients of less than 0.30 are shown for faired blown HV configurations. This is in the arena of streamlined sports cars. The drag coefficient of a 1999 Corvette coupe is C_D = 0.29. Figure 17 shows drag reductions as high as 590 to 600% of the input blowing momentum for the Figure 16 configurations, with the greatest reductions occurring on the previous "worst" unblown configurations due to their large regions of separated flow. Figure 18, originally intended to show that the drag curves tend to converge onto one slope independent of Reynolds number, also shows a measured drag coefficient of 0.13 for a Pneumatic Heavy Vehicle. This is less than half the drag coefficient value of the Corvette as well as the new Honda Insight (C_D=0.25). Even though not achieved in the most efficient blowing operation range, this is an 84% drag reduction compared to the unblown baseline configuration. Note that the tractor cab in Figure 18 has “gap plates” (or fairing extensions) instead of the full “No Gap” fairing, and is thus much closer to actual tractor/trailer configurations.

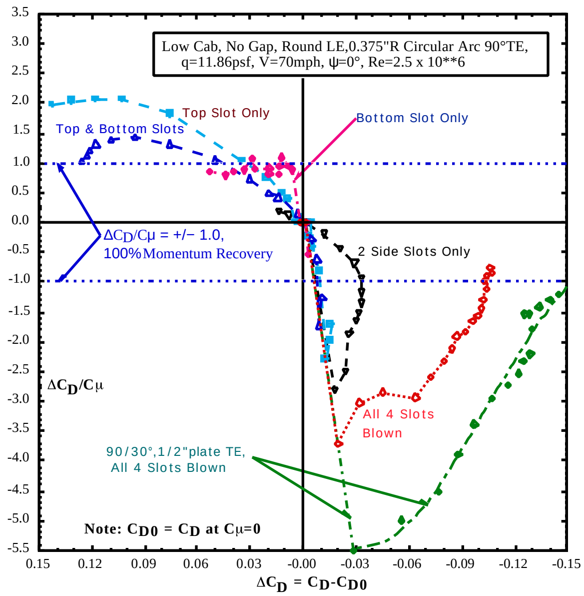


Figure 15 - Blowing Efficiency & Drag Increments due to Blowing Slot Configuration

