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AERODYNAMICS OF HIGH SPEED GROUND TRANSPORTATION

RESEARCH AND DEVELOPMENT PLAN

ANDREW G. HAMMITT

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FINAL REPORT

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16. Abstract

The aerodynamic problems of high speed ground transportation systems have been examined for both conventional rail and other high speed systems. An aerodynamic research and development program has been developed to provide the required information.

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NOMENCLATURE

A	air cushion area
A_{1L}, A_{2L}	flow area below edge of air cushion (Figure D-1)
A_u	flow area above edge of air cushion (Figure D-1)
A_v	frontal area of vehicle
A_{wL}	surface area of vehicle below edge of air cushion
A_{wu}	surface area of vehicle above edge of air cushion
A_∞	cross sectional area of tunnel
AR	aspect ratio of air cushion, b/ℓ
b	width of air cushion
C	circumference of air cushion
C_d	drag coefficient based on frontal area
C_F	length of front edge of cushion
C_ℓ	lift coefficient
C_R	length of rear edge of cushion
c_f	skin friction coefficient
ΔC_p	change in pressure coefficient
D	drag of vehicle
G	$\frac{A_{wu}}{A_u} c_f + 1$
H	$\frac{A_{wL}}{A_\infty} c_f R^2 + 1$
h	height of air cushion gap
h_o	height of gap at rear of dynamic air cushion
h_1	height of gap at front of dynamic air cushion
Δh	$h_1 - h_o$
J	$\frac{A_u}{A_\infty}$

J_γ	momentum flux in boundary layer air up to height γ
$J_{\delta-\gamma}$	momentum flux in boundary layer air between γ and δ
L	lift
ℓ	length of cushion
m_γ	mass flow of air in boundary layer up to height γ
m_δ	mass flow of air in boundary layer up to height δ
P	power
P_T	thrust power
p_c	air cushion pressure
Δp_c	change in air cushion pressure
p_L	pressure below edge of air cushion
p_t	total pressure
p_u	pressure above edge of air cushion
Q	volume flow
q_∞	free stream dynamic pressure
R	$\frac{A_{2L}}{A_{1L}}$
V	velocity
V_e	velocity behind propulsion fan
V_c	velocity in air cushion
V_{1L}, V_{2L}	velocity below edge of air cushion (Figure D-1)
V_j	velocity of jet from cushion relative to vehicle
V_t	total velocity of jet from edge of cushion relative to ground
V_u	velocity above edge of air cushion (Figure D-2)
V_∞	free stream velocity

X	$\frac{A_{2L}}{A_V}$
y	distance measured perpendicular to vehicle
β	blockage ratio $\frac{A_V}{A_\infty}$
γ	maximum distance from surface to boundary layer streamline which enters fan
δ	distance to edge of boundary layer
ρ	density of air
ω	frequency of oscillation in heave (radians/sec)

1. INTRODUCTION

Aerodynamics becomes an important consideration for ground transportation systems as the speed of the vehicles increase. A low speed system can be, and traditionally is, designed with very little attention to aerodynamics. However, at speeds less than 100 mph aerodynamic drag has become the dominant resistance force and at speeds of 200 mph it is very possible to develop lift forces on the order of the weight of the vehicle. In addition to the direct forces there are other aerodynamic effects that are important to a high speed system. A high speed vehicle causes a pronounced velocity and pressure field in its vicinity which may have deleterious effects on people, structures, and other vehicles. Such a vehicle dissipates large amounts of power of which a small part may find its way into sound and produce noise beyond allowable limits. Tunnels cause special aerodynamic effects which must be considered. At speeds in excess of about 150 mph wheels are no longer a good means of support and an aerodynamic system is one of the viable alternatives.

In planning an aerodynamic research and development program, it is useful to approach the problem from two different directions: technological and systems. The aerodynamic problems should not be studied just in relation to one particular system since the technology may be common to a variety of different systems. On the other hand, if the technology is developed independently of the various ground transportation system, then the resulting product may not be suitable for application to the systems of interest. In order to avoid either of these hazards, the problem will be considered from both points of view. To do this, it will be necessary to project systems needs somewhat in the future with the result that the plan will have to be re-examined and updated as the programs become more definite and better defined.

To make these two aspects of the problem more definite, Tables 1 and 2 have been prepared. Table 1 defines the different technologies that are involved in the aerodynamics of high speed ground transportation and

Table 1. Aerodynamic Technology Categories for High Speed Ground Transportation

1) External aerodynamic forces

    Drag, lift, rolling moments, etc.

2) Wayside environment

    Pressures and velocities caused by vehicle

    Effects on wayside structures, people and other vehicles

    Vehicle aerodynamic noise

3) Aerodynamic suspension

    Static and dynamic air cushions

4) Aerodynamic propulsion

    Power requirements for efficient propulsion

    Noise of aerodynamic propulsion

5) Aerodynamic effect of tunnels

    Effects on forces on vehicles

        Drag, lift, etc.

    Tunnel environment

    Pressure, velocities and temperatures

Table 2. High Speed Ground Transportation Systems

1) High speed conventional rail systems

   Speeds to 150 mph

   Semi-conventional equipment and track

   Semi-conventional wayside environment

2) High speed magnetic levitated systems

   Speeds to 300 mph

   Attractive or repulsive magnetic systems and appropriate guideway configurations

   Aerodynamic propulsion to be considered

   Guideway at grade, elevated, and in tunnels

   Stations located in approximately the center of long tunnels

   Single vehicles and trained vehicles both of interest

3) High speed static air cushion levitated systems

   Speeds to 300 mph

   Conventional static air cushion, peripheral jet or plenum configurations

   Cushion pressure greater and less than ram pressure

   Aerodynamic propulsion to be considered

   "U" shaped guideway configuration

   Guideway at grade, elevated, and in tunnels

   Stations located in approximately the center of long tunnels

   Single vehicles and trained vehicles both of interest

4) High speed dynamic air cushion levitated systems (ram wing)

   Speeds to 300 mph

   Single dynamic air cushion providing large clearances at front and rear

   Vehicle may or may not be air levitated at low speed (150 to 200 mph or less)

   Aerodynamically propelled

   Configuration generally as described in Reference 2 but with considerable variations possible

   Guideway at grade, elevated, and in tunnels

   Single vehicles of primary interest, trains not considered essential

Table 2 lists four principle systems programs. Table 2 also lists what are considered to be the appropriate characteristics of these systems as they apply to aerodynamics.

In the process of developing an aerodynamic research plan the different technological aspects will first be discussed and then the various aerodynamic research and development tasks and the way these tasks serve the needs of the four principle ground transportation programs.

2. EXTERNAL AERODYNAMICS OF GROUND TRANSPORTATION VEHICLES

In this category we will consider the flow about a ground vehicle operating in the open. This flow about the vehicle causes forces on the vehicle, forces on objects or people along the guideway, and noise. These effects exist at all speeds but at low speeds they can be neglected; however, they grow rapidly with speed since the forces and pressure vary as the square of the velocity. At about 100 mph the aerodynamic drag forces exceed all other drag forces and at about 200 to 300 mph the lift forces can be of the order of the weight of the vehicle. Therefore, it is important to know the magnitude of these aerodynamic effects with sufficient accuracy to be able to predict when problems might develop and how they can be solved.

2.1 DRAG FORCES

2.1.1 Conventional Rail

Conventional rail systems are assumed to resemble present day rail systems and operate at speeds up to 150 mph. As the speed of such vehicles increases, it becomes important to consider aerodynamic effects in the design of the vehicle. Figure 1 shows typical power requirements for such vehicles. The power to overcome aerodynamic drag exceeds that to overcome the mechnaical resistance at steady speeds in excess of about 75 mph. At 150 mph, the aerodynamic drag power requirement is about 3 times that of the mechanical drag power requirement. Under severe crosswind conditions, the aerodynamic drag can be considerably higher. By good aerodynamic design it should be possible to reduce the drag of the train by about a factor of 2 below that achieved by conventional existing designs and eliminate most of the increase in drag caused by crosswinds. The streamlining techniques to accomplish these improvements are generally well known. The most important features are a nose with reasonable radii at the corners, say at least 0.15 of the width or 0.3 times the height (whichever is the smallest number), and a smooth surface along the vehicle. The potential gains at the rear are not large unless quite elaborate methods are to be used, such as boundary layer suction, which are probably

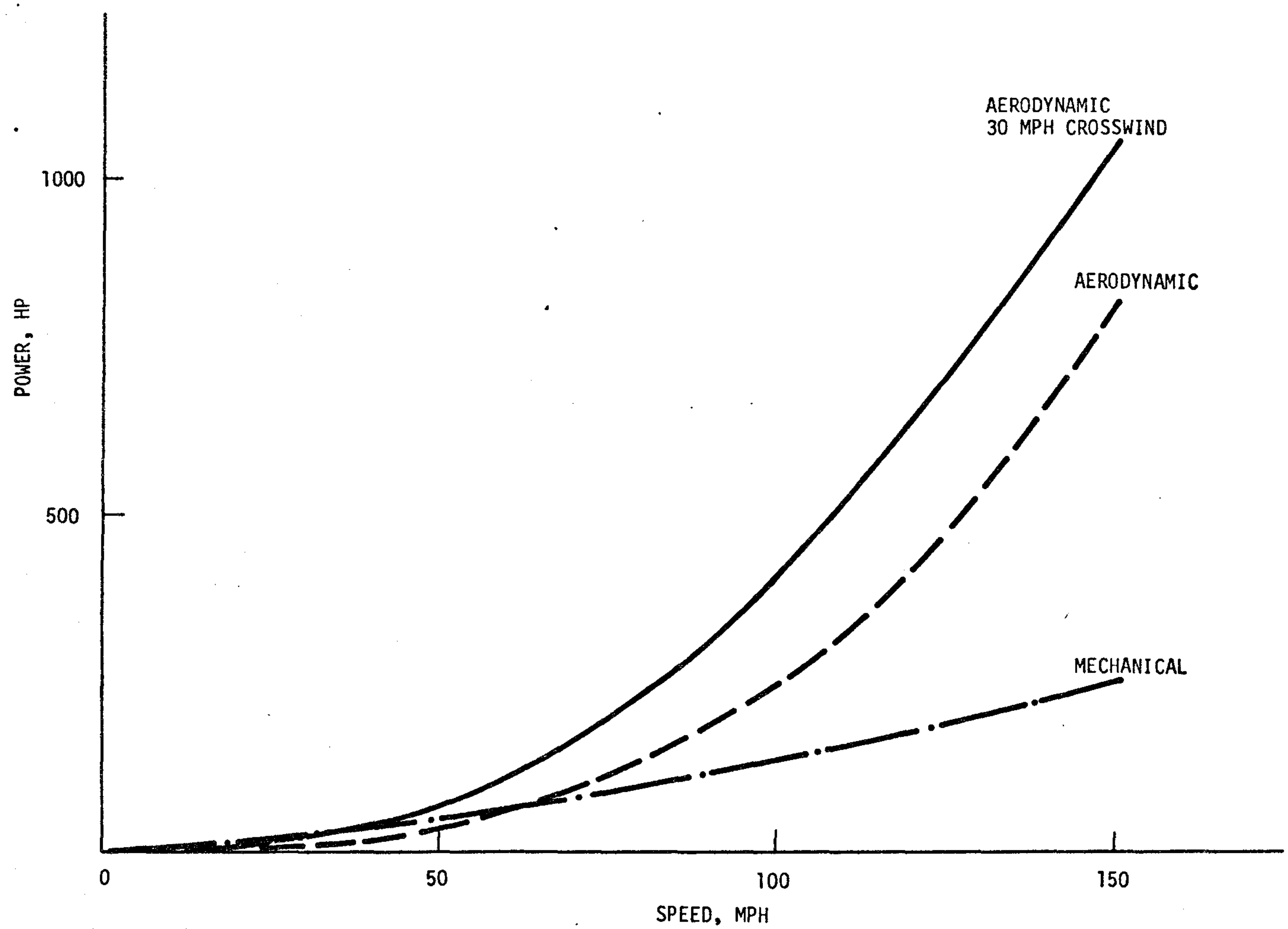


Figure 1. Aerodynamic and mechanical power requirements of Metroliner type vehicle (based on References 1, 12, and 13)

not justified for this type of equipment. A smooth surface involves not only a smooth skin but covering the gaps between the cars and at the wheel trucks. While it is good to have these coverings as smooth as possible, the main purpose is to block crossflow through these gaps. The principle cause of the increased drag for crosswind conditions is air blowing into these gaps and then being accelerated to the velocity of the train as the air passes through the gap (Reference 1).

The possible gains to be achieved by changes of these types are quite well understood. Additional basic research on this problem is not warranted. Applied research is needed to determine how much drag reduction can be achieved at what cost. In order to assess the extent to which such features should be incorporated into future designs, data is needed to determine the aerodynamic advantages to be gained for designs which embody different fabrication and maintenance costs. The features which need consideration are windows, doors, skin construction methods, protuberances, between car fairings, wheel truck and undercar car fairings, nose, and tail configurations.

2.1.2 High Speed Systems

A high speed system is one which may operate up to speeds of 300 mph. At these speeds the aerodynamic drag is very high. Since the suspension system may be either of several forms of magnetic or aerodynamic systems, it is difficult to provide a good comparison between the power needed to overcome drag and that needed by the suspension system. A comparison for different aerodynamic suspension systems is shown in Figure 5 (p. 26). The power needed to overcome drag is larger than the most inefficient of the two aerodynamic suspension systems considered. A low aerodynamic drag is therefore very important for a successful high speed ground transportation system. Vehicles of this class can be designed to be more nearly ideal aerodynamic shapes than is practical for lower speed vehicles. The drag of a vehicle is often expressed as a drag coefficient based on frontal area. While this is a useful representation of the drag, it can also lead to some confusion. A minimum drag per unit frontal area for a blunt based body occurs at about a length to diameter ratio of 6 with a value of drag coefficient, C_d, equal to 0.18. If separation at the rear of the body could be prevented by using a body with a streamlined tail this drag coefficient could be reduced to $C_d = 0.07$ and to an even lower value for a shorter body without separation. However, such short bodies are not really appropriate for a ground transportation vehicle. A vehicle must contain a certain amount of volume to accommodate equipment and passengers. If the problem is posed, what is the best length to diameter ratio for a blunt based vehicle of a given volume, the result is a length to diameter ratio of around 15 with a $C_d = 0.21$. For an actual ground transportation vehicle, the frontal area is more or less fixed by the need to accommodate passengers and require the minimum size of right of way. Therefore, the length of the vehicle must be sized to provide the necessary volume. Length to diameter ratios of the order of 10 to 15 seem reasonable with respect to the non-aerodynamic criterion and are not too far from an optimum blunt-based body. If longer vehicles are desired they can be made up of trains of vehicles of shorter length. For a fixed frontal area, the aerodynamic drag divided by the volume of the vehicle continually decreases as the length of the vehicle increases. Long vehicles, or properly trained vehicles, always have less drag than several short vehicles of equivalent volume traveling alone. However, there is not much to be gained from vehicles longer than a length to diameter ratio of 50 or more. If frontal area were not limited, a shorter vehicle with the same volume could be designed to give lower drag, but, for a fixed frontal area, the long vehicle is the best solution.

The length to diameter ratio for ground transportation vehicles seems to be controlled by features other than aerodynamic. There is not much potential for gain with respect to this parameter. The two areas which offer the greatest potential in providing a low drag vehicle are: the use of a smooth skin with a minimum of protuberances and a reduction of the base drag. This latter will be of greatest importance if single vehicles or short trains, with a length of 20 diameters long or less, are used. For vehicles or trains longer than about 50 diameters, there is little to be gained by reducing base drag. If vehicles are to be trained, it should be done in such a way to minimize drag from the connection. Base drag can be reduced by using a long streamlined tail, which is probably not practical, or by using some form of boundary layer control at the rear of the vehicle. Attached flow at the rear of the vehicle can be promoted by sucking off the boundary layer directly ahead of the tail section, by sucking in the base region to maintain a stable vortex, by energizing the boundary layer in the base region or by a cowl. The sucking off or energizing of the boundary layer can possibly be combined to advantage with an aerodynamic propulsion system to provide a vehicle requiring less net propulsive power.

