A REVIEW OF THE STATUS OF
AIR CUSHION TECHNOLOGY

including
SUGGESTIONS FOR THE ORGANIZATION

of
A CANADIAN RESEARCH & DEVELOPMENT
PROGRAMME

by
P. A. Sullivan
and
R. Placek

May, 1971.
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We would like to thank Mr. W. R. Buckley and Mr. N. K. Seth for their assistance with editing and drafting of figures.
This review is a response to the question: "Given that there is growing interest in Canada in a number of possible applications of air cushion technology to transport problems, what research should be undertaken at this time, if any?". To answer this question with some semblance of rationality, we found ourselves venturing outside our immediate fields of competence. In addition to surveying the status of technological developments, in order to elicit a coherent pattern, we found ourselves examining the innovation process itself and policy matters relating to R & D priorities. We hope that in this way we have provided a better framework for discussion; and if we have oversimplified we would ask those who disagree strongly to let us know.

P. A. Sullivan
R. Placek
SUMMARY

This review attempts to present a basis for discussion of research and development requirements for effective exploitation of air cushion technology in Canada. Detailed reviews of the status of two important applications, namely amphibious air cushion vehicles (ACV) or Hovercraft and tracked ACVs or Hovertrains, are given. An examination of the relationship of R & D to transportation vehicles is also included to provide a basis for taking an adequate perspective of needs in this new technology. Some recommendations on the form of an appropriate R & D programme are also made in the light of trends in other fields. A summary of available information on amphibious ACV costs, and an annotated bibliography of the research literature together with a subject index, completes the review.
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PART I  OVERVIEW AND RECOMMENDATIONS

1) INTRODUCTION

The recent publication of the NRC sponsored market survey entitled "Air Cushion Vehicles (ACV) - Their Potential for Canada" (German et al., 1969) highlighted the growing interest in this Country in the opportunities presented by the air cushion suspension principle. These opportunities fall into two classes; potential solutions to some difficult Canadian transportation problems and the establishment of innovative manufacturing industries with an export potential. The present study is intended to complement the NRC sponsored Survey and similar investigations currently being undertaken by the Canadian Transport Commission of the potential of tracked ACVs or "Hovertrains" by presenting an evaluation of the status of the technology and by suggesting R & D requirements for effective exploitation of the manufacturing opportunities which may occur in Canada.

This study is based on a detailed evaluation of the published literature together with technical discussions with groups in the Industry and in Government and University Laboratories in Britain, France and the USA actively involved in R & D. For the convenience of the reader the report has been cast into three parts. Part I contains an overview and some specific recommendations for an R & D programme, while Part II consists of a sequence of appendices containing detailed information and observations. Part III consists of an annotated bibliography of available references in the technical literature. The principal technical framework for the recommendations is given in Appendices B and C, which are surveys of the status of the technology of two principal applications. However, our studies have also revealed the existence of a number of organizational problems which have already arisen in the industry, and which are essentially part of the usual innovation process. To set these problems in context, and to define more clearly the manufacturing opportunities presented to Canada, a review of the features of the innovation process together with inferences for the development of air cushion technology in this Country has been given in Appendix A.

Active development of the air cushion suspension concept for application to a variety of transportation problems has been underway since the early 1950s. There is a wide spectrum of potential applications but the following four characterize the type that might be especially useful to Canada and at the same time present manufacturing opportunities:

i) Serious attention is currently being given by the Department of Industry, Trade and Commerce, to the development of an amphibious vehicle for cargo lighterizing purposes in the Canadian Arctic.

ii) There is a growing interest in the application of tracked ACVs (TACV), or "Hovertrains" to suburban transit, since they present distinct possibilities for significant reductions in system costs and for improvement in ride quality, noise and other environmental problems over both expressways and conventional rail technology.

iii) The technical feasibility of using an air cushion as an aircraft landing system (ACLS) has recently been demonstrated. Although there are problems, if properly developed and applied to STOL aircraft for example, it could confer improvements in safety and greatly reduced dependence on the quality of the landing surface and wind direction. These could have important consequences in
operational feasibility, reliability and system costs. Its application to the NASA Space Shuttle concept is currently being studied by Bell Aerosystems.

iv) An Ontario ACV consulting group is examining the feasibility of using the principle in moving heavy loads over the roads under half load restriction during the Spring break up period.

It is helpful in assessing the potential importance of the technology to evaluate the interest in the various applications in the light of the criteria suggested by the Science Council for major programmes. These are given in Appendix E.

Let us examine first the amphibious ACV application. The first Science Council criterion requires that the programme must be of real importance and perhaps even peculiar to Canada. At first thought this certainly seems to be especially true of the ACV because it has unique abilities to travel unimpeded over ice, snow and muskeg. However, a number of factors suggest a more modest evaluation. The Market Survey, (German et al, 1970) indicated that there may be a modest potential market. Their results suggested that by 1974 the Arctic lighter ing application could absorb perhaps 20 ACVs and the off-road application upwards of 25 ten-ton payload and 50 one-ton payload vehicles. Both of these applications would require vehicles designed specifically for Canadian Arctic conditions and which will not likely be developed by other National efforts. Typically, the French Bertin consortium is attempting to develop a concept known as the Terraplane for off-road use in undeveloped areas. This vehicle uses wheels for control and propulsion; but we have reason to believe that it would require modifications which would greatly increase its operating costs before it would be reasonably suited to the Canadian applications. The limitations of the concept are discussed in Appendix B.

The Market Survey made no attempt to account for the possible effect of a new technology in speeding up development of certain areas such as the North. This is of course extremely difficult to accomplish, but an upper limit can be postulated. For example, the actual population in the NWT is relatively small, in 1961 it was some 23,000 with an annual growth rate of about 3.8%. Even if one assumes that, as a direct result of the impact of ACV on transportation problems, the rate of population growth is increased by a factor of three, the population in 20 years time will still be less than 300,000. Furthermore, although much excitement has been expressed by ACV enthusiasts about the recent move by the State of Alaska to ban the off-road use of wheeled vehicles in the summer, informal discussions with officials of the Department of Indian Affairs and Northern Development have indicated that the areas of the Canadian North where a similar ban will be required are quite small. Hence we must conclude that the market for ACVs that might be generated in the North Country as a direct result of their unique capabilities is likely to remain relatively small and that its widespread use depends critically on its ability to compete with other transportation modes.

A major barrier to extensive use of ACVs is that currently available vehicles are prohibitively expensive to operate, and generally speaking, they are only competitive with the helicopter (see Appendix B). This has caused disillusionment amongst those who saw it as a possible solution to many Northern transportation problems. The problem has been aggravated by some manufacturers who have made exaggerated claims as to the abilities of their vehicles. But to be realistic, the currently widely used criticism that ACVs are expensive does not allow for the development of cost cutting innovative designs. Our studies have indicated that a reduction of direct operating costs by a factor of two or even three in the
next 10 years given steady development does not seem unattainable, and this might radically change the prospects (see Appendix B). At this point the ability of the ACV to reduce other system costs such as are associated with construction of roads and airports can give it a considerable advantage. Of course the comfort, convenience and very high transportation efficiency of the modern aircraft is such that even the fully developed ACV could only complement this vehicle rather than supplant it to any extent in any well established transportation system. However, if properly developed, the ACV might easily eliminate the need to install roads in many parts of the North, for example.

In attempting to arrive at a balanced view of the potential of the ACV for development of the North it should be borne in mind that recent developments in resource exploitation imply that it could assume an importance out of all proportion to the actual numbers of vehicles involved. For example, Humble Oil Ltd. recently announced that it was abandoning the Manhattan icebreaking tanker project, so that the oil in the North will probably be transported out by pipeline. As is well known, the engineering problems associated with this project are very considerable. The difficulties associated with construction on permafrost, and maintenance and safety patrolling are such that the lines may well be built on a route which will include in part, following closely the course of the Mackenzie River. ACVs could probably play a very useful role, since the river itself would form a natural route for year-round operation of these vehicles.

It should also be borne in mind that the ACV could be useful in areas in Canada other than the North. For example it could be the basis of certain year-round commuter services between Toronto and various communities on Lake Ontario. The prohibitive cost of installation and relatively low transportation efficiency of the expressway-automobile system is now widely accepted and alternate solutions are now being investigated. Hence the possible impact of an ACV service between Toronto and say, St. Catharines, should not be overlooked. Given adequate development, a 30 minute trip time and a fare basis of less than 5¢/seat mile seem attainable.

Consideration of many factors such as those discussed above lead us to conclude that while the amphibious ACV may not play a role comparable to aircraft or railways in the future economic development of Canada, there are a number of potentially significant applications which justify establishment of a modest industry. Furthermore, Canada's needs in this field are sufficiently specialized that current foreign developments will not likely produce vehicles especially suited to these needs (qv Appendix A, Section A5), so that there is a minimal risk of excessive duplication of technological development. In this respect an ACV development programme would satisfy the Science Council's second criterion for major programmes.

It should also be noted that establishment of a programme will most likely generate significant export possibilities. The recently issued Science Council Report on the aeronautical industry in Canada (Green, 1970) stated that the export market absorbs the dominant fraction of that industry's sales; in 1968 the fraction was about 75%, and this is being used as an argument to justify development of a major programme in STOL aircraft.

The second potentially important application of air cushion technology is to guided vehicles or trains (TACV). A summary of current developments is given in Appendix A, and a survey of the status of the technology is given in Appendix C. At first sight one might feel that this is an area that Canada should not actively develop, but instead rely on importing the technology, as suggested in the second Science Council Criterion. Three nations, France, Britain and the U.S.A.,
are mounting fairly extensive programmes. However, with the exception of the French activities the primary emphasis in this field has, until recently, been towards the development of high speed intercity links operating at speeds as high as 300 m.p.h. There is evidence of growing interest in Canada in the application to suburban transport with operating speeds up to 100 m.p.h. Only two groups, both in France, have expended any significant effort on this application. Yet there are clear indications that it can bring considerable reductions in system costs over superhighways and afford significant noise reductions and improvements in ride comfort when compared to modern rapid rail transit. There may therefore be an important conjunction of a need and an opportunity which could be the basis of an important manufacturing industry with a considerable export potential. Depending on foreign developments it is not beyond the bounds of possibility that this application could be the basis of a major programme.

Another important factor to be considered when planning exploitation of air cushion technology in Canada is that the mere fact that there is already industrial activity in developing certain applications in other countries is no guarantee that these efforts will produce the best, or economically optimal designs. In fact, as is suggested in Appendix A, being first in the field may be a hindrance to a company’s chances of producing innovative designs. The record seems to show that there is a tendency for a firm to become locked into a particular line of development, and that the successful innovations often are developed by companies attempting to break into the field. Hence, it may be that Canada has a very strong opportunity in the 100 m.p.h. TACV application, for example.

Once it is recognized that there exist opportunities for the establishment of innovative manufacturing industries in Canada, then a major question to be faced is the nature, extent and timing of the Government initiative required to actively foster the establishment. Clearly such initiative can be extremely important, even crucial; but the problem is that such initiative also involves pitfalls. Some remarks on the problems associated with Government intervention are given in Appendix A (Sections A3 and A6). Some of the possibilities for action include demonstrator projects; however both the timing and nature of such projects must be carefully chosen to ensure that they are compatible with the existing state of the technology. Hence in the amphibious or marine application it appears reasonable to proceed with an Arctic lighter project; whereas more research, development and trials are required before the ten-ton off-road application can be exploited with any confidence. Also it would seem to us that installation of a demonstrator TACV project might be premature at this time. There is no information accessible to us on the effects of ice accumulation on vehicle dynamics, and the choice of the guideway section to give good ride consistent with the best economics is still a matter of controversy.

Other useful forms of Government action are the establishment of mechanisms to ensure adequate communication between those in Government, the Industry and the Universities who are involved in the development of the technology; and timely establishment of an R & D programme. This report is concerned principally with the latter objective. It is our judgement that such a programme should be established in the immediate future.

An important question to be faced in deciding on the establishment of an R & D programme at this time is whether or not such a programme should precede the establishment of an industry. Apart from the sports ACV, with one or two exceptions, there is no significant established industry in Canada making use of air cushion technology. Accordingly, one might ask: why not delay the formulation
of a programme until an industry is established and the R & D priorities have been expressed by that industry? To establish a programme now might risk wasting funds and furthermore, there is a very real risk that even if an industry is established the R & D programme might be of little value since it could examine problems which turn out to be of little importance. In fact the latter problem has already arisen in Britain, as is noted in Appendix A.

The response to this observation is in the nature of the programme that is set up. ACV experience in other countries and the series of trials conducted in Canada have already revealed many deficiencies and important gaps in our understanding of ACV properties. Typically, for amphibious ACVs, the choice of an appropriate flexible skirt geometry is a question surrounded by considerable controversy and an almost complete absence of comparative data on the performance of available systems. In the TACV field an important question which has special implications for Canada is the effect of ice and snow on typical track sections in terms of vehicle design requirements and safety. Hence a properly chosen R & D programme should radically reduce the time in which an emerging industry could produce economically viable vehicles.

There is another powerful argument for the establishment of a modest air cushion technology R & D programme in Canada. Even if all air cushion technology is imported so that future industrial activity in this field is limited to manufacturing of designs produced in other countries, the governments and other potential users will need access to objective information on the merits of competing designs. Furthermore, variations of designs to suit special Canadian requirements are certain to be required. It is now well established (qv Bright, 1968) that the only reasonably reliable way in which this can be done is to sponsor a group actively involved in R & D. In the language of technological forecasting this is called "connecting research":

"Connecting Research is the research an organization does for the purpose of remaining in touch with the world of science - to see what is going on. In order to keep up with the latest activities in any field of science the organization has to have a ticket to the club. The ticket is being able to say something which is of interest to the other researchers in the field. In short, if an organization is to keep in touch with the latest activities in any field of science, it must have at least one man who is doing high-quality research in that field of science." (Bright, 1969, p.267).

There is little doubt that the potential opportunities and challenges presented by air cushion technology are such that, at the very least, the Federal Government should actively support some R & D in order to undertake "connecting research" or keep a "watching brief". In keeping with the spirit of the Science Council's fifth criterion, this programme should be aimed at the technology as a whole and not at specific applications.

2) SUGGESTIONS FOR A CANADIAN R & D PROGRAMME

2.1) Organization

In making suggestions for an appropriate programme for the development of air cushion technology in Canada at this time, comments on the appropriateness of organizations are probably much more important than suggesting specific topics
in need of attention. A major reason for this observation is the emergent state of Canadian applications, so that R & D priorities almost certainly will change in time, and adequate communication between, and recognition of the roles that can be played by those in Government, the Industry and the Universities is the most important objective at this stage.

Those responsible for establishing mechanisms would do well to bear in mind the remarks made in Appendix A on the relationship of R & D to the innovation process. The comments in Section A6 are especially appropriate. The principal points which should be borne in mind are:

(i) The strong tendency for relevant inventions to come from sources other than the industrial laboratory intimately associated with, and servicing a particular production line; and the consequent need for free and open discussions of development problems, even though this may be inhibited by commercial security blankets;

(ii) The dubious long-term value of patents to the overall development of the technology;

(iii) The tendency for many of those actively involved in air cushion technology to think in terms of special purpose roles and technical advantages rather than viewing it for what it is; that is, just another potential element in a transportation system, which has to prove its economic merits.

(iv) The strong tendency for the innovation with radical breakthroughs in technical performance or operating costs to be developed by a competent company trying to break into a field in which it previously had a small or non-existent position in the market.

(v) The dubious value of operating subsidies when used as a method of stimulating technological development.

(vi) The tendency for University research groups to examine problems which are interesting and amenable to analysis rather than being especially relevant either in the short or long term.

Many of the elements necessary for an effective Canadian programme exist already. For example the Federal Government and especially the Department of Industry, Trade and Commerce has a number of programmes particularly suited to assistance with the task of vehicle development. The role of these in relation to air cushion technology has been described by Lockhead (1969). The Country is amply supplied with scientists and engineers, both in Government Laboratories and the Universities, who can contribute to many aspects. Facilities such as the NRC Ship Section towing tank and the NAE 30ft V/STOL wind tunnel may also play a role. Finally the NRC University Grants system forms a useful basis for funding and ultimately for influencing University research.

However, some specific steps need to be taken to take full advantage of these elements:

(i) An appropriate advisory committee with representatives from the three relevant sectors is required to act as a focus for R & D in Canada.

(ii) R & D priorities as established by this committee should be used to
influence university grants. Some, but not all, funds for the Universities should be made available through the industry. This would ensure a measure of relevance and encourage communication.

(iii) Finally and perhaps most difficult of all, efforts must be made to avoid the long term damaging consequences of commercial rivalry in inhibiting free exchange of information.

2.2) Suggested Research Topics

Using the detailed review of the status of air cushion technology given in Appendices B and C, suggestions for a Canadian R & D programme are given below. These suggestions are a revised and extended version of work statements produced by the ACV Sub-committee of the Associate Committee on Aerodynamics. They are not in any particular order or priority. The basic principles on which they have been selected are to complement existing activities in Britain, France and the U.S.A., and to provide background information on the various fundamental design decisions that have yet to be made. For detailed discussions of the basis of the programme please consult the Appendices.

1) Air Cushion Vehicles and Landing Systems

1) Development of novel methods of thrust augmentation or increasing propulsive efficiency for purposes of propulsion and manoeuvrability when plenum air is used as a source.

2) Studies of the aerodynamics of flow involving flexible membrane boundaries with particular reference to static and dynamic stability of skirt systems.

3) Development of design methods for inflatable structures with reference to ACV's.

4) Investigations of the properties of composite materials such as glass reinforced plastics in order to develop more effective quality control and design methods.

5) Investigations of the deflection of jets by aerodynamic means.

6) Research which is basic to the development of flexible materials which better resist abrasion and wear.

7) Interaction of jets with liquid and particulate matter with a view to understanding the mechanisms of spray and dust generation.

8) Theoretical and experimental investigation of the static and dynamic performance of the existing and projected skirt systems. Development of designs with increased ratios of beam to hard structure clearance.

9) Design of propeller and ducted fan systems for ACV propulsion with particular reference to distorted flow conditions.

10) Investigation of acoustic characteristics of ACV propellers with a view to formulating design recommendations for minimizing the noise emanation.

11) Studies aimed at understanding modelling characteristics.
12) Value engineering, mode comparison and system studies to examine ways of cutting ACV first and operating costs, and to establish in detail its potential in transport systems.

13) Assessment of the control forces required for operations over land and in the Canadian north.

14) Investigation of the effectiveness of the various kinds of control systems currently used on ACVs with a view to selection of optimum designs.

ii) Tracked Air Cushion Vehicle (TACV)

1) Theoretical and experimental studies of existing and projected suspension designs to facilitate selection of optimal systems for the 100 m.p.h. application.

2) Evaluation of the effects of choice of guideway section on ice and snow accumulation.

3) Techno-economic studies of vehicle and guideway design to provide objective information leading to a rational choice of the most economic system for Canadian environments.

4) Investigation and methods, such as the linear gas turbine, for obtaining compact and efficient fluid for mechanical propulsion of TACVs.

3) CONCLUSION

The items suggested in the previous section as a starting point for a Canadian programme are not the absolute minimum necessary to perform the "connecting research" task discussed in the Introduction. It is based on the assumption that air cushion technology manufacturing industries will be established in Canada in the next five years or so, and that they will need support both in R & D and in personnel trained in the technology.

It is emphasized that any programme that is set up must be flexible and capable of supplying information relevant to a number of potentially important applications; in particular it must be capable of reorientation as clearer indications of Canadian use patterns emerge. In this respect it is better at this stage to encourage a variety of investigations, each at a modest level of funding rather than exclusive development of certain selected problem areas; this will help to avoid deep commitment to a line of development that may turn out to have little real importance. Considerable insight into the problems listed in Section 2 can be obtained with only a modest expenditure of funds and many of them are suitable for University Laboratories operating on the traditional NRC Grant system. Others are perhaps more suitable for Government or Industrial Laboratories.

Although the primary objective of the present study has been the evaluation of the status of air cushion technology and its problems, we must note that it is essential for the success of any R & D programme that is set up to have adequate communication and co-ordination between those involved in the R & D and the Industry. It has been noted in Appendix A that this field seems especially prone to generating research which is not as relevant as it might have been.

It has to be acknowledged that pessimism about the future of this new
technology is frequently voiced in responsible circles in Canada. However, we believe that some of this pessimism is not based on an adequate long term perspective of the way in which technologies tend to develop. Kahn and Weiner (1967) in their book "The Year 2000" note that many successful technologies are viewed with some disillusionment in their development phase. In the early innovation period many exaggerated claims are made and this is followed by disillusionment and a trend to overconservative predictions. Then, when the learning period has been navigated, many of the early expectations are exceeded. In the same book it is noted that there is a tendency for the technology to find its major applications in areas unforeseen by the original inventors. Typically, although the English ACV inventor Cockerell was originally looking for ways of decreasing the resistance of boats, it may be that TACVs or the ACLS turn out to be more important than amphibious vehicles. It is worth remembering an assessment of the gas turbine made in 1940 by the Gas Turbine Committee of the U. S. National Academy of Sciences:

"Even considering the improvements possible......the gas turbine could hardly be considered a feasible application to airplanes, mainly because of the difficulty in complying with the stringent weight requirements..........."
APPENDIX A: OBSERVATIONS ON THE OPPORTUNITIES PRESENTED BY AIR CUSHION TECHNOLOGY

A.1 Preamble

One of the most attractive features of current developments in air cushion technology is the opportunity presented for the establishment of innovative industries in Canada. Consequently, to better understand the nature of the problems and opportunities presented it is pertinent to examine some of the features of the innovation process, especially as it has occurred in the evolution of transport vehicles. This fund of experience should provide insight into the current state of air cushion technology developments, and suggest some guidelines for the assistance of the process in Canada. In this respect, the experiences of the aviation industry are particularly relevant, since it has a strong tradition of R & D, and because it should be a useful guide to the effects of Government intervention in the technical development of an industry.