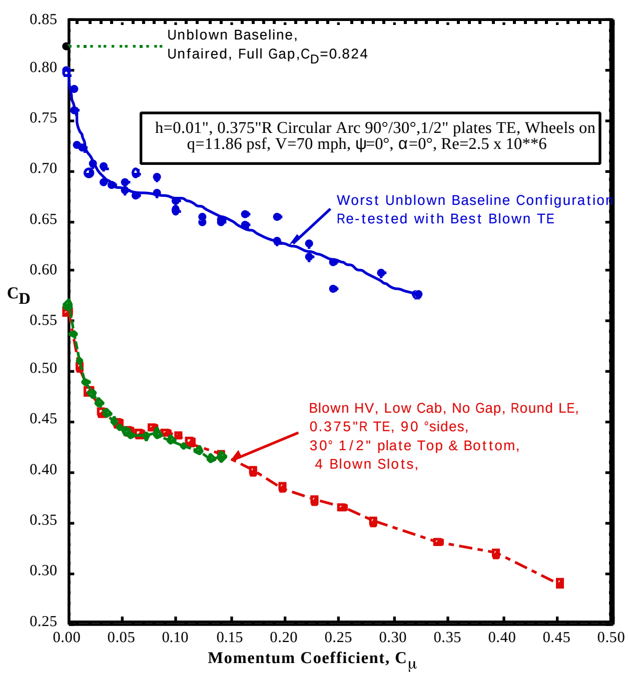


Figure 16 - Additional Drag Reductions and Comparative Configurations

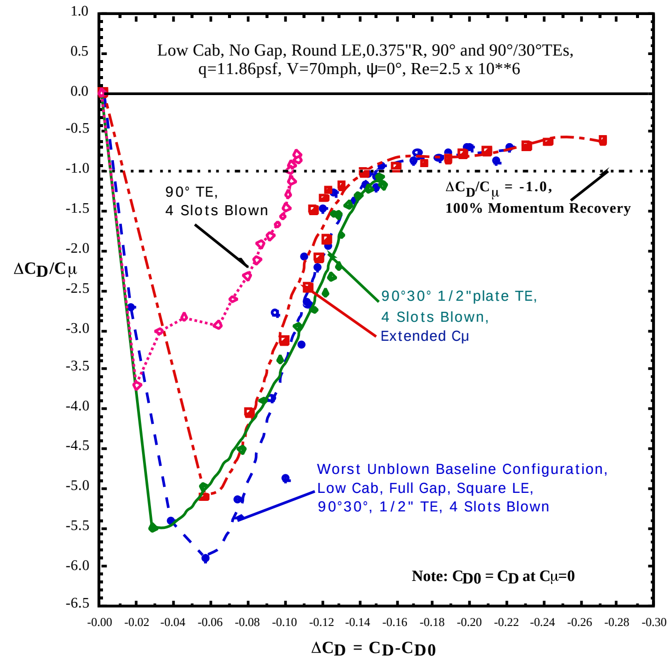


Figure 17 - Blowing Efficiencies and Drag Increments at Increased Blowing Levels

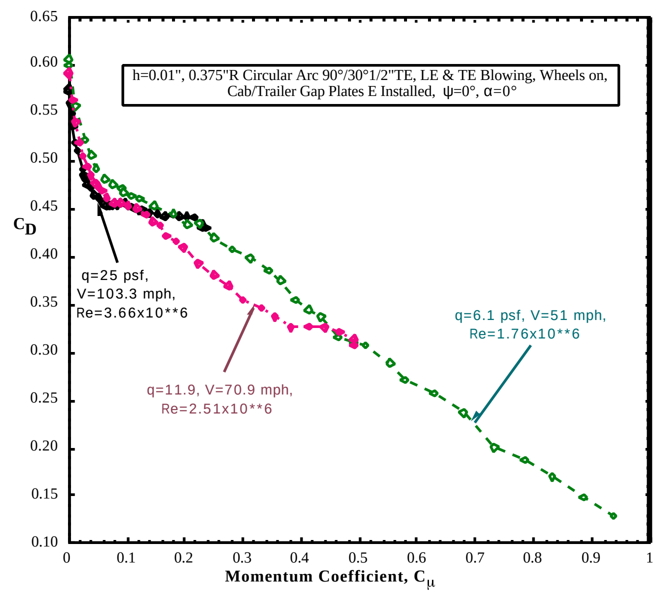


Figure 18 - Reynolds Number Effects and Increased Blowing Values, Plus Leading-Edge Blowing and Cab Gap Plates

It should again be mentioned when comparing these data to other experiments on similar GTS models being conducted by other researchers, that these GTRI data above and below include simulated wheels, which as Figure 8 shows, should add about ΔC_D = 0.18 to these non-wheeled vehicles’ C_D values, perhaps more, depending on how well the tunnel ground effects are treated experimentally. GTRI measured data are generated using test section tangential floor blowing to eliminate the floor boundary layer interference, as discussed in References 3 and 11.

Lift and Down Force Generation- Figure 19 shows lift and down force generated by various slot combinations for the blowing configurations of Figure 14. The baseline unblown configurations show slight positive lift due to underbody overpressures and cab upper surface curvature. Blowing the trailer upper slot alone can more than triple these values, which can be used to "lighten" the vehicle and thus reduce tire rolling resistance. Conversely, blowing the bottom slot can generate a down force increment 2.5 times the unblown lift, which can thus increase traction, increase braking, and reduce hydroplaning.