The guideway configuration can have an appreciable effect on the vehicle drag. This effect can be caused both by special protuberances required by the particular levitation system being employed and by the restrictions on air flow caused by the guideway. This latter point is of particular interest in connection with the "U" shaped guideway where the flow from in front of the vehicle is restricted from flowing around the sides of the vehicle and also restricted from filling in behind the vehicle. All other things being equal, this confinement will increase the drag of the vehicle. The use of vents at the corners of the "U" will alleviate the effect to some extent, but if the vents are only a small part of the sidewall their effect will be small. An analytic study is now being carried out to assess the magnitude of this effect, but a test program is required to obtain reliable results. It should be possible to design the nose of the vehicle so that there is little loss caused by the "U" shaped guideway. The base drag will be increased and a base drag alleviation system will be more difficult with this guideway configuration. However, this configuration provides a vehicle of less surface area than other proposed configurations and, therefore, lower friction drag.

2.2 LIFT AND OTHER FORCES

For the low aspect ratio vehicle being considered, lift and other forces are relatively small at low angles of attack except for lift forces caused by the flow under the vehicle for certain configurations such as the ram wing. This underbody flow is closely related to aerodynamic support systems and will be considered in greater detail in that area. For conventional type rail equipment operating up to speeds of 150 mph the aerodynamic lift force is small with respect to the weight and may generally be neglected. Side forces and rolling moments are also small enough so that generally they are not critical. However, they do provide an input to the wheel/rail dynamic interaction and should be considered in this respect. Available data is probably adequate to evaluate these effects and additional data does not appear to be needed until more definite needs are established. Under conditions of extreme crosswind it is not absolutely clear that a rolling moment cannot be developed that would endanger the safety of the train. This effect, while unlikely to be critical, cannot be completely dismissed at this time.

For high speed lightweight vehicles, lift and side forces can be considerably more critical. Unless the vehicle is adequately designed, lift forces on the order of the weight of the vehicle can be developed at 200 mph and also large side forces, pitching, and rolling moments. The guideway design can have a large effect on these forces, particularly the "U" shaped guideway being considered. Some general data is available for these configurations both with and without consideration of the guideway. More general data, particularly on the effect of the "U" guideway, would be useful and detailed tests should be provided for any configuration receiving specific consideration.

Under crosswind conditions, it makes a difference whether the guideway is elevated or at grade level. Much is made of the ground effect on the aerodynamics of ground transportation vehicles but it must be realized that an elevated guideway allows the crossflow to pass under as well as on top of the combined vehicle and guideway. Lift forces and rolling moments can be quite different for an elevated guideway than for a grade level guideway and both conditions must be considered in the design of a system.

These side forces, rolling moment, and lift force are not sensitive to small changes in the configuration in the same sense as the drag force. The rounding of the corners at the roof (which promotes attached flow across the roof), is the most important variation possible. The moment can be considerably affected by major contour changes. For instance, a semi-circular shape has zero moment about the baseline. However, there appears to be little to be achieved by changing the existing shapes to improve the crosswind aerodynamics.

2.3 WAYSIDE ENVIRONMENT

A vehicle passing through the air causes a flow field about the vehicle that can have an effect on other objects in the vicinity of the vehicle. This effect is negligible for a low speed vehicle but since its effects increase as the square of the velocity, it can be quite important for a high speed vehicle. The vehicle causes an inviscid flow field which is only important around the nose of the vehicle. In the vicinity of the nose distinct changes in pressure and velocity take place. Figure 2 shows the changes in pressure, on a nearby object, which will be caused by the passage of a vehicle. A viscous flow field builds-up along the sides of the vehicle and a viscous wake behind the vehicle. Only small static pressure changes are associated with this viscous flow field but the velocities can be quite large. Figure 3 shows the magnitude of the velocities which may be expected. The deficit of momentum in the viscous wake is approximately equal to the aerodynamic drag of the vehicle for a vehicle propelled by thrust from the ground. The wake may be considerably reduced for an aerodynamically propelled vehicle. The wake will also be turbulent and have large fluxuations in velocity around the mean value shown.

This flow field generated by the train can have important effects on other passing vehicles, structures along the guideway, and people. For a conventional high-speed rail system operating on existing or only slightly modified track systems, these effects can expose existing vehicles and structures to conditions for which they were not designed. Also, track-side workers and passengers on open platforms may be subject to dangerous

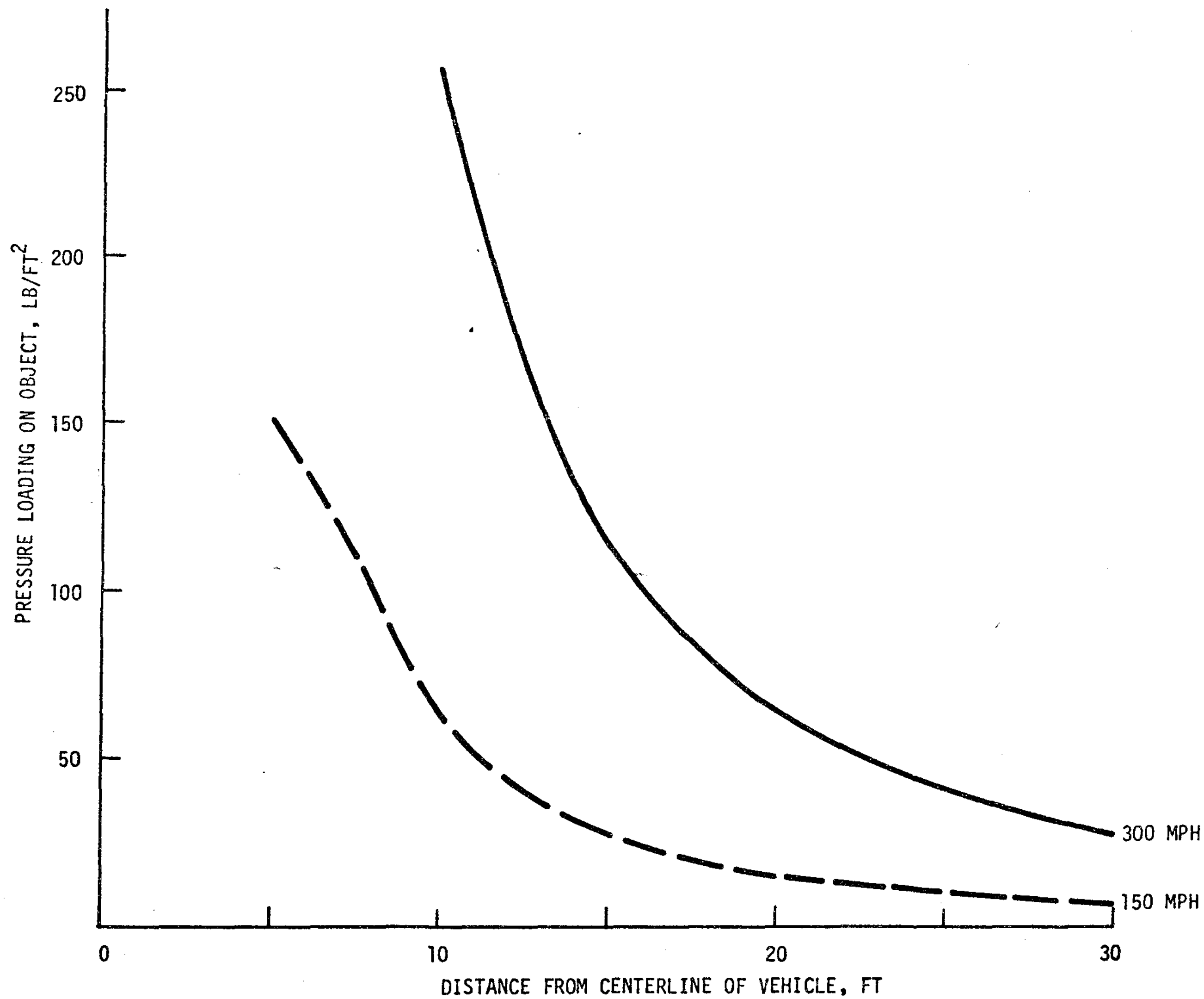


Figure 2. Pressure pulse on stationary object caused by passage of the nose of 10 foot wide vehicle

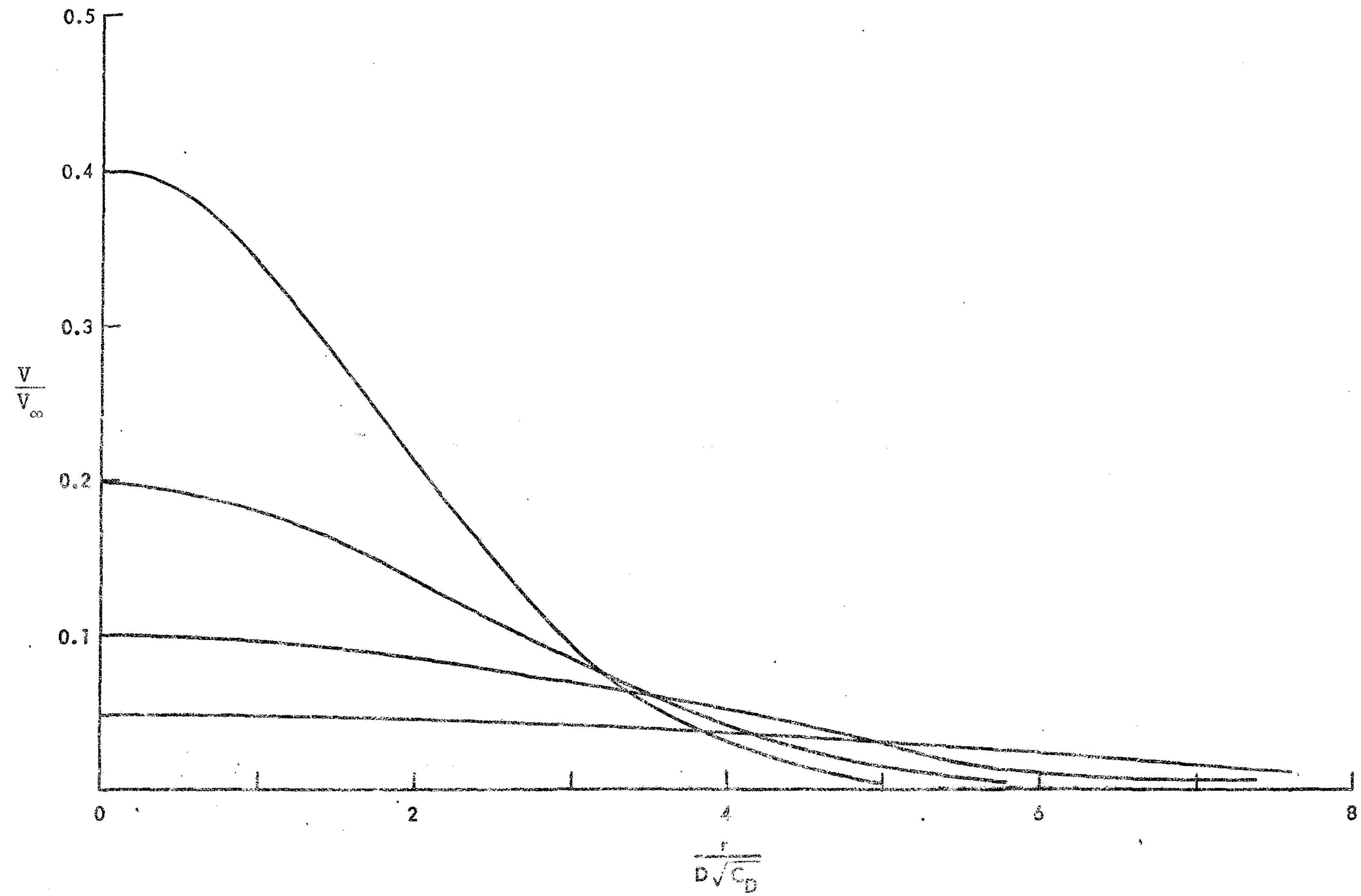


Figure 3. Wake velocity behind vehicle as a function of distance from centerline over vehicle width and square root of drag coefficient

and uncomfortable conditions. For this case, a knowledge of these conditions is needed to evaluate hazardous conditions that may be created by high speed trains and to set limitations or suggest remedial actions that may be required. For future high speed systems, these problems will be more severe, but the systems can be designed to account for the effects. A knowledge of their magnitude is needed to set design standards.

A basic understanding has been achieved of the nature and magnitude of these effects. This knowledge is adequate to identify critical problems. Future research should be applied to determining more specific results for particular configurations of interest.

The noise caused by a passing vehicle is another very important effect on the wayside environment. Noise can be caused in many ways. For conventional rail systems the principle sources of noise are mechanical and from the onboard prime mover, the diesel engine. The turbulent boundary layer and wake are a source of noise but are not important at the speeds of such systems. For high speed systems, supported magnetically or aerodynamically, the mechanical noises are small. A magnetic propulsion or levitation system can be an important source of noise through vibrations induced in closely coupled structural parts. The most important sources of aerodynamic noise are an onboard gas turbine prime mover, an aerodynamic propulsion system, the jets and fans of an air cushion support system, and boundary layer and wake noise. This list is roughly in order of importance but all of the listed items may not be found on some vehicles. The development of adequate muffling techniques for gas turbines and ducted fans is of critical importance if systems using these components are to be considered. Noise reduction is always difficult because of the large reduction of noise energy required to appreciably improve its acceptability. The aerodynamic noise level predicted for systems using onboard gas turbines is marginal and reduction of this noise level would be an important improvement.

3. AIR SUPPORTED VEHICLES

One means of supporting a vehicle at high speed is by means of aerodynamic forces. If this is to be done near the ground it involves forming a cushion of high pressure air under the vehicle to provide a lift equal to the weight. The weight of a high speed ground transportation vehicle is of the order of about 50 pounds per square feet. Since a dynamic pressure of this amount corresponds to a speed of about 150 mph, at speeds greater than this it is reasonable to consider suspending a vehicle by means of the dynamic pressure alone, but at lower speeds a fan will be needed to increase the dynamic pressure. A vehicle which uses dynamic pressure alone to achieve suspension is called a ram wing and one which also uses a fan will be called an air cushion. A vehicle operating over a speed range from 0 to 300 mph may operate in a variety of modes. The two existing air cushion vehicles which have been built for the Department of Transportation (DOT) both operate at speeds below that for which dynamic pressure is equal to cushion pressure. The vehicle built by Grumman and designed for speeds up to 300 mph uses air cushions considerably smaller than the plan form area of the vehicle and operates at a cushion pressure above the dynamic pressure. In this way the problem of operating the cushion over a wide range of dynamic to cushion pressure, q/p_c, was avoided and the cushions were made small enough so that they could be conveniently mounted on mechnaical secondary suspension systems. The vehicle built by Rohr uses a different approach. This vehicle is designed for low enough speeds so that almost the entire planform area can be used for the air cushion and still have dynamic pressure less than cushion pressure. In this vehicle a secondary air suspension system is used which is closely integrated with the air cushion and uses the same air and blower system. On both of these vehicles a secondary suspension system is required since the air cushion itself is thin and stiff. A proposed vehicle concept being studied by DOT called the Tracked Ram Air Cushion Vehicle (TRACV), is designed to cruise at speeds with a dynamic pressure considerably in excess of the cushion pressure and use a thick air cushion so that a secondary suspension is not necessary.

3.1 STATIC AND DYNAMIC CUSHION

Air cushions can be classified as static and dynamic. A static cushion is one in which the air has only a low velocity with respect to the vehicle and the pressure is almost uniform throughout the cushion. In a dynamic cushion, the air has a high velocity with respect to the vehicle (an appreciable fraction of vehicle velocity). In this case the static pressure may vary throughout the cushion depending on how the velocity varies. This variation of static pressure makes it possible to achieve a variety of forces and moments from a single cushion instead of just the lift force which can be provided by a static cushion. Static cushions are probably only appropriate when the free stream dynamic pressure is less than the cushion pressure, and dynamic cushion when the free stream dynamic pressure is greater than the cushion pressure.