A.2 General Features of the Innovation Process

A striking feature of the development of transport vehicles is the time and the number of prototypes which may lie between the basic invention and its widespread application as an economic unit in a profitable operation. The Wright Brothers' first successful flight took place in 1903, yet it is commonly accepted that the Douglas DC3, which first flew in 1935 was among the first, if not the first, economic commercial vehicle. It was only in the 1930's that the airplane evolved to the form we know today: a well streamlined monoplane using a low cantilevered wing, variable pitch propellers, flaps and retractable wheels, and built out of light alloy using stressed skin techniques. Although airlines were operating in Europe in the early 1920's, they had to be heavily subsidized in order to stay solvent; during this period (Miller and Sawers, 1968), commercial revenue could supply only about one-fifth of the operating costs, and even as late as 1933 the British subsidy was 39% of operating costs. The development of the automobile is also extended over a protracted period. The French inventor Joseph Lenoir was, in 1862, among the first to build a vehicle powered by an internal combustion engine. But it was not until about 1920 that the major features of automobile design became stabilized and the vehicle assumed the degree of reliability and economy which was necessary to allow it to become a significant factor in transportation systems.

These observations can also be stated in the following way. Studies aimed at developing methods of technological forecasting (qv. e.g., Utterbach, 1969) have suggested that for a wide spectrum of technological developments which have occurred in the twentieth century, the gestation period between the original act of invention and the emergence of commercially viable designs may be as long as several decades. Furthermore, in contrast to some popular notions on technological evolution, the evidence seems to suggest that the gestation period is not necessarily decreasing with the passage of time. Of course an invention may be put to use long before commercially viable designs emerge. Aircraft were used in the First World War, and a community may decide to use TACV's to alleviate transportation problems before they are economically mature. However, such evidence as is available (qv Miller and Sawers, 1968) suggests early application may actually inhibit the innovation process.

One factor which may shorten this "incubation" period is the application of system concepts. It is only in the past decade or so that such concepts and ideas as the fallacy of suboptimization have gained widespread use in industry.
These approaches should accelerate the development of optimized designs once all the basic inventions have been made. They may be especially effective for TACV developments since this application requires very careful tradeoffs between vehicle and suspension sophistication on the one hand, and guideway precision and rigidity on the other, in order to develop the most economic system.

Another important feature of the development process is that for a given state of supporting technologies, such as materials and control, the drive to minimize operating or system costs usually results in the evolution of one or possibly a few basic configurations for a well defined application. Minor variations are permitted, but there is a strong tendency for a convergence of different lines of development. The aircraft industry provides a good example of this process. By the 1930's all the basic features now almost universally used in commercial aircraft had emerged. The success of the DC3 is closely related to the fact that it was the prototype of modern aircraft; a low wing, cantilevered monoplane, well streamlined and built out of metal using stressed skin construction techniques. The only major innovations in commercial aircraft technology that have occurred since the DC3 are the swept wing and the jet engine. The history of the automobile also shows a similar pattern; typically, in spite of its clear superiority in handling and traction characteristics, the front wheel drive has not found universal acceptance largely because of the expense of building and maintaining it.

Development by prototype seems to be required, even when the major design features have been evolved, as they had for the aeroplane by the early 1930's. The Douglas DC1 and DC2 were essentially development prototypes of the DC3. Boeing profited greatly from their experience with the tanker version of the 707 when developing it for commercial use, and had military experience with the B-47 to call on. Usually attempts to circumvent the expensive process of development by prototype have led to problems. Miller and Sawers (1968) note that attempting to tool for production before the aeroplane flew has generally ended in the manufacturer having to modify half-finished aeroplanes or finished tooling. This attempt to cut corners is reported to have cost Douglas dearly on the DC8.

An unfortunate consequence of the protracted nature of the development process is that the early vehicles are often mismatched to the first applications, which in turn may cause loss of user confidence and commercial failure. Typically, out of the 77 airlines formed in the U.S. between 1925 and 1932, only 17 were still operating at the end of that period (Miller and Sawers, 1968). Similar patterns can be found in other transportation industries; a contemporary example is the problems currently facing U.S. hydrofoil operators. In a review of that industry, Narodick (1969) stated:

"Operators in the United States have by and large been romantics, impressed with the speed and beauty of hydrofoil operations and have of late come to realize that romanticism and beauty do not pay fuel, maintenance and crew costs".

and

"Vessels unsuitable for the sea state in which they are operated resulted in passenger rejection of the service and damage to the boats".

It might be expected that similar patterns will develop in the ACV industry; indeed, it can be argued that it has already occurred.
Cockerell (1966) stated that a study undertaken at Hovercraft Development Limited (HDL) has suggested that about 60 prototypes might be required to bring the amphibious ACV close to full development. Allowing that about 30 design variations have already undergone trials in France and Britain, and even assuming that the estimate was overly pessimistic, it is likely that the truly economic equivalent of the DC3 may be as much as a decade away.

Of course long before transport vehicles reach economic maturity, they can often be very effectively applied to special purposes such as military activities. A special purpose role is emerging for the amphibious ACV in Canada's North. As the history of the aircraft clearly shows, technological development can be effectively stimulated by exploitation of the special purpose role. But it is clear that this approach can be a stumbling block to evolution of economic vehicles, since by its nature the special purpose application does not encourage the art of cost cutting in the evolution of design practices.

We shall review briefly some relevant characteristics of the three steps leading to innovation. First, as to the invention itself, a basic question is: what is its most likely source? Traditionally this has been the lone individual or the university department; but the early twentieth century has seen the emergence of the industrial research laboratory and very sweeping claims are often made about its benefits and potential. Firms often establish a laboratory in the hope that it will solve the knotty problem of linking the inventor and industry. The belief seems to be that if the inventors are subject to industrial discipline and loyalties, then their ideas will evolve in the context of the manufacturers' interests. Furthermore, it solves the awkward problem of commercial security.

Hence the question may be rephrased: is the growing practice of combining research and manufacturing within the one corporation likely to contribute greatly to the flow of inventions which are relevant to current manufacturing interests? At this stage the distinction between invention and development is crucial. For example, du Pont discovered nylon and they also developed it, whereas Eastman Kodak developed but did not invent Kodachrome, which was the first single film colour photography process. Such evidence as is available suggests that, in spite of the claims, the industrial research laboratory is not an especially effective source of relevant inventions. In a detailed examination of the case histories of 61 commercially successful or militarily important inventions which occurred in a period when the industrial laboratory was well established, Jewkes et al. (1958) show that over half came from the traditional sources. The remainder can be directly traced to industrially financed programs, but only a very few can be regarded as the result of directed research towards a preconceived end. Miller and Sawers (1968) examine the origins and affiliations of the inventors who made the most significant contributions to the airplane and conclude that the universities, government financed research institutes, and individuals acting privately are almost wholly responsible. An example with a Canadian flavour is the development of the variable pitch propeller. The electrically operated propeller was invented by a wealthy Canadian amateur, Rupert Turnbull, at a time when the concurrent efforts of propeller manufacturers to produce a variable pitch design were unsuccessful.

The reasons why a research laboratory which is in close contact with the production line and intended to support it is not a favourable environment for relevant invention are not hard to isolate. Some are related to the nature of commercial enterprises. For example, the efficiency of business administration has been greatly increased in recent years by cost accounting, but the essence of
research is that it cannot be costed in any systematic way. Other examples can be quoted which show that in general the pressures intrinsic to a profit making system involve departures from the conditions ideal for research and invention. Another major source of difficulties is that in the typical industrial environment there is a strong tendency of any R & D program to be oriented towards obtaining quick solutions to development problems. The continuing need to support existing vehicles and to obtain answers urgently needed to prevent expensive production halts will mean that the long term program designed to understand problems encountered in development will not have much chance of success. Yet the increasing level of sophistication associated with the development of a technology usually implies that, except in the earliest phases, a thorough scientific understanding of the problems is an almost indispensable prerequisite for effective invention.

In the 1920's the German Professor Junkers gave the pressure of production needs as a reason for the failure of his factory to design commercially successful aircraft; he stated that "increased production results in research being sidetracked when it is a function of the same factory" (Miller and Sawers, 1968). Conversely, if the industrially based laboratory is sufficiently well managed and isolated from the production line to adequately foster invention, then the chances are that the inventions will not be in the area of manufacturing interest.

Considering now the second phase of the innovation process, a fundamental question is: what type of business organization is most likely to undertake the risky and very expensive process of applied research and development of an invention? J. K. Galbraith (1956) has suggested that the large monopoly is the firm most likely to innovate. It is argued that only a firm large enough to afford the high costs of development and protected by master patents, so that it is able to set the price of its products, is likely to take the plunge. This is a widely held view and it is impossible in the space of a few lines to provide a balanced analysis of it. Instead a few cases will be cited to suggest that the converse can be true, that is the smaller firm attempting to gain a foothold in a market may be the most likely candidate. Miller and Sawers (1968) quote a number of studies to suggest that the optimum size for innovating varies with the industry; among the U.S. steel manufacturers the smallest companies innovated most. In their analysis of the aviation industry, the same authors point out that innovators in airliner design all shared one common feature: they were comparative outsiders anxious to break into the market. Douglas in 1932, Vickers and deHavilland in 1945, and Boeing in 1952, all had very weak or even nonexistent positions in the large commercial aircraft market. The implication is that the newcomer cannot easily displace the already successful supplier unless his product is clearly superior. This appears easier to achieve through innovation than through minor modifications of existing designs. Further, the outsider is more likely than the manufacturer of a product to see how the design might be improved. And again, the manufacturer with an established market is not likely to incur the expense involved in innovation unless his sales position is threatened, so that the lesson is that competition stimulates innovation.

The third stage in the process is the commercial exploitation. Although technical advance is commonly seen as a sufficient reason for marketing a developed invention, it is often not adequately appreciated that in the vast majority of cases, it is economic questions which decide the success of the invention. This lack of awareness seems to be endemic to inventors, but surprisingly, sometimes even manufacturers do not fully appreciate the significance. Consider aircraft operating costs as an example. It has already been noted that the DC3 was probably the first aeroplane to make commercial flying profitable. Its fuel costs per seat
mile were 40% lower than those of the Ford Trimotor, which entered service in 1928 (Miller and Sawers, 1968). This was despite an increase of 50% in the operating speed and was due partly to economies of scale, reduction in profile drag and the use of the variable pitch propeller. Maintenance costs were 60% lower. The only major innovation since the DC3 has been the application of the jet engine, and as is well known, the advent of the Boeing 707 and the Douglas DC8 have brought with them a huge increase in seat miles flown. This is due in large measure to reductions in operating costs associated with economies of scale, speed, and structural efficiency that the more powerful yet lighter jet has brought with it. Table A.1 shows the operating costs, with and without depreciation, of some of the more widely used airliners introduced since 1935. The operating costs in a particular year may be used to correct for the effects of inflation. The trend is clear; even when depreciation is included, there is a progressive reduction in operating costs from the DC3 to the DC8, for the airliners that were used widely.

A similar pattern exists in other fields. The Diesel-electric locomotive rapidly became the prime mover on railways because its fuel costs in the USA were about one-quarter those of the steam locomotive. Moreover, terminal expenses were greatly reduced, and the far greater concentrations of power made possible by the introduction of multiple units under the control of one crew also permitted operating cost reductions. This was in spite of the much higher first costs. The dominance of the commercial considerations in all but a few cases is effectively demonstrated by an example which is almost always justified in terms of its technical advance. In 1832 the 2-ton steam coach operated by Gurney in England between Gloucester and Cheltenham was able to make a profit with fares which were half those charged by the operators of horse-drawn vehicles.

The lesson that the commercial function is dominant should be obvious, but an analysis of the aviation industry suggests that this is not so. With a few notable exceptions such as the Sud-Aviation Caravelle and the Vickers Viscount, the U.S. civil aircraft manufacturers have almost completely dominated world markets, and this has been achieved virtually without any U.S. Government intervention. In contrast, the British Government lost over $80 million on civil aircraft development in the 10 years after World War II, and its efforts have ended in almost total failure. Miller and Sawers (1968) suggest that a primary reason is the insensitivity the Europeans have shown to the commercial function of the airliner. Since the inception of the industry, operating costs of European airliners have consistently been higher than those of U.S. built aircraft. It is to be noted that the large military orders obtained by U.S. Manufacturers after World War II are not an adequate explanation of their success. European military aircraft designs have always been superior or at least technically equal to those built in the U.S. The recent U.S. military orders of the British Hawker Harrier VTOL fighter is a good example. It has been remarked by a Boeing designer that "the more an airliner resembles a bomber the less successful it will be".

A.3 Comments on Government Involvement in the Innovation Process

It is appropriate to examine the effectiveness of Government involvement in the innovation process. The examples available in the aviation industry do not present a very encouraging picture. The failure of the British industry to significantly penetrate the field in spite of massive Government spending appears to be traceable to government induced conservatism in design. In the 1920's when advanced designs were evolving rapidly towards the DC3, officially approved construction was a steel-framed bi plane with a fabric covering, and the Air Ministry experts of the time opposed development of the variable pitch propeller, on the
TABLE A.1

Typical Direct Operating Costs for Some Commercially Successful Airliners

U.S. Cents/ seat miles available

Source: Miller and Sawers (1968)

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>With Depreciation</th>
<th>Without Depreciation</th>
<th>Year of Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-3</td>
<td>2.558</td>
<td>2.565</td>
<td>2.669</td>
</tr>
<tr>
<td>DC-4</td>
<td>2.268</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Constellation</td>
<td>1.630</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DC-6</td>
<td>1.495</td>
<td>1.819</td>
<td>1.992</td>
</tr>
<tr>
<td>Convair 240</td>
<td>2.236</td>
<td>3.132</td>
<td>2.800</td>
</tr>
<tr>
<td>DC-6B</td>
<td>1.725</td>
<td>2.169</td>
<td>1.949</td>
</tr>
<tr>
<td>Convair 340</td>
<td>1.874</td>
<td>2.016</td>
<td>1.603</td>
</tr>
<tr>
<td>DC-7</td>
<td>2.111</td>
<td>2.616</td>
<td>2.696</td>
</tr>
<tr>
<td>Viscounet</td>
<td>1.937</td>
<td>1.965</td>
<td>2.079</td>
</tr>
<tr>
<td>Super Constellation</td>
<td>2.513</td>
<td>2.600</td>
<td>1.773</td>
</tr>
<tr>
<td>F27</td>
<td>2.468</td>
<td>2.220</td>
<td>2.323</td>
</tr>
<tr>
<td>707</td>
<td>1.551</td>
<td>1.299</td>
<td>1.221</td>
</tr>
<tr>
<td>DC-8</td>
<td>1.531</td>
<td>1.308</td>
<td>1.228</td>
</tr>
<tr>
<td>720</td>
<td>1.462</td>
<td>1.283</td>
<td>1.279</td>
</tr>
<tr>
<td>727</td>
<td>1.462</td>
<td>1.512</td>
<td>-</td>
</tr>
</tbody>
</table>
seemingly reasonable grounds that it was not needed for the bi-plane. It is known that the Ministry did not publish results obtained by the Short Brothers on the strength tests of stressed skin metal construction because it considered them irrelevant. Perhaps one of the reasons for the success of the DC3 was the ability of the U.S. designers to start without the traditions of World War I military experiences to forget. And again, British policy for airliner development after World War II had been laid down by high level Government committees sitting from 1942 to 1945. It is interesting that the only jet aircraft included in their plans was a mail plane carrying six passengers. The deHavilland Comet was built outside of Government plans.

The subsidies that were used by several European governments in the 1920's and 1930's to help establish aviation seems to have had the opposite effect in the long run. The French airlines were the most heavily subsidized and they also had the lowest utilization factor; in 1932 their average was 230 hours per year compared to 800 for the unsubsidized KLM, and airlines in the U.S.A. The heavy French subsidies were used to encourage the use of government approved design features, yet they seemed to merely encourage inefficiency. Paradoxically, the record even seems to suggest that military interest in the airplane has had an inhibiting effect on innovation. Typically, in the late 1920's, the biplane was standard equipment in British, French and U.S. Air Forces. Even in Germany, the home of the monoplane, the government ordered biplanes, at a time when the monoplane was already demonstrably superior. The Vickers Supermarine Spitfire, that most successful of British war-planes, was designed as a private venture under company orders to keep Air Ministry officials away from the plans!

A.4 The Relevance of Research Programmes

It has been repeatedly pointed out that the rapid increase in the pace of engineering development that occurred in the middle of the nineteenth century was due in large measure to the application of scientific knowledge and the scientific method to engineering problems (Kirby et al, 1956). The success of this union has been so spectacular that it is now usually taken for granted that any development programme should almost always have an associated programme of applied research designed to understand the phenomena involved and avoid the painful and costly blunders inevitably associated with the "cut and try" approach almost exclusively used before the 1850's.

The aviation industry is the classic example in the transportation field where research has contributed successfully. The tradition extends back to the Wright Brothers; these remarkable men were using a wind tunnel as early as 1901 to measure lift and drag on airfoils. They also expended considerable effort in developing a propeller theory, since they had found that marine engineers used only empirical formulae and:

"As we were not in a position to undertake a long series of practical experiments to discover a propeller suitable for our machine, it seemed necessary to obtain such a thorough understanding of the theory of its reactions as would enable us to design them from calculation alone". (McFarland, 1953).

The early work by Lanchester and Prandtl on the theory of lift resulted in such fundamental ideas as the importance of high aspect ratio wings; and Prandtl's basic contributions to the theory of drag laid the foundations of the concepts of streamlining (Von Karman, 1954). When the manufacturers listened to the scientists, they were able to make significant improvements in the performance of
their vehicles; typically the profile drag ratio (ratio of total to skin friction drag) of the DC3 was roughly half that of the Ford Trimotor (Miller and Sawers, 1968).

But the applied research programme has not always been used to support the transportation developments that have taken place since about 1850. On the one hand, both the aeronautical and the shipping industries have used research tools fairly extensively; both use model tests carried out in Government research stations, and have spawned specialized engineering departments in universities. In contrast both the railway and the automobile industries have relied heavily on the "cut and try" approach, and it is interesting to explore the reasons for these traditions. The long history of failures and the approach taken by the Wright Brothers is testimony to the fact the achievement of powered flight was sufficiently marginal that the physics had to be reasonably clearly understood as a condition for success. However, it was possible to make a tolerably satisfactory automobile by simply mounting an engine in a carriage designed for horses. No sophisticated understanding of vehicle dynamics was required to make the vehicle move; the contribution of nineteenth century science to the automobile was the theory of heat engines. A consequence of this type of tradition is that the industry often shows resistance to application of a more scientific approach when such an approach might be fruitful; the typical claim might be that the problem or engineering system is "too complex" to allow development through the use of models or an experimental and theoretical programme designed to understand principles. In amphibious ACV circles it is frequently suggested that this vehicle is similar to the automobile, that is, it is so complicated that development must inevitably follow the "cut and try" path. It is true that, in the early stages of the development of this vehicle, an extensive sophisticated research programme would have been inappropriate, but the need for the controlled experiment designed to understand the many problems confronting the ACV is becoming increasingly important.

The Advanced Passenger Train Programme conducted by the British Railways is an excellent example of the success that can be achieved through application of a scientific approach to a technology developed almost entirely by a trial and error process. The British Rail research group at Derby have used techniques evolved by aeronautical engineers to mathematically model the dynamical behaviour of a railway vehicle. Their work has shown that the traditional eight wheeled car has some serious instabilities and that a four wheeled vehicle with a flexible lateral suspension has the capability of giving stability to very high speeds "notably in excess of those which can be achieved using a bogie configuration" (Smith, 1968). It is interesting to note that an electrical engineer skilled in the techniques of mathematical modelling had pointed out in 1928 that it was the vehicle and not, the track which was the factor limiting speed; his findings were ignored by the railway engineers of the day because they considered it the product of an overidealized analysis.

In general the importance of a balanced research programme can hardly be underestimated. German leadership in high speed aerodynamics in the 1940's, which but for World War II would have enabled them to dominate the aviation industry, can be traced to Prandtl's scientific ability and the creation of the famous school at Gottingen. Their wind tunnel work led to the development of the swept wing and the leading edge flap, both of which have been adopted on high subsonic aircraft. Furthermore, because they had done more theoretical work than the British or the French, they were not misled by early wind tunnel work which at transonic speeds predicted excessive drag owing to interference effects between the model and its support.
However these remarks should not be taken as a plea for uncritical support of research programmes in Universities and Government Laboratories. Priorities must be established and mechanisms must be found to assert them, otherwise their activities will rapidly diverge from problems currently in need of examination. A pertinent example in the ACV field is serious dearth of information in the literature on the dynamics and aerodynamics of flexible skirt systems. But the unskirted peripheral jet cushion system has been extensively examined; and this has long been believed to be impractical except possibly for tracked vehicles.