Stability and Control-Strong directional instability can be experienced by Heavy Vehicles at yaw angles (i.e., experiencing a side wind) because of large side forces on the flat-sided trailers (see Figure 11). Figure 20 shows the yawed model and the unblown aft pneumatic surfaces. This yaw sensitivity is confirmed by the unblown (C_μ = 0) half-chord yawing moment C_N shown in Figure 21, where yaw angle as small as -8° produces a large unblown yawing moment coefficient of C_N=-2.0 about the model mid-length.

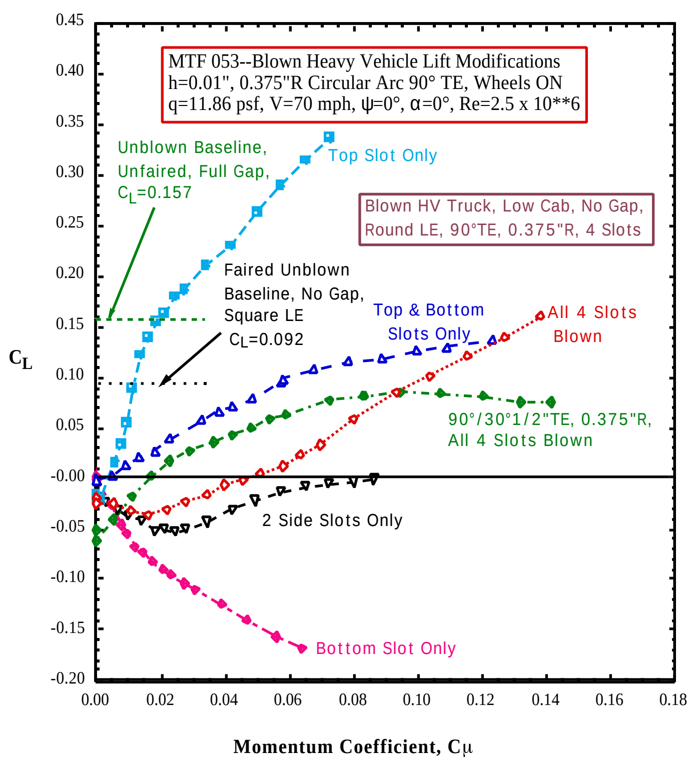


Figure 19 -Lift and Downforce Generation on Blown Trailer with 0.375"R Turning Surface

Figure 20 - Pneumatic Heavy Vehicle Model Installed Yawed (at Side-Wind Angle) in the GTRI Model Test Facility Subsonic Wind Tunnel

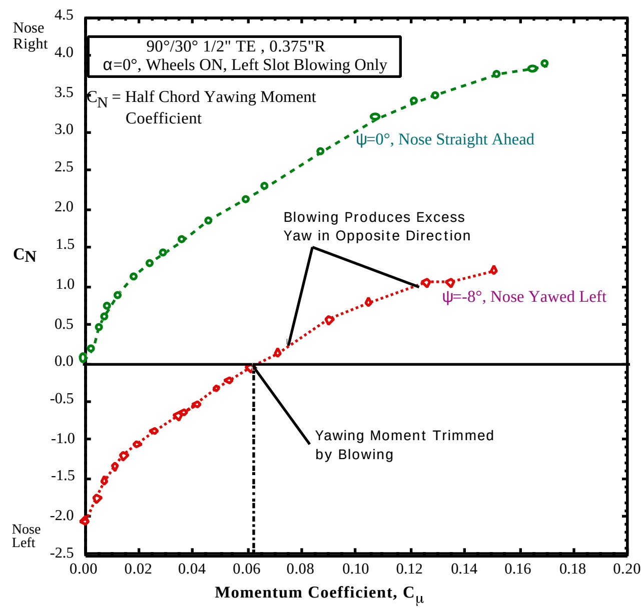


Figure 21 - Directional Control Capability Provided by Blown HV Configuration

Blowing only one side slot can easily correct this: with the nose straight ahead, blowing the left slot at C_μ = 0.06 yields the equivalent opposite yawing moment (C_N=+2.0). With the nose yawed left (for example, ψ = -8°), slightly higher blowing (C_μ = 0.065) returns this unstable yawing moment to C_N=0.0. Then, increasing the blowing a bit more causes the nose to yaw in the opposite direction, to the right. The opportunity for a no-moving-part quick-response aerodynamic control system is apparent.