3.2 POWER DISSIPATION OF AIR CUSHIONS

Most aerodynamic suspension systems dissipate power both when hovering and when moving. When the energy for powering the lifting system is derived from an increase in drag, it is usually called induced drag. The power dissipated by either an air cushion or a ram wing lifting system is the kinetic energy left in the air flowing from the cushion area under the vehicle. For a low speed air cushion system, $q/p_c << 1$, most of the velocity of the jets passing under the edges of the cushions is dissipated and it makes little difference which edge of the cushion is considered since the vehicle speed is low compared with the jet speed. At higher speeds, when $q = p_c$, no air flows through the front edge of the cushion and the air leaving the back edge of a static air cushion is at the same speed as the free stream. The air issuing from the sides of the cushion is moving with the speed of the jet away from the vehicle and is carried along in the direction of vehicle motion. All of this kinetic energy is dissipated. At this speed the only loss is that associated with the side edges of the cushion (none with the forward and trailing edge of the cushion). This same result holds approximately true for all higher velocities. For this reason a ram wing can operate with large front and rear clearances without large losses as long as flow is restricted from passing out the sides of the cushion.

The efficiency of an air support system can be improved by optimizing the cushion pressure, decreasing the length of cushion periphery, and using a dynamic instead of a static cushion. A decrease in cushion periphery can be accomplished by joining together some of the cushions required for lift and guidance. The minimum number of cushion edges will occur if lift and guidance can be obtained from a single cushion. Possible ways of accomplishing this are the use of a dynamic cushion or by joining together multiple static cushions along a common edge so that leakage from one cushion passes into an ajoining cushion.

The fundamental power dissipated by an air cushion, neglecting internal ducting and other losses that are not inherent to the cushions themselves, is that contained in the form of kinetic energy in the flow leaving the cushion. For the forward and rearward edges of the cushions, the forward motion of the vehicle directly adds to the jet velocity relative to the vehicle so that the losses associated with this flow are very dependent on the vehicle velocity. For the side edges of the cushion the jet velocity and vehicle velocity are perpendicular and must be added vectorially. For a static air cushion, the fluid within the cushion is stationary with respect to the vehicle with the result that the jet velocity from the sides of the cushion is perpendicular to the vehicle velocity and the resulting velocity increases continuously with vehicle velocity. The amount of air escaping from the edge of the cushion depends on the length of the edge and cushion pressure. The amount of flow decreases as the cushion pressure increases since the length of the cushion edge decreases. The kinetic energy lost consists of both the jet velocity and the velocity due to vehicle motion with the result that minimum losses occur theoretically when the jet velocity is equal to the vehicle velocity.

For a dynamic cushion, the air has a velocity with respect to the vehicle opposite to the direction of vehicle motion. The velocity of the jet from the side curtain maintains this component in the direction opposite to the vehicle motion which, when added to that velocity, partially cancels it. Therefore, the resulting velocity in the jet, for cases of high vehicle velocity, is much less than in the case of a static cushion. The minimum loss from the side edges occurs when the velocity of the air within the cushion is equal to the vehicle velocity. For this condition to exist, the total pressure of the fluid within the cushion would have to be increased by an amount equal to the cushion pressure. If the vehicle is operating as a ram wing with the total pressure in the cushion equal to the ram pressure, then the velocity within the cushion will have to be somewhat less than the vehicle velocity by the amount necessary to cause the increase to the cushion pressure. For this case the losses will be somewhat higher. A more thorough explanation of the losses associated with air cushions is given in Appendix A. This method of analysis lumps together the total power required for suspension into one quantity. In the past, fan power, inlet momentum drag, and induced drag have all been used to describe part of the power dissipated by air cushion systems. (Drag can be directly converted to power by multiplying by vehicle velocity.) The approach used here does not distinguish between the amount of power, which varies for the different cushions, supplied by a fan or by the propulsion system.

The power required for the suspension of a particular vehicle, that described in Reference 2, has been analyzed, Appendix A, and the results are shown in Figures 4 and 5. Figure 4 shows the power required by an air cushion in which stability is achieved using only a single cushion. (Multiple cushions with a total of two side edges, one cushion leaking into another, would also qualify.) A low pressure and high pressure static air cushion design are shown. The low pressure cushion is at its optimum condition, $q = p_c$, at 136 mph and the high pressure cushion is at its optimum at 272 mph. The low pressure cushion requires less power at speeds under 190 mph and the high pressure cushion, less power at higher speeds. Two dynamic cushions are also considered, both using the same cushion pressure as the low pressure static cushion. For dynamic cushions such as these, power is always minimized by using the lowest cushion pressure possible. The ram wing cushion cannot operate below 136 mph and has the same power consumption as the low pressure static

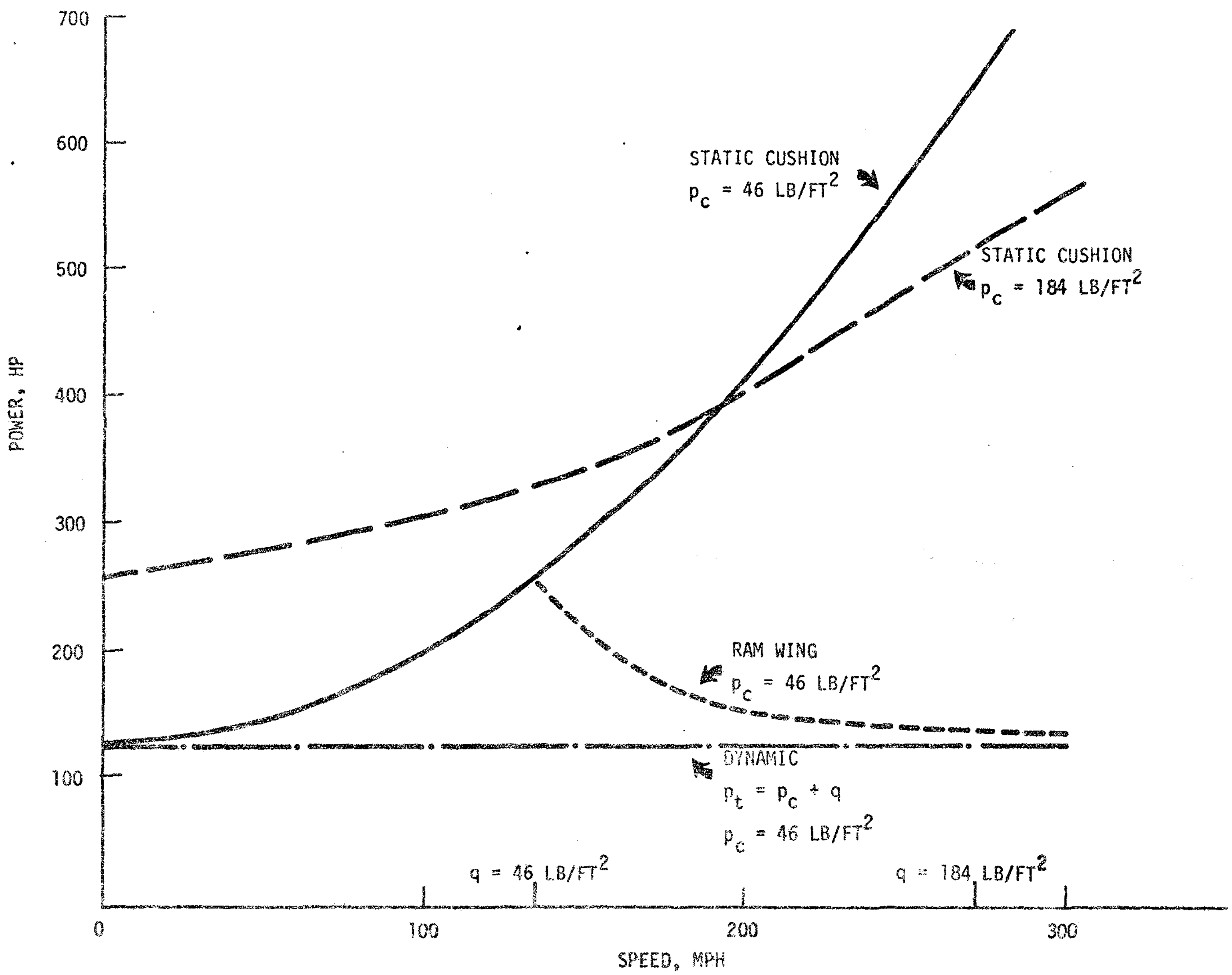


Figure 4. Power required for various single air cushion configurations. Vehicle weight = 92,000 lb

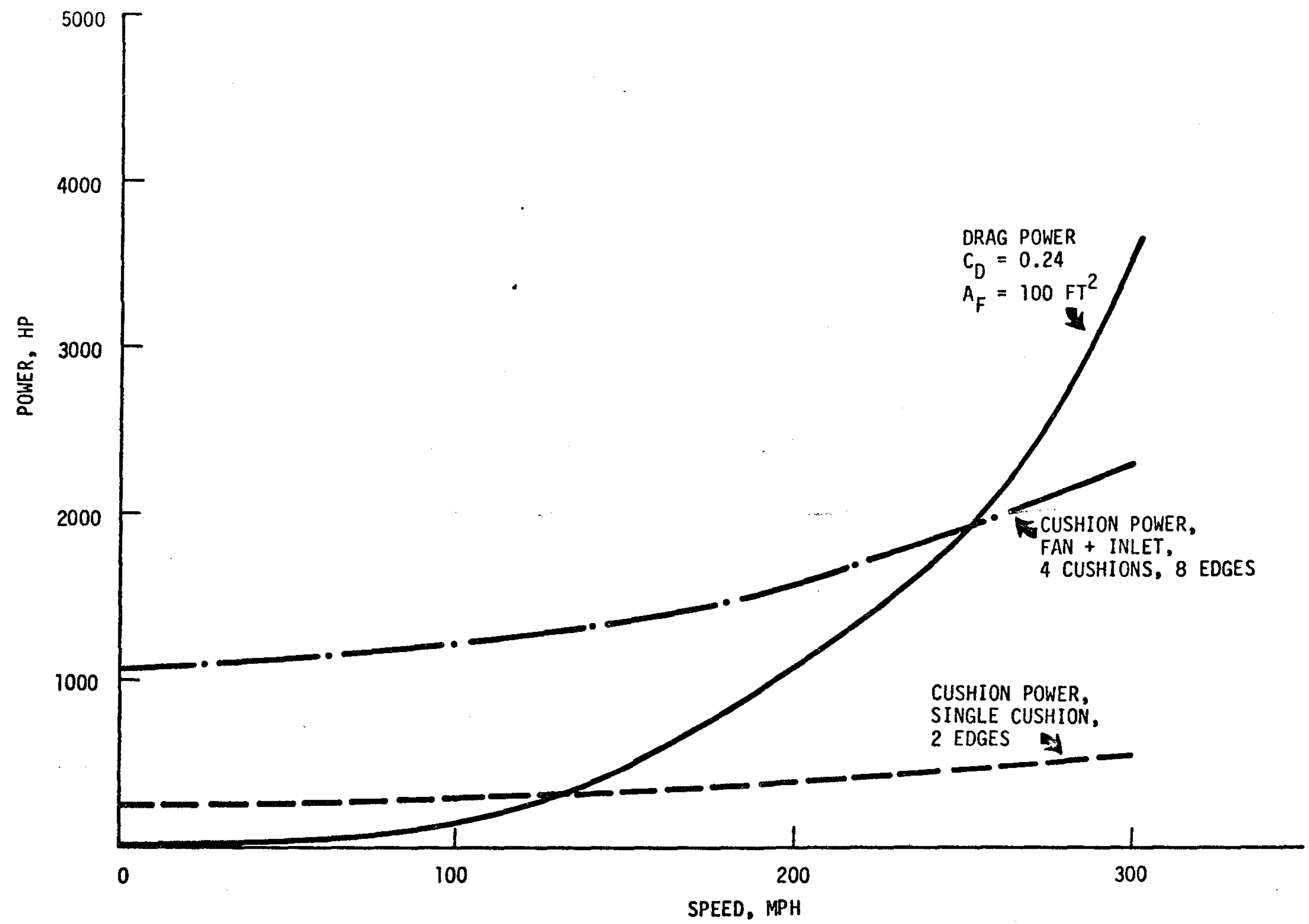


Figure 5. Power requirement for single and multiple static air cushions compared with drag power. Cushion pressure = 184 lb/ft^2. Vehicle weight = 92,000 lb. Frontal area = 100 sq ft. Drag coefficient = 0.24

air cushion at this speed. At higher speeds, however, it has considerably lower power consumption. The fourth curve is for a dynamic cushion with a fan which provides an increase in total head equal to the cushion pressure at all speeds. For this case the power is the same as the low pressure static air cushion at zero velocity and does not increase with speed. All of these cases are idealizations and do not correspond exactly to real cases. However, they do provide useful and meaningful comparisons between the different cushion configurations.

Figure 5 shows the power required by the high pressure static cushion discussed in connection with Figure 4 and a system cushion using the same pressure but having two separate levitation and guidance cushions to provide stability so that there are a total of eight cushion edges instead of two. The result is a fourfold increase in power. The drag power for the vehicle is also shown for comparison. The drag power and the cushion power for the four cushion arrangement is on the order of that required by the Grumman test vehicle which uses roughly the same configuration. For this case the cushion power exceeds the drag power except at the highest speed. However, if a single cushion can be used instead of the four separate cushions then the cushion power is reduced to what may be considered an acceptable level. Figure 4 shows that by using a dynamic cushion instead of a static cushion, considerable additional savings in suspension power can be accomplished but the power may already be low enough that the additional reduction is not important.

3.3 STABILITY OF AIR CUSHIONS

An air cushion support system must be stable and this requirement imposes important restrictions on the cushion configurations used. Stability can only be obtained if static pressures above the nominal value can be achieved when required and an increase in cushion pressure in one location can be isolated from the rest of the cushion area. In the two existing DOT vehicles (the Grumman research vehicle and Rohr 150 mph prototype vehicle), the eight separate cushions are used to provide stability in heave, pitch, roll, sway, and yaw. Use of these separate cushions makes it possible to isolate the increased or decreased cushion pressures needed to provide stability to the area where it is needed. It is also necessary to provide for isolation in the ducting system. The use of peripheral jet cushions, as on the Grumman vehicle, provides this isolation and no additional provisions are needed. On the Rohr vehicle, two separate fans are used and each fan is divided into two parts to feed four separate ducts. Orifices, which are also part of the secondary air suspension system, are then used which provide additional isolation. In these systems, there are two support and two guidance cushions in the front and rear of the vehicle. Because of the low aspect ratio of these cushions, the leakage from the leading and trailing edges is not as important as from the sides of the cushions. As already discussed, a considerable reduction in power requirement could be achieved if the four cushions at each end of the vehicle had common side edges so that there would be a reduction from eight to two side edges from which air is leaked to the atmosphere. The use of orifices or other power dissipating devices in the ducting system also increases the suspension power requirement.

The dynamic cushion concept is a way of achieving stability without the use of as many separate cushions. If the total head of the air in the cushion is considerably higher than the required static pressure, the air will flow at high speed and have a considerable reserve of dynamic pressure that can be converted into static pressure when required. Pitch and heave stability can be achieved in this way and the high velocity air flowing along the vehicle provides an adequate isolation of the parts of the cushion separated in a fore and aft direction. It has also been shown that some roll, sway, and yaw stability is possible. It will be more difficult to provide adequate roll and sway stability without dividing the cushion laterally by curtains than it is to provide pitch and heave stability.

The dynamic concept is a good one for isolating one cushion area from another. The divided fan used in the Rohr vehicle is a limited application of this principle. On this vehicle, the total pressure of the air is increased from the free stream value by a fan and then enters two separate ducts where it is diffused to the required static pressure and led to the appropriate cushion. On one of the proposed TRACV concepts, the oncoming air has its total pressure increased by the fan and then flows to the cushions. In this case, no ducting is required and the flow is through the cushion itself. To what extent dividers between the flows to these different cushions are required is not yet established. The amount of overpressure that can be achieved in any cushion configuration depends on this ratio of total pressure behind the fan to the nominal cushion pressure. In certain configurations total pressure may vary between fans or between ducts behind the fan since the pressure rise depends upon the volume flow through the rotor. If the suspension system is to be efficient, the excess total pressure provided for stability must be used and not dissipated. The way that this is done in the dynamic cushion configuration is to have the air escape at high velocity from the rear of the cushion to provide a forward thrust.