A.5 Summary of Major Air Cushion Technology Developments

In the amphibious and marine ACV field serious innovative activity is occurring in Britain, France and the U.S.A. In Britain, the major developments are as follows:

i) The British Hovercraft Corporation's (BHC) SRN4, an 165 ton fully amphibious vehicle capable of 70 m.p.h. speeds has been in use as a cross channel ferry since 1968. After numerous developmental problems and considerable adverse publicity arising directly out of attempts to use the vehicle before it had been given adequate trials, it is now developing into a reasonably reliable vehicle, and will likely return a profit to its operators in the near future.

ii) The 6.8 ton BHC SRN5 and its stretched version, the 10 ton 38 passenger SRN6 have seen service in a wide variety of applications ranging from coast guard rescue activities in Vancouver, military operations in Borneo through to profit-making passenger ferry operations in the south of England. The U.S. licensed versions, namely the Bell SK-5 and SK-6 have seen service in Viet Nam. Although they are very expensive to buy and to operate and had many early teething troubles, all who have used them have been unstinting in their praise of the ability of the vehicles to operate in extremely adverse environment, terrain and weather conditions, and to take considerable damage and punishment before failure. Typically, the Canadian Coast Guard reported that their vehicle had never been stopped by very bad weather.

iii) BHC has also built a 48 ton amphibious vehicle, the BH7, which is primarily intended to be a weapons platform. It follows the traditional BHC design philosophy which includes air propeller propulsion, full skirts and use of basically aircraft construction techniques.

iv) Vosper Thornycroft, a firm which has had extensive experience in building high speed gas turbine driven gun boats, has built an 85 ton passenger/car ferry (the VT-1) to the specifications of a British operator, Hovertravel. This vehicle represents an interesting innovation over the design philosophies adopted by BHC because it relies heavily on marine construction techniques and uses water propeller propulsion. Vosper Thornycroft claims that this approach will cut direct operating costs by a factor of two or three.

v) The rigid sidewall or captured air bubble (CAB) type vehicle was
first developed by Denny and then Hovermarine. The latter company built a number of 60 passenger 16 ton ferries having a maximum service speed of 35 kt. This vehicle also was subject to a number of serious incidental developmental problems, but operational experience has shown that they are rather unsuited to rough water operation. The sidewall concept is probably only feasible for open sea use in very large sizes.

vi) Cushioncraft Limited developed an 8 to 10 passenger vehicle, the CC7, which uses centrifugal fans for propulsion. The vehicle is quiet and very controllable, but is extremely expensive to buy. We understand that the owners, Britten Norman, are hoping to sell the Company.

In France, the major ACV developments have derived from the R & D efforts of Bertin et Cie, a technology development company. Detailed design and construction is handled by an affiliate, SEDAM. The major developments are:

i) The N300, a 27 ton, 100 passenger air propeller driven vehicle has seen service on the Cote D'Azur. A small 10 passenger vehicle called the N102 has been built and is undergoing development trials, and plans are in hand for a 200 ton plus open sea vehicle, the N500.

ii) The other major line of development is the Terraplane series, which uses an air cushion for partial support and wheels for control and propulsion. It is intended for use on natural or only roughly levelled tracks or trails. Trials of this vehicle in Canada have revealed some conceptual difficulties and we understand that it is now being "redesigned". The problems are discussed in Appendix B.

In the U.S.A. the major activity stems mainly from military need. Two principal projects are underway. These are:

i) A 4000 ton 80 to 100 kt. CAB transoceanic military and commercial cargo vehicle is being developed to U.S. Navy specifications. Both Bell Aerosystems and Aerojet General are competing for contracts. The programme calls for a 100 ton prototype to be tested in Aug, 1971.

ii) The US. Navy has let contracts for development of an amphibious assault landing craft having an empty weight of about 70 tons. Both Bell and Aerojet General are actively engaged competing for this project. The Bell version is known as the SK-10.

In Canada two major developments have occurred in recent months:

i) Bell Aerosystems has established a plant in Grand Bend, Ontario for construction of the 25 ton payload "Voyageur" arctic transporter,

ii) Arctic Systems Ltd. of Calgary is constructing a 100 ton oil rig platform.

Air cushion technology is being applied to guided transport or trains over a wide range of speeds and stage lengths. However, it is useful to think in terms of three characteristic applications. These are:

i) Low speed personal transit in densely populated areas with maximum speeds up to 60 m.p.h.
ii) Outer suburban mass transit systems with operating speeds up to 100 m.p.h. and stage lengths of a few miles.

iii) High speed transportation between large city centres operating at speeds up to 300 m.p.h. and stage lengths of 100 miles or more.

In this study we have not considered application type (i). The major developments to date for the other two applications are:

1) The French Bertin - Aerotrain consortium began testing and development of a half scale experimental model of an intercity vehicle on a 4.2 mile guideway at Gometz, near Paris in 1966. Speeds of 215 m.p.h. have been reached. A 12-mile full-scale test track has been built north of Orleans and testing of an 150 m.p.h., 80 passenger prototype has commenced. This track is intended to form part of an Aerotrain link with Paris. An inverted T section guideway and shrouded fan propulsion are used.

ii) The same company has built a 44 seat linear induction motor (LIM) driven vehicle designed for application type (ii): It also uses the inverted T Section, with the vertical fin as the aluminum reaction rail for the LIM. A two-mile test track has been built at Gometz.

iii) The Compagnie d'Energetique Lineaire of Lyon, France, has been developing a suction suspended LIM driven TACV system for the application (ii) and called URBA. The vehicles run beneath the track, which has a wide inverted U-section integral with a box supporting beam. A demonstration line is being installed at Lyon.

iv) The British Tracked Hovercraft Limited (THL), which was formed in 1967, is now building a 250 m.p.h. LIM driven development vehicle which will run on top of a box section test track near Cambridge.

v) The U.S. Department of Transportation, High Speed Ground Transportation (HSGT) programme is now proceeding rapidly as a result of the recent award of a test vehicle contract to Grumman of Long Island and a LIM contract to Garrett Airesearch, California. The test track site is to be built at Pueblo, Colorado. The test vehicle, which will run in a trough section track, has both turbofan and LIM propulsion. Detailed design is now well underway. These activities are being supported by a research group at the Massachusetts Institute of Technology.

vi) Vought Aeronautics and the Rohr Corporation, which is the U.S. Bertin affiliate are competing for a contract from the U.S. Urban Mass Transit Authority to construct a 150 m.p.h. demonstrator line from downtown Washington, D.C. to the Dulles Airport.

The air cushion landing application (ACLS) has only recently seen some significant activity. The developments are:

i) Bell Aerosystems has successfully demonstrated the technical
viability of an ACLS on a small amphibian aircraft. It has enabled the plane to land on water, ice and snow and to be moved over ditches and other obstacles. The plane has also landed in crosswind conditions crabbed at angles up to 25°.

ii) Bell has recently secured a contract to examine the feasibility of applying the system to the proposed NASA space shuttle.

iii) A joint U.S. - Canadian agreement has recently been set up to fit a Bell ACLS to a deHavilland Buffalo.

A.6 Comments and Discussion of Opportunities for Canada

We comment on the developments described in the previous section in the light of the general features of the innovation process discussed in this Appendix.

Both the amphibious/marine ACV and TACV developments are at an early stage and it could be many years yet before reasonably optimized designs are evolved. Using the history of the twentieth century transportation developments as a guide we might suggest 25 to 30 years as the incubation period. Hence, since the air cushion principle was first given serious attention in the mid fifties it is possible to argue that it might be as late as 1980 or 1985 before the ACV and TACV design equivalents of the DC3 emerge. This prediction does not of course imply that ACVs or TACVs should not be used before that period. Special purpose roles such as the Arctic lighter could perhaps successfully go forward in the next few years, but the widespread use of the technology depends on the evolution of optimized designs.

The forecast given above may be somewhat pessimistic because it does not include any possible effects of systems approaches. It has already been noted that these techniques have only found widespread use in recent years. Optimization of TACV performance is especially sensitive to such concepts, since there are important tradeoffs between vehicle and guideway design and socio-economic considerations. Usually, track depreciation and maintenance costs tend to predominate. Experience with modern rapid rail transit suggests that of the total system costs, track costs average more than 50%, while vehicle costs range from 7% to about 19% (Ross, 1966). Hence, it may be necessary to tolerate higher vehicle costs in order to reduce overall system costs, for example.

The industry is already showing signs of the classic innovation pattern, this is the strong tendency for the design with performance or economic breakthroughs to be produced by a company attempting to establish a foothold in the market. The prime example is the cost-cutting VT-1 produced by Vosper Thornycroft. There are other clear indications that the companies first in the field are locked into certain design concepts which may not be anywhere near optimal. Typically, the Societe Aerotrain, the most advanced TACV builder to date, is committed to the inverted T track section and hinged rigid wall cushions (see Appendix C), even though there are indications that this might be particularly troublesome in Canadian weather conditions. Flexible skirts may be required to overcome icing problems, for example. BHC remains wedded to aircraft type construction techniques, even though there are clear indications that these will have to be simplified if operating costs are to be reduced (see Appendix B).

There seems to be three primary opportunities for using air cushion technology in Canada in manufacturing industries in a way which could be important
for national development, which would likely not duplicate overseas efforts and at the same time provide export opportunities. The first is general purpose transport vehicles with a payload of perhaps 10 tons and a truly amphibious and Arctic capability. These might be used in a wide variety of modes from supply of oil and other resources exploration, Arctic lightering and Coastguard activities. Secondly, the 100 m.p.h. outer suburban commuter train is worthy of serious consideration. This would complement the activities of the U.S. H3GT programme and furthermore, the Government funding required should be modest compared to other possible projects. Typically, the total funds allocated to the U.S. TACV programme for FY'70 were only $5.2 million compared with $96 million for the SST project. It is noted that there have recently been contacts between the U.S. DOT and the corresponding Canadian authorities, regarding possible cooperation. The third area is the use of ACLS in STOL aircraft systems. Canada's already acknowledged competence in STOL technology will likely be the basis of a major programme, and ACLS should be considered as a possible component of this. At the time of writing recent Canadian developments were not known to the authors.

One of the problems surrounding the air cushion technology field is the bewildering number and variety of patents that have been granted; and this has been the source of considerable confusion amongst competing developers about infringement problems. Typically, we are aware of cases where the solutions to development problems that have been adopted are aimed as much as at avoiding infringement as at solving the problem. A detailed discussion of the legal and other problems would be inappropriate here but some comments can be made from a technical viewpoint. The attempt to corner markets has led some developers to try to obtain very wide ranging patents; for example, at one stage the British Hovercraft Corporation stated that it believed it had patent rights on all types of flexible skirt design. Secondly, it has been observed quite rightly that some groups have shown "an obsession with patenting everything in sight". Many of the patents which have been granted are for trivial and obvious solutions to various development problems and not for designs which are the result of extensive experiment or experience. Typically, THL very recently applied for a Canadian patent on a concept aimed at solving some of the problems surrounding low speed switching of their Hovertrain. This concept was to hinge the side cushions so that they could be swung into the horizontal plane and allow the vehicle to be moved on flat surfaces. In a recent discussion of switching problems we also had thought of this solution along with many others; it hardly seemed so brilliant as to be worthy of a patent! The problem of patent infringement is clearly going to become very acute for the innovative company trying to enter the field with improved second generation design. It seems to us that no group should be frozen into inaction over this question; the approach should be to proceed on the basis of accumulated experience and engineering judgement and then sort it all out later by negotiation. It is worth noting that the U.S. commercial aircraft manufacturing industry, which has been the foremost innovator, has demonstrated its low opinion of patents by arranging a patent sharing system (Miller and Sawers, 1968, p.255).

It is most important that those responsible for developing the amphibious ACV for use in Canada be made fully aware of the ultimate importance of developing vehicles which have competitive operating costs. There is a widespread tendency among ACV enthusiasts, both in Canada and elsewhere, to think in terms of the unusual characteristics of the vehicle, and to relate these to special Canadian problems. It is true that the vehicle has some impressive and even spectacular features which may help solve some of Canada's difficult transportation problems, such as travel in muskeg areas. However, cases such as the rescues by the Canadian Coast Guard Rescue Unit's SRN5 in Vancouver, where its unique capabilities
will be the criteria for use, will be a very small minority. Where alternatives exist the ultimate criterion is always cost effectiveness.

We conclude with some observations on the organization of R & D in Canada. Firstly, it is well to remember that the inventions required for full development of the vehicles, some major and many minor, will most likely come from outside any industry that is set up. In view of this, commercial secrecy surrounding development problems can be a major stumbling block. Further, any attempts to foster a monopoly in Canada at this early stage of ACV development in the hope that this will insure industrial strength might hinder the long term development of the vehicle. Further, wherever possible, ways must be found to make available to those in a position to invent, and presumably outside the industry, information on operating costs to help establish research and development priorities. Finally, Government involvement, which will no doubt occur in Canada, must be applied with extreme caution. In particular the British record in commercial aviation suggests that technical decisions either expressly made or implied should probably be scrupulously avoided. Attempts should be made to foster technical competition, and operating subsidies are clearly a treacherous tool, when used as a method of stimulating technological development. Methods must be found to ensure effective interaction of universities and Government Laboratories with Industry. Priorities based on such criteria as controllability, noise and other environmental problems, and especially on operating costs analyses should be used to influence traditional University research funding sources such as NRC operating grants. Perhaps some, but definitely not all, Federal research funds should be made available through the industry so that the manufacturers can exercise some direct control over University programmes. Also, Federal development funds to industry can be used as a lever to obtain up-to-date, accurate information on operating economics to guide research programmes and to ensure that commercial secrecy is not used to hide development problems.
APPENDIX B: REVIEW OF THE STATUS OF AMPHIBIOUS AND MARINE ACV TECHNOLOGY

B.1 Introduction

This appendix summarizes the status of air cushion technology as it has been applied to amphibious and marine air cushion vehicles. Although not specifically mentioned, this discussion is also applicable to air cushion landing systems (ACLS) for aircraft. A disconcerting feature of this summary is that it is largely qualitative, in contrast to the summary given for TACVs. This is partly a result of the unusually complex nature of the dynamics of the vehicle. A full description of the vehicle's behaviour requires an adequate understanding of external aerodynamics, effects of random wind and ground or wave inputs, flexible skirt and cushion dynamics, and many other effects. Furthermore, it is often difficult to treat these effects in isolation. Another reason is that the vehicle is in a relatively early stage of evolution so that a great variety of vehicle configurations are still being tried and evaluated; in other words it is just emerging from the "cut and try" phase. Research programmes are inevitably tied to a specific geometry so that they easily run the risk of having no long term value.

Nevertheless, in spite of this difficulty, it now is possible to discern areas where a modest programme will yield information of lasting value; one of the aims of this review is to try to isolate them.

B.2 Current ACV Economics and R & D Priorities

Basic guidelines for R & D priorities can be obtained from the analysis of operating costs; and since available data for the ACV suggests that they are very high, these guidelines are extremely important. A major difficulty involved in such an analysis at the present time is that the only available data on operating costs applies to marine operations in a European environment. However, even bearing this in mind, the analysis provides some very useful insights. A detailed summary of available information on ACV costs is given in Appendix D.

Figures B2.1 and B2.2 are plots of ACV first and direct operating costs (DOC) as a function of productivity WpV in ton-knots, together with some comparisons with other vehicles commonly considered as competitors. The DOC's include depreciation, interest on employed capital, insurance, fuel, maintenance and crew costs in common with the usual accounting practice. Before making any observations we note that these curves should be interpreted with considerable caution for several reasons. Firstly the relative economic merits of different vehicle types can only be firmly established by a complete systems analysis, which includes all indirect operating costs (IOC). For example, if the Government is contemplating the development of a remote area, then mode comparisons with aircraft must include the costs of airport construction. Secondly, the only ACVs which have seen extended commercial service are BHC's SRN6 and SRN4, the SEDAM N300, and the Hovermarine HM2 sidewall. All other operating costs are projections. Thirdly, because of lack of available data on typical service speeds, the curves were compiled using the nominal maximum speed. This probably unduly favours the ACV because its ratio of service speed to maximum speed may be lower than that for other vehicles. Fourthly, no attempt has been made to classify vehicles according to country of manufacture and use; this probably accounts for some of the scatter. Nevertheless, although these curves are of very limited value for assessing the current utility and potential of ACVs they give some important insights into R & D priorities.

The tentative conclusions to be drawn are of course that the fully
Figure B2.1 Maximum work capacity of typical ACVs as a function of initial Price, together with some comparisons with potential competitors.

Figure B2.2 Maximum work capacity of typical ACVs as a function of direct operating cost, together with some comparison with potential competitors.
amphibious vehicles are expensive to buy and to operate, and that currently their primary competition seems to be the helicopter. A similar conclusion is reached by Igglesden (1969). The figures suggest that economies of scale favour the ACV; the initial cost of the BHC SRN4 is comparable to that of a large jet aircraft having a similar $V_\text{LP}V$. However, vehicles the size of the SRN4 are not likely to play a significant role in Canada's ACV industry and it is necessary to seek other sources of cost improvement. The curves illustrate the financial penalty that has to be paid for retaining the fully amphibious capability typical of the SRN6. The DOC estimates of the Vosper Thornycroft VT-1, an 85 ton fully skirted hydrodynamically propelled vehicle, sidewall craft such as the HM2, and the wheeled ACV such as the Bertin BC-7 Terraplane, are all significantly lower than those of the fully amphibious vehicle.

The nominally superior performance of the Bertin BC-7 Terraplane concept, which relies on wheels for control and propulsion, merits special comment, since if the figures are realistic, it would appear to offer an attractive possibility for Northern Development in Canada. It was used by the authors of the Market Survey (German et al, 1969) in their simulations of offroad operations, so that their overall conclusion that the ACV could compete in these tasks depends heavily on the accuracy of their DOC estimates. But it is to be noted that a technically satisfactory vehicle of this type is yet to be demonstrated. It seems that the modifications required to make it suitable for Canadian use would make its DOCs comparable to those of the SRN6 type.

Table B2.1 presents a breakdown of DOC for some ACVs, together with comparisons with some other vehicles. Two points can be noted. Firstly, at least for the European ferry operations, fuel costs are not a major component of the DOCs of the amphibious vehicle. This is in spite of its inherent thermodynamic inefficiency. It expends energy just to hover and may dump 50% or more of its propulsion power into the kinetic energy of the propeller slipstream. Secondly, maintenance costs can be high. However, because developments have been very rapid, and because European experience has almost entirely been in a marine environment, it is not possible to give a meaningful breakdown of the maintenance costs. But judging from the experiences of Canadian ACV Trials (Department of Transport 1968 and 1970, Defense Research Board (1966) maintenance costs associated with operating overland and in an Arctic environment will also be very high. Serious attention will have to be given to skirt wear, propeller erosion, and spray and dust ingestion by the engine in order to significantly reduce these costs.

Igglesden (1969) has given a very useful insight into the ACV cost problem by breaking down the DOCs into the fractions attributable to various craft components. His results for the SRN6 and SRN4, and the HM2 side wall craft are given in Table B2.2, together with some results obtained from a simulation of a routine cargo haulage operation in the Canadian North. The figures for hull, power systems and skirts include both depreciation and maintenance costs. Hull costs are clearly important targets for attention. Since operational experience such as that quoted by Stratton (1967) suggests that hull repair costs are usually considerably less than engine, propeller, or skirt costs, the source of the problem is manufacturing cost. Stratton has also noted that the expensive overheads inherited from an aircraft constructional philosophy may be a major culprit. Although fuel costs are not a problem, the cost of providing and maintaining the power sources for propulsion and control clearly are. Surprisingly, skirt costs appear as a minor component in this breakdown, but overland operation may change this. Clearly one solution to the cost problem lies in adopting the special configurations described above, but it is also highly desirable to try to improve the
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**TABLE B2.1** BREAKDOWN OF DIRECT OPERATING COST (D.O.C.).
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**TABLE B2.2** BREAKDOWN OF DIRECT OPERATING COST BY CRAFT'S COMPONENTS.
fully amphibious vehicle since its flexibility gives it the greatest potential of all for widespread application. The simulation of the Canadian Northern operation is based on the results of the Canadian trials and questionnaires. Although the accuracy of individual fractions are open to question, the most striking feature is that the pattern of the breakdown is not greatly different from that of the European operation.

The seriousness of the cost problem is illustrated by some estimates of 7-year system costs for a cargo operation in the Canadian North based on an SRN6-type technology ACV and a deHavilland Buffalo STOL aircraft. The system costs are as comprehensive as possible; for example, aircraft costs include preparation and maintenance of a landing strip at one end and road transport a nominal distance from the landing strip to the site. The ACV costs include some route preparation. The comparison, which is given in Figure B2.3 shows clearly that current ACVs are limited to very short trips indeed. However, there does not seem to be any fundamental reason why the DOCs of an ACV cannot be considerably reduced. By careful attention to design and to appropriate R & D a factor of at least two seems attainable. Since the slope of the curves given in Figure B2.3 depends almost entirely on the DOC, such a reduction would clearly have a radical effect on the commercial viability of the ACV.

B.3 Flexible Skirt Systems

In the eleven years since SRNl first hovered a number of designs of cushion and flexible skirt systems with widely differing characteristics have emerged. These designs may be grouped into three types which are currently employed on commercially available vehicles:

i) Hovercraft Development Limited (HDL) open looped finger skirt
ii) British Hovercraft Corporation (BHC) bag and finger combination
iii) Bertin-SEDAM multiple "jupe" system

This grouping is neither fundamental nor necessarily up to date, but it serves to focus the discussion.

The HDL skirt philosophy was developed by the HDL Technical Unit in its heyday when Cockerell was its Technical Director. Although Cockerell's first experiments used unskirted vehicles, his early reports showed that he was aware that "wave conforming flexible extensions" (ACVs 1963) would be required to keep lift and propulsion power requirements reasonable in any but the smoothest sea-states, and he can be credited with the recognition of the need for a two stage, or fingered, skirt system to provide good sealing and low drag in both short and long waves. Other aims of the HDL programme were to make the cushion dynamics insensitive to skirt wear and damage, and to enable the skirt to be repaired quickly and cheaply without any special equipment such as a hoist.