BLOWING EFFECT ON PERFORMANCE AND BLOWING POWER REQUIRED

To evaluate the effects on performance which can be produced by the above pneumatic changes in aerodynamic lift and drag, required power was calculated for a range of highway speeds. Figure 22 shows the results for a hypothetical 65,000 pound 18-wheel tractor-trailer rig with a frontal area of 107.5 sq. ft. traveling over flat highway at sea level. Three cases are considered: a conventional rig with $C_D = 0.80$ (from Reference 1, typical); a pneumatic rig showing a 35% drag reduction (i.e., the Reference 3 pneumatic streamlined car's drag reduction levels); and a pneumatic rig with a 50% drag reduction below the conventional rig (from Figure 14). This produces the three "Aerodynamic" horsepower-required curves, where drag force $D = C_D\, q\, A = C_D\,(0.5\, \rho\, V^2)\, A$, and $HP_{req'd} = DV/550$. Thus the required *aerodynamic* horsepower reduces in the same proportion as the drag coefficient, i.e., 35 or 50% at any given speed. Also included here is horsepower required to overcome rolling resistance of the tires, which is directly proportional to effective weight on the wheels times the effective tire friction coefficient, taken here to be 0.015. For the conventional rig, the HP to overcome rolling resistance varies linearly with velocity. For the blown configurations, lift varies with blowing available and dynamic pressure, so the "effective weight" of the vehicle reduces as the lift increases proportional to V^2. The upper curves are the total horsepower required at the wheels (exclusive of gearing and internal engine losses), so total engine horsepower required would be greater. For these cases, at a sample speed of 70 mph, the horsepower required for the conventional rig to overcome drag plus rolling resistance can be reduced 24% by the lesser pneumatic configuration and 32% by the more effective one. If fuel consumption is reduced proportionally, these numbers indicate considerable increase in cruise efficiency for these blown vehicles. Note also how blowing lessens the dominance of aerodynamic drag at higher speeds. For the conventional Heavy Vehicle, horsepower required to overcome drag is equal to horsepower to overcome

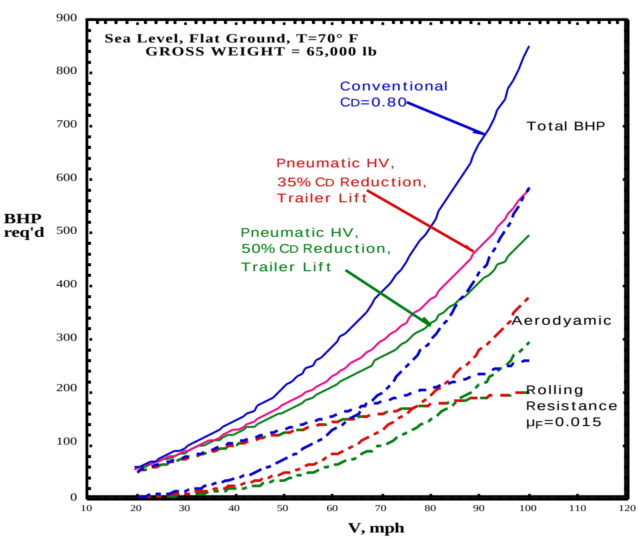


Figure 22 – Comparative Blowing-Produced Reductions in Power Required to Overcome Drag and Rolling Resistance blown vehicles

rolling resistance at about 66 mph, but that speed moves to about 77 mph for the 35% C_D reduction curve, and to 86 mph for the 50% C_D reduction.