There would be considerable advantage if a dynamic air cushion could be designed that would provide adequate stability and large clearances everywhere except along the side edges as has been suggested in Reference 2. The difficulties of achieving such a cushion have been considered in Appendix B. The limited analysis presented there suggests that the amount of isolation that can be achieved across a dynamic cushion is related to the lift coefficient and the aspect ratio

$$\Delta C_p \sim (1 - C_\ell)(AR)^2$$

A low aspect ratio lifting surface is dictated by the vehicle configuration, so it may be necessary to operate a dynamic cushion at quite low lift coefficients in order to achieve adequate stability. The available stability data for dynamic cushions was also considered to try to ascertain whether there would be any problem in designing a dynamic air cushion vehicle that would provide the required stability. Based on the available results, the conclusion was that it would be difficult to design a dynamic cushion to meet the side force specifications of the Grumman research vehicle. As better data becomes available, it may be determined that this is not a problem as it now appears to be. One solution is the use of three longitudinal dividers to separate the cushion into four separate cushions to provide roll and sway stability. Such a solution imposes additional mechanical problems in allowing the large displacements in heave and sway required in the primary cushion if a secondary suspension is to be eliminated.

The frequency of oscillation of a dynamic cushion in heave was also considered in Appendix B. Unfortunately, this analysis is of very limited meaning since it neglects the coupling with pitch which is very likely to be a dominant effect. The conclusions are that the frequency of oscillation is dependent on the lift coefficient and that the restoring forces are too low until a vehicle speed is reached which allows operation at a lift coefficient considerably less than one. From both of these stability points of view, it appears necessary to delay the take-off of a pure ram wing vehicle (elimination of dependence on wheels), from the order of the 150 mph previously suggested to about 200 mph.

The achievement of stability by using several air cushions, differential heave between the cushions, and a secondary suspension system, is the approach that has been used on the existing tracked air cushion vehicles and is fairly well understood. It has been proposed that a dynamic air cushion operating at speeds for which dynamic pressure is greater than cushion pressure can eliminate the need for mechanically dividing the cushion area and also eliminate the secondary suspension. The characteristics of such a cushion are not yet well enough understood to demonstrate whether these advantages can be realized. It should be recognized that such an air cushion is considerably more complicated from an aerodynamic aspect than the static air cushions previously used. The use of a single air cushion increases the coupling between the different vehicle motions so that more complicated analyses requiring more and better data are needed to determine the vehicle motion and there is a greater chance of unanticipated difficulties developing. The suspension characteristics of the vehicle are less easily modified than if a secondary suspension is used since there are fewer parameters than can be modified. Such a vehicle must depend on wheeled landing gear or other secondary suspension systems up to quite high speeds or it must be designed to operate on its air cushion over a very wide range of dynamic to cushion pressure. This would require that the stability and suspension characteristics have to be satisfactory at design speed and over a wide range of dynamic to cushion pressure ratios.

A possible solution, if the natural characteristics of the vehicle prove to be unsatisfactory, is the use of an active control system using deflectable flaps or jet curtains. This would have to be a fast acting system and probably require a fail safe design. Such a system increases the number of parameters that are available for adjustment but requires a considerable increase in the amount of aerodynamic data required. The dynamic cushion should be regarded as an advanced concept which holds considerable promise of producing a superior air cushion vehicle.

3.4 TRAINING

In a high speed ground transportation system, it may be necessary to operate vehicles coupled together in trains. If these vehicles are supported by air cushions for which the dynamic head of the oncoming air is important, then the dynamic head at the location where it is picked-up by the vehicle must be essentially undisturbed by the vehicle ahead or the air cushion must be designed to accept the range of dynamic pressure which it will receive at different locations in the train. Cushion designs which use a cushion pressure which is high with respect to the dynamic pressure would be less susceptible to changes in dynamic pressure. A ram wing design where the total pressure in the cushion is equal to the dynamic pressure and where the air is picked-up near the bottom of the vehicle would be particularly susceptible to this problem. The aerodynamically propelled TRACV vehicle proposed in Reference 2 combines propulsion with suspension so that the dynamic pressure of the jet from the rear of the vehicle varies depending on whether the vehicle is accelerating or decelerating (when it requires the use of a thrust reverser). Such an arrangement would impose a particularly wide range of dynamic head on a following vehicle.

The coupling of vehicles together is designed to provide forces between the vehicles to limit their fore and aft movement with respect to each other, i.e., surge. It is also likely to provide forces that couple their heave and sway motions. Such couplings would further complicate the stability requirements of the vehicles. If a soft primary aerodynamic suspension is to be used, the aerodynamics of this system would be further complicated by this additional requirement. The use of a stiff primary aerodynamic suspension and a soft secondary suspension appears to simplify the aerodynamic problems but may do so only at the expense of shifting the problems onto the secondary suspension.

4. AERO PROPULSION

For high speed vehicles that do not use wheels for support, propulsion must be furnished by magnetic or aerodynamic means. No attempt will be made to compare their relative advantages but only to discuss some of the features of aerodynamic propulsion. For any high speed vehicle most of the drag is aerodynamic, all for an air cushion vehicle, so it is logical and natural to overcome this drag by aerodynamic thrust. An aerodynamic propulsion system is light in weight and well developed. If an onboard prime mover is to be used aerodynamic propulsion is much lighter than magnetic propulsion, but if electric power is to be used the weight advantage is not as large. Aerodynamic propulsion's chief disadvantage is the noise that it may generate.

An aerodynamic propulsion system can be used to cancel out rather than overcome the aerodynamic drag of the vehicle. As air flows along the vehicle, friction with the skin slows down the air with respect to the vehicle. If energy is then applied to this decelerated air to reaccelerate it to the free stream velocity, the vehicle will have no net drag. The thrust to accelerate this air exactly balances the drag that decelerated it, and the result is that there is no wake behind the vehicle. Such a system is also very efficient since it recovers the kinetic energy which is contained in the boundary layer air. The analysis presented in Appendix C shows the magnitude of the potential gain. In the ideal aerodynamic system, the power requirement is about 0.9 of that required by a system that applies a thrust from the ground to the vehicle. For a more realistic system, which applies a uniform total head increase to the boundary layer air, the power required is 0.93 of the thrust system. For the latter arrangement, the maximum efficiency is achieved when only about half of the boundary layer air is passed through the ducted fan propulsion system.

Another feature of an aerodynamic propulsion system of this type is that the fan sucks off and energizes the boundary layer air so that separation at the rear of the vehicle can be eliminated or substantially reduced and less propulsion power is required. Separation at the rear of a vehicle is caused by the fact that the boundary layer air would have to undergo a pressure rise if it were to remain attached. Since this air is moving at low speed, it does not have enough kinetic energy to accomplish this pressure rise. In the ducted fan propulsion system being discussed, this pressure rise takes place through the fan. The air flowing on the outside of the shroud has substantial kinetic energy and can accomplish the required pressure rise.

An aerodynamic propulsion system can also be combined with an air cushion system as has been proposed in Reference 2 for the TRACV. This combination is not new to air cushion vehicles and is the one that was used on most of the original ground effect machines as they were then called. Later versions of such devices such as the Hovercraft have used separate suspension and propulsion systems. This change was to achieve greater flexibility and the uncoupling of these two important functions. Whether the advantages of having only one fan on a TRACV will out-weigh the flexibility of a two fan system has not yet been determined. In order to do so, the compatibility of the suspension and the thrust requirements over the full range of operating conditions is needed. An appraisal of the efficiency of this arrangement can then be obtained by an evaluation of the energy required over a realistic mission.

The training requirement does not appear to be incompatible with the use of aerodynamic propulsion even with fans near the centerline of the vehicle. If it is realized that an aerodynamically propelled vehicle leaves essentially no wake, it does not seem unreasonable to have one vehicle directly behind the other. A close coupling in which one vehicle mates directly onto the rear of another vehicle is not possible. This arrangement is probably not practical for any vehicle unless different vehicles are used in the center and at the ends of the train.

5. TUNNELS

Tunnels are expected to be part of a high speed ground transportation guideway. The long turning radius required to maintain lateral accelerations within acceptable limits combined with the need to avoid both man-made and natural obstructions requires the use of tunnels. High speed operation through metropolitan areas may require the guideway to be underground to provide adequate safety and noise reduction. The operation of a high speed vehicle in a tunnel introduces additional aerodynamic problems beyond those that are caused by operation in the open. The forces on the vehicle, both drag and lift may undergo large changes. These forces may change rapidly both at the entry and exit of tunnels resulting in what has been called buffeting. The passage of the vehicle through the tunnel effects the environment in the tunnel by causing pressure, velocity and temperature changes. The rapid pressure changes during entry, exit and at other points within the tunnel may require special vehicle construction to isolate the passengers from these changes and impose structural design limitations on the vehicles. Temperatures and velocities through the tunnel may be modified so that heat rejection equipment on the vehicle no longer functions adequately. Changes in pressure, velocity and temperature may also create conditions within the tunnels which are incompatible with the conditions required for workmen within the tunnel or passengers at stations within the tunnel.

5.1 COMPRESSIBLE AND INCOMPRESSIBLE TUNNEL FLOW SOLUTIONS

Air is a compressible fluid but under many conditions, especially for low speed flows, the change in density is not appreciable. If it can be assumed that the density is a constant, then the fluid dynamic equations are considerably simplified. Experimental studies can more easily be performed if the requirement is that the fluid density is approximately constant but actual variations do not have to be matched. For these reasons, many of the analyses and experiments which have been performed in the study of tunnel flow have been for the incompressible case.

The assumption that the fluid is incompressible has two important implications: 1) the density does not change, and 2) pressure waves propagate at infinite speed. The incompressible assumption leads to slug flow or the condition that the air throughout the tunnel all moves at the same velocity as a single slug. Actually it takes a finite length of time for a change in vehicle conditions to be communicated to air which is far from the vehicle. For a vehicle traveling at 75 mph the vehicle will have traveled 0.1 percent of the way through the tunnel before the fluid at the far end will have been effected by the entry of the vehicle into the tunnel and almost 0.2 percent of the way before the conditions in front of the vehicle will be effected by the open far end of the tunnel. An incompressible analysis is a useful first step in predicting the general flow conditions in a tunnel. For tunnels open at both ends, this is a reasonably good prediction of the average flow conditions throughout the tunnel for most conditions of interest. A compressible analysis that accurately accounts for the wave phenomena will be necessary to predict the pressure and velocity fluxuations which occur. The incompressible analysis will also overestimate the pressure rise that occurs in front of the vehicle when it first enters the tunnel.

An aerodynamically propelled vehicle will cause considerably less aerodynamic disturbances than a vehicle propelled by thrust from the ground. If both types of vehicle propulsion are to be considered, separate analyses will have to be performed for each. The results found for one case are not directly applicable to the other. However, if because of the high drag in the tunnel the aerodynamic thrust is only a small part of the drag, the effect of the aerodynamic propulsion on the flow field may be small.

5.2 DRAG FORCES

The drag on a vehicle increases considerably when it enters the tunnel. The increase in drag depends on how much of the cross sectional area of the tunnel is blocked by the vehicle. This problem has received significant study both analytically and experimentally and is now quite well understood. Numerous incompressible analyses and experiments have been performed (Reference 1). Most analyes and all successful experiments have been performed for the case of the vehicle propelled by a thrust from the ground. The research aspect of the incompressible problem can be considered complete and further work would only be justified if needed for more exact results on a particular configuration of interest.

Results which include the effects of compressibility are not nearly as well established. The available analyses do show that, for speeds up to 300 mph and tunnel lengths up to a few miles, choked flow conditions, for which the effect of compressibility on drag is most important, will not occur. At the present time, at least three analyses are known to be nearing completion which should provide additional information on the effects of compressibility on drag (References 3,4,5). When these results become available, it is to be expected that further general studies will not be necessary and a determination of what further work is needed will have to be made. Experimental studies of compressible tunnel flow have not been very productive. The difficulties have been related to the problems of achieving high enough velocities to match the prototype Mach numbers and correct tube length and end conditions. All of the high speed studies have been for tube vehicle systems for which data in very long tubes was required. These experiments were not highly successful at achieving such results since it was difficult to simulate the proper tube length and launch conditions. The tunnel problem, however, where the vehicle enters a reasonably short tunnel at high speed, is much easier to simulate. Using the small-scale facilities previously developed, it should be possible to model conditions in tunnels up to several miles in length and at speeds up to several hundred miles per hour.

5.3 LIFT AND OTHER FORCES

The other forces on a vehicle in addition to the drag force are also modified by the tunnel environment and under certain conditions these changes may be critical. The problem which would appear to be the most critical is the disturbance in the lift force caused by the confinement of the tunnel walls when the vehicle is supported by a low pressure air cushion. If the air is not restricted from circulating around a vehicle, then it is reasonable to expect that the pressure on all sides will be approximately the same. An air cushion system implies that air is trapped under the vehicle at higher pressure than on top of the vehicle and that the top and bottom of the vehicle do not communicate freely. In a tunnel, there can be a static pressure gradient along the length of the vehicle equal to several times the value of the dynamic pressure. If support for the vehicle is provided by ram pressure alone or supplemented with a blower for which the air inlet is at the front of the vehicle, the pressure in the cushion will be about the same relative to that in front of the vehicle as when the vehicle was in the open. Outside of the cushion, toward the rear of the vehicle, the pressure can be considerably less resulting in an increased lift toward the rear of the vehicle. The magnitude of this effect depends on the ratio of cushion pressure to dynamic pressure. If the cushion pressure is many times larger than the dynamic pressure, then a change in the pressure on top of the vehicle by an amount equal to several times the dynamic pressure will have little effect; but, if the cushion pressure is about equal to or less than the dynamic pressure, the effect can be very large. A crude first order analysis of this problem is presented in Appendix D.

This same effect which causes a disturbance in the lift force can also have a major effect on the pitching moment. The indication is that the point of application of the lift force will shift aft resulting in a nose down pitching moment which may be strongly coupled with the lift. Since the lateral guidance cushions are symmetric, one would not expect any major effect on the lateral forces or moments. The magnitude of this effect on lift force and pitch moment will depend on the amount by which the vehicle blocks the tunnel. The effect can always be reduced until it is unimportant by increasing the size of a tunnel. Since this also increases tunnel costs, it is important to know how tunnel size effects vehicles having different air suspension systems.

5.4 WAYSIDE TUNNEL ENVIRONMENT

The environment created within the tunnel may have significance depending on the way in which the tunnel is used. The velocity, pressure, and temperature conditions must be compatible with the heat rejection requirements of the vehicle and with the structural integrity. The location of people within the tunnel is also an important consideration. People within the vehicle can be shielded by the vehicle which must be designed to be compatible with the tunnel environment. It may be necessary to have workers within the tunnel at the same time vehicles are passing through the tunnel and this would impose more severe restrictions on the tunnel environment. The most severe condition would occur if a station with open platforms was located in the tunnel as might occur when the tunnel is used to pass through a metropolitan area.

A rather extensive study has been performed in this area (Reference 6) for subway systems using vehicles traveling at speeds up to the order of 70 mph. In this study the conclusion was reached that incompressible theory provided an adequate prediction of conditions in the system. A computer program has been written to predict conditions in the tunnels and stations. This program should be available for use on high speed rail systems. However, at the higher speeds envisioned for such systems, a theory based on the assumption of an incompressible fluid is probably inadequate, particularly with respect to pressure and velocity transients. The program provides a useful first step in approaching these problems and should be particularly useful in assessing temperature problems.

The noise problem is also one which may be considerably aggravated by operating in a tunnel. The confinement of the tunnel will eliminate the attenuation achieved in the open by the sound spreading out in all directions. On the other hand, it confines the noise so that it will not be heard by people living along the right-of-way. The noise would seem to be a problem only to workers in the tunnel and to passengers on open platforms. The best solution is probably to provide special provisions to protect these people.