The principal elements of the skirt system are outlined in Fig. B3.1. It is a single plenum chamber which uses skirt geometry changes effected by contact with the surface to generate centre of pressure shifts for roll and pitch stiffness. The individual segments or "fingers" which are capable of shearing relative to each other were developed to meet the low drag and damage insensitivity requirements. Cockerell's original peripheral jet idea was fairly quickly abandoned because the engineering difficulties of meeting the design objectives and at the same time maintaining a stable jet proved formidable. Damage insensitivity is obtained by shaping the fingers so that if one is torn or even completely removed, its neighbours expand under the action of the cushion pressure and tend to fill the gap. The segments, which may extend up to the level of the hard
FIGURE B2.3 COMPARISON OF PROJECTED SYSTEM COSTS FOR A TYPICAL CARGO TRANSPORTATION OPERATION IN THE CANADIAN NORTH.
Figure B3.1: Basic Principles of HDL Open Loop and Finger Skirt.

Figure B3.2: Illustrating Development of BHC Skirts.
structure, are connected by a loop of material to the outboard extremities in such a way that when the vehicle is off-cushion, the entire skirt system is accessible. Since the segments are sloped inwards at about 45° to achieve the desired stiffness levels, the loop ensures that the effective cushion area is kept reasonably large. The curvature of this loop is greatly reduced in the bow area to avoid the possibility of waves or other obstacles suddenly moving the segments rearward and causing a nose down pitching moment. Across the stern the basic finger cannot be used since it tends to act as a scoop. One solution is to use conical segments.

The BHC skirt system has evolved as a result of that company's extensive operational experience since the SRN1 was fitted with flexible extensions to its peripheral jet nozzles in 1960. By 1964 the skirt design had evolved to the type shown in Figure B3.2. This consisted of a deep bag fed directly from the plenum integrated with a nozzle whose shape was maintained by chains or diaphragms. Because this type of skirt produced excessive wear and drag and was difficult to repair (Creve, 1969), it was modified to include the finger concept developed by HDL. At first the fingers occupied 30% of the cushion depth, and in 1967 they were increased to 50% to improve ride and drag. The basic elements of the BHC system currently in use are given in Figure B3.3. The cushion air is fed from the bag through holes into the fingers. Roll and pitch stiffness is obtained by using inflated bags to divide the cushion into three or more compartments (Figure B3.4). Since the fan plenum is common to all compartments, the pressure differentials required for correcting moments are obtained by allowing pressure losses to occur through cushion feed holes. A diaphragm is included in the bag to help prevent a vertical oscillation commonly called "bounce". As on the HDL skirts the geometry is modified in the bow regions to prevent large bow-down pitching moments associated with skirt "tuck-under", as it is commonly called. Air may also be bled out through holes in the fingers in the bow area to reduce skirt drag generated by wave impact or bow-down moments, and to thereby reduce the possibility of the associated phenomenon of "plough-in". Also, as on the HDL skirts, the fingers cannot be used at the stern or on transverse compartment dividers. Both inflated bags and individual conical segments have been used.

The origin of the French Bertin-SEDAM skirt system can be traced back to 1957 when Bertin et Cie, a technology development company, was studying the properties of inducing annular jets (ACVs, 1962). The basic concept is illustrated in Figure B3.5. It comprises of 8 or more plenum chambers, each consisting of a slightly tapered truncated cone. An outer peripheral skirt fed from the cones may also be used. Stiffnesses are obtained by separately feeding each cone, and if a single fan is used then fluid dynamic losses must be provided either by ducts or orifices. Alternatively, the fan characteristic can be used, but this requires multiple fans or independent fan outlets. On the 33 ton SEDAM N300 the differential feed is obtained by using the fan characteristics in an ingenious way. The four axial-flow lift fans are mounted immediately above the top of the cones so that about one third of the flow area exhausts directly and independently into each of two cones and the outer skirt. Feeding ducts are completely eliminated.

Currently, there is an almost complete absence of any data in the accessible literature on the dynamics and other suspension characteristics of the various skirt systems. This information is very badly needed because the qualitative discussion given below shows that all of these systems have their advantages and limitations.

There can be no doubt that the HDL multiple segment or finger concept is an important advance in ideas, since it has low drag in rough water and is
Figure B3.3 Basic Principles of BHC Bag and Finger Skirt.

Increase mass flow increases \( p_b - p_c \) and decreases \( p_c \).

Figure B3.4 Original Compartmentation on SR.N4. A keel has been added to improve roll stiffness.
remarkably insensitive to finger damage. Although it makes a feature of the absence of compartmentation there are some attendant disadvantages. For example, there is evidence that the stiffness and damping may not be adequate for many purposes. The trials of a Cushion Craft CC7 in Northern Canada by the Department of Transport in the summer of 1969 reported that in a brisk headwind the tendency of the bow to drop had to be corrected by opening the reverse thrust doors on the top of the vehicle! Also the single plenum chamber principle is the most sensitive of all to lift loss over ditches; the problems experienced by the same vehicle over the fissures characteristic of polygon terrain in the Arctic suggest that this could be a serious limitation.

The basic Bertin multiple cone skirt is an elegantly simple concept, and may be particularly suited to overland operation since, of the three, it is the least sensitive to catastrophic lift loss over ditches. Also the suspension stiffness can be simply regulated by controlling the losses in the feeding ducts. However, it also has its problems. The geometry has a comparatively large ratio of air escape peripheral area to cushion area so that lift power requirements are intrinsically higher than on British vehicles unless the outer skirt is used. Also the cones and outer skirt do not have the basic advantages of the finger skirt, that is, they are relatively damage sensitive and give a poorer cushion seal over waves and irregular ground. The outer skirt has other inherent problems. The outer skirt greatly reduces the roll stiffness of the basic multiple cell concept, because it introduces a significant cushion area not subject to pressure differentials resulting from mass flow differentials. This effect is strongly dependent on the outer skirt pressure; in current designs the outer pressure is about 80% of the cone pressure, so that the reduction is quite large. The other major disadvantages of current peripheral skirts is associated with the transverse members required to maintain its shape. On the SEDAM N300 these consist of a number of wires tethering the pinch to a post which extends downwards about half the cushion depth. The obstacle clearing ability is greatly reduced by this arrangement; furthermore, very large loads have to be accommodated in the skirt material at the wire attachment points. These two disadvantages have led Canive, a Canadian licensee of the Bertin system, to adopt a circular peripheral skirt together with four additional cones mounted well outboard to give the needed roll stiffness (Fig. B3.6). Another problem encountered with the basic Bertin cone is the presence of a toroidal vortex (see Fig. B3.5) which under some circumstances can cause it to collapse. The solution to this problem has been obtained on the N300 at the expense of hard structure clearance by using a wire grid mounted directly below the fan entrance to break up the flow. Recently Walker and Bonsall (1969) reported some experimental tests on Bertin lifting cells in which they showed that if the vehicle rolled to an angle greater than about twice the cone taper then the cones collapsed. They did not explain the mechanism but presumably it is related to the toroidal vortex effect. Much more is required in the way of tests of this type.

The BHC skirt has the distinct advantage of being the only one which has any extensive operational and development experience, but again, this has been almost entirely in operations over water. The BHC skirt is probably stiffer and better damped in heave, pitch and roll than the HDL skirt; however, this is obtained at the expense of complexity and power. Typical bag and finger construction is shown in Fig. B3.7. Later designs such as are used on the 45 ton BH7 have modified the finger attachments to include connections to the bag along the entire bag-finger contact line because the original mounting placed excessive loads on the bag in the larger skirts used on the BH7 and SRN4. Incidentally, this change should reduce the ability of a finger to expand in the event that its neighbour is catastrophically damaged. Bag pressure may be as much as 40% higher than cushion
LOSSES IN DUCTS OR FAN CHARACTERISTIC GENERATES STIFFNESS

CONES TAPERED FOR STABILITY

HOLDING CABLES

OUTER SKIRT

\[ p_{co} = 0.8 p_{cj} \]

CONES

BERTIN SKIRT SYSTEM
(e.g. BC 7 TERRAPLANE, SEDAM N 300, CANIVE VEHICLES)

FIGURE 83.5  BASIC PRINCIPLES OF BERTIN SKIRT SYSTEM.
A SCREEN IS INCLUDED AS AT "A" TO BREAK UP CONE-COLAPSING TOROIDAL VORTEX AS AT "B".
FIGURE B3.6 CUSHION GEOMETRY ADOPTED BY "CANIVE" ON ITS BV 106, 8 PASSENGER VEHICLE.

FIGURE B3.7 DETAILS OF FINGER ATTACHMENT ON BHC VEHICLES.
pressure, and the lift power penalty is in direct proportion to the total pressure loss across the feed holes. It is also worth noting that although BHC vehicles nominally use compartmentation to obtain stiffness, they have been known to run without them (Thompson, 1969), implying that skirt contact and geometry changes play a role.

The BHC skirts have encountered a number of development problems, some of which have been overcome, but not necessarily understood. Furthermore, because they have only been experienced on BHC skirts it is not reasonable to assume that they are peculiar to that technology. There is good reason to believe that they may occur on all skirt systems.

One phenomenon (Crago, 1968) is described as "skirt bounce", and manifests itself as a roughly vertical oscillation of the bag which can produce undesirable side effects such as increased drag and skirt wear. This has been stopped by adding the diaphragm shown dotted in Fig. B3.3. It appears to belong to a class of oscillatory phenomena involving possible interactions between:

(i) cushion aerodynamics,
(ii) flexible material dynamics,
(iii) internal aerodynamics,
(iv) fan characteristics and inertia,
(v) hard structure (vehicle) dynamics.

Very little is known about them and they seem to be very difficult to reproduce consistently in the laboratory. Sometimes they can be merely annoying, but they can add to maintenance costs by inducing rapid wear, and can be very dangerous. There are reported cases of the sudden appearance of vehicles heave oscillations; fortunately these seem to occur over only smooth surfaces, but nevertheless they cannot be predicted. Some progress is being made, for example, unpublished analyses (Croix-Marie, 1969) of the Bertin cones which allow for the fan and duct characteristics, compressibility of the air, and the membrane properties of the material have been able to predict natural frequencies on model tests to 2% and damping to within 10%. It is also known that the internal aerodynamics can be important. For example, early models of HDL's HD2 test vehicle did not accurately reproduce the air distribution. The original model used a single large fan in the horizontal plane. The full size vehicle showed certain instabilities which were not predicted by the model, and subsequently it was found that they could be reproduced by incorporating a more accurate representation of the internal aerodynamics. It is known that small changes in details of skirt geometry can affect the onset of oscillations; this has been demonstrated on a rig simulating the HDL skirt at the NPL Hovercraft Unit. In general much more theoretical and experimental work is required in order to understand them. Because of their complex nature it is doubtful if any engineering predictions can come from analysis; but an understanding may provide helpful guidelines. Understanding of this problem may also improve the potential usefulness of model testing.

Another important problem in cushion dynamics is the rough ride often called "cobblestoning". This is potentially serious; even in a moderate sea the bumpiness of the SRN4 is quite unpleasant; indeed the legend of the rough ride has even reached the gossip columns of the Toronto daily press, (Toronto
Cobblestoning may be described as an unexpectedly hard heaving motion over short choppy seas, and there are several schools of thought on its origin. One possibility is the so-called "volume effect". The argument is that a cushion having a good seal, such as is afforded by the use of fingers, has to accommodate to short wavelength surface irregularities partly by compression of the air in the cushion, since there is sufficient time to allow enough to escape. The argument is plausible, because isentropic compression corresponding to a 1% cushion volume change leads to a 50% or more increase in cushion pressure. Other possible sources are fan surging and bag oscillations. Spectral analyses by BHC have shown that a large fraction of the energy content in the ride trajectory is at the natural frequency of the bag. Careful experiments leading to a better understanding of cushion dynamics are needed to understand the problem.

B.4 Skirt Wear

This problem is sufficiently important to warrant separate discussion. For operation over water great strides have been made in improving life, especially on the SRN6. Finger life on this vehicle has been increased from a few hours to as long as 700 hours by a combination of improved materials, better designs and more considerate operation by the drivers. Apparently BHC experience on their N6 did not help them on the N4 because finger life was initially very short, although again improvements have been made. The other major skirt systems have not been subject to similar extended periods of development, so data on life is not readily available. SEDAM however claims a life of about 800 hours for each cone.

There is an important difference in the skirt material practices adopted by BHC and HDL. HDL chose to use relatively light materials in the belief that lower inertia allows the skirt to accommodate to irregularities more readily. The unit weight of the neoprene coated nylon used on the Vosper-Thornycroft VT-1 is 30 ozs/sq.yd. In contrast BHC claims that their experience has led them to use material which is about 3 times as heavy. At the moment there does not seem to be sufficient evidence to justify a choice between these two philosophies.

One important problem which has been studied by BHC is known as delamination. It is thought to be caused by "a high frequency oscillation particularly associated with the skirt moving over water" (Crago, 1968). The phenomenon was puzzling because normal fatigue testing did not reveal it and several schemes were tried before the mode of failure, which was a breakdown of the fabric and rubber sandwich could be simulated. Eventually, it was found that a specimen mounted at the nozzle exit of a blower and made to flap could produce a similar failure, and this allowed BHC to examine the material parameters which affect finger life and thereby adopt more suitable materials. However, no work is available which describes the nature of oscillation originally supposed to be causing the failure.

Tests currently being conducted at NPL HU on a "wooden wave" belt have revealed an interesting failure mode. These use an ingenious technique which involves coating the model skirts with a flexible plastic paint which abrades and cracks off at points of folding. This allows failure patterns to be observed long before actual material failure occurs. One of the failure modes is a complete cyclic collapse or knuckling of the finger as it moves, at about half way up its length. This correlates with practice since holes have been observed in fingers on the SRN6 at about the point where knuckling would occur. Clearly more work of this type is required. That the nature of the skirt wear problem is highly dependent on the geometry of the skirt is illustrated by some problems which have
arisen on the Bertin skirts used on the N300. Elementary hoop stress theory shows that, for a given cushion pressure, the stress in the skirt fabric is proportional to the radius of curvature of the skirt element and its thickness. Hence for a given material thickness the Bertin-SEDAM outer skirt inherently has a much higher stress for the BHC or HDL skirt, since the radius of curvature of the former is sized by the beam of the vehicle while on the British skirts it is sized the hard structure clearance. Clearly this aggravates damage sensitivity. As might be expected this damage sensitivity is particularly acute at the rear of the outer skirt; whereas stresses caused by surface contact will tend to oppose the hoop stress caused by the cushion pressure at the front they will add at the front they will add at the rear. On the SEDAM vehicles attempts have been made to overcome this by introducing an ability to give laterally. One approach currently in use on the N300 is the spring system depicted in Figure B4.1.

Very little knowledge is available on skirt wear problems arising from operation over land, ice, and snow. However, the recent trials held in Canada provide some guidelines. For example, the Churchill Trials of an SRN6 (Department of Transport, 1968) suggested that, given a minimal amount of route preparation in the worst areas, skirt wear could be held to reasonable limits. The report stated that "skirts were doing extremely well in spite of the environment". In fact, except for several isolated events which caused severe damage, but which can hardly be described as representative of a routine operation, the skirt wear was described as "slight". The quantitative implications of this remark are not available. That report also notes a finger failure mode similar to that occurring in the NFL HU tests. (Fig. B4.2). The low temperature stiffening and cracking problems experienced in the trials of an SRN5 at Tuktoyaktuk (Defence Research Board, 1966) appear to have been solved. However, the CC7 trials gave much more discouraging results in its overland tests, finger losses occurred at the rate of about 1 every 3 miles. The difference may have been due to terrain differences, but it is also worth recalling that the HDL skirt relies on ground contact to generate its stiffness, so that this may have been a contributing factor.

The discussion in this and the previous section has clearly emphasized that skirt technology is currently in a rapid state of evolution. The recent Canadian Patent of a new, radically different BHC skirt (Fig. B4.3) designed to resist "corrosive buckling" (Hovering Craft & Hydrofoil, 1970) and Aerojet General's attempts to evolve their own "pericell" design, are both clear testimony to the fact that much progress is yet to be made. Furthermore, most of British and French efforts have been aimed at development of skirts for high speed over water use, whereas typical Canadian applications may involve extensive overland operation. It follows that a major part of any Canadian R & D programme must include evaluation of existing skirt designs and perhaps even development of new designs suitable for the typical Canadian applications.

B.5 Propulsion Systems

Air reaction propulsion, which plays such an important part in giving the fully amphibious ACV its unique capabilities, brings with it some disadvantages. The major problem areas can be (1) low efficiency, (2) high maintenance costs, (3) noise, (4) relatively poor controllability. Consider items (1), (2) and (3); item (4) is discussed in Sec. B.8.

Of the total installed power of perhaps 80 to 100 HP/ton in an air propelled ACV, 2/3 or more may be dumped into propulsion. This stems in part from the relatively low aerodynamic efficiency of the typical ACV system. The source of this low efficiency is best seen by reference to the simple actuator disc
FIGURE B.4.1  STRESS RELIEVING MECHANISM IN THE REAR OF THE OUTER SKIRT ON THE N 300.

FIGURE B.4.2  FINGER WEAR ON BHC SR.N6 USED IN CHURCHILL TRIALS. CROSS HATCHED AREAS INDICATE EXPOSED FABRIC AND BLACK AREAS INDICATE HOLES.
FIGURE B4.3 ILLUSTRATING NEW BHC FINGER SKIRT DESIGNED TO RESIST "CORROSIVE BUCKLING". EACH FINGER CONSISTS OF TWO RUBBER TUBES JOINED IN A "VEE", WITH A NOZZLE DEFLECTOR AT THE END.
It presents an over-simplified picture but it does illustrate basic principles. This shows that the Froude efficiency is given by:

$$\eta = \frac{TV}{P} = \frac{2}{1 + \sqrt{1 + CT}}$$

where

- $T$ = thrust developed
- $V$ = vehicle forward speed
- $P$ = power dumped into propulsive stream
- $CT$ = disc loading number = $\frac{2T}{\rho AV^2}$
- $A$ = disc area

It shows that a low $CT$ is required to obtain high $\eta$. Typical values of $CT$ and the associated ideal efficiency are given in Table B5.1. The discrepancy between the values for the aircraft and the ACV illustrate the problem. Vehicles such as the SRN4, which has four 19 foot propellers in two banks, must have actuator disc areas which are close to the practical limit. There is evidence that banking may cause significant reductions in efficiency; a recent NPL HU report states that on HD2, 50% of the slipstream velocity increment from the forward propeller is effective at the after propeller (Barratt, 1969). Rough calculations based on this rule and allowing for the unsteady state of the input air suggest that the effective thrust per unit power at the rear propeller may be less than half that of the forward propeller. If this is the case, the close multiple banking that has been contemplated on modular systems such as the BAC P50 described in the Market Survey (German, 1969), must be rejected as impractical. These arguments show that the amphibious ACV must operate at as high a block speed as possible; otherwise alternative methods of propulsion must be sought.

The aircraft type variable-pitch propeller has been the natural choice for the larger ACV since the designs are readily available. However they are decidedly not the optimum for ACV application since they are expensive to buy and to maintain, especially in the dust or spray of the typical ACV environment, and they are unnecessarily noisy. Stratton in 1967 quoted costs of propeller operation on a SRN6 in a marine environment as $6/hr, and this figure included funding of replacements for fatigue contingencies. He compared this with the Fokker P27 costs of $1/hr. The major source of this cost appears to be the effects of erosion caused by spray, there are cases where adhesive tape used to protect the leading edge of propeller blades has to be replaced after every few hours of operation.

The external noise generated by ACVs comes from several sources, but it is suggested by Wheeler and Donno (1966) that, for propeller driven vehicles, the dominant source is the rotating pressure field created by the propeller blades. It is also known that the noise increases very rapidly with tip Mach number. Hubbard and Reiger (1950) have shown experimentally that for a given power coefficient $C_p = P/V^3D^2$ the sound pressure level (SPL) generated by a two bladed propeller is reduced by about 8 dB by reducing the tip Mach number from unity to 0.60. If the tip Mach number is high, increasing the number of blades does not help much; however, if it is low, some gains can be made. The same experimental results show that, at a tip Mach number of 0.6, increasing the number of blades from 2 to 4 drops the SPL by another 4 dB. Trillo (1966) reported some measurements
of noise of ACV propellers and found a discrepancy between his results and the classical theory which was attributed to vortex shedding noise.

<table>
<thead>
<tr>
<th>VEHICLE</th>
<th>$C_T$</th>
<th>IDEAL EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller</td>
<td>0.01</td>
<td>99.95%</td>
</tr>
<tr>
<td>Aircraft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propeller</td>
<td>6.0</td>
<td>55%</td>
</tr>
<tr>
<td>driven ACV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plenum fan</td>
<td>22.0</td>
<td>35%</td>
</tr>
<tr>
<td>driven ACV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Speed</td>
<td>0.80</td>
<td>85%</td>
</tr>
<tr>
<td>Boat</td>
<td></td>
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</tbody>
</table>

Generally speaking aircraft type propellers have been optimized for high efficiency and low weight. This has led to the development of low solidity designs and high rotational speeds, and tip speeds have been in the range 850 to 1000 ft/sec. It is fortunate that the demand for quiet propellers for STOL aircraft has led re-activated interest in propeller design; and some progress has already been made. Dowty Rotol in England have been developing high solidity propellers for both ACV and STOL applications. They are made out of high strength carbon fibre composites, and although no information is available on their acoustic performance, typical tip speeds will be about 600 to 650 ft/sec. An important consequence of the use of carbon fibres is the weight saving; the original 19 ft. propellers on the SRN4 weigh about 1000 kg, whereas the 21 ft. composite replacements weigh only 310 kg. It remains to be seen how these materials will stand up to the spray and dust of the gruelling ACV environment, but this is a good example of the way in which modern developments in many areas will help to produce optimized ACV designs.