To the discussion above must be added a consideration of any power expended to compress (pump) the air for blowing. Figure 23 makes this comparison, where the blowing performance is derived from the lowest C_D vs C_μ curves of Figures 14 and 16 (these are the same configurations). In Figure 23, the C_D is converted to horsepower required at a typical speed of 70 mph using the equations above with q=11.86 psf. This yields Curve A, $HP_{aero\ required}$, which when subtracted from the HP value for the baseline unblown reference configuration yields Curve B, showing $HP_{aero\ saved}$. At this truck speed, the compressor HP required to compress the air from ambient to the C_μ required is given by Curve C, $HP_{pump} = \Delta P\, Q / 33000$, where ΔP is the pressure rise required in psf and Q is the volume flow rate through the slots in ft^3/min. Then the net HP_{saved} is Curve D, which is the difference $HP_{aero\ saved} - HP_{pump}$. A maximum HP_{saved} occurs between $C_\mu = 0.05$ and 0.06, and is 43% below the baseline vehicle, slightly less than the 50% HP_{saved} from C_D reduction alone without compressor power removed. HP_{saved} continues to be positive until about $C_\mu = 0.355$, at which point $HP_{aero\ saved} = HP_{pump}$. Note, however, that if the blowing power were obtained totally from the output of a turbocharger waste gate at cruise speed (i.e., no extra compressor power required),

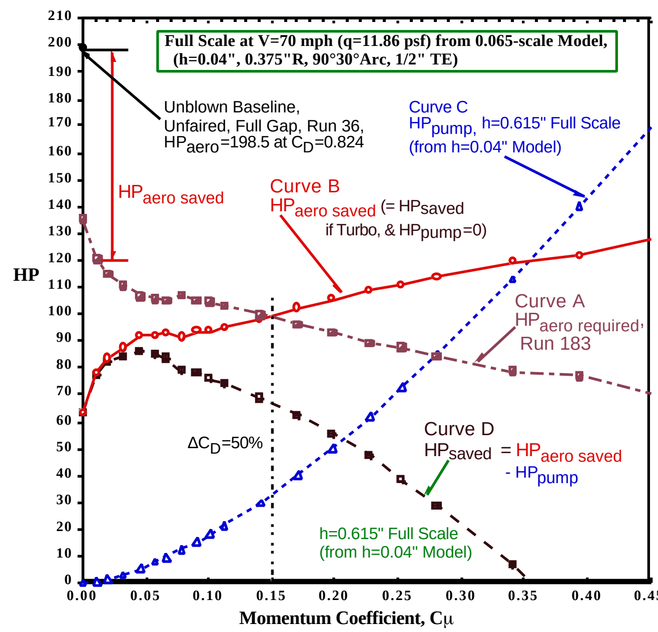


Figure 23 – Horsepower Required to Overcome Drag at 70mph, plus Required Compressor Power and Horsepower Saved

then $HP_{pump} = 0$ and HP_{saved} would convert to Curve B, which continues to increase until C_μ reaches the limits of the turbo output. In reality, the saved-horsepower curve would probably end up somewhere between Curves B and D depending on the turbocharger, but this still represents HP_{saved} of at least 43% of the baseline vehicle's aerodynamic horsepower required.

ADDITIONAL APPLICATIONS OF PNEUMATIC AUTOMOTIVE AERODYNAMICS

In addition to Heavy Vehicle application, the above results appear quite promising to other forms of automotive vehicles. Clearly, buses and Sports Utility Vehicles are also prone to large drag values and directional stability issues due to aft flow separation and large side panels exposed to side winds. These vehicles do offer the built-in advantage that rear corners as well as front corners are usually already at least partially rounded, and thus application of a blown system like that above would be easier than on square-edged HVs whose trailer designers don't want to yield internal volume. Discussions between GTRI personnel and representatives of these industries are already underway. The possible payoffs are implied in Figure 24, which plots yearly fuel consumption in the US for various vehicle types (from References 12 and 13). Whereas automobile fuel usage is relatively level in recent and projected years, values for HVs and buses continue to rise with year, but light trucks and SUVs continue to rise at a much greater rate and to a much higher yearly fuel consumption. Reduction in drag levels could help considerably here, especially relative to fuel usage at highway "cruise" speeds.