Another possible noise problem is at the ends of the tunnel. The noises generated by the train will be transmitted almost without attenuation to the ends of the tunnel and pressure waves generated by the vehicle may be a source of noise when they are reflected from the ends of the tunnel (Reference 7).

6. NOISE

The sources of noise generated by a ground transportation system are from mechanical parts, propulsion and aerodynamics. The aerodynamic sources of noise are from the turbulent boundary layer and separated turbulent flow, an on-board prime mover, an aerodynamic propulsion system, and jets issuing from the curtains of an air cushion suspension system. A preliminary estimate indicates that if an on-board prime mover such as a gas turbine is used, it would be the most important source of noise and a ducted fan propulsion system would be next. The noise of both of these devices can be considerably reduced by using a low exhaust velocity from the turbine, a lightly loaded high solidity ratio fan, and sound absorbing muffling material in the ducts. An air cushion would be the next most important source of noise. For present designs, the least important source of aerodynamic noise is the turbulent boundary layer and separated flow regions. Reduction of these noises by removal of protuberances is practical but reduction in the noise caused by the turbulent boundary layer is not. Reduction of all noise sources to the level of the noise caused by the turbulent boundary layer is a reasonable objective of a noise reduction program.

Turbo machinery, both in the form of a gas turbine of a ducted fan, tend to be major sources of noise. Any irregularities in the flow cause an increase in noise since it subjects the blades to fluxuating pulses. Non-uniform conditions in front of the fan or rotor blades followed by stator blades (or vice versa) are all sources of such noise. The noise can be muffled by using sound absorbing material in long length to diameter ratio ducts both in front of and in back of the fan. Long ducts can be formed by dividing the passages using longitudinal dividing walls of sound deadening material. Such small diameter passages increase the friction losses and inefficiencies of the system. A compromise design must be reached which provides enough sound reduction without too large losses in aerodynamic efficiency. A good muffler design appears to be the most important concern with respect to noise reduction if on-board power plants and aerodynamic propulsion are to be used.

Jets are another important source of noise. For the high velocity jets used in a turbojet engine, the turbulent mixing of the high speed jet with the surrounding air is the main source of noise. The intensity of this noise goes as the 7th power of the jet velocity. Only relatively low velocity jets are expected on ground transportation vehicles, so this type of jet noise should not be too loud. When a turbulent boundary layer flows over an edge, the pressure fluctuations that have been exerted on the wall are suddenly released so that their energy is radiated as noise. This is expected to be the principle noise mechanism for low velocity jets of the type which would come from both the propulsion system and the air cushions of the ground transportation vehicle.

The turbulent boundary flow over the vehicle and the separation in the wake is another source of aerodynamic noise. This represents a basic noise level for high speed ground transportation vehicles which would be difficult to reduce by any practical means. Fortunately the noise from this source does not appear to be greater than the level which can be accepted. Small protuberances and roughnesses on the skin of the vehicle can considerably increase this basic noise level which can be eliminated by maintaining a smooth skin.

In summary, for conventional rail systems up to about 150 mph, the noise problem is a serious one but is not caused by aerodynamics. For high speed systems the propulsion and suspension systems, both magnetic and aerodynamic, can be serious sources of noise. The aerodynamic noises with which this report is concerned are caused mainly by gas turbines, compressors and fans. The development of methods for reducing noise levels for such equipment seems to be of primary importance.

7. AERODYNAMIC RESEARCH AND DEVELOPMENT PROGRAM

In this section a variety of research and development tasks will be described and presented for different technical areas. After the tasks are described, the next section will show the relationship between these tasks and the different ground transportation programs, Table 3.

7.1 AERODYNAMIC FORCES

7.1.1 Aerodynamic Drag Reduction for Conventional Rail Systems

It has been shown that aerodynamic drag is the principle consumer of power on conventional rail systems traveling at a speed of 150 mph, and of considerable importance at lower speeds. A reduction in this aerodynamic drag could therefore result in a substantial savings in power and in the equipment needed to supply this power. Such a program should consist of an evaluation of changes that can be made to the type of equipment currently in use and being considered in new applications giving full consideration to the practical consequences of such changes. The result should be a ranking of possible changes in terms of both their aerodynamic drag reduction aspects and practical aspects. In this way it would be possible to select the modifications that provide the greatest benefits at the least cost. A preliminary analytic evaluation of aerodynamic concepts and existing data followed by wind tunnel tests should be used to provide the aerodynamic data on the different configurations. An evaluation of the costs of these features both from a production and maintenance point of view should be made with manufacturers and operators of such equipment. An evaluation of the potential power savings accomplished through drag reduction should be made considering typical missions.

7.1.2 Effect of Suspension Systems on Drag of Magnetically Levitated Vehicles

There are two principle magnetically levitated systems of interest: an attractive and repulsive system. The guideway and levitation parts of the vehicle are different for these two systems. Since the aerodynamic drag is the principle power consumer on high speed vehicles, it is necessary to determine the effect of these different levitation systems on the aerodynamic drag. The evaluation should consist of a preliminary analytic study of the two different vehicle configurations and the aerodynamic implications. Wind tunnel tests should then be designed to determine the effects of these features on aerodynamic drag and also to evaluate any changes that can be made to improve the aerodynamics without degrading the levitation system.

7.1.3 Development of a Low Drag Vehicle

Since aerodynamic drag is the principle consumer of power for high speed vehicles, it is important to develop low drag configurations. The object of this task will be to develop low drag vehicle configurations in conjunction with the guideway. The vehicle cannot be considered independent of the guideway configuration, particularly with respect to the semi-enclosed or "U" shaped guideway. The nose and the tail of the vehicle are the areas offering the greatest flexibility and possibility of drag reduction. The flow about the nose of a vehicle operating in the open can be shaped in a way to cause minimum drag by well known techniques. A "U" shaped guideway may complicate the flow but low drag configurations should be achievable for any reasonable guideway configuration. The tail presents a more difficult problem. A long streamlined tail is generally not appropriate because of its low internal volume. Boundary layer control offers a possible solution. The coupling of boundary layer control at the base with an aerodynamic propulsion is an attractive possibility which is also considered in Task 4.1. A "U" shaped guideway also complicates the base flow region. For minimum drag a smooth skin is also required. The effects of windows, doors and other protuberances should be considered. The program should consist of an analytical and experimental study of different drag reduction methods. Wind tunnel tests because of their simplicity should form the backbone of the experimental study but track tests in both air and water should also be considered. The analytical effort could be carried out as a first phase followed by the experimental work. An additional feature of these tests should be the measurement of other forces, particularly side force and roll forces for different guideway vehicle configurations. Another feature that should be considered, depending on its importance in operational plans, is vehicles in a trained configuration. Both the approach of using closely coupled vehicles with special lead, intermediate, and tail vehicles as well as basic low drag vehicles not closely coupled should be considered.

7.2 WAYSIDE ENVIRONMENT

7.2.1 Evaluation of the Pressure and Velocity Effect of Vehicles Passing Wayside Objects

When a high speed vehicle passes a wayside object, it is subject to both a pressure and velocity effect. In this respect the wayside object may be either a stationary or a moving vehicle. Enough information is now available so that reasonable preliminary estimates could be applied to the configurations of interest to both conventional rail systems and high speed systems. The objectives would be somewhat different in these two cases. For conventional rail systems, many of the conditions of operation are prescribed by existing situations. In this case, the purpose of this task would be to anticipate problems that might be expected to develop as operating speeds increased and to help arrive at solutions. High speed systems have not yet been built so there is considerably more flexibility. In this case the purpose would be to help set the design standards in order to avoid problems in this area.

7.2.2 Tests of the Aerodynamic Effects Caused by Moving Vehicles

This task consists of the measurement of the pressure and velocity fields generated by vehicles. A wind tunnel provides the simplest way of performing such measurements. Wind tunnel measurements sould be made in a coordinate system fixed with the vehicle in which the phenomenon is steady. The unsteady phenomenon can then be obtained by a simple transfer of coordinate systems. In wind tunnel tests a variety of configurations could be considered ranging from conventional trains to high speed vehicle configurations. Such tests would provide results for the flow field generated by the vehicle itself, in the absence of other objects. The interaction between other objects and the vehicle would be neglected. The available results show that this interaction is not a major part of the problem. The most important interaction is that with a long wall, and the interaction with an infinitely long wall can be simulated in the wind tunnel (at least the inviscid part of the interaction). The effect of angles of yaw on the viscous flow field associated with the boundary layer and wake should also be included in such a program.

Additional tests should also be run on full-scale vehicles in the field. Such tests should include both conventional rail equipment on existing track and high speed configurations at the Pueblo Test Center. Caution must be used in controlling conditions for such tests particularly with respect to crosswinds. The configurations that can be run on such tests are also limited to existing vehicles since the cost of special configurations would be prohibitive. For these reasons, wind tunnel tests should be used as the prime source of data and full-scale tests used to confirm the results.

An alternate to the wind tunnel tests would be model track tests either in air or water. The additional difficulties and lower quality of data associated with such tests makes the wind tunnel the preferred mode in spite of the better simulation that can be obtained in this way.

7.2.3 Measurements of Noise Generated by Air Cushions

Aside from the noise caused by turbo machinery, which is associated with both propulsion and air cushion fans and will be considered in Task 4.2, the noise of jets from an air cushion is the principle source of noise expected. Experiments to better evaluate the importance of this source of noise should be undertaken. These experiments should be carried out on both model and prototype scale. The possibility of making tests on existing air cushion vehicles should be examined. The difficulty anticipated is that the noise from associated turbo machinery will mask the cushion noise. However, the situation should be carefully examined to try to find a method for removing or filtering out the background noise. If a satisfactory system is found, measurements should be made on these vehicles.

Because of the difficulties and inflexibility of full-scale experiments, model experiments are very desirable. The first step is to examine the scaling laws to determine how best to perform such experiments. If it is determined that worthwhile experiments can be made at small scale, then a program to determine the noise level generated by different cushion configurations should be performed.

7.3 AERODYNAMIC SUSPENSION

7.3.1 Low Power Consumption Air Cushions

The power consumption of the air cushions on existing vehicles is an important part of the total power consumption. It is important to examine methods of reducing this power to more acceptable levels. An examination of the different methods of achieving reduced suspension power should be undertaken. A first step would be an analytic study of the different possible arrangements such as reduction in the length of cushion edges, use of different cushion pressures, and static and dynamic cushions. A second step would be an experimental examination of the more promising configurations.

7.3.2 Determination of Stability Derivatives for Dynamic Air Cushions

The aerodynamic properties of a dynamic air cushion are not yet established. An important aspect of the TRACV concept is that stability can be obtained using a single dynamic cushion. Studies have been and are being carried out in this area but final results have not yet been obtained. The first objectives of a combined analytical and experimental study are to determine the basic parameters and an analytical study of the way in which the aerodynamic characteristics depend upon these parameters. Experiments should then be performed over a sufficient range of these parameters in the range for which the aerodynamic characteristics appear to be useful for air cushion vehicles in order to confirm or modify the analytic predictions.

7.3.3 Preliminary Design of a Dynamic Air Cushion Vehicle

A preliminary design of a dynamic air cushion vehicle should be made in conjunction with the determination of the aerodynamic characteristics as a guide to the range of variables that should be considered in that investigation. The preliminary design should determine the values of the aerodynamic characteristics that are required to produce a dynamic air cushion vehicle. This design must cover all phases of operation, acceleration, cruise, and deceleration for different loading, guideway, and wind conditions. New results on aerodynamic characteristics should be continuously appraised to determine which configurations show promise of satisfying the needs of a ground transportation vehicle. The conclusions reached from this investigation should be used to direct the investigation into aerodynamic characteristics.

7.4 AERODYNAMIC PROPULSION

7.4.1 Evaluation of Aerodynamic Propulsion

Aerodynamic propulsion is one of the means of propelling a high speed ground transportation vehicle. Except in the area of noise, it appears to have advantages over magnetic systems. This task would be a study of aerodynamic propulsion systems designed to evaluate their performance in relation to various configurations. Particular attention should be paid to the possibilities of reducing vehicle drag and power requirements by using boundary layer air in the propulsion system and to the advantages to coupling the propulsion to an air cushion levitation system. The first phase of this study would be analytical followed by an experimental program.

7.4.2 Noise Control for Ducted Fans

A ducted fan is needed for an aerodynamic propulsion system and is a principal source of noise for such a system. It is also very similar to the fan needed for air cushion systems and compressors used in gas turbine prime movers. It is important to develop methods to quiet or muffle fans of this type with minimum penalties in performance. The first phase of this task would be an analytic study for noise level reduction and the noise reduction and performance penalties expected. An examination of the use of model experiments to develop and prove these methods should also be made. The next phase would depend on the results of the first phase, but might include the development of better muffling techniques and a demonstration of their success using model experiments.

7.5 AERODYNAMIC EFFECTS OF TUNNELS

7.5.1 The Effect of Tunnels on Vehicle Characteristics Other than Drag

When a vehicle enters a tunnel, the flow field about the vehicle is very different from when it is in the open. Preliminary investigations indicate that the lift force and pitching moment can be considerably modified from the values in the free stream for low pressure air cushion vehicles. The characteristics of such vehicles should be obtained as a function of tunnel blockage ratio in order to determine how vehicles and tunnels must be designed in order to be compatible. The first phase of this task would be an analytical study to arrive at a better understanding of the problem and to predict the anticipated effect. The second phase would be an experimental investigation, probably carried out in a wind tunnel, designed to determine the validity of the predictions.

7.5.2 Experimental Measurements of the Effects of High Speed Vehicles Passing through Tunnels

Experimental confirmation of the aerodynamic effects caused by the passage of high speed vehicles through a tunnel is needed.

There are no experimental studies at speeds for which compressibility is an important consideration. Experimental techniques developed in the tube vehicle work are suitable for this tunnel flow problem. A vehicle should be launched at high speed (up to 300 mph) into a tube which is open at both ends. The vehicle can be heavy enough to coast through the tube at essentially constant velocity. A 100-foot long tube, one inch in diameter, similar to the old GASL facility (Reference 7) simulates a tunnel two miles long. While experiments in this facility were only of limited success in simulating tube vehicle flight conditions, it seems very appropriate to the tunnel problem.

7.5.3 Predictions of the Aerodynamic Environment in Tunnels

A method of predicting conditions in tunnels in which high speed vehicles are traveling is necessary for providing design conditions for both vehicles and tunnels. Considerable work has been accomplished and is now going on in this field so that the objective is about to be achieved. This task can be divided into two phases. In Phase I, the present status of the analytical work should be reviewed and a determination made of what is needed to make it into a working tool which will be available to provide the needed predictions. Phase II should perform the work determined in Phase I and should result in a working method. The analytical results should also be used to design experiments and to compare the results of these experiments.

Almost all of the results now available are for the case of a vehicle propelled by a thrust from the ground. If an aerodynamically propelled vehicle is to be used, the tunnel flow field would be quite different. The present methods can be modified to include that case if it seems desirable to do so. Such a modification should wait until Tasks 4.1 and 4.2 have been completed and the likelihood of using aerodynamically propelled vehicles is better established.

8. RELATIONSHIP OF AERODYNAMIC TASKS TO GROUND TRANSPORTATION SYSTEMS

The way in which the fourteen aerodynamic tasks discussed in the last section support the high speed ground vehicle programs is shown in a matrix form in Table 3. The tasks are listed under the programs which they support. It is seen that many of the tasks support more than one program.

8.1 HIGH SPEED CONVENTIONAL RAIL

Five tasks directly support the high speed conventional rail program. These tasks are designed to develop less power consuming trains, to provide information on the aerodynamic conditions to which these trains will subject other trains and objects along the right-of-way, and to predict the effects of passing through tunnels.

8.2 MAGNETIC LEVITATED VEHICLES

Eight tasks support this program. Their purpose is to provide aerodynamic data on the special configurations used for magnetically levitated vehicles, to develop low drag vehicles, to determine the conditions that high speed vehicles of this type will impose on their surroundings, to assess the use of aerodynamic propulsion on such vehicles, and to predict the effect of passing through tunnels.