There are alternative approaches to the noise and maintenance cost problems. Plenum fan propulsion, such as is used on the Cushion Craft CC7 or the Canive BV102 and BV106, eliminates the periodic noise associated with any type of externally mounted impeller. Tests on the 2 ton BV106 have shown that the major source of noise is the engine exhaust. It is also mechanically simpler and much more rugged. Furthermore, if the impeller is mounted such that the axis of the intake is normal to the direction of motion of the vehicle, again such as on the CC7, much of the dust and spray will be separated out, thus affording some protection. These advantages are offset by the higher disc loading usually associated with this type of design and increased losses associated with the much larger mass flows that have to be handled in the plenum chamber. It is usually difficult to design an ACV fan installation to recover much of the dynamic head leaving the impeller. Furthermore, because the propulsion air is subject to turning, greater losses can be expected to occur at speed, so that the thrust falls off more rapidly with increase in forward speed when compared with a propeller.

Figure B5.1 shows some calculations of shaft power requirements for a
FIGURE 85.1 THRUST POWER REQUIREMENTS FOR PROPELLER AND PLENUM PROPULSION. THE CALCULATIONS ARE FOR ZERO FORWARD SPEED AND TYPICAL ACV PROPELLER WAS SELECTED FROM REF 45.

FIGURE 85.2 DUST SUPPRESSION FLAP USED BY "AIR CUSHION EQUIPMENT" ON THEIR HDL SKIRT.
small ACV having a static thrust of 225 lbs; it is obvious that plenum fan propulsion may require much more power to achieve the same thrust levels. Although generalization is difficult because the actual performance depends strongly on particular geometries, useful guidelines are about 4 lbs/HP into the fan for a good plenum fan design, compared to upwards of 7 or 8 lbs/HP for a well designed propeller installation. However, this advantage is offset somewhat because it is known that the propeller thrust falls rapidly with increase in yaw angle, whereas plenum fans will not be so sensitive to the large yaw commonly experienced in ACV operations. Only as operational experience accumulates will it be possible to ascertain which system is the more economic for a given operation. The merits of other forms of propulsion such as wheels for over land operation and water propellers for purely marine applications are discussed in Sec. B.8.

It has already been noted that dust and spray can present expensive maintenance problems. Trials of an SRN5 in the Sahara (Tomlinson, 1967) demonstrated just how serious this can be in overland operation. More recently the report on the trials of the CC7 in Northern Canada stated that;

"When travelling on land, especially at low speeds, the craft is enveloped in a cloud of dry peat dust, leaves, fine mud and debris". (Dept. of Transport, 1969. p.44)

Much has already been learned in the art of protecting engines operating in a marine environment. By drawing engine air from the plenum and then using a secondary stage of filtration, typical TBOs have reached 2500 hrs on the SRN6. No doubt corresponding techniques will emerge for overland operation; if the CC7 trials in Northern Canada are any guide, new filter designs may have to be evolved. However, engine maintenance is not the only problem; propeller erosion can be expensive and dust can be an outright nuisance and even a safety hazard. Clearly the ideal solution is to attempt to suppress spray and dust formation, and it may be possible to modify skirt geometry to help. Air Cushion Equipment, an English firm which uses the HDL skirt in a variety of industrial and other load moving applications, includes a flap just above the fingers (see Fig. B5.2) with this purpose. Almost nothing is known about the details of the entrainment process; this is a problem on which a modest laboratory programme might provide a significant payoff.

Even when TBOs have been increased to reasonable lengths, the cost of buying and maintaining the aircraft gas turbine frequently used remains a major contributor to the DOCs. The problem is particularly vexatious in the 500 to 1500 h.p. bracket; typically Igglesden (1969) has noted that the maintenance cost of the 3600 h.p. Marine Proteus used in the SRN4 may actually approach that of the 1000 h.p. Gnome used in the SRN5 and 6. Fortunately some recent developments in gas turbine technology for truck transport and industrial applications suggest that significant strides may be made in the next few years. Typically, Ford is now marketing an industrial engine which produces about 400 HP at a specific fuel consumption of about 0.45 lb/BHP-hr. and which costs about the same as a diesel engine of the same power. It is on the heavy side, weighing over 4 lb/HP but it is a clear indication that units suitable for ACVs will no doubt become available in the next few years.

B.6 Special Problems over Water

The major thrust of British ACV R & D has been the development of marine applications. Important design problems posed by operation at sea are prediction
of calm and rough water drag, cushion power requirements in waves, and corrosion and other maintenance difficulties. Some useful reviews are now available (Hogben, 1967, and Barratt, 1969) and the reader is referred to these for details. Here it will be sufficient to summarize the state of the art.

Figure B6.1 (Hogben, 1967) shows a typical analysis of the total drag experienced by an ACV operating in calm water. A distinguishing feature is the presence of drag caused by wavemaking, one or more peaks occur as the vehicle makes the transition from the displacement to the planing mode. The prediction of the magnitude of the peak is an important design problem but it is also theoretically complex. However, some progress has been made. The linear free surface theory, which is based on the assumption that the wave height is small compared its length and water depth h, gives a functional dependence of the wave drag $D_w$ on a rectangular planform in the form

$$
\psi_D = \frac{D_w \rho_{wg} g}{p_c^2 \sqrt{L/B}} = f \left( \frac{Fr}{B/L, h/L} \right)
$$

Here $p_c$ is the cushion pressure, and the cushion is assumed rectangular in planform with width $B$ and length $L$. $Fr$ is the usual Froude number $V^2/Lg$. The theory predicts two peaks at about $Fr = 0.5$, typically for $B/L = 0.5$, the maximum value of $\psi_D$ is about 2.2 in very deep water. It also predicts a very strong dependence on $h/L$ for values of $h/L$ less than about 0.25; typically for $h/L = 0.10$ the drag on the same planform has increased to about $\psi_D = 8$. The theory fails for very small $h$ and at large $p_c$, or very low $Fr$, directly as a result of the nonlinearities associated with wave steepness. The actual value of the hump drag is higher than that predicted by the linear theory owing to the presence of skirt contact and spray making drag. Skirt contact drag is generally considered to be very difficult to analyze, but is thought to be caused primarily by inertia and pressure forces and therefore above a certain critical value, should be independent of Reynolds Number. As the results given in Fig. B6.1 show, skirt contact drag is strongly dependent on cushion air flow rates, as regulated by the fan speed. Current engineering practice for predicting the total hump drag is to use the linear theory together with some empirical correction coefficients to account for the other components. These correction factors are a strong function of the geometry of the skirt system cushion air flow rate and other parameters.

ACVs are known to be very sensitive to the sea state, and drastic reductions in speed occur for even moderate sea state. Figure B6.2, taken from Tonkin and Raybold (1969), shows that the ACV is more adversely affected than the hydrofoil. It is a very serious problem; and the understanding of the mechanisms involved is an important part of current British efforts. Even in regular waves it is theoretically very complex, as it depends on a large number of interacting parameters such as cushion stiffness, vehicle attitude, wave height and length, cushion flow, and skirt geometry (Hogben, 1967). The ability to dynamically model ACVs is especially important for this problem because its complexity suggests that theoretical treatments will be unlikely to give engineering design information.

In estimating cushion power requirements, it is reported by Barrett et al (1969) that current design practice is to seek an optimum for calm water conditions between the opposing penalties associated with increasing daylight clearance and the associated lift power and increasing skirt contact drag. The same authors also note that there is an increasing awareness that allowances have to be specifically made for rough water, but that no established procedure exists, and some
Figure B6.1 Typical drag measurements for an ACV over water. Source: Hogben (1987).

Figure B6.2 Comparison of the speed losses of ACV and hydrofoils in waves. (Source: Tonkin & Raybold 1969).
controversial issues such as ride comfort criteria are involved. Some empirical formulae are quoted by the authors.

One problem associated with operating a marine environment and first encountered by BHC vehicles is known as "plough-in". Under certain circumstances, skirt drag can combine with thrust, wind and deceleration forces to exert a powerful destabilizing couple, which may lead to overturning. The problem has been discussed in detail by Crago (1968) and the remedy is to reduce contact drag, especially in the bow area, by providing vent holes and strakes to encourage air lubrication.

B.7 Internal and External Aerodynamics

Although the design problems associated with the internal and external aerodynamics of the amphibious ACV are not usually considered to be as critical as the other problems discussed in this review, nevertheless the evolution of optimal vehicles will require careful consideration of these areas.

Fan design for the ACV presents an interesting challenge, because the specific speed $NQ/gh^{3/4}$ is usually such that conventional fan technology indicates axial geometries for maximum total efficiency $\eta_T$. However with some notable exceptions, such as the lift fans on the SEDAM N300, the fan geometry is usually centrifugal. The reason is that vehicle configurations typified by BHC practice usually require the air to be delivered to a plenum in which the basic flow direction is in a plane normal to the axis of the fan intake (see Fig. B3.3). The problem is particularly serious when plenum fan propulsion is used, such as on the Cushioncraft CC7. To do this with an axial installation would incur serious losses since the plenums are inherently quite shallow, whereas the centrifugal fan has the natural geometry for the purpose. Special designs have been evolved to handle the high volume flow; the principal features are a very large value of impeller blade depth relative to diameter, and blade geometries aimed at giving a high static pressure efficiency in the absence of a diffusing scroll, rather than a high total efficiency. A very detailed study has been reported by Brotherhood (1966) and although this work was aimed at a specific vehicle, the Britten-Norman CC2, many useful guidelines are presented. For example, unless very careful attention is given to the upper shroud and intake geometry, separation can occur and cause a loss in $Q$ and static efficiency, $\eta_S$. Values as low as 42% were recorded for the original CC2 fans. It was also found that the gap between the shroud and the intake lip could be used to provide boundary layer control and thus delay separation, so that there is an optimum value of the gap to achieve maximum efficiency. (Fig. B7.1). Some diffusive action was obtained by ensuring that the plenum height was matched closely to the fan height at exit, thus gaining an efficiency increase of 5% to 10%. Any discontinuity at the exit such as drawn in Figure B7.1 was found to ensure the loss of such action through the dissipation inherent in the separation. Brotherhood reported total efficiencies $\eta_T$ of over 90% and static efficiencies approaching 80% in some of his tests; however a figure of $\eta = 65\%$ seems a more practical design rule since attainment of these efficiencies is strongly dependent on operating on the right part of the characteristic, especially in the case of static efficiency.

The air that escapes from the cushion will be subject to losses on its journey from the fan; and the magnitude of these losses will be a strong function of internal ducting and flexible skirt geometry of the particular design. It is possible to measure the extent of these losses by means of suitably defined
efficiencies. Care must be used in the way they are defined however, because there is no general agreement as to where to account for air bled off the plenum for cooling control and other purposes. For example, Keiller (1968), in describing some early work on unskirted peripheral jet models, defines a hovering efficiency $\eta_H$ as the ratio of the power of the flow in the outer peripheral jet to the fan shaft power, and a duct efficiency $\eta_D$ such that $\eta_H = \eta_T \eta_D$. This means that the stability jet flow power and the ratio $\eta_s/\eta_T$, which is governed strongly by fan geometry, are lumped together with the true duct losses. Keiller reported hovering efficiencies in the range 40% to 70% depending on duct cleanliness, and duct efficiencies the order of 60% in some cases, but this is clearly a strong function of vehicle geometry. He also reported some calculated results of hovering efficiency for the jetted skirts first used on the BHC SRN5; these were 20% and lower, but no explanation of the reason was given.

There seems to be a complete lack of published data on the hovering performance of the contemporary vehicle designs; some calculations for a small 2 man ACV using Bertin skirts with plenum fan propulsion and orifices to provide stiffness showed that they could be very low. Typical values of $\eta_H$ were about 25% and $\eta_D$ about 35%. While such losses are clearly undesirable, a difficulty is that attempts to reduce them may involve tradeoffs which actually increase DOC’s. This factor has always to be borne in mind when examining ways of improving the technical performance of components of the vehicle. However, Keiller’s work did underline the need for model tests for each new design configuration to ensure that internal flow is not subject to serious losses. The risks associated with attempting to generalize experiences with a particular design, has been rather graphically illustrated by the fan tests described by Brotherhood (1966). His measurements of efficiency included examination of the effect of obstructions and in some cases these were shown to improve efficiency.

The external aerodynamics of an ACV are important since the forces generated by the wind motion relative to the vehicle can form large, even dominant, inputs to the vehicle dynamics. They can constitute a serious control problem, especially at low speeds, since the effective yaw angle can be anywhere between $\pm 180^\circ$. The nature of the problem has been given an excellent analysis by Andrews (1970) and the reader is referred to this paper for a detailed discussion. The basic problem seems to be that changes in vehicle yaw angle associated with change in vehicle speed or direction and wind speed and direction can cause sudden changes in vehicle handling characteristics. However pitch and roll angles can also be important. There are problems other than control associated with the external aerodynamics. For example, it is possible that considerable momentum interference can occur between the essentially perpendicular lift and propulsion streams. This effect is obviously dependent on the relative location of intake and propellers. It has been claimed that this can have a profound effect on system efficiency, although no published data is available.

A typical example of a handling problem is the differences between an upwind and downwind low speed turn into a cross wind (see Fig. B7.2). The upwind case is relatively easy, whereas the downwind case is associated with excessive drift and perhaps a tendency to weathercock instability if the vehicle has fins.
EXCESSIVE DRIFT TURNING DOWN-WIND

CONTROL UP-WIND RELATIVELY O.K.

FIGURE B7.2 UPWIND, DOWNWIND CONTROL.

FIGURE B7.3 LIFT AND DRAG COEFFICIENT OF ACV MODEL.

FLOW THROUGH GAP USED AS BOUNDARY LAYER CONTROL

SHAPE CHOSEN TO AVOID SEPARATION

EXIT HEIGHT MATCHED TO FAN HEIGHT. OTHERWISE SEPARATION WILL CAUSE LOSS OF RECOVERY

FIGURE B7.1 ILLUSTRATING HIGH DUTY FAN.
Typical measurements of lift and drag as a function of yaw angle $\beta$ made by Andrews for a basic shape are given in Figure B7.3. They show the rapid increase in drag in both drag and lift that occurs beyond a certain small value of $\beta$. There is a tenfold increase of lift in beam wind conditions, and as Andrews notes, when associated with skirt drag these can generate overturning moments. (Fig. B7.4). In general the results demonstrate the need to keep the external shape simple, and as close as possible to an inverted saucer. But even this shape involves compromises between various ideals. Typically it would be desirable to have a high crosswind force in yaw to facilitate high speed turns, and this would not be generated by the saucer shape.

It seems reasonable to conclude that the solution to the handling problem posed by external aerodynamic effects will not be found in configuration design but in providing the vehicle with force and moment devices which may have to be automatic and which are sufficiently powerful for the purpose.

B.8 Control

Although there are obviously problems, the control characteristics of the fully amphibious ACV operating over water are acceptable, since normally there is adequate space, grades do not occur, except perhaps at landing ramps, and skirt drag may be used to provide some braking. However this is not the case for overland operation. Space may be much more constricted and skirt drag is ruled out as a braking mechanism so that operation over unexplored terrain or in close quarters can be extremely difficult and very fatiguing. The three trials undertaken to date in Canada which involved overland operations revealed serious deficiencies. All craft had inadequate reverse thrust, so that steep gradients had to be descended by reversing the vehicle and then backing down; and braking was often obtained by using the "semi-pirouette" manoeuvre (Fig. B8.1), a tactic which is unacceptable in any routine operation. Informal discussions with operators who have had Northern experience indicates that this deficiency must be taken very seriously. Part of the problem is the design of the propellers, which as noted earlier follow aircraft traditions. They tend to use relatively high camber blades to obtain a high section lift/drag ratio at good efficiency in the forward thrust direction, whereas symmetrical blades are required for equal performance in either direction. This means that reverse thrust is usually less than 60% forward thrust. Designs of propellers especially suited to the ACV are required; and as for the noise problem higher solidity blades with smaller camber are indicated. However, propeller design may not be the entire story. For example, on vehicles such as the BH6, SRN6, the lift fan intake is directed forward and below the reverse flow slipstream, so that momentum interference may play a role. As in so many problems currently surrounding ACV development, no published data is available.

There are other problems associated with operation overland. Crossing slopes required yawing the craft into the slope, and tailwinds were found to be a serious problem since they were apt to cause loss of rudder control. Built up areas were described as "difficult but not impossible to negotiate" (Dept. of Transport, 1968, p.33), and it was stated that the problem was aggravated by the sudden wind changes associated with passing buildings. It is virtually impossible to drive amphibious vehicles on a crowned road; (Dept. of Transport, 1969, p.34) the vehicles slide off at the slightest perturbation.

All three reports emphasized that the seriousness of the control problem is related to the depth of the skirt. Currently, hard structure clearance seems to be limited to about one-sixth of the beam of the vehicle, so that for vehicles
FIGURE B7.4 EFFECT OF HIGH LIFT IN YAWED MOTION. EXTREME CASE (90° YAW) IS SHOWN HERE, BUT FOR NON ZERO YAW, THE GENERAL EFFECT IS TO PRODUCE A DESTABILIZING COUPLE.

MARKERS 50 YARDS APART

CRAFT APPROACHES AT STABILISED SPEED

FIGURE B8.1 TRAJECTORY OF TYPICAL "PIROUETTE" MANOEUVRE IN THE SR.N5 TRIALS AT TUKTOYAKTUK.
the size of the SRN6, this clearance is a little over 3 ft. The figure of 7-foot clearance has been quoted for Arctic operations over ice; and development of skirts to approach this ideal seems to be a worthwhile project.

A more radical solution to the control, propulsion and noise problems of the amphibious ACV can be adopted if the vehicle is to operate in only one environment. For example the 65 ton Vosper VZ-1 "hybrid" uses variable pitch hydrodynamic propellers and rudders and this can greatly reduce operating costs. The sidewall vehicle such as the HM2 has the added advantage of lower cushion air power requirements.

The equivalent approach for overland use, which is also potentially capable of greatly reducing operating costs, is to use wheels for propulsion and control. The classical example is the Bertin Terraplane. Designs of this type were used in the Market Survey for the simulation of off-road applications. However there are grounds for believing that the concept may not be as successful as the "hybrid" is likely to be for operations over water. The difficulty arises because to be really useful, the vehicle still requires a limited amphibious capability. Trials of the Bertin BC7 undertaken at the Canadian Armed Forces Land Engineering Test Establishment (Dept. of Transport, 1969, p.32) showed that it was immobilized by swampy ground and grassland traversed easily by the Cushioncraft CC7. The BC7 had to be fitted with an aircraft engine and propeller to make it pass these tests and to enable it to operate in rivers.

The British Central Electricity Generating Board has been investigating the use of an air cushion transporter for off-road handling of heavy equipment such as transformers and a recent report (Air Cushion Vehicles, 1970) on this vehicle commented on the propulsion problem. The solution adopted was an onboard winch; and although this approach may be acceptable for activities such as heavy equipment handling, it seems out of place in a routine transport operation. An additional complication is introduced if the vehicle is intended for use over any Northern terrain areas where there are load bearing pressure restrictions. It seems reasonable to suggest that there will be a role for this type of vehicle in operations such as the equipment handling noted above, or for cargo haulage on roads having short stretches which often become impassable to conventional lorries in certain weather conditions. However, it does not appear to be a practical solution for general off-road transportation.

It is our opinion that, whereas other problems facing the ACV contribute primarily to increasing the DOCs and adequate development should bring these down, the control problem presents an obstacle to the technical viability of ACVs for overland operation. The problems are difficult but not perhaps insurmountable. One solution to the low speed manoeuvering problems is essentially the inverse of the Terraplane concept and is to use light retractable undercarriages which are lowered to give resistance to side forces associated with winds or crossing gradients. Even if only 20% of the vehicle weight was transferred to wheels, for typical vehicle geometries sidewinds as high as 50 m.p.h. could be handled. Very recently, the Canive BV104 was fitted with a retractable undercarriage for this purpose; the improvement in low speed handling qualities is very encouraging.

Existing amphibious vehicles use a very wide range of control devices and they vary widely in their effectiveness. For example, the BHC SRN6 uses an aileron and a skirt lift system to control pitch and roll trim. Rudders are used for turning at high speed, and puff-ports and plenum air blown over the rudder surfaces are used for side forces and moments at low speeds. A variable pitch
propeller is used for thrust control. Larger BHC vehicles such as the SRN3 and SRN4 use variable angle propeller pylons for thrust vectoring. The SEDAM N300 uses a much simpler system; two constant speed variable pitch propellers are used to obtain thrust and braking forces and turning moments. The rudders are passive and are used merely to give some high speed weathercock stability. There is no provision for roll and pitch trim control. The Cushioncraft CC7 has forward and reverse thrust louvres on both of its two centrifugal fans; these may be opened in pairs or differentially to obtain both forward and reverse thrust and pure moments. Turning is augmented by rudders located in the forward thrust streams. Pitch trim tabs are also placed in these streams. The opportunities for inventiveness in this area seem endless; typically the Canive BV106 uses transverse thrust ports on the top of the vehicle mounted so that when used, they induce roll and create an additional component of cushion force in the transverse direction. Both the variety of the types of control system currently in use and the way they are presented to the driver are a clear indication of the emergent state of ACV technology. Very little quantitative information is available on the relative merits of the various control systems both in terms of their effectiveness to perform their assigned task or the power penalties incurred. Qualitative observations however clearly indicate that there is considerable variation in effectiveness. For example, the low speed manoeuverability of the CC7 is known to be exceptionally good: it has received favourable comment in many reports (qv, e.g., Dept. of Transport, 1969). On the other hand it has been reported that the trim tabs were not adequate for the purpose in both overland and overwater operations (op cit. p.22 & 43). It seems that this craft should employ the skirt shift mechanism which is usually an integral part of the HDL skirt concept. It has been reported that the SRN6s used on the Solent crossing in Britain were never really in trim because the block time was fairly short. Rudders can be a liability, since in a following wind they can induce a weathercock instability. Another complication is that the control elements often induce undesirable responses in the vehicle which may have to be cancelled by another control system. For example a variable angle pylon used for turning induces a roll which in turn can cause skirt drag to generate a moment in the sense opposite to that required. Also a component of cushion force may generate sideslip, and on BHC vehicles this has been countered by using skirt lift.