GTRI personnel have also been contacted by motor home users, as these vehicles are likely to have squared and draggy front and rear corners causing high drag and fuel consumption. Another possible application is relative to improving aerodynamic performance of trains, not only high-speed bullet trains but also the very boxy freight trains. For these boxy trains, the key to large economic improvements depends on the average operating speed of these connected vehicles, and again, drag versus rolling resistance.

In a related application, GTRI is also currently developing a patented aerodynamic heat exchanger that is based on these pneumatic principles . This can further reduce the drag associated with the vertical conventional radiator and related cooling system, while also adding favorable aerodynamic characteristics to the vehicle. Of course, the application of improved blown aerodynamics to increase the performance, traction, braking and handling of race cars is a very related and promising subject.

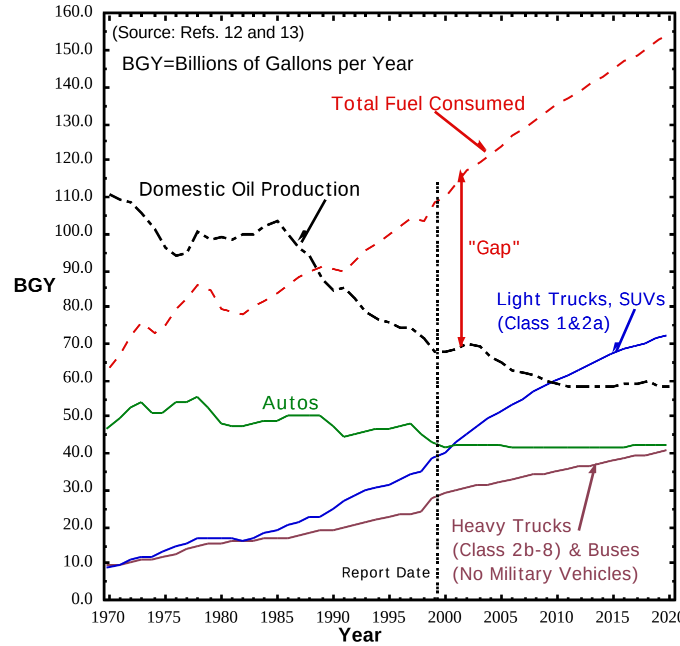


Figure 24 - Highway Energy Usage Comparisons (Billions of Gallons per Year) by Vehicle Type

CONCLUSIONS

Blown and unblown wind-tunnel evaluations have been completed at GTRI in a research program conducted for the DOE Office of Heavy Vehicle Technologies to develop, evaluate, and apply pneumatic aerodynamic devices to improve the performance, economy, and safety of operation of Heavy Vehicles. The data presented above confirm the aerodynamic potential of these new Pneumatic Heavy Vehicle configurations.

Summarizing the above:

- Drag coefficient can be pneumatically increased or decreased as desired in increments of as high as 600% of the input blowing momentum coefficient, $C\mu$.

- Drag coefficient reductions of as much as 50% were produced by blowing with internal pressures of only 1.0 psig; C_D values as low as 0.13 (an 84% drag reduction from the baseline HV model) were measured at increased blowing rates.

- Variable slot combinations and blowing $C\mu$ variations yielded drag decrease for fuel efficiency, or drag increase for braking and stability.

- Variable slot combinations and blowing $C\mu$ variations yielded lift increases for reduced rolling resistance, or down force increases for additional traction and/or greater braking.