8.3 AIR CUSHION VEHICLES (STATIC)

Ten of the tasks support this program. These tasks are to develop low drag vehicles, determine the effects the vehicle will have on their surroundings, determine the noise level created by an air cushion, evaluate and develop air propulsion both from an efficiency and noise aspect, determine how to improve air cushion efficiency, and determine the effect of the vehicle passing through a tunnel including the effect on lift and pitching moment.

Table 3. Aerodynamic Research and Development Program

<table>
<tr><th rowspan="2"></th><th rowspan="2">HIGH SPEED CONVENTIONAL RAIL</th><th rowspan="2">MAGNETIC LEVITATION</th><th colspan="2">AIR CUSHION VEHICLES</th></tr>
<tr><th>STATIC AIR CUSHION</th><th>DYNAMIC AIR CUSHION (RAM WING)</th></tr>
<tr><td rowspan="2">1. EXTERNAL AERODYNAMIC FORCES
DRAG, ETC.</td><td rowspan="2">1.1 AERODYNAMIC DRAG REDUCTION FOR CONVENTIONAL RAIL SYSTEMS</td><td>1.2 EFFECT OF MAGNETIC SUSPENSION SYSTEMS ON AERODYNAMIC DRAG</td><td></td><td></td></tr>
<tr><td colspan="3">1.3 DEVELOPMENT OF LOW DRAG VEHICLE (INCLUDES INTERACTION WITH GUIDEWAY, BOUNDARY LAYER CONTROL, AND FORCES OTHER THAN DRAG)</td></tr>
<tr><td rowspan="3">2. WAYSIDE ENVIRONMENT</td><td colspan="4">2.1 EVALUATION OF THE PRESSURE AND VELOCITY EFFECTS OF VEHICLES PASSING WAYSIDE OBJECTS (APPLICATION OF THE EXISTING INFORMATION TO THE CONFIGURATIONS OF INTEREST)</td></tr>
<tr><td colspan="4">2.2 DETERMINATION OF AERODYNAMIC FLOW FIELDS CAUSED BY VEHICLES (MODEL AND FULL SCALE TEST PROGRAM)</td></tr>
<tr><td colspan="2"></td><td colspan="2">2.3 MEASUREMENTS OF NOISE GENERATED BY AIR CUSHIONS</td></tr>
<tr><td rowspan="2">3. AERODYNAMIC SUSPENSION</td><td rowspan="2"></td><td rowspan="2"></td><td colspan="2">3.1 LOW POWER CONSUMPTION AIR CUSHIONS (DEVELOPMENT OF LOW POWER CONSUMPTION AIR CUSHION CONFIGURATIONS)</td></tr>
<tr><td></td><td>3.2 DETERMINATION OF STABILITY DERIVATIVES FOR DYNAMIC AIR CUSHIONS
3.3 PRELIMINARY DESIGN OF DYNAMIC AIR CUSHION VEHICLE</td></tr>
<tr><td rowspan="2">4. AERODYNAMIC PROPULSION</td><td rowspan="2"></td><td colspan="3">4.1 EVALUATION OF AERODYNAMIC PROPULSION (INCLUDING COUPLING WITH BOUNDARY LAYER CONTROL AND SUSPENSION)</td></tr>
<tr><td colspan="3">4.2 NOISE CONTROL FOR DUCTED FANS</td></tr>
<tr><td rowspan="3">5. AERODYNAMIC EFFECTS OF TUNNELS</td><td></td><td></td><td colspan="2">5.1 THE EFFECT OF TUNNELS ON VEHICLE CHARACTERISTICS OTHER THAN DRAG</td></tr>
<tr><td colspan="4">5.2 EXPERIMENTAL MEASUREMENTS OF THE EFFECTS OF HIGH SPEED VEHICLES PASSING THROUGH TUNNELS</td></tr>
<tr><td colspan="4">5.3 PREDICTIONS OF THE AERODYNAMIC ENVIRONMENT IN TUNNELS</td></tr>
</table>

Numbers refer to tasks in Section 7 (initial digit omitted).

8.4 DYNAMIC AIR CUSHION (RAM WING)

Twelve tasks support this program. These tasks will provide data on low drag vehicles, the effect of the vehicle on their surroundings, evaluate aerodynamic propulsion and the noise created, determine the feasibility of a vehicle supported by a single dynamic air cushion, and the effects caused by the vehicle passing through tunnels.

APPENDIX A. LOSSES ASSOCIATED WITH AIR CUSHIONS

The fundamental losses associated with any air cushion, in addition to those caused by friction both internally and externally, are equal to the kinetic energy dissipated by the jets which escapes from the cushion edges. The velocity of these jets, with respect to the cushion, has a component perpendicular to the cushion edge driven by the pressure difference between the pressure in the cushion and the atmosphere, and may have an additional component in the direction of vehicle motion. If the air within the cushion is only moving slowly with respect to the cushion it will be referred to as a static cushion and, if moving rapidly, as a dynamic cushion.

First consider the case of a static cushion on a stationary vehicle. The cushion pressure is

$$p_c = \frac{L_c}{A_c} \tag{A-1}$$

The jet velocity is

$$V_j = \sqrt{\frac{2p_c}{\rho}} \tag{A-2}$$

The volume flow escaping from the cushion is

$$Q = \sqrt{\frac{2p_c}{\rho}}\ Ch = \sqrt{\frac{2LA}{\rho}}\ \frac{Ch}{A} \tag{A-3}$$

and the power dissipated is

$$P = \rho Q \frac{V_j^{\,2}}{2} \tag{A-4}$$

or

$$\frac{P}{V_\infty L\ Ch/A} = \sqrt{\frac{p_c}{q_\infty}} \tag{A-5}$$

For a low aspect ratio cushion such as used on a tracked vehicle the side edges of the cushion are much longer than the front and back so, in the limit of zero aspect ratio

$$\frac{Ch}{A} = 2\,\frac{h}{b} \tag{A-6}$$

It is clear that the least power is required for the lowest jet velocity or cushion pressure requiring the cushion area be as large as possible.

If the cushion has forward velocity, the conclusions are somewhat different. At forward speed several different cushion designs need to be considered.

[1] The total pressure behind the fan is equal to the cushion pressure at all forward speeds. This situation would exist if a constant volume flow fan were used.

[2] There is no fan or the fan blades are feathered at speeds where the ram pressure is greater than the cushion pressure.

[3] The fan increases the total pressure of the flow by an amount equal to the cushion pressure. This situation would occur if a constant pressure rise fan were used.

When the cushion is moving forward, the jet velocities and losses associated with the forward, rear, and side edges of the cushion are different. Since the side edges of the cushion are the longest, they may be the most important and will be considered first. Case [1] is a reasonable idealization to the way a fixed geometry constant speed axial flow fan would operate. Under this condition the cushion is a static cushion. The jet velocity has a component perpendicular to the direction of motion which is caused by the cushion pressure and a component in the direction of vehicle motion equal in magnitude to the vehicle motion. The volume flow is the same as given by Equation (A-3) and the total velocity is

$$V_t^{\,2} = \frac{2p_c}{\rho} + V_\infty^{\,2} \tag{A-7}$$

The total power dissipated is

$$\frac{P}{LV_\infty \; Ch/A} = \left(1 + \frac{q_\infty}{p_c}\right)\sqrt{\frac{p_c}{q_\infty}} \tag{A-8}$$

The power required is shown in Figure A-1. The minimum power occurs when the cushion pressure is equal to the dynamic pressure of the oncoming air. The power requirement increases less rapidly if the cushion pressure is less than the dynamic pressure than if it is greater. For maximum efficiency, a vehicle of this type should probably be designed so that the dynamic pressure is somewhat higher than the cushion pressure at the cruise condition. How much higher would depend upon the amount of time that the vehicle is expected to spend at reduced velocities. A minimum value of the cushion pressure is, of course, fixed by the available planform area of the vehicle and the weight. However, for this case, the minimum cushion pressure may not be optimum.

The second case would occur if the vehicle is capable of changing to a ram wing mode of operation when the dynamic pressure exceeds the cushion pressure. This condition also requires that a dynamic cushion be used since the total pressure in the cushion is greater than the static pressure. The air in the cushion is flowing in the same direction as the free stream but at enough lower velocity so that the static pressure has increased to the cushion pressure. Under this condition the jets have a velocity component in the direction normal to the cushion caused by the cushion pressure and a velocity in the direction of vehicle travel by an amount equal to the difference between the free stream velocity and the velocity in the cushion. The volume flow is still given by Equation A-3 and the velocity in the cushion relative to the vehicle is given by the relation

$$V_c = \sqrt{V_\infty^{\;2} - 2\,\frac{p_c}{\rho}} \tag{A-9}$$

The power loss is then

$$\frac{P}{LV_\infty \ Ch/A} = 2 \left(1 - \sqrt{1 - \frac{p_c}{q_\infty}}\right) \sqrt{\frac{q_\infty}{p_c}} \qquad \text{(A-10)}$$

This power requirement is also shown in Figure A-1. The ram wing is most efficient when operating at a dynamic pressure much larger than cushion pressure. For a given speed of operation the cushion pressure should be as low as possible. This result is similar to that found for ram wings in Reference 8.

The third case would occur for a constant pressure rise fan and a dynamic cushion. Since the fan imparts a pressure rise of p_c the cushion velocity must always be equal to the free stream velocity. The jet velocity from the cushion is perpendicular to the cushion edge and caused by the cushion pressure. The volume flow is that given by Equation (A-3) and the jet velocity by Equation (A-2). The resulting expression for power is

$$\frac{P}{LV_\infty \ Ch/A} = \sqrt{\frac{p_c}{q_\infty}} \qquad \text{(A-11)}$$

This result is also shown in Figure A-1. This case gives the lowest power. It is asymptotic to Case 1 at low speed and Case 2 at high speed. It gives considerably better performance than either in the neighborhood of dynamic pressure equal to cushion pressure.

The front and rear edges of the cushion are somewhat different. When the vehicle is stationary, all the edges are the same as has already been discussed. The result for the stationary vehicle, Equation (A-5), is the limit, at zero velocity, for Case 1, Equation (A-8). The power requirements for the front and back edges of the cushion are similar to that given for Case 1, Figure A-1. For Case 1, there is a flow out the forward and rear edges of the cushion for $q < p_c$. In the front of the cushion, the jet velocity is related to the difference between cushion

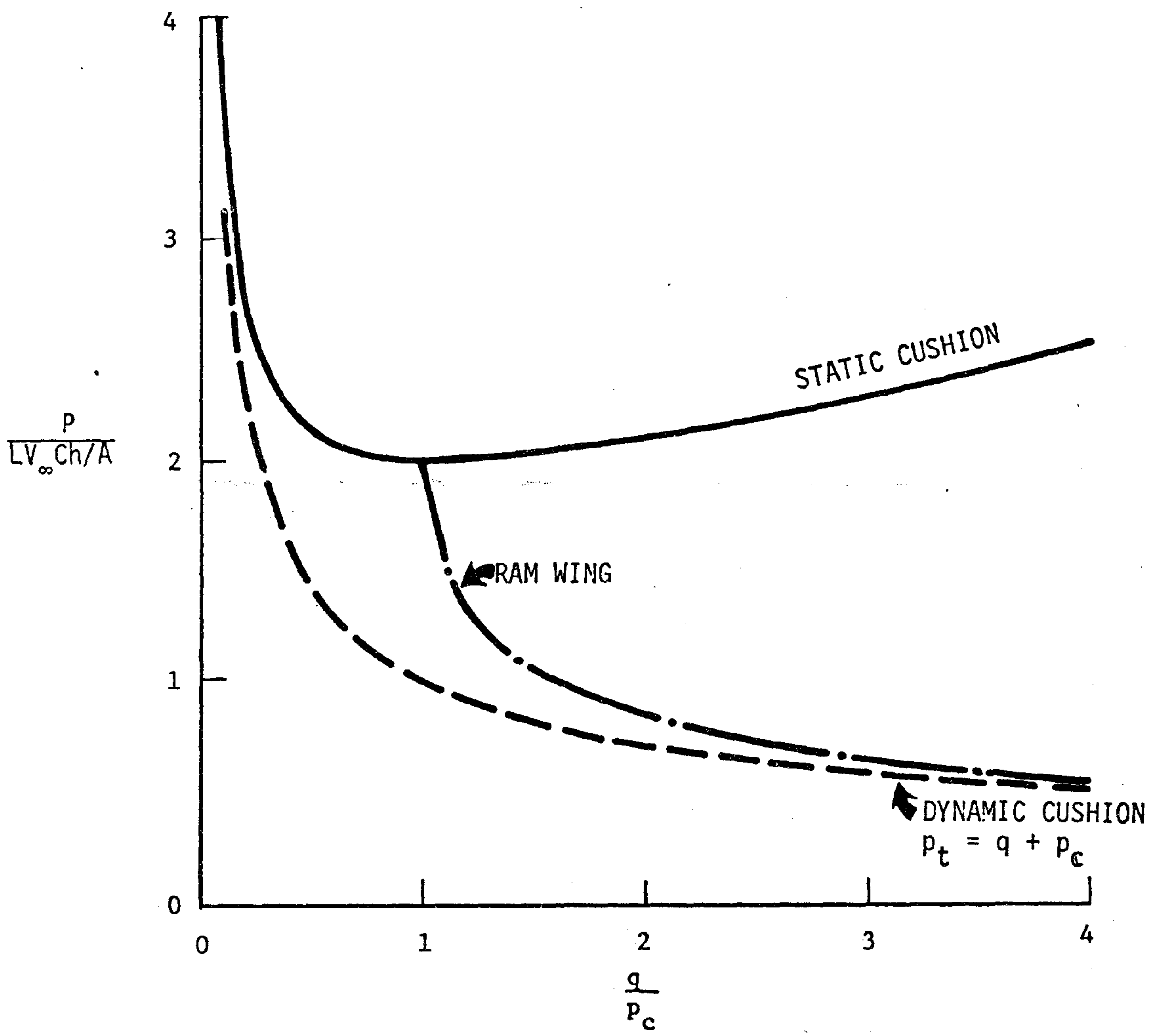


Figure A-1. Power required for side edges of various single air cushion configurations and dynamic pressure

$$V_j = \sqrt{\frac{2(p_c - q_\infty)}{\rho}} \tag{A-12}$$

The volume from the leading edge is

$$Q = V_j \; C_F \; h \tag{A-13}$$

and the power dissipated is

$$\frac{P}{LV_\infty \; C_F \; h/A} = \sqrt{\frac{p_c}{q} - 1} \left[1 + 2 \sqrt{\frac{q}{p_c} \left(1 - \frac{q}{p_c} \right)} \right] \tag{A-14}$$

At the rear of the cushion, the jet velocity is

$$V_j = \sqrt{\frac{2p_c}{\rho}} \tag{A-15}$$

The volume flow is

$$Q = V_j \; C_R \; h \tag{A-16}$$

and the power dissipated is

$$\frac{P}{LV_\infty \; C_R \; h/A} = \sqrt{\frac{q}{p_c}} + \sqrt{\frac{p_c}{q}} - 2 \tag{A-17}$$

The total power dissipated at both the front and the rear edges is

$$\frac{P}{V_\infty \; L \; \frac{C_{F+R} \; h}{A}} = \frac{1}{2} \left\{ \sqrt{\frac{q}{p_c}} + \sqrt{\frac{p_c}{q}} - 2 + \sqrt{\frac{p_c}{q} - 1} \left[1 + 2 \sqrt{\frac{q}{p_c} \left(1 - \frac{q}{p_c} \right)} \right] \right\} \tag{A-18}$$

The power dissipated is then

$$P = \frac{1}{2}\rho Q\ (V_j + V_\infty)^2$$

$$\frac{P}{L\ \frac{C_R h}{A}} = \frac{1}{2}\sqrt{\frac{p_c}{q}}\ \frac{1 - \frac{q}{p_c}}{1 + \sqrt{\frac{q}{p_c}}}\ \left(1 + \frac{q}{p_c} + 2\sqrt{\frac{q}{p_c}}\right) \qquad \text{(A-21)}$$

At the rear edge the jet velocity is then

$$V_j = \sqrt{\frac{2(q + p_c)}{\rho}}$$

and the power is

$$P = \frac{1}{2}\rho Q\ (V_j - V_\infty)^2$$

$$\frac{P}{L\ V_\infty\ \frac{C_R h}{A}} = \sqrt{1 + \frac{p_c}{q}}\ \left[1 + 2\frac{q}{p_c} - 2\sqrt{\left(\frac{q}{p_c} + 1\right)\ \frac{q}{p_c}}\right] \qquad \text{(A-22)}$$

All of these results are shown in Figure A-2. For Case [1], the result is the same as given previously in Reference 1. Figure A-2 shows that the differences between the three cases are not very significant. The power dissipated is only important when $q < p_c$. For Case [3], some thrust will be obtained. The power that is dissipated in obtaining this thrust may be no more than would have been dissipated by the regular propulsion system which would not be a disadvantage. These results would appear to bear out the original suggestion that the important dissipation comes from the sides and not the front and rear. A possible exception might occur if the clearances at the front and back are much larger than at the sides.

assuming that the two edges are of equal length. There is zero loss for both the front and rear edges at $q = p_c$. At higher velocities there would be no outflow from the leading edge so losses could occur only at the trailing edge. Equation (A-17) can be used for these trailing edge losses. It should be realized that there is some inconsistency in having flow enter the cushion at the forward edge and maintaining static cushion conditions at a total pressure of p_c. The flow under the forward cushion should be small with respect to that through the fan so that neglecting it may be justified in this simple analysis.