Clearly, in the interests of reduction of DOCs, it is essential to employ the minimum number of control elements necessary to achieve a satisfactory level of controllability. Given adequate field experience and research, considerable progress will no doubt be made. For example one of the operators of the SRN4 service across the English Channel has asked BHC to lock the two front pylons. Recently, Flower (1970) proposed a means of modifying the fins to provide neutral or positive stability for all wind directions and thus eliminate the problems associated with their use in low speed manoeuvering. In the laboratory, much can be learned about the vehicle dynamics and the effectiveness of various control systems. Both model tests and computer simulations can be used. Because of the nonlinearities in the differential equations, a hybrid analog-digital computer is often recommended as being the most suitable for such simulations (Silverleaf, 1968). The circular track testing technique (see Sec. B.11) can be used to examine the dynamic behaviour of the vehicles, and in this area much is to be done; in general it is not known which terms in the differential equations describing the vehicles are important and which can be omitted. The British Hovercraft Corporation have made extensive use of radio controlled free flight models at their testing laboratories on the Isle of Wight, and have gained useful information on handling characteristics and such problems as plough-in boundaries.
Any systematic examination of control systems should include investigation of the methods of presentation to the driver. As for the control elements themselves, simplification and evolution of optimum layouts is required. This can drastically assist fatigue problems and the level of driver training necessary, both of which in turn can affect operating costs. Currently there is a very wide variety of methods of presentation of controls. The BHC SRN6 has an 8 position skirt lift switch mounted on a column between the driver's knees; the rudders are operated by foot pedals; while the propeller pitch and speed are regulated by a lever and twist grip throttle mounted on the lever respectively. The puff-ports are operated by toggle switches. The SEDAM N300 uses a single control column on which is mounted a steering wheel. Fore and aft motion of the column gives forward and reverse thrust, while turning the wheel gives differential propeller pitch for turning moments. The only other primary controls are the two turbine governor setting levers. The CC7 uses two sticks which may be moved fore and aft in unison for thrust, or differentially for turning moments. The rudders are operated by pedals and the trim tabs by electrical switches.

Clearly evolution of optimized designs will depend heavily on experience, but the emerging techniques of human pilot dynamics and ergonomics will be able to make useful contributions.

B.9 Structures

In Sec. B.2 it was noted that equipped hull costs are a major target for reduction in vehicles designed along the lines of the SRN6. The hard structure of these vehicles is based on riveted and bolted high strength light alloy techniques derived from aircraft practice, where safety and weight reduction are dominant constraints. If these constraints can be relaxed somewhat for ACVs, alternative methods become possible. For example, Vosper Thornycroft have adopted the philosophy that a lower structural efficiency may be tolerable if constructional costs can be radically cut. The basic structure of their VT-1 uses relatively low strength aluminum alloys and a mixture of rivetting and welding. It is claimed that this may cut unit costs to perhaps half that of BHC vehicles, which are currently about $9,000/seat; but to be entirely fair it is not clear how much of this reduction is attributable to the adoption of hydrodynamic propulsion and control. Vosper Thornycroft vehicles should also have lower hull maintenance costs and should be more resistant to accidental rough handling. Only operational experience will decide, but the approach does illustrate the importance of evolving constructional practices suited to the ACV.

It has been suggested that developments in composite materials such as glass reinforced plastics may provide some interesting opportunities for ACVs. Typically, Marchant (Ref. 27) stated that even the present technology may allow as much as a five-fold reduction in manufacturing costs with only a 30% increase in structural weight. However, in attempting to assess their impact on the economics of the ACV it must be borne in mind that any radical structural innovations which could result from the development of cheap but exotic fibres such as carbon or boron can be applied to its competition as well (see Fig. B.9.1). Hence it seems likely that the use of composites may only be important insofar as they present an opportunity to eliminate the aircraft construction philosophy.

Another area of considerable importance to ACVs, yet about which relatively little is known, is the properties of air-supported flexible structures. In addition to the obvious application to flexible skirts, they may find use on other parts of the ACV, and operational and operating cost advantages. The flexible side bodies currently available on the Cushioncraft CC7 are a good example of a typical application. But as the BHC experience shows, much has yet to be learned in methods of predicting stresses, stability and failure; and about the fatigue properties of the materials currently used. The air supported structure would seem
FIGURE B9.1 STRUCTURAL POTENTIAL OF COMPOSITES.
to be especially suited to vehicles designed for overland use since their inherent softness might confer some immunity to impact damage.

Design codes for ACVs operating over water have been evolved in Britain and, currently, commercial ACVs have to meet the requirements of the U.K. Air Registration Board. The principal design cases have been summarized by German et al (1969, p.269). For craft below about 50 tons displacement the maximum stresses in overall bending are developed by wave impact forces. For larger craft, the maximum stresses are developed in the static displacement case. A detailed discussion of the design cases is given by Elsley and Devereux (1968). No equivalent code has been evolved for overland or Arctic operations.

B.10 Modelling

Dynamically sealing ACVs for model tests is a more difficult problem than for either aircraft or ships because the number of parameters that may be involved is much greater. Froude scaling, that is constancy of \(V^2/Lg\), is required for over-water modelling and if the vehicle dynamics overland is being investigated. Other important parameters are the "cushion loading coefficient" \(p_c/\rho_vgL\) which must be scaled for over water operation, and the dynamic head coefficient \(\frac{\rho v^2}{\Delta p}\), and these can be readily scaled. As for ships and aircraft it is not possible to obtain scaling of the Reynolds Number \(\frac{V}{L}\) or \(\frac{V}{\nu}\), and it is not in general yet known when this condition can be relaxed. It has already been noted that skirt contact drag is thought to be mainly caused by pressure and inertia forces. However, internal aerodynamics may be strongly Reynolds Number dependent, and this could be important in examining such problems as cushion heave dynamics. It has been suggested also that fan inertia might have to be scaled when examining cushion dynamics. Other numbers which may be important for over water operation are the Weber Number, which measures surface tension effects \((\sigma_v\sqrt{\frac{L}{\rho_N}})\) and the cavitation number \((\frac{\rho_w - \rho_v}{\rho_w}V^2)\), but in general it is not possible to scale these parameters in a typical ACV test.

Perhaps the biggest problem in realistic ACV modelling is the correct scaling of skirt behaviour. It is obvious that the skirt dynamics play a critical role, yet in general it is impossible to model them and at the same time retain the basic Froude scaling. For example, correct modelling of the inertial properties of the skirt material requires that the skirt weight per unit area be scaled in direct proportion to \(L_j\). Since typical skirt material thickness is about 3 mm on full scale vehicles, model material is usually impossibly thin. Membrane and bending properties may also be important; however the exact role of these quantities is a subject of some controversy. It has even been observed that the anisotropic properties of the typical fabric and rubber sandwich may have an effect; tests on the cones used in the Bertin skirt revealed different results for natural frequencies when the orientation of the cords was rotated through 45°.

It is fair to state that the modelling problem remains unsolved, so that full scale performance cannot be predicted with any reasonable certainty (Barrett et al 1969, p.20). It is very important to know what can be achieved through modelling, since it can have a radical effect on development costs. Some suggestions have been made for evolving various rules based on a better physical understanding of ACV behaviour, analogous to those used in building aerodynamics and ship testing. An additive rule intended to separate out the effects of various modelling numbers has been proposed in the above survey, but it is not known how useful this will prove to be, or even if such a separation is reasonable.
Partial modelling rules may be evolved for examining specific problems. For example, the ratio of cushion pressure to skirt weight/unit area is usually so high (greater than about 50:1) that the overland behaviour of skirts in the absence of vehicle dynamics could be examined by relaxing the Froude scaling. One of the problems in this area is the lack of data on comparable full scale and model tests which is both accessible and in a form amenable to analysis. Also the importance of simple theoretical analyses, which although unable to give useful engineering data, may give physical insight, should not be overlooked.

B.11 Facilities

Many of the research problems discussed above will require rigs designed specifically to examine particular aspects. The "wooden wave" belt at NPL HU is a good example. Nevertheless, it is appropriate to comment on some general facilities which may be required.

Test vehicles such as HDL's HD1 and HD2 have been employed extensively by both Government and University Laboratories. They have the supreme advantage of generating information about the real environment and therefore provide valuable guidance on research priorities. However, they have some very serious disadvantages which must be clearly recognized. These are:

(i) Any tests are undertaken in a largely uncontrolled environment, which implies that it is often difficult to interpret results.

(ii) All the problems are wrapped up within one experiment, and this also makes interpretation difficult.

(iii) They tend to be very expensive and to suffer from development problems in areas such as engines and hydraulics, which are not really part of the test programme, but which absorb time and money.

(iv) They tend to enslave the minds of some who see them as an end in their own right, rather than as a means to information.

Objections (iii) and (iv) can create management problems; and the solution is to use commercially available vehicles rather than attempt to build a vehicle as an "in-house" project, wherever this is possible. This approach has the added advantage of generating reliable data on manufacturer's products; something that is often difficult to obtain! The point of objections (i) and (ii) is that in the normal course of events, a trials programme must be complemented by a laboratory programme in order to derive maximum benefit from both. The trials programme defines problem areas and suggests solutions to the simpler problems, while the laboratory programme enables the more difficult problems to be understood.

There is probably no single major facility which will find general application for ACV R & D equivalent to the role the wind tunnel has played in aircraft R & D. For marine ACVs the towing tank has already made valuable contributions, and the "round-the-pole" or circular track technique using self-propelled models has also been widely used for both ground and over-water applications. An extension of this idea, which is due to Etkin of UTIAS, and
which may be very useful for both cushion and vehicle dynamics research, is to use a tethering cable which is sufficiently light that it behaves quasistatically in terms of its contribution to the vehicle dynamics. A 20 foot diameter pilot facility was built some years ago at UTIAS. The test programme showed that to be of real value, such a facility might have to be at least 100 feet in diameter so that models up to 10 feet long could be used. This was to allow an adequate instrument package to be carried and ensure reasonably acceptable modelling. For vehicle dynamics, it was found that at least five, and possibly the full six, degrees of freedom could be studied in a single experiment. The two objections commonly levelled at the concept are that the vehicle travels in its own aerodynamic wake and that the centrifugal forces may distort the skirts. Tuft tests have shown that the first is never a problem since the wake spills radially. Also the centrifugal forces are usually less than 1% and are therefore usually much less than the cushion pressure forces so that skirt distortion is negligible. To use the technique over water it is necessary to provide an annular tank lined with some form of wave absorber, otherwise it becomes a good "confused sea" experiment.

The wind tunnel will probably only have a relatively minor role to play in ACV R & D. It is very difficult to simulate the ground environment and information on vehicle dynamics and control systems can probably be more readily obtained on a circular track. The circular track does not require the expensive and complicated lift and moment balance essential for obtaining this type of data in a wind tunnel test.

B.12 Suggestions for a Canadian R & D Programme

The fundamental point to be remembered when suggesting problem areas for study is that, it is not at all certain what the major Canadian use patterns will be, and consequently, which vehicle geometries will evolve as the most economic choices corresponding to those patterns. For example, some major unsettled questions are:

(i) Which skirt systems will be the most suitable for overland operation?

(ii) Is the low speed control problem so intractable that all off-road applications might have to use the wheeled ACV, in spite of the limitations this might bring?

(iii) Is the dust and spray problem sufficiently serious that the plenum fan type of propulsion system will turn out to be more economic than propeller propulsion? Can any changes be made in skirt geometry which will drastically reduce dust and spray entrainment?

(iv) Is the large over water application sufficiently important that methods should be found to circumvent current marine propeller limitations?

Two points follow immediately. Firstly, the need for a continuing Canadian trials programme is obvious. Presumably these would be organized along the lines of the SRN6 Trials at Churchill. The programme should examine a wide range of vehicles as they become available and they should be supervised by a Co-ordinating Committee containing representatives from Government Departments, Laboratories, Universities and Industry. When serious commercial use becomes established, the
programme could be discontinued, as this would then provide the necessary operational experience.

Secondly, such laboratory research as is undertaken should, for the present, be aimed at providing background information to allow the necessary major design decisions to be made, rather than at optimizing the performance of a particular vehicle geometry. This applies to both value engineering and transportation studies as well as research into purely technical problems. Furthermore, although some specific problem areas requiring immediate attention are stated below it is expected that priorities will change as operational experience accumulates. The Co-ordinating Committee suggested above should issue statements of research priorities on a regular basis, and these should be used to influence research funding.

Almost all of the topics suggested below are aimed at giving some insight into the many important problems facing ACV development. It has been assumed that the major thrust of British activities, namely development of marine ACVs, will continue, so that problems specific to that environment have not been included. Since much information can be gained without detailed full scale simulation of the problems, only a relatively modest expenditure is required at this stage. The list has been compiled with the assistance of the ACV Sub-Committee of the NRC Associate Committee on Aerodynamics. They are not given in any particular order of priority.

The problems are:

1) Development of novel methods of thrust augmentation or increasing propulsive efficiency for purposes of propulsion and manoeuvrability when plenum air is used as a source.

2) Studies of the aerodynamics of flow involving flexible membrane boundaries with particular reference to static and dynamic stability of skirt systems.

3) Development of design methods for inflatable structures with reference to ACV's.

4) Investigations of the properties of composite materials such as glass reinforced plastics in order to develop more effective quality control and design methods.

5) Investigations of the deflection of jets by aerodynamic means.

6) Research which is basic to the development of flexible materials which better resist abrasion and wear.

7) Interaction of jets with liquid and particulate matter with a view to understanding the mechanism of spray and dust generation.

8) Theoretical and experimental investigation of the static and dynamic performance of the existing and projected skirt systems. Development of designs with an increased hard structure clearance to beam ratio.

9) Design and propeller and ducted fans systems for ACV propulsion with particular reference to distorted flow conditions.
10) Investigation of acoustic characteristics of ACV propellers with a view to formulating design recommendations for minimizing the noise emanation.

11) Studies aimed at understanding modelling characteristics.

12) Value engineering, mode comparison, and system studies to examine ways of cutting ACV first and operating costs, and to establish in detail its potential in transport systems.

13) Assessment of the control forces required for operations overland and in the Canadian North.

14) Investigation of the effectiveness of the various kinds of control systems currently used on ACVs with a view to selection of optimum designs.

B.13 CONCLUSION

Of the many problems that remain to be solved before the air cushion vehicle reaches a reasonable level of technical maturity and economic viability, two stand out as requiring special attention. These are: the high first and operating costs, and the control problem for vehicles intended for extensive overland use. However, there does not seem to be any basic reason why these problems cannot be conquered, given adequate R & D.
APPENDIX C: REVIEW OF THE STATUS OF TRACKED ACV TECHNOLOGY

C.1 Review of the Limitations of Mechanical Suspensions

Cl.1 Function of a Suspension System

To set this discussion of TACV technology in context, it is useful to define the basic purpose of a suspension system and then to summarize briefly the limitations of mechanical systems. The purpose of a suspension system is of course to guide the vehicle along the guideway and stabilize its translational and angular motions within limits set by passenger comfort requirements. The formulation of ride comfort criteria is a complex task, since it involves a considerable element of subjective judgement. However, some progress in quantification has been made. For example, Figure C1.1, taken from McFarland (1969), shows some data on the effect of sinusoidal vibrations on man. The results indicate that he is most sensitive in the frequency range of approximately 2 to 10 Hz. Typically, at 5 Hz the threshold of perception corresponds to a vibration with a peak acceleration of about $0.3 \times 10^{-2} \text{ g}$. and the sensations become unpleasant at about $0.5 \times 10^{-1} \text{ g}$.

The guideway inputs to the suspension system will normally have to be described by probabilistic or random variable techniques. However, a useful insight can be obtained by calculating the peak accelerations experienced by an object following exactly a prescribed sinusoidal waviness at a constant speed. Values are given in Figure C1.2 for irregularities which might be typical of the current attainable standards of guideway smoothness. It is to be noted that the peak accelerations increase as the square of the speed and decrease as the square of the wavelength.

The design of suspension systems to meet the various criteria involves some difficult compromises. For example to obtain good ride comfort in heave requires a soft suspension, on the other hand this results in poor roll characteristics. And again, the soft suspension requirement results in relatively large suspension motions in response to guideway inputs; whereas the actual motions that can be tolerated are severely limited by practical configuration requirements. Whatever suspensions are used for high speed guided transport, one interesting question which has yet to be settled is whether or not active control will be required to circumvent the compromises mentioned above.

Cl.2 Limitations of Mechanical Suspensions

The potential limitations of mechanical (wheel) suspensions may arise from

i) centrifugal stresses
ii) contact stresses, wear and heating
iii) loss of friction and adhesion
iv) instabilities

For steel wheels centrifugal stresses are not a limiting factor, since they impose a maximum speed of about 700 m.p.h. It is known that contact stresses, fatigue and wear become increasingly severe as speeds are increased; however, in general, little quantitative information is available for speeds above 100 m.p.h. The wheel life on the vehicles on the New Tokkaido Line (NTL) which run at speeds up to 130 m.p.h., have been quoted as about 60,000 miles.
FIGURE C.I. VIBRATION TOLERANCE CRITERIA. AVERAGE PEAK ACCELERATION AT VARIOUS FREQUENCIES AT WHICH SUBJECTS PERCEIVE VIBRATION (CURVE I), FIND IT UNPLEASANT (CURVE II), OR REFUSE TO TOLERATE IT FURTHER (CURVE III). SUBJECTS WERE WITHOUT BODY RESTRAINT. SHADED AREAS ARE ABOUT ONE STANDARD DEVIATION ON EITHER SIDE OF MEAN. (SOURCE: DIAMANT-1969).

FIGURE C.II. PEAK VALUES OF PERIODIC ACCELERATION IMPOSED ON SUSPENSION SYSTEM RESULTING FROM SINUSOIDAL VARIATIONS OF GUIDEWAY ALIGNMENT, VERSUS VEHICLE SPEED FOR SEVERAL VALUES OF MISALIGNMENT WAVE LENGTH AND AMPLITUDE. (SOURCE: SURVEY OF TECHNOLOGY FOR HSGT-MIT JUNE 1965).

\[
V (\text{ft/sec}) = \text{VEHICLE SPEED} \\
Y_0 (\text{in}) = \text{MAXIMUM AMPLITUDE} \\
\lambda (\text{ft}) = \text{VARIATION WAVE LENGTH} \\
g = 32.2 \text{ ft/sec}^2
\]
(M.I.T., 1965). Figure C1.3, taken from M.I.T. (1965) gives some measured figures of
coefficient of adhesion for a conventional Diesel locomotive; at 100 m.p.h. it is
less than 3%. At speeds above about 120 m.p.h. aerodynamic drag becomes predomi-
nant and this increases approximately with the square of forward speed, so that
traction by means of steel wheels becomes impossible at speeds above about 250
m.p.h. This loss of traction is related to a dynamic instability known as "wheel
hop", which is a resonance condition occurring at fairly high frequencies.
Figure C1.4, taken from Diamant (1969) gives the results of some calculations
of the wheel - rail force for vehicles used on the NTL. These show that the
wheel is expected to "hop" at speeds somewhere between 200 and 250 m.p.h.

Another problem is the appearance of lateral oscillations associated
with clearances between the track and flanges and wheel conicity, and excited by
track roughness. The M.I.T. survey (1965) quotes a critical speed at which more
energy is fed into lateral oscillations of the vehicle than is dissipated, resul-
ting in flange contact and periodic excursions of the vehicle from one side of
the track to the other. Some values of critical speed are given in Figure C1.5,
taken from that report. These results show the importance of having a high
natural frequency of roll of the body and as few axles in the car as possible.

Figure C1.6, also taken from the M.I.T. Survey (1965) gives measurements
of the vertical and lateral accelerations experienced in the passenger cars on
the NTL. The vertical movement is seen to be quite good but the lateral move-
ment quality is relatively bad.

These observations relate to essentially standard railway technology.
The British Rail research group at Derby has been mounting an extensive programme
to improve conventional trains (see for example, Smith 1968; and Wickens 1969).
These have indicated that much can be done to vehicle design technology to obtain
superior ride quality at speeds up to 155 m.p.h. on existing tracks. This de-
velopment is potentially very important, because it may extend the usefulness of
existing rights-of-way, and hence put advanced conventional technology in an
extremely competitive position.

Some improvements might be obtained by using pneumatic tires. For well
designed tires, the centrifugal stress limitation is about 500 to 600 m.p.h. and
the adhesion is known to be much better than for steel wheels. The factor limit-
ing their use at high speeds seems to be the drastic reduction in life associated
with material failure caused by the heating associated with the hysteresis of
the rolling deformation. For example, passenger car tires running at 300°F last
only for a few hundred miles whereas at 250°F the life is several thousand miles.
Nevertheless, it is technologically feasible to build tires with 100,000 miles
life for speeds up to 300 m.p.h. on controlled surfaces. Apparently a very impor-
tant factor for ensuring long tire life is to ensure that all wheels carry
minimum lateral loads; this implies that wheels are required for lateral guidance.
Figure C1.7, taken from the M.I.T. Survey (1965) gives some data on load and
speed characteristics for conventional track tires.

C.2 Status of Air Cushion Suspension Technology

C2.1 Basic Concept

The distinguishing feature of a TACV is the use of a mass of air con-
tained by fluid dynamic means as a primary suspension element. Statically, this
element behaves as a spring but its dynamic behaviour is more complex, as the
FIGURE CI.4 WHEEL/RAIL FORCE FOR NTL VEHICLE AND TRACK. ROUGHNESS PEAK DYNAMIC FORCE OCCURS AT 34 CPS. (SOURCE: SURVEY OF TECHNOLOGY FOR HSGT-MIT JUNE 1965).