- Blowing one side slot alone generated sufficient yawing moment to restore directional stability and to offset side force due to gusts or side winds on large trailer side panels.

Thus all the original objectives for this Pneumatic Heavy Vehicle program have been experimentally confirmed: drag, lift, down force, side force and all corresponding moments can be significantly augmented (increased or decreased as needed) by blowing, and improved to the point where appreciable increases in Heavy Vehicle performance, economy, stability and safety of operation should result.

Prediction of on-the-road performance of a pneumatic Heavy Vehicle using blown drag reduction coupled with lift-enhanced reduced rolling resistance suggests that these aerodynamic improvements can result in 24% to 32% reductions in horsepower required to overcome drag plus tire rolling resistance. Even when the compressor power for blowing is factored in, savings of up to 43% are calculated in horsepower required to overcome the aerodynamic drag alone. Higher savings appear possible if turbocharger wastegate flow is used. The potential of pneumatic aerodynamic devices applied to Heavy Vehicles can be summarized as:

- Pneumatic devices on back of trailer, blowing slots on all sides and/or front top can yield dramatic improvement in aerodynamic performance, efficiency, stability, control, and safety of large commercial Heavy Vehicles
- Control of all aerodynamic forces and moments from the same pneumatic system using existing on-board air sources, which can be driver or system controlled
- Separation control and base pressure recovery = drag reduction; or base suction = drag increase
- Leading-edge (LE) suction on trailer = drag reduction
- Additional lift for rolling resistance reduction ($F_{Rolling} = \mu N$, where N = Weight - Lift), or reduced lift (increased download) for traction, braking and reduced hydroplaning
- Blowing slots and their corresponding effects can be instantaneously interchanged
- Partial slot blowing or differential blowing can yield roll control & lateral stability
- One-side blowing can yield yaw control & directional stability
- Non-moving external components = all-pneumatic systems and components with very small (if any) component drag
- Very small-size aft trailer extension = no length limitations; minimal front or top add-ons
- Splash, spray & turbulence reduction accompanies drag reduction
- Use of existing on-board compressed air sources (exhaust, turbocharger, brake tank)
- Advanced pneumatic aerodynamic cooling systems can further reduce drag by reducing radiator size
- Fast response and augmented forces = safety of operation
- For safety, stability and/or economy, positive use can be made of aerodynamic forces/moments (lift, download, side force, yaw, roll) which are not currently employed in Heavy Vehicle operation, and drag control can be used for braking as well as fuel efficiency.

RECOMMENDATIONS

The above aerodynamic data confirm the Pneumatic Heavy Vehicle as a viable concept for improving the aerodynamic performance, economy, stability, handling and safety of operation of large tractor trailers. Data presented has exceeded the 35% drag reductions (previously demonstrated on streamlined cars) that the American Trucking Associations claim will result in savings of more than 1.2 billion gallons of diesel fuel per year for the US heavy trucking industry, and as much as 1.7 billion gallons per year can be saved at the 50% drag reduction level. The following recommendations are made to suggest a meaningful continuation of this program:

- Additional wind-tunnel evaluations should be conducted to even further reduce the required blowing momentum which needs to be acquired from some air source on board the tractor-trailer rig. These tests might include slot height variation, improved blowing surface geometry, alternate jet turning characteristics, pulsed blowing, or other innovative means.

- Continued feasibility studies are needed, where the above results are transferred to the HV industry and interactions occur with tractor and trailer manufacturers, as well as with engine manufacturers, turbocharger builders, or other possible air-supply specialties.

- Preparation for a full-scale on-the-road demonstration of this technology should be begun, including further study of available air supplies and any associated penalties, plus design of a full-scale demonstrator configuration.

It is thus felt that the proof-of-concept has been successfully completed in smaller model scale, and it is recommended that a full-scale on-the-road demonstration of the Pneumatic Heavy Vehicle soon be undertaken.

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