Case 2, the ram wing, can only be considered when $q > p_c$. There is no outflow through the front of the cushion and the flow leaves the rear of the cushion with free stream velocity so there are no losses associated with these edges.

For Case 3, the static pressure in the cushion equals p_c and the dynamic pressure equals $p_c + q$. Because the dynamic pressure is greater than in Case 1, the flow from the leading edge will be reduced if the flow from the fan is directed away from the leading edge. The jet velocity is the difference between the total pressure in the cushion and the free stream.

$$V_j = \sqrt{\frac{2(q + p_c - q)}{\rho}} = \sqrt{\frac{2p_c}{\rho}} \tag{A-19}$$

In order for the flow from the fan to be turned around and escape in the forward direction, its momentum must be overcome by the difference between the static pressure in the cushion and the stagnated free stream flow. A momentum balance can be performed to determine the amount of air escaping under the forward cushion.

$$(p_c - q)\ hC_F = \rho Q(V_\infty + V_j)$$

$$\rho Q = C_F h \ \frac{\left(1 - \frac{q}{p_c}\right)\sqrt{\frac{\rho p_c}{2}}}{1 + \sqrt{\frac{q}{p_c}}} \tag{A-20}$$

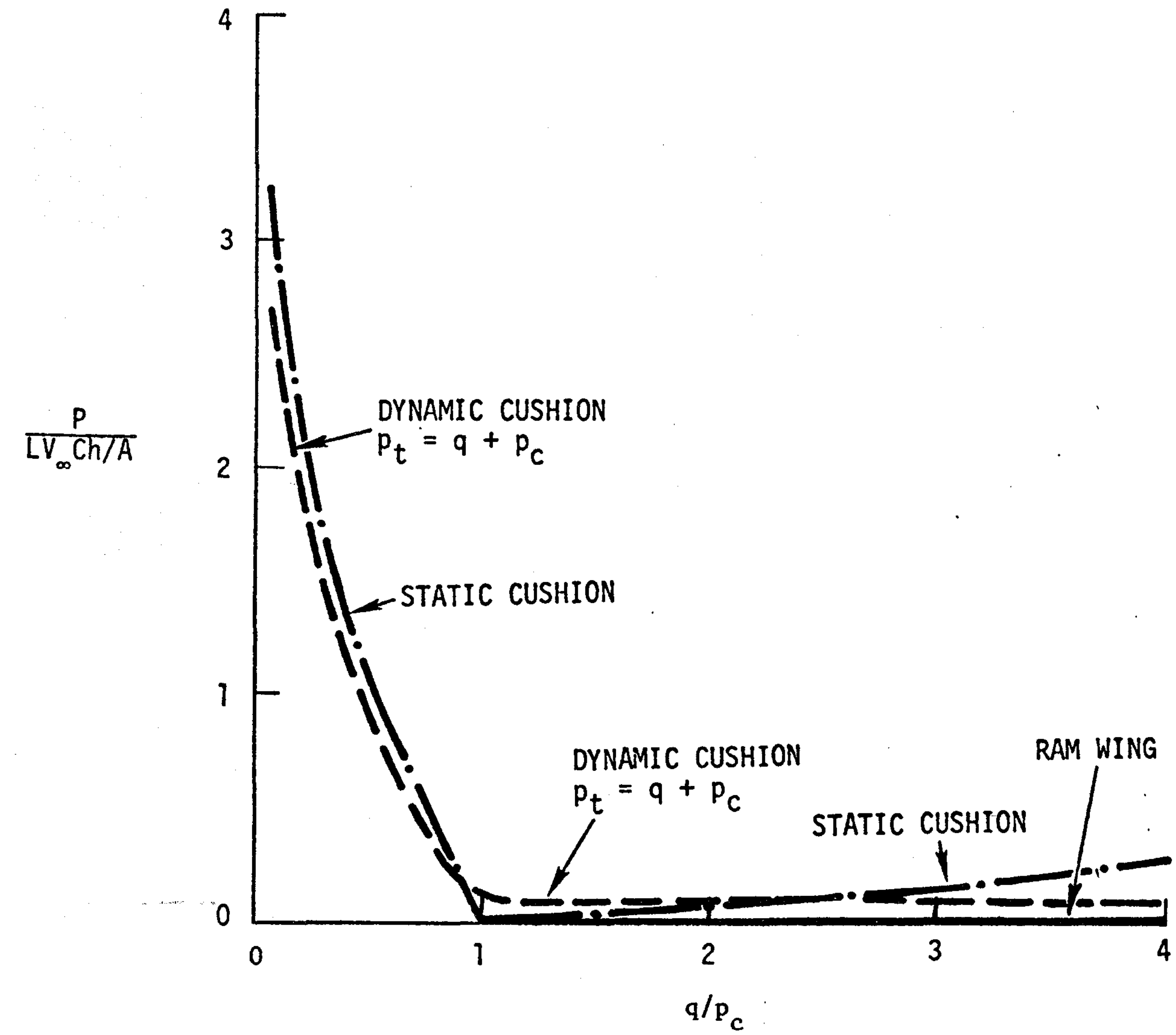


Figure A-2. Power required for front and rear edges of various single air cushion configurations

In order to assess the importance of these different cushion configurations, a vehicle of the type described by the TRACV study, Reference 2, was considered. The important characteristics as applied to the suspension system are:

Vehicle weight	92,000 lb or 41,730 kg
Available cushion area	2000 ft^2 or 186 m^2
Cushion clearance	0.025 ft or 0.0076 m
Minimum cushion pressure	46 lb/ft^2 or 0.0224 kg/cm^2

Using these characteristics, the cushion power as a function of speed was calculated and has been presented in Figure 4 (p. 25). All three cases were presented for the minimum cushion pressure. At high speed the static cushion is seen to require considerably more power than the other two arrangements. The static cushion is operating considerably away from the optimum condition at maximum velocity. For this reason a cushion design with four times the pressure is also shown which is close to the optimum pressure for maximum speed. Power savings are made at the high speed condition at the cost of increased power at the low speed condition.

The results just discussed are for the case where the guidance and levitation cushions are so arranged that there are only two edges leaking to the atmosphere. The power requirement for any of the cushions is quite low. However, if an arrangement of four cushions is to be used, two levitation cushions side by side and two guidance cushions, the number of cushion edges and the power requirement will be increased by a factor of four. The power requirements on the vehicle for the high pressure air cushion and the aerodynamic drag are shown in Figures 4 and 5 (pp. 25,26). If the four separate cushions are required, the cushion power is of the same order as the drag power.

If the power for an air cushion suspension system is not to be excessive, it would appear necessary to find some way of combining the air cushions so that the number of edges leaking to the atmosphere is reduced to two. This change appears to reduce the required power to the level where it is a small part of the drag power. Additional improvements, such as can be achieved by using dynamic instead of static cushions, offer a further considerable reduction.

These results are probably on the optimistic side for both the vehicle drag and the cushion power. Viscous losses both in the cushions and the ducting have been neglected. When all the additional effects such as orifice losses and differences in aerodynamic drag due to different frontal areas are included, it is not immediately clear if the relative energy advantage of the dynamic cushion increases or decreases.

APPENDIX B. STABILITY OF DYNAMIC AIR CUSHION OPERATING AT LOW CUSHION PRESSURES

The dynamic air cushion may offer several advantages over the static air cushion. This is particularly true if a single thick air cushion can provide sufficient stability and acceptable ride quality without a secondary suspension.

In order to provide stability, the cushion must be capable of sustaining different values of static pressure in different areas. The dynamic cushion concept, in which the total pressure within the cushion is larger than the static pressure, is capable of achieving this result. It is obvious that the ratio of static pressure to dynamic pressure, which is closely related to the lift coefficient, is an important parameter in determining how much dynamic action is possible. It also appears to be obvious that, for a low aspect ratio configuration such as is appropriate to a ground transportation vehicle, it is easier to maintain different static pressure levels along the length of the vehicle than in the direction across the vehicle. There are two major questions which have to be considered: 1) does the dynamic cushion provide capability of developing sufficient force to balance the expected loads, and 2) are the stiffness characteristics of the cushions suitable for providing an adequate ride without a secondary suspension. If the natural characteristics of the cushion are not adequate to satisfy the second requirement, it may be necessary to improve the characteristics by the use of controlled flaps or jet curtains.

As a first step, it is useful to try to express quantitatively the effect of aspect ratio on the isolation between different parts of the cushion separated in an athwartship direction. If the fluid were constrained to flow in the longitudinal direction only, then a change in one part on the cushion would effect conditions only along that longitudinal line. However, a change in pressure along one longitudinal line will cause a cross flow that will allow the fluid to escape from that longitudinal line and move to a different one. If the cushion has the length, ℓ, and width, b, the amount of crossflow velocity required to relieve differences in static pressures across the cushion is

$$\frac{V_c}{V_e} \sim \frac{b}{\ell} = AR \tag{B-1}$$

The longitudinal velocity is related to the difference between static and total pressure and the crossflow velocity is related to the pressure differences across the vehicle

$$V_e = \sqrt{\frac{2(p_t - p_c)}{\rho}}, \quad V_c = \sqrt{\frac{2\ \Delta p_c}{\rho}} \tag{B-2}$$

Therefore,

$$\frac{\Delta p_c}{p_t - p_c} \sim (AR)^2 \tag{B-3}$$

and using the total pressure as the reference quantity

$$\Delta C_p \sim (1 - C_\ell)(AR)^2 \tag{B-4}$$

Based on this very simple analysis, one might expect there to be some similarity between possible athwartship pressure differences, for different cushions, if the quantity on the right hand side of this equation is constant. This relation also points out the need for a small ratio of dynamic to total pressure ratio (a low lift coefficient), if substantial pressure differences are to be sustained across the cushion.

If adequate stability cannot be obtained with a fully open cushion, the use of longitudinal separators would be required. Such separators would probably not have to be as close to the guideway as the curtains along the edges of the cushion, but unless they were flexible and designed to prevent contact, they would restrict the motion of the vehicle and inhibit the ability of the air cushion to act as the entire suspension system. The use of a single keel or longitudinal separator along the centerline was considered in the analysis presented in Reference 9. In that analysis, it was assumed that the keel sealed perfectly against the guideway and that the dynamic effects provided no additional isolation. As that analysis indicates, there is a very strong roll sway coupling, which appears to be unacceptable. If the pressures on each side of the keel, both under the vehicle and on the side of the vehicle, are the same then no side force can be sustained unless a rolling moment is also applied, and vice versa. This arrangement would only be capable of resisting a side force applied at one particular vertical location. Separation into four basic cushion areas, either by the dynamic effect or by longitudinal separators, is required to provide stability.

An attempt has been made to estimate whether the stability in roll and sway would be adequate for a dynamic air cushion without longitudinal separators. Using Reference 9 and the additional side force data available from Reference 10, the side force requirements to which the Grumman TLRV was designed, Reference 11, were compared with the capabilities of the dynamic air cushion. The conclusion is that considerably more side force is needed than appears to be available. This conclusion is based on very preliminary data and may prove premature. It does point out, however, that this is a potential problem area and that the investigation of dynamic cushions should concentrate on designs that can be expected to satisfy such criteria.

The heave and pitch stiffness of the cushion is also another property that needs examination. A simple analysis of the stiffness in heave is instructive. Consider the configuration shown in Figure B-1. It will be assumed that perfect side curtains are provided or that the configuration is of infinite aspect ratio. The continuity equation gives

$$Vh = V_\infty h_o \tag{B-5}$$

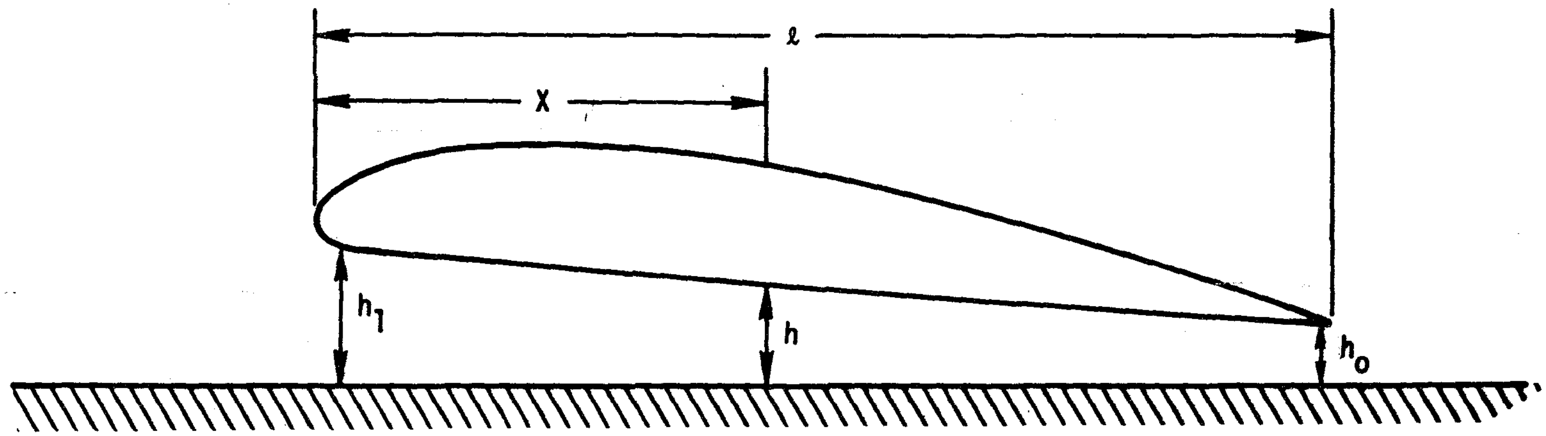


Figure B-1. Schematic diagram of ram wing configuration

The Bernoulli equation can then be used to calculate the pressure.

$$p - p_\infty = \frac{1}{2} \rho V_\infty^{\;2} \left[1 - \frac{1}{1 + X/\ell \; (h_1/h_o - 1)} \right] \tag{B-6}$$

The lift can be obtained by integrating along the length of the vehicle.

$$C_\ell = \frac{L}{qA} = \frac{\Delta h}{h_1} \tag{B-7}$$

where

$$\frac{\Delta h}{h_1} = \frac{h_1 - h_o}{h_1}$$

The lift can be differentiated with respect to the cushion height of Δh constant

$$\frac{h_o}{C_\ell} \frac{dC_\ell}{dh_o} = - \frac{\Delta h_o}{\Delta h + h_o}$$

The frequency of vertical oscillation can then be related to this result.

$$\omega \sqrt{\frac{\Delta h}{g}} = - \sqrt{C_\ell}$$

This result is of limited interest since it was derived under the assumption that the heave motion is independent of the pitch motion (Δh=constant). Actually, it is very likely that there is a strong coupling between them, and that the coupled results would be very different. However, this result does illustrate that the heave frequency is closely coupled to the lift coefficient and the speed of the vehicle. Also, it should be realized that a vehicle could not operate satisfactorily on aerodynamic lift alone at speeds which require a lift coefficient near 1 since an adequate amount of increased lift is not available to provide vertical acceleration over bumps.