FIGURE CI.3 ADHESION OF STEEL WHEEL ON STEEL RAIL FOR A TYPICAL DIESEL LOCOMOTIVE. (SOURCE: SURVEY OF TECHNOLOGY FOR HSGT-MIT JUNE 1965).
FIGURE C1.6 VERTICAL AND LATERAL ACCELERATIONS OF PASSENGER CARS ON THE TOKAIDO LINE AT 112-124 MPH. DEFINITION OF COEFFICIENT OF RIDING COMFORT: 1 = EXCELLENT, 1 TO 1.5 = GOOD, 1.5 TO 2 = NOT GOOD, 2 TO 3 = BAD.

FIGURE C1.5 EFFECT OF THE LENGTH OF A RIGID WHEEL BASE ON CRITICAL SPEED FOR VARIOUS NUMBERS OF EQUALLY SPACED AXLES (f = 10). [SOURCE: SURVEY OF TECHNOLOGY FOR HSGT - MIT JUNE 1965].

\[ V_{cm} = \left( \frac{8 f}{n} \right) \sum_{i=1}^{n} \sqrt{x_i^2 + \left( \frac{s}{2} \right)^2} \]

WHERE:
- \( f \) - NATURAL FREQUENCY OF THE ROLL OF THE BODY
- \( n \) - NUMBER OF AXLES IN THE RIGID WHEEL BASE
- \( s \) - TRACK GAGE
- \( x \) - LONGITUDINAL DISTANCE FROM CENTER OF ROTATION TO AN AXLE
FIGURE C1.7 EXTRAPOLATED LOAD AND SPEED CHARACTERISTICS FOR SEVERAL TIRE GEOMETRIES (SERVICE LIFE OF 50,000 TO 100,000 MILES) ON CONTROLLED SURFACE WITH NO LATERAL FORCES.
fluid capacitances introduce lead and lag time constants into the dynamics. At least in principle, there is no contact between the vehicle structure and its guideway, and given proper design this may confer important advantages over both conventional and advanced wheeled railway technology. The more important ones are:

1) improvements in vehicle stability and ride comfort;
2) reduction in noise;
3) significant decreases in maintenance costs of both vehicles and guideway;
4) improved structural efficiency resulting from the ability to spread the vehicle load, and elimination of certain dynamic forces arising from vehicle guideway interaction.

Air cushion support can be obtained using at least four different principles, which are:

1) the air bearing;
2) plenum chamber;
3) air curtain or peripheral jet;
4) ram wing.

The air bearing principle (Fig. C2.1) uses very small clearances to generate supporting pressures by means of fluid frictional losses. In practice this requires clearances of the order of one-thousandth of an inch or less and it is not considered practical for transport vehicles. The plenum chamber (Fig. C2.2) uses the pressure drop associated with a curved lip or a vena-contraccta generated by the flow past a sharp edged wall to sustain a lift pressure in the plenum. The air curtain (Fig. C2.3) uses the basic principle that to turn a jet of fluid, and hence change its momentum, requires a pressure difference across the jet. The plenum concept requires either an orifice constriction or equivalent loss mechanism, or a pressure supply source with a decreasing pressure - volume flow characteristic to obtain stable spring action (that is, increasing force with decreasing gap $h_0$), whereas the peripheral jet inherently has a stable spring action for a constant supply pressure $p_s$, since decreasing $h$ increases the jet curvature. The ram wing (Fig. C2.4) uses the forward motion of the vehicle to generate lift. It is basically a wing in ground effect, and is not practical, since there is a minimum critical speed below which it is not self-sustaining. Of the two practical concepts, the Bertain Aerotrain is based on the plenum chamber, while the British Tracked Hovercraft Limited (THL) and Grumman TACV designs use the peripheral jet. The General Motors Hovair paid is a flexible skirted plenum chamber, whereas the URBA vehicles use an inverted plenum principle to obtain vehicle support through suction.

The air required for the suspension can be supplied either from a power source on the vehicle or distributed through the guideway. The latter approach has been used in solving materials handling problems but the costs incurred in distributing the air through the guideway are such that this concept is quite impractical except where the traffic density approaches that found in a factory production line. Such concepts may be feasible in passenger handling systems at an airport for example.

To illustrate the effects of various design decisions a hypothetical vehicle will be used in this report. Since an 80-seat Orleans-Paris Aerotrain vehicle has been built, this will be used as a basis for comparisons. The
FIGURE C2.1 ILLUSTRATING AIR BEARING PRINCIPLE. THE FUNDAMENTALLY DISTINGUISHING FEATURE OF THIS DEVICE IS THE USE OF FLUID FRICTION TO SUSTAIN PRESSURE DIFFERENCES. THE OTHER PRINCIPLES RELY ON FLUID INERTIA TO SUSTAIN THE DIFFERENCE.

FIGURE C2.2 PRINCIPLE OF THE PLENUM CHAMBER. THE ACCELERATION OF THE AIR FROM APPROXIMATELY REST IN THE PLENUM PAST GAP GENERATES PRESSURE DROP.

FIGURE C2.3 PRINCIPLE OF THE PERIPHERAL JET. VISCOS MIXING ENSURES THAT THE CUSHION IS SUPPLIED WITH AIR FROM THE JET CURTAIN.

FIGURE C2.4 PRINCIPLE OF THE RAM WING. THE FORWARD MOTION OF THE VEHICLE GENERATES LIFT. FOR A TYPICAL TACV LOADING OF 0.5 PSI, THIS WOULD REQUIRE A MINIMUM FORWARD SPEED OF ABOUT 120 MPH.
basic characteristics of this vehicle are (McLeavy, 1969):

<table>
<thead>
<tr>
<th>Dimensions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall</td>
<td>84 ft.</td>
</tr>
<tr>
<td>Beam</td>
<td>10.5 ft.</td>
</tr>
<tr>
<td>Height</td>
<td>10.8 ft.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weights</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty</td>
<td>24,800 lbs.</td>
</tr>
<tr>
<td>Passenger &amp; Luggage</td>
<td>16,000 lbs approx.</td>
</tr>
<tr>
<td>Fuel</td>
<td>3,280 lbs.</td>
</tr>
<tr>
<td>Total:</td>
<td>44,000 lbs = 19.6 tons</td>
</tr>
</tbody>
</table>

Two speeds, 100 m.p.h. and 300 m.p.h. will be used in the calculations. It should be emphasized that the numerical comparisons given below are meant only to allow insight into the various design choices which have to be made. They should not necessarily be interpreted as accurate engineering values as in many cases they have been based on very simple analyses.

C.2.2 Structural Efficiency

In general the air cushion principle allows improvement in structural efficiency over that attainable in a conventional vehicle such as an eight-wheeled car. The 80 passenger Bertin Aerotrain prototype vehicle has an empty weight of 24,800 lbs or 310 lb/passenger (McLeavy, 1969). However, it should be noted that this vehicle is intended for 150 m.p.h. top speed, and uses a turbine driven fan for propulsion; if LIM propulsion is used the equivalent power installation will likely be heavier. Although LIMs are themselves relatively light, perhaps weighing as little as 1 lb/HP, the power conditioning equipment required for efficient and flexible operation will bring the weight of a typical LIM installation up to 3.5 lb/HP. Also, the relatively high aerodynamic drag at 300 m.p.h. will require very high powers (see Sec. 6.5). Estimates of the weights of a LIM driven vehicle operating at various cruise speeds have been given in a recent report submitted to the U. S. Office of High Speed Ground Transportation (OHSGT) by TRW, (1970). These estimates are reproduced in Table C2.1, together with some additional comparisons of structural efficiency and productivity. They may also be compared with 700-800 lb/passenger for typical automobiles having comparable comfort, 900-1000 lbs/passenger for large airliners and 500 lb/passenger for small, all metal aircraft. The vehicles on the Japanese New Tokkaido Line (NTL), which may be regarded as state-of-the-art for advanced conventional trains, average an empty weight of 1450 lb/passenger (Berthelot, 1969). Note that TACV weight increases rapidly with increase in top speed, but so would that for a conventional vehicle. Hence the appropriate comparison to make for gauging the benefits conferred by being able to spread the structural load is between the 150 m.p.h. TACV typified by the Bertin Aerotrain and the NTL technology.

Whether or not this efficiency is reflected in reductions in the guideway costs compared to the track costs of conventional technologies is a matter of some controversy, especially for the 100 m.p.h. suburban application. The basic vehicle cost is closely related to its structural efficiency;
<table>
<thead>
<tr>
<th>WEIGHT (lb) WITH 4 SEATS PER ROW AND 36 in PITCH</th>
<th>PASSENGERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 CRUISE SPEED (mph)</td>
</tr>
<tr>
<td></td>
<td>150  250  350</td>
</tr>
<tr>
<td>FIXED LOAD</td>
<td>1,100  1,100  1,100</td>
</tr>
<tr>
<td>POWER MODULE</td>
<td>18,385  31,634  57,967</td>
</tr>
<tr>
<td>LIM</td>
<td>7,480  9,720  12,630</td>
</tr>
<tr>
<td>POWER CONDITIONING UNIT (PCU)</td>
<td>5025  15,510  37,910</td>
</tr>
<tr>
<td>ROTARY ELECTRIC MOTOR (REM)</td>
<td>1,070  1,460  2,230</td>
</tr>
<tr>
<td>COMPRESSORS</td>
<td>293   237   290</td>
</tr>
<tr>
<td>CUSHIONS</td>
<td>2,520  2,620  2,820</td>
</tr>
<tr>
<td>WHEELS SUSPENSION</td>
<td>2,087  2,087  2,087</td>
</tr>
<tr>
<td>STRUCTURE</td>
<td>14,823 14,903  15,063</td>
</tr>
<tr>
<td>BODY SHELL</td>
<td>14,010 14,090  14,250</td>
</tr>
<tr>
<td>INTERNAL</td>
<td>813    813    813</td>
</tr>
<tr>
<td>LIVE LOAD</td>
<td>16,250 16,250  16,250</td>
</tr>
<tr>
<td>PASSENGERS</td>
<td>8,500  8,500  8,500</td>
</tr>
<tr>
<td>BAGGAGE</td>
<td>1,500  1,500  1,500</td>
</tr>
<tr>
<td>FURNISHINGS</td>
<td>6,250  6,250  6,250</td>
</tr>
<tr>
<td>MISCELLANEOUS</td>
<td>2,472  2,493  2,526</td>
</tr>
<tr>
<td>GROSS WEIGHT</td>
<td>53,030 66,380  92,900</td>
</tr>
<tr>
<td>EMPTY WEIGHT</td>
<td>35,680 49,030  75,556</td>
</tr>
<tr>
<td>STRUCTURAL EFFICIENCY (EMPTY W. PAX.)</td>
<td>715    980    1,510</td>
</tr>
</tbody>
</table>

**TABLE C2.1** SUMMARY OF ESTIMATES OF TACV WEIGHTS BREAKDOWN.  
(SOURCE - TRW 1970)
and in general it will increase as the empty weight/passenger decreases. Undoubtedly special design techniques appropriate to the TACV application will have to be evolved. The aircraft type construction techniques currently used by Aerotrain which is clearly the most effective for increasing structural efficiency, may not necessarily be optimal. The TRW study (1970) was based on modern lightweight railroad car techniques. The use of aircraft techniques in the amphibious ACV in an attempt to obtain high structural efficiency is currently the source of a serious problem in their application. These vehicles are extremely expensive to operate and analyses have shown that the greatest component of the cost is hull or vehicle manufacturing costs. The industry is currently evolving its own design philosophy which will be different from the techniques used for high speed boats or aeroplanes. It should be noted that since guideway costs may be expected to dominate system costs, the actual vehicle cost may play a relatively minor role; and it may therefore pay to design light weight vehicles in order to reduce guideway costs.

C2.3 The Plenum Chamber or the Peripheral Jet?

A fundamental decision facing the designer is the choice between the plenum chamber and the peripheral jet cushion concepts. Generally speaking a well designed peripheral jet requires less power and is less stiff than the plenum designed to carry the same equilibrium load at the same clear air gap. Figures C2.5 and C2.6, taken from the TRW report (1970) give some comparisons of plenum and peripheral jet power requirements at 150 mph and 300 mph respectively as a function of jet thickness for various clear air gap heights. Their calculations include estimates of the power required to overcome momentum drag and internal losses and the benefit from ram recovery. The curves show two interesting features; firstly for a given clear air gap there exists an optimum jet thickness and secondly the advantage of the peripheral jet increases with increase in forward speed. The exact way in which the optimum occurs is not explained in that report, but it must be related to losses associated with capturing and processing the cushion air at speed, since in simple theory indicates that the basic power required to form the cushion decreases monotonically with increase in jet thickness. Likewise the greater mass flow required for the plenum cushion results in increasing disadvantage as the vehicle speed increases.

Consider the power required by the hypothetical vehicle to hover at a rigid or hard structure clearance which is adequate to negotiate ice, small stones and other debris, say one inch. The theoretical power dissipated by the fluid flow in the lift cushions, the estimated total installed suspension power, and the total mass flow are given in Table C2.2 for three cases:

<table>
<thead>
<tr>
<th>Case</th>
<th>Support Method</th>
<th>Base Area Used for Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Plenum chamber</td>
<td>80% of the base area used for support</td>
</tr>
<tr>
<td>B</td>
<td>Plenum chamber</td>
<td>40% of the base area used for support</td>
</tr>
<tr>
<td>C</td>
<td>Peripheral jet</td>
<td>80% of the base area used for support</td>
</tr>
</tbody>
</table>

The theoretical lift power and mass flow have been calculated using the results presented by Richardson and Captain (1968). Comparisons of cases A and C show the gains to be made by using a peripheral jet, both in reduction of lift power and improvement in ride quality through reduction of stiffness. Comparison of cases A and B show the penalty that has to be paid for not using the maximum possible base area for cushions. A practical upper limit is perhaps 70%.

In spite of these basic advantages, there are a number of practical requirements which favour the plenum chamber. Consider the total installed power required for support and to provide adequate transverse restoring forces.
Figure C2.5 Variation of the plenum to peripheral jet required power ratio with jet thickness. (Source: TRW 1970)

Figure C2.6 Variation of the plenum to peripheral jet required power ratio with jet thickness. (Source: TRW 1970)
These have been calculated under the following assumptions:

(i) the transverse suspension must be capable of providing up to 50% of vehicle weight as a restoring force;

(ii) the actual compressor dynamic supply pressure is greater than the equilibrium lift cushion pressure by a factor \( k \) to account for variations in cushion pressure associated with suspension action and duct losses. Experience suggests that for a plenum \( k = 3 \), while for a peripheral jet, \( k = 2-1/2 \) will give a useful estimate of installed power;

(iii) a compressor efficiency of 70% and a transmission efficiency of 90%;

(iv) an installed compressor-turbine system weighing 1.6 lb/HP.

For case "A" the installed power is 6100 h.p., or about 310 h.p./ton, which in turn would require a compressor installation weighing 490 lb/ton so that this is clearly impractical. The mass flow is also excessive if duct losses are to be kept tolerable. The exit velocity at the compressor should be no more than about 200 ft/sec, which in this case would require ducts having something like 41 ft\(^2\) section or 35% of the entire vehicle cross-section. The peripheral jet (case C) offers significant improvement, but at least 130 to 150 h.p./ton will be required. These figures may be compared with a typical value of about 30 h.p./ton for a flexible skirted amphibious ACV such as the SRN6 used at Expo '67.

The most practical way of reducing this power is to reduce the clearance, since the lift power scales linearly with \( h^* \). Hence, to achieve the level typical of amphibious ACVs using a plenum, clearances of the order of 0.1 inch are required. The Bertin Aerotrain is claimed to have equilibrium values of this order and smaller (McCabe et al, 1969, Part II). Clearances this small favour the plenum, which is inherently more robust than the peripheral jet. A variety of reasons can be cited. Firstly some intermittent vehicle-guideway contact is inevitable, so that a replaceable wear strip is necessary. In a plenum this should be cheaper and more reliable. Secondly, as will be shown in the next section, some form of flexible skirted or secondary suspension is mandatory if ride comfort is to be tolerable. As experience with the amphibious ACV has shown, it is very difficult to maintain a stable, reliable peripheral jet in a flexible structure. If a secondary suspension is used, the mass of the air cushion hardware should be small, and this again suggests the plenum. Thirdly, the cushion should be able to negotiate small stones and ice and other short wavelength irregularities of the order of 1/2 inch so that again a flexible skirt is desirable even if it is not intended to act as a secondary suspension element.

* Reynolds number effects are usually negligible.
TABLE C2.2  ESTIMATED LIFT POWER REQUIREMENTS
AT HOVER NOMINAL CLEARANCE,
h_c = 1 inch

<table>
<thead>
<tr>
<th>Case</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid Lift Cushion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power HP</td>
<td>804</td>
<td>1,608</td>
<td>450</td>
</tr>
<tr>
<td>Installed Compressor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power HP</td>
<td>6,100</td>
<td>12,200</td>
<td>2,560</td>
</tr>
<tr>
<td>Compressor Mass Flow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lb/sec</td>
<td>614</td>
<td>614</td>
<td>453</td>
</tr>
<tr>
<td>Suspension Vertical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness lb/inch</td>
<td>27,300</td>
<td>27,300</td>
<td>20,760</td>
</tr>
<tr>
<td>Vertical Natural Frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPS</td>
<td>2.5</td>
<td>2.5</td>
<td>2.15</td>
</tr>
<tr>
<td>Lift Power System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight lbs.</td>
<td>9,760</td>
<td>19,500</td>
<td>4,090</td>
</tr>
</tbody>
</table>

The figures in Table C2.2 are probably the basis of reason why both the British (THL) and U.S. (Grumman-Garrett Airesearch) TACV programmes employ peripheral jets, since their clearances are about 1/2 to 1 inch. At the time of the author's visit to THL, a flexible extension was apparently not contemplated, but it is significant that the Grumman research vehicle will use them. The tradeoffs involved in the choice between the plenum and the peripheral jet give a good example of the type of decision where operational experience is essential if the best choice is to be made. It is part of the more basic problem of obtaining that tradeoff between vehicle sophistication and complexity on the one hand, and guideway precision and rigidity on the other, which will lead to reasonably optimized economics. It is noteworthy that, in the amphibious application, the tendency has been to employ the plenum chamber; however there is no guarantee that this guideline can be extended to TACVs.

C2.4 The Need for a Secondary Suspension

An attractive feature of the basic rigid structure air cushion suspension is its extreme mechanical simplicity. However, it is now known that the ride comfort for such a suspension would be intolerable. Some form of secondary suspension has to be employed; and given this, it becomes possible to optimize the suspension design to provide ride comfort which may be superior to that obtained in conventional trains. Figure C2.7 gives the ride quality objectives of the U.S. HEGT programme. Comparison with human tolerance curves given in Figure C1.1 show that the goal is very good indeed.

The statement that some form of secondary suspension is required can be given a quantitative basis by referring to the analysis of heave (vertical acceleration) dynamics for motion over irregular guideways presented by Richardson,
Figure C2.8: Power spectral density measurements for typical guideways. (Source: H.H. Richardson 1967).

Figure C2.7: Ride quality objectives of the US HSGT Program.
Captain and Ribich (1967). For random irregularities, the appropriate mathematical tool is the power spectral density function, which visualizes the irregularities as a sum of sine waves of varying wavelengths $\lambda$ ft and wave number $\Omega = 2\pi/\lambda$ rad/ft. The spectral density $\Phi_y(\Omega)$ is a measure of the root mean square (rms) irregularity at some value $\Omega$ in a bandwidth $\Delta\Omega$. Formally, if $y$ is the height of the irregularity above some datum, then

$$\Phi_y(\Omega) = \lim_{\Delta\Omega \to 0} \left[ \frac{\Delta y^2(\Omega)}{\Delta \Omega} \right] = \frac{dy^2}{d\Omega}$$

The actual rms irregularity is given by the sum over all wavelengths or in the limit

$$\sigma_y = \sqrt{\langle y^2 \rangle} = \sqrt{\int_{0}^{\infty} \Phi_y(\Omega) \, d\Omega}$$

Figure C2.8 shows measurements made by several organizations of the power spectral density of various roadways. This data is limited to wavelengths less than 200 ft. while much longer wavelengths must be considered for TACVs. But they do show that a quantitative trend of the form

$$\Phi_y(\Omega) \approx A/\Omega^2 = A\lambda^2/4\pi^2$$

can be used for analysis. Here $A$ is a roughness parameter for the guideway.

For the best state-of-the-art concrete runways, $A = 1.5 \times 10^{-6}$ ft. Using the theory presented by Richardson, Captain and Ribich (1967), it can be shown that for a clearance of 0.1 inch and the guideway standard suggested above, rms accelerations of the vehicle of the order of 1.3 g at 100 m.p.h. are to be expected. The theory also shows that the effect of capacitances of the air cushion is to cause an acceleration response which is proportional to the square root of the forward speed, so that at 300 m.p.h., the rms accelerations should be about 2.2 g. It is clear that the simple rigid air cushion is impractical. The same analysis also gives an indication of the amount of cushion-guideway contact to be expected; the rms excursion of the plenum from its equilibrium position is estimated to be 0.153 ins. and 0.264 ins. at 100 and 300 m.p.h. respectively, and these values are quite unacceptable. To keep the excursions less than the nominal equilibrium clearance for about 99% of the time, the rms excursion should be no more than about 0.4 ins., or 0.04 ins. in this case. The theory can also be used to put the dilemma in a different way; it shows that to achieve acceptable ride quality in heave, clearances of the order of 100 inches are required. The problem is further complicated by the tendency of the cushion to have its natural frequency and therefore greatest response in the range where the human is most sensitive, namely 2 to 10 Hertz. Figure C2.9, taken from the TRW report (1970) shows calculated dynamic performances of peripheral jet and plenum cushions for an 120,000 lb vehicle subject to inputs characteristic of those experienced on the NTL. The lift power was assumed to be the same for both cases.