Both the consideration of adequate heave stiffness and dynamic separation of cushion areas suggests that dynamic cushion vehicles should not operate at high lift coefficients. This may impose an additional limitation on the take off speed of a dynamic air cushion vehicle which depends only on the ram pressure to achieve lift. For instance, if the maximum lift coefficient that could be allowed at take off were reduced from 1 to 0.5, the take off speed, or the speed of which partial wheel support is no longer needed, of the ram version of the TRACV vehicle (Reference 2), would be 200 mph (322 km/hr), instead of 150 mph (241 km/hr).

APPENDIX C. AERODYNAMIC PROPULSION BY DUCTED FAN OF GROUND VEHICLE

A ducted fan is a good means of propelling a ground vehicle. If the fan is located at the rear of the vehicle, it need not increase the cross-section of the vehicle and can still be of large enough diameter to give efficient propulsion. The momentum theory of a propeller shows that an efficient system requires a large diameter and low disc-loading. However, the efficiency of an actual propeller acting as an actuator disc decreases if the disc loading becomes too small so that the optimum propeller diameter is limited. For a ducted propeller located on the rear of an approximately axially symmetric vehicle using boundary layer air, the maximum momentum efficiency is obtained at a finite diameter.

The ideal fan would ingest only the boundary layer and increase the total pressure in a selective way so that the total pressure of the boundary layer air is restored to the free stream value. If the entire drag of the vehicle is caused by the friction with the air in the boundary layer, such a fan will produce a thrust just equal to the drag. In practice, it is difficult to prevent the boundary layer air ingested into the duct from mixing with itself so that it does not achieve a condition of uniform total head before it reaches the fan. A real ducted fan should probably be designed to accept a uniform total pressure of incoming flow and restore it to somewhat above free stream total pressure. If all the flow which enters the duct mixes to achieve a uniform total pressure, it is advantageous to ingest only a part of the total boundary layer flow, so as to limit the mixing between air of different total pressure.

In order to achieve an initial understanding of this problem, let us assume a turbulent boundary on the vehicle with a velocity profile given by the 1/7 power law.

$$\frac{V}{V_\infty} = \left(\frac{y}{\delta}\right)^{1/7} \qquad \text{(C-1)}$$

Consider that the entire boundary layer will not be ingested into the duct but only the fraction γ of the total boundary layer thickness δ. The amount of mass taken into the duct is then

$$\frac{m_\gamma}{\rho V_\infty \delta} = \int_0^\gamma \frac{V}{V_\infty} d\,\frac{y}{\delta} = \int_0^\gamma \left(\frac{y}{\delta}\right)^{1/7} d\,\frac{y}{\delta} = \frac{7}{8}\,\gamma^{8/7} \tag{C-2}$$

and the momentum associated with this mass is

$$\frac{J_\gamma}{\rho {V_\infty}^2 \delta} = \int_0^\gamma \left(\frac{V}{V_\infty}\right)^2 d\,\frac{y}{\delta} = \int_0^\gamma \left(\frac{y}{\delta}\right)^{2/7} d\,\frac{y}{\delta} = \frac{7}{9}\,\gamma^{9/7} \tag{C-3}$$

If this entire mass mixes so that a uniform velocity is achieved, the resulting velocity is

$$\frac{V_\gamma}{V_\infty} = \frac{J_\gamma}{m_\gamma V_\infty} = \frac{8}{9}\,\gamma^{1/7} \tag{C-4}$$

The fan must increase the total pressure of this flow so that it can be ejected at a velocity enough higher than the free stream velocity so that the excess momentum in the slip stream will compensate for the deficiency in the part of the boundary layer which was not ingested.

$$m_\gamma V_e = V_\infty m_\delta - J_{\delta-\gamma} \tag{C-5}$$

Where m_δ is the entire flow through the boundary layer and $J_{\delta-\gamma}$ is the momentum in the boundary layer flow that is not ingested into the fan.

$$\frac{m_\delta}{\rho V_\infty \delta} = \int_0^1 \frac{V}{V_\infty} d\,\frac{y}{\delta} = \int_0^1 \left(\frac{y}{\delta}\right)^{1/7} d\,\frac{y}{\delta} = \gamma^{8/7} \tag{C-6}$$

$$\frac{J_{\delta-\gamma}}{\rho V_\infty^2 \delta} = \int_\gamma^1 \left(\frac{V}{V_\infty}\right)^2 d\,\frac{y}{\delta} = \int_\gamma^1 \left(\frac{y}{\delta}\right)^{2/7} d\,\frac{y}{\delta} = \frac{7}{9}\,(1 - \gamma^{9/7}) \qquad \text{(C-7)}$$

Therefore, the exit velocity from the fan must be

$$\frac{V_e}{V_\infty} = \frac{1}{9\gamma^{8/7}} + \frac{8}{9}\,\gamma^{1/7} \qquad \text{(C-8)}$$

The ideal fluid power of the fan is then

$$\frac{P}{\rho V_\infty^3} = \frac{m_\gamma}{2\rho V_\infty}\left[\left(\frac{V_e}{V_\infty}\right)^2 - \left(\frac{V_\gamma}{V_\infty}\right)^2\right] = 0.0054\,\gamma^{-8/7} + 0.08642\,\gamma^{1/7} \qquad \text{(C-9)}$$

The power required to tow the vehicle is

$$\frac{P_T}{\rho V_\infty^3 \delta} = \frac{D}{\rho V_\infty^2 \delta} = \int_o^1 \frac{V}{V_\infty}\left(1 - \frac{V}{V_\infty}\right) d\,\frac{y}{\delta} = 0.09722 \qquad \text{(C-10)}$$

Therefore, the ratio of fan power to towline power is

$$\frac{P}{P_T} = 0.0554\,\gamma^{-8/7} + 0.88889\,\gamma^{1/7} \qquad \text{(C-11)}$$

Figure C-1 shows the power required by the fan as a function of boundary layer mass flow ingested. The minimum power occurs when a little more than half of the boundary layer air is ingested. The fluid power is less than the towline power. This reduction is caused by the fact that the fan is using air which is at lower velocity relative to the vehicle than the free stream air and part of the energy lost to the boundary layer can be recovered.

An even lower power could be achieved if an increase in total pressure could be given selectively to each boundary layer streamline to restore it to free stream total pressure. If this can be done without mixing

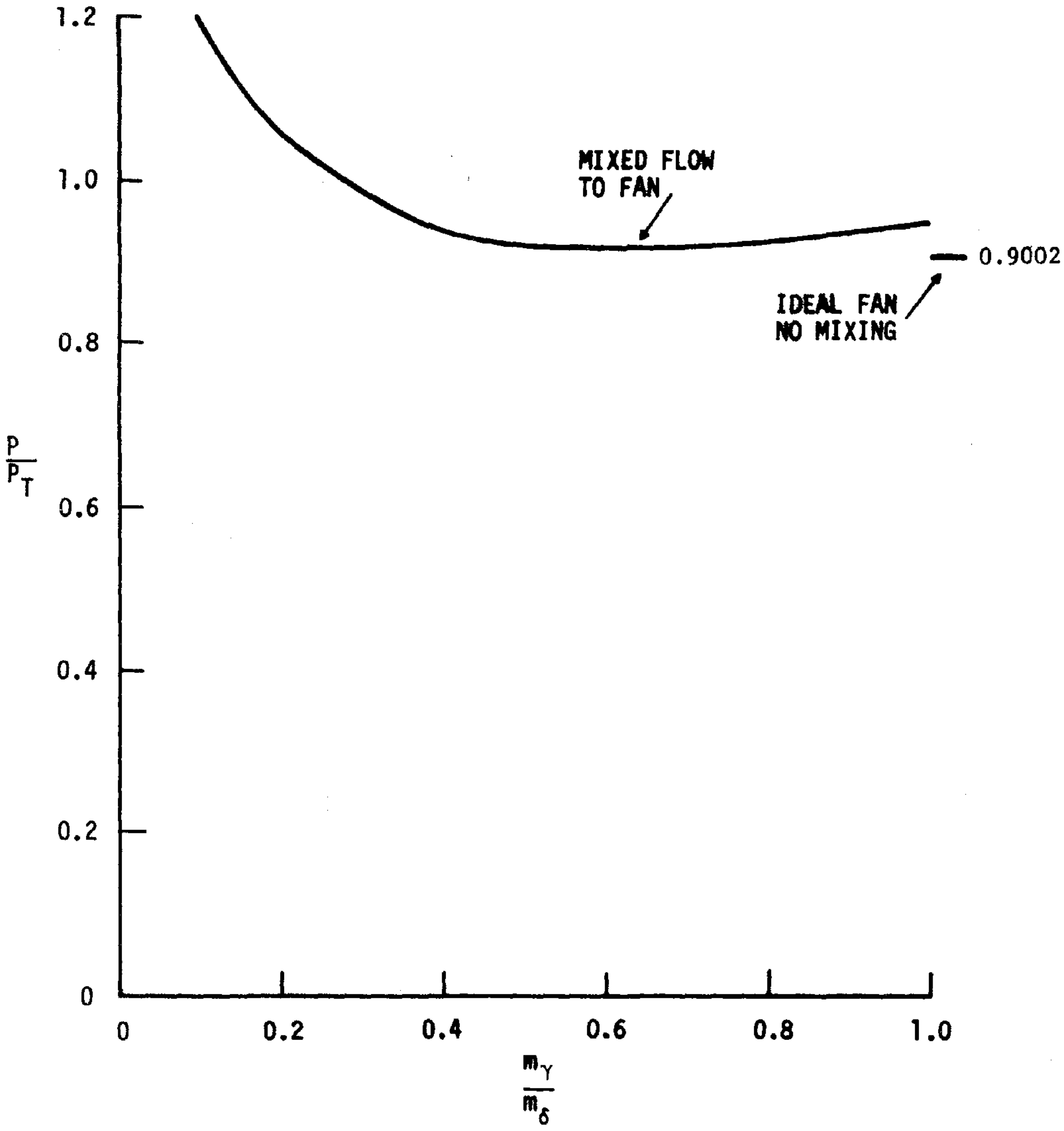


Figure C-1. Power required for boundary layer aerodynamic propulsion compared with thrust power as a function of boundary layer mass ingested into fan occurring through the fan, then the required power is reduced to

$$\frac{P}{P_T} = 0.9002$$

and all of the boundary layer air must pass through the fan. This power is only slightly less than can be achieved by the more realistic case of allowing for mixing in the flow to the fan. The shaft power would be somewhat higher than the fluid power. A fan efficiently of 0.8 to 0.85 is probably realistic.

APPENDIX D. AIR CUSHION PASSING THROUGH TUNNEL

The purpose of this analysis is to provide a crude first order evaluation of the effect on lift that may be expected when an air cushion vehicle passes through a tunnel. Although only the case of the ram wing will be analyzed, the effects would be similar for any air cushion vehicle for which the cushion pressure is not considerably in excess of ram pressure.

The configuration that will be considered is shown in Figure D-1. It will be assumed that the vehicle spans the tunnel and that there is no leakage between the flow under and on top of the vehicle. The flow area above the vehicle is assumed to be of constant area and the flow passage under the vehicle is also considered constant except for the lip at the trailing edge. The mass continuity equation requires that

$$V_\infty A_\infty = V_u A_u + V_{1L} A_{1L} = V_u A_u + V_{2L} A_{2L} \tag{D-1}$$

If it is assumed that the static pressure at the exit of the upper and lower passages is equal to the pressure behind the vehicle, then Bernouli's equation can be applied along both the upper and lower passage with the result that

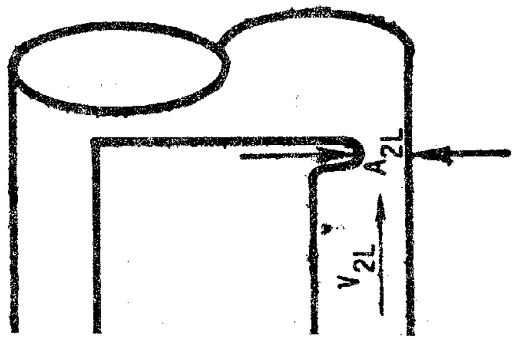
$$V_u^{\,2} \left(c_f \frac{A_{wu}}{A_u} + 1 \right) = V_{1L}^{\,2}\; c_f \frac{A_{wL}}{A_{1L}} + V_{2L}^{\,2} \tag{D-2}$$

Now introduce the following dimensionless notation

$$\beta = \frac{A_v}{A_\infty} = 1 - \frac{A_u + A_{2L}}{A_\infty},\; J = \frac{A_u}{A_\infty},\; R = \frac{A_{2L}}{A_{1L}},\; X = \frac{A_{2L}}{A_v} \tag{D-3}$$

From the continuity relation the velocities in the upper and lower passages can be related.

$$\frac{V_{2L}}{V_\infty} = \left(1 - \frac{V_u}{V_\infty} J \right) \frac{1}{X\beta} \tag{D-4}$$



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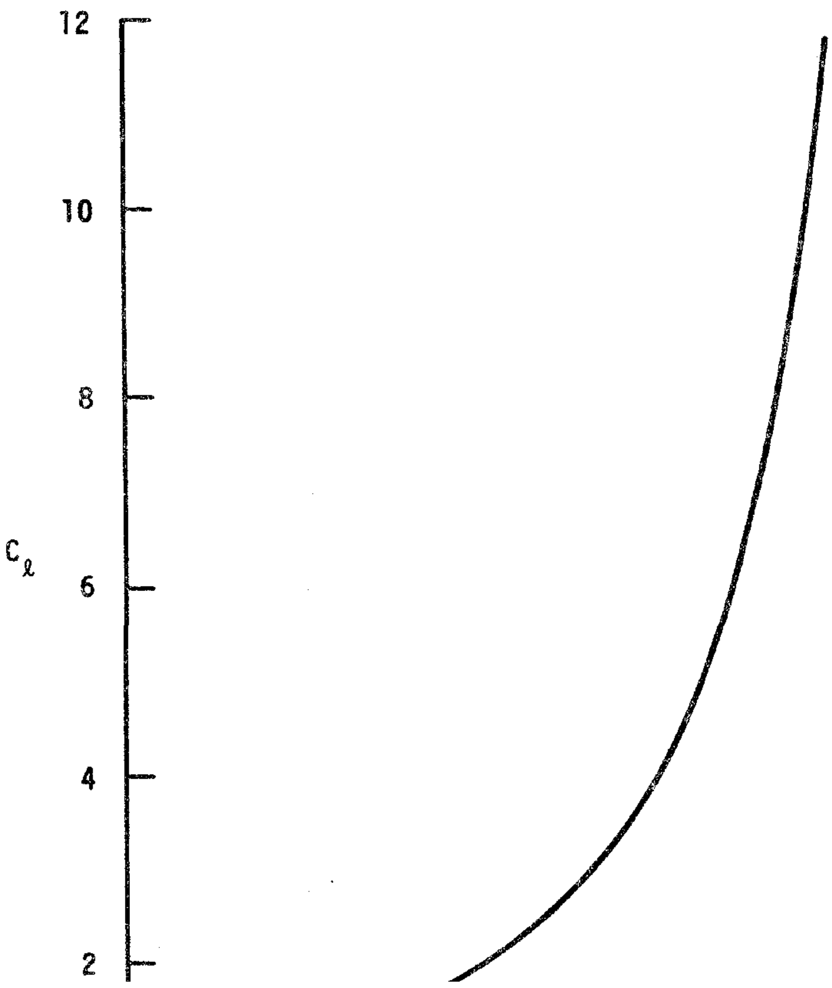

be determined separately for conditions in a tunnel. The vehicle will have to be designed to have satisfactory stability and ride qualities both in the open, in a tunnel, and while entering and leaving a tunnel.

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