The analysis presented above includes important simplifications which should not be overlooked. Firstly, a more appropriate measure of comfort levels is given by the rms response in certain critical frequency ranges suggested by Fig. C1.1, rather than the rms level taken across the entire range, as was done here. Secondly there are grounds for belief that angular accelerations and the
rate of change of linear acceleration, are also significant factors (Clarke et al, 1971). However, in spite of these limitations, the analysis gives useful insights into the design problems.

In general the rigid cushion design problem involves a tradeoff between basically opposing requirements. A very low stiffness and low natural frequency are desirable in order to achieve good ride characteristics, on the other hand in order to minimize the wear associated with occasional but unavoidable cushion-guideway contact, a high natural frequency is required. It is not possible to achieve these goals and at the same time keep pumping power reasonable without the inclusion of additional suspension elements.

The above analysis was based on the assumption that the wavelengths of the irregularities are much greater than the cushion length. An analysis by Ribich et al (1967) examined the effect on heave dynamics of irregularities which have wavelengths much shorter than the cushion length. This showed that they were very much attenuated by the cushion, and thus supports the argument of TACV proponents that the air cushion acts to filter out small irregularities because of the averaging effect obtained from the cushion volume. There is no such comparable filtering effect in wheel-rail dynamics.

The solutions to the ride problem are currently being sought in the adoption of flexible skirts and secondary suspensions. In terms of the vehicle dynamics, there is no fundamental difference between these two approaches, but there are practical distinctions. The flexible skirt suspension can be mechanically much simpler than the secondary suspension, and if appropriately designed, may confer some insensitivity to small obstacles such as stones and ice. (See Fig. 2.10). There are also some grounds for belief that active control of the suspension system may be required to achieve the target ride comfort levels at the higher speeds.

The research group at MIT have been actively investigating the heave dynamics of flexible skirted suspensions and are currently investigating the improvements that can be obtained by combining skirts with secondary suspensions. An analysis of a skirted configuration with rigid lip (Fig. C2.10) undertaken at that laboratory and reported by Captain and Richardson (1969) showed that the cushion lift power required to achieve a given level of ride comfort could be cut by a factor of 10, while at the same time maintaining the guideway contact probability at a very small level. A further reduction of the power required by a factor of 2 could be obtained by adding an optimal amount of damping to the skirts. Since flexible skirts are inherently poorly damped, this has to be achieved by inclusion of a damper or including orifices in the skirt geometry to generate aerodynamic damping.

There is no general agreement on what type of suspension will be required to achieve performance levels for given operating speeds. For example, considerable theoretical work on the selection of optimal suspensions is being conducted by both MIT and Grumman. The former group believes that a combination of flexible skirts and secondary suspension will be required for the 300 m.p.h. application (See Appendix A, p.26 for these definitions), whereas the latter believe that active control is also necessary. Clearly if possible, active control should be avoided since it involves additional mechanical complexity and a power penalty which is about 12 HP/ton at 300 m.p.h. No equivalent work on the 100 m.p.h. application (see Appendix A, p.26 for these definitions) is known to the authors, but during informal discussions with those involved in suspension
Figure C2.10 illustrating concepts of different types of suspension systems.
design at MIT, it was suggested that active control would certainly not be required, and it may be possible to eliminate secondary suspensions. The Bertin suspension is essentially a damped flexible skirt without secondary suspension elements.

C2.5 Some Current Suspension Designs

The Orleans Aerotrain (Fig. C2.11b) has a total of six lift pads and six side force pads, three each on each side of the fin. Clearances are nominally 3 mm and the cushion pressure is about 80 lbs/sq. ft. Figure C2.11a is a cross-sectional diagram of the cushion. Air is fed from supply ducts into a plenum box connected to the cushion proper by feed holes. The sidewalls of the cushion are hinged so that they can rotate and thus act as the equivalent of a flexible skirt. The rotating sides also provide the input to an aerodynamic dashpot which is formed by using a loop of flexible material to join the bottom of the walls to the top of the plasma box, and thus enclose a volume communicating with the box by an orifice. This design is obviously the result of considerable development, although with some important exceptions (qv eg Giraud, 1968) little published information is available. The bottom of the walls are equipped with detachable plastic wear strips, which have to be changed after every 100 hours of operation.

The General Motors "Hovair" pad (Fig. C2.12) is a loop of flexible rubber having a geometry chosen so that the air pressure differential set up across the feed holes into the cushion proper and into the escape gap maintain a statically stable shape. Its principal virtues are the low pumping power required and its simplicity. However, this type of skirt, which is reminiscent of the simple bag skirt sometimes used on small amphibious ACVs, is rather susceptible to wear and damage and its particularly subject to self-excited oscillations of various kinds (see Section C2.6) which can have dangerous consequences. We do not believe it is suitable for application to high speed trains.

The Grumman TACRV has a very complex suspension system, but it must be realized that this is a research vehicle designed to investigate various alternatives. The main body is supported on the chassis by means of the secondary suspension, which includes springs, damper and force actuators. The body can move in 6 degrees of freedom with respect to the chassis, translational movements up to ± 6 inches and a roll of ± 13° are permitted. Hence the body can bank with respect to the guideway for passenger comfort in turns. The chassis is supported and guided by four lift and four side force cushions. These cushions, which have an operating pressure of 200 psf, use peripheral jets. They are connected rigidly to the chassis, but later developments call for introduction of suspension elements between the cushions and the chassis. The vehicle can thus be operated in a variety of configurations by locking off various elements, and in both the active and passive mode. The LIM has its own completely separate air cushion suspension (a common air supply is used), and is connected to the chassis through a drag link. This arrangement allows close tolerances to be maintained on the LIM motion. Specifications call for a LIM motion relative to the guideway of no more than ± 0.1" laterally and ± 0.2" vertically. The nozzles on the peripheral jet suspension pads include replaceable rubber extensions for wear purposes but these do not intentionally form part of the system dynamics.

Tracked Hovercraft Limited (THL) are building two remote controlled test vehicles to be used on their 18 mile long test track near Cambridge. One, RTV 31 is designed to examine air cushion suspensions (Charity, 1971). The basic
FIGURE C2.11a DETAIL OF THE CUSHION USED ON THE 80 PAssenger ORLÉANS AÉROTRAIN.

FIGURE C2.11b THE AÉROTRAIN 250-80 (ORLÉANS TYPE). DIMENSIONS: LENGTH-65 FT, WIDTH-10 FT 6 IN, HEIGHT-14 FT. TOTAL WEIGHT: 44,000 LB.
FIGURE C2.12 GM "HOVAIR" PAD. CUSHION AIR CAN BE FED IN EITHER THROUGH FEED HOLES "A" OR "B".

FIGURE C2.13 MODE OF OSCILLATION COMMONLY OBSERVED ON A BAG TYPE SKIRT USED ON AMPHIBIOUS ACV'S. THIS SKIRT IS FUNDAMENTALLY THE SAME AS "HOVAIR" PAD.

FIGURE C2.14 DETAILS OF THE URBA SUSPENSION SYSTEM.
concept is apparently closely similar to that outlined in Figure C.10e. The nominal hoverheight is about 0.5 to 1.0 inch and one of the functions of the vehicle will be to examine a variety of secondary suspensions. Investigation of active control is not contemplated at this time.

Figure C2.14 illustrates the principle of the URBA suspension. Each vehicle has a number of air bogies along its length which ride inside the inverted U of the guideway. All machinery is contained in the air bogies, and the body of the vehicle is connected to them by a secondary suspension in order to improve ride quality. The suspension air is drawn into the passages formed by the guideway and the bogies first through one constriction to give a pressure drop for side force spring action, and then through a secondary constriction near the corners of the inverted U to give vertical spring action. Each bogie has four compartments and four suction fans to give roll and pitch stiffness. The LIM is mounted in the bogie, and unlike the Garrett vehicle does not have its own suspension. The primary advantage of this system is that gravitational forces have a stabilizing effect in roll, and consequently the inventors claim that the guideway can be some 40% narrower than is required for positive pressure systems (Barthalon et al., 1969). A secondary advantage, which may be important for Canadian applications, is that it should be relatively insensitive to weather problems. However, there are some possible disadvantages. Since the LIM, lift fans and air cushions are all mounted in the one structure, the "air bogies", the effective "unsprung" or suspension mass is high, which may lead to difficulties in achieving good ride comfort at high speed. Furthermore, both the Grumman TACRV and the Bertin 100 m.p.h. Suburban vehicle (Fig. C2.15) have arrangements to allow the LIM to move relative to the vehicle (qv eg Bliss, 1970). The URBA vehicle apparently does not, so that the designers are faced with a difficult compromise between the opposing needs to keep the LIM motion small relative to its rail in order to achieve high efficiency, and to transmit small accelerations to the bogie. A further possible complication arises from the use of the same airflow in both side force and lift chambers, as shown in Figure C2.14. Since the side force chambers are effectively the reservoirs from which the lift force chambers are supplied, any pressure disturbances in the side force chambers must cause corresponding disturbances in the lift chambers. It is not clear whether this produces undesirable dynamic effects, as no published information is available.

C2.6 Potential Problem Areas

Although the flexible skirt appears to provide one simple solution to the ride comfort problem, amphibious ACV experience has shown that it tends to be plagued with various oscillatory phenomena which can lead to excessive wear and even dangerous vehicle instabilities. Figure C2.13 illustrates one form of oscillation frequently observed on a "bag" skirt. The nature of these oscillations is not very well understood, but interestingly enough they tend to be especially prone to occur on smooth surfaces. There is evidence that skirt instabilities may depend on such factors as the elastic properties of the skirt material, compressibility of the air, internal aerodynamics, and even lift fan inertia. It is not usually possible to predict the occurrence of the oscillations. They can contribute to an uncomfortable ride and even in some extreme cases excite vehicle oscillations, and usually the more complex the skirt, the greater potential it has for oscillation. Fortunately, in the case of the TACV, it is possible to adopt relatively simple skirt geometries, because unlike amphibious ACV skirts, it does not have to accommodate large amplitude small wavelength disturbances. Hence it would seem that, in the absence of a complete understanding of the
FIGURE C2.15 THE AÉROTAIN 180-44 (SUBURBAN TYPE). DIMENSIONS: LENGTH-47 FT, WIDTH-9 FT, HEIGHT-10 FT. TOTAL WEIGHT: 26,500 LB.
dynamics of flexible skirts, it is better to obtain skirt action through the use of schemes similar to that adopted on the Bertin Aerotrain.

Very little work has been done on vehicle dynamics in modes other than heave. It is inevitable that other oscillations and instabilities of various kinds will occur. A yawing and swaying motion was encountered at certain speeds in the early Aerotrain trials, but it was apparently cured by some simple changes in the internal aerodynamics. Because the dynamical nature of TACV behaviour is complex and will depend heavily on the particular geometry, it seems unlikely that general design rules for the avoidance of such instabilities can be formulated. Consequently, each new design will have to be subject to a set of thorough evaluation trials. An important problem that is now being recognized is the interaction of guideway and vehicle dynamics. The programmes at both MIT and Grumman include studies of this phenomenon. The TACV guideway is apparently sufficiently flexible to significantly affect ride qualities.

A characteristic feature of extremely high speeds is known as the "jet flap" or "ram wing" effect. As the speed increases and the dynamic pressure of the free stream approaches the cushion pressure, the simple basic cushion flow pattern breaks down, and a much more complex system is set up. This, in turn, may result in significant changes in the suspension characteristics such as a shift of the centre of cushion pressure. For our hypothetical vehicle, which has a cushion pressure of 62 psf, the dynamic pressure equals the cushion pressure at 155 m.p.h., so that the phenomenon is relevant to high speed applications. Little experimental information is available on the effects of high speeds on cushion flow. Hence it is not easy to say at this stage to what extent it will prove to be a problem, but it has been reported that the Aerotrain has run safely at speeds corresponding to dynamic pressures in excess of cushion pressure (McCabe et al, 1969, Part II).

C.3 FACTORS AFFECTING GUIDEWAY DESIGN

C3.1 Choice of Section

The choice of guideway section is probably the most crucial design decision to be made, since it can have far-reaching effects on vehicle performance and system costs. The implications are probably comparable in scope and impact to the railway gauge decisions made in the nineteenth century, and it is very important that an appropriately long term view is taken. While it is true that TACV systems will run in isolation, undoubtedly they will be extended, and through running will become desirable. One does not want to be faced with the equivalent of the situation that occurred in Australia where each state chose its own railway gauge. There is much controversy surrounding the subject, and unfortunately, with one or two notable exceptions such as the TRW Report (1970), there is virtually nothing available in the way of analyses presented in sufficient detail in order to permit critical evaluations.

Some of the more important criteria to be considered in making a choice are:

i) the economic balance to be struck between suspension sophistication on the one hand, and guideway precision and rigidity on the other to achieve target comfort levels;
ii) effects of guideway shape on sidewind and other aerodynamic loads on the vehicle;

iii) switching and propulsion problems at low and high speed;

iv) effects of snow, ice, and debris, and other safety considerations.

Some of the sections which have been considered are given in Figure C3.1, and some qualitative remarks on their relative merits are made below.

The inverted V was considered in some early design studies because it offered mechanical simplicity of the vehicle, relative immunity to debris collection and a strong bending section. However, it was soon rejected because calculations suggested that it would be difficult to achieve adequate roll stability, and there would be undesirable coupling between lateral and vertical motions of the vehicle. Furthermore, switching problems would be especially severe, as the vehicle cannot be handled on a flat surface. Even at low speeds, entire sections of the guideway would have to be moved. The Bertin-Aerotrain consortium adopted the inverted T in an effort to achieve simplicity and thereby low structural costs. Low speed switching can be achieved by employing a removable vertical fin together with some auxiliary low speed guidance, such as pneumatic tires which are lowered for the purpose. Disadvantages are that the vehicle inherently has a relatively high centre of gravity and that the basic T does not provide adequate track stiffness; the Orleans test track has incorporated two additional ribs under the base of the T. (See Fig. C.8b). The U.S. programme is based on a trough or U-section, which shields the vehicle from sidewinds and allows the vehicle to have a relatively low centre of gravity. It is often criticized as the most susceptible to debris collection, but the latest designs are vented in the hope that they will be self cleaning. It also probably permits the highest standard of guideway precision since the side guidance panels are adjustable. Like the inverted T, it should be relatively adaptable to low speed switching. Earlier OHSGT plans had called for two parallel box beams arranged such that the supporting surfaces formed inverted L's facing each other, but this was abandoned because a vehicle designed for this section could not be moved over a flat surface on its own cushion. The British THL programme is based on a box beam section with the longer side vertical. This gives very good rigidity, but since the vehicle runs on top of the section it has a relatively high centre of gravity and an exceptionally large side area exposed to cross winds. Also, it cannot be handled for switching on flat surfaces unless the side cushions can be swung out of the way. It was noted in Section C2 that the URBA guideway can be made narrower than the sections in Figure C3.1 because gravitational forces act to stabilize the vehicle in roll. However, it is not obvious that the developer's claim that the section is therefore inherently cheaper, than say that used in the suburban version of the Aerotrain, is necessarily valid. It has a relatively complicated shape, and application of concentrated loads to the lower lips cannot be avoided when a vehicle is off cushion. Furthermore, the switching problem will be relatively complex.

Even this simple discussion highlights the difficulty of making a choice at this stage of development. For example, almost nothing is known about the effects of debris and ice and the switching problem has not really been investigated in any detail. Figure C-3.2, taken from the TRW report (1970) gives an idea of the complicated and expensive engineering that will be required if high speed switching is to be employed.
FIGURE C3.1 POTENTIAL GUIDEWAY SECTIONS.

FIGURE C3.2 HIGH SPEED SWITCHING CONCEPT.
(SOURCE: TRW 1970)
C3.2 Aerodynamic Side and Lift Forces

Because the TACV may travel at relatively high speeds, aerodynamic forces can be major, even dominant, inputs to the vehicle dynamics. This remark applies to lift, drag, and side forces. Drag forces are discussed in Section 5. The forces that are generated depend critically on vehicle speed and shape of the guideway. Table C3.1, taken from McCabe et al (1969) illustrates the effect of guideway configuration, and demonstrates the greatly reduced aerodynamic effects conferred by the U section guideway.

Table C3.1 Comparison of Crosswind Effects for Two TACV Configurations at 300 m.p.h. Forward Speed with 60 m.p.h. Cross Winds. Force Expressed as a Fraction of Vehicle Weight

<table>
<thead>
<tr>
<th>Force Effect</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inverted T</td>
</tr>
<tr>
<td>Lift</td>
<td>0.74</td>
</tr>
<tr>
<td>Side Force</td>
<td>0.31</td>
</tr>
</tbody>
</table>

The same paper also demonstrates the effect of body shape on forces and moments for a range of yaw angles. Figure C3.3 taken from that paper, gives results of wind tunnel tests for three basic body sections, a circle, half circle and a square. The coefficients are defined in the usual way, that is, forces are non-dimensionalized with respect to the free stream dynamic pressure \( q = \frac{1}{2} \rho V^2 \) multiplied by the frontal area \( A \), and moments are nondimensionalized with respect to this reference force and a reference length \( d_e \), which is taken to be the diameter of a circular section having the same cross-sectional area. The angle of yaw \( \beta \) is defined by \( \tan \beta = U/V \), where \( U \) is the cross wind velocity. Clearly body shape is an important parameter, typically the square section has lower pitching moments than a half circle but it is subject to much higher side forces.

Based on results presented by McCabe et al in the same paper, in a 60 m.p.h. crosswind our hypothetical vehicle would experience aerodynamic side forces which are about 9,000 lbs at 100 m.p.h. and 27,000 lbs at 300 m.p.h. if it operated on an inverted T guideway. These are 20% and 61% of vehicle weight respectively. If say 0.15 g centrifugal accelerations are permitted in turns, the total maximum loads that have to be carried by the side force cushions are 35% and 76% of vehicle weight respectively. Clearly these have to be accounted for in the basic design of the vehicle suspension. Furthermore, gusts can generate quite significant step function inputs into the vehicle dynamics. In building aerodynamics it is usual to allow for 30% gust speeds; this corresponds to up to 70% changes in aerodynamic forces.

The sidewind effect also places constraints on the width of the guideway, since the lift cushions have to counteract any rolling moment required. Figure C3.4, taken from Diamant (1969) gives the cushion pressures for a range of guideway widths required to counteract rolling moments for a large rolling moment vehicle such as the Aerotrain and for a small moment vehicle such as the Grumman TACRV. Based on these considerations, the U-shaped guideway would seem to be the most desirable for high speed applications; however it may incur...
FIGURE C3.3  TESTS OF AERODYNAMIC FORCES AND MOMENTS DUE TO WINDS ON TYPICAL TACV SHAPES.

FIGURE C3.4  EFFECT OF CUSHION PRESSURE AND GUIDEWAY TREAD "T" ON MAXIMUM ALLOWABLE FORWARD SPEED
some aerodynamic drag penalties associated with the interference with the flow about the vehicle. This is discussed in Sec. 5.

These few comments indicate just some of the factors involved in the choice of guideway design. Aerodynamic considerations are probably overriding for the 300 m.p.h. application, whereas the guideway choice for the 100 m.p.h. application can be based much more heavily on other considerations such as cost of construction. It seems that in both cases, wind tunnel tests should be conducted on new configurations of guideway and vehicle as a routine development procedure, because the magnitudes of the forces and moments generated are very strongly dependent on the particular geometry adopted.

The complicated nature of the aerodynamics is effectively illustrated by some estimates of the effect of wind direction on side force and yawing moment obtained from experimental data by Palm-Leis (1971) and presented in Figure C3.5. These show that the maximum values of these quantities do not occur when the wind is normal to the direction of vehicle motion.

C3.3 Some Comments on Guideway and System Costs

Correct assessment of guideway costs is of fundamental importance owing to its strong influence on system economics. A thorough review of the current situation is outside the scope of this report, however in any study of the vehicle dynamics some knowledge of the guideway cost problem is essential if proper design of both vehicle and guideway is to be achieved. Here we confine ourselves to a brief statement of some of the factors affecting cost and some observations on the reliability of available data.

In general, it appears that the typical TACV guideway will be more expensive than conventional tracks. Reported basic costs of conventional rail tracks (qv eg Acres, 1969, Appendix III) are a minimum of $100,000/track-mile in reasonably flat country to perhaps as high as $350,000/track-mile in mountainous areas. Estimates of the cost of an elevated guideway, not including piers or footing or any electrification, quoted by Diamant (1969) range from $4 \times 10^5$ to as much as $1.4 \times 10^6$ for each route (double track) mile. Figure C3.6 gives some idea of the effect of choice of span, section shape, and method of construction on these costs. Figure C3.7 shows the effect of bending frequency on guideway cost. According to these figures, for a given span, the inverted T seems to be the cheapest, although for a given unit cost, the box and the trough section seem to have a higher bending frequency and rigidity. In general it also seems cheaper to use an integrated reinforced concrete structure rather than steel beams and concrete. Vehicle cruise speed does not seem to strongly affect guideway cost strongly if the guideway is elevated; however the effect is more noticeable if the guideway is at grade. Table C3.2 shows estimates given by Bertin for U.S. conditions and quoted in the TRW report (1970, p.A-11).
FIGURE C3.5 CALCULATED SIDE FORCE AND YAWING MOMENT ASSOCIATED WITH CROSSWIND.

FIGURE C3.7  EFFECT OF BENDING FREQUENCY ON GUIDEWAY COST. COST OF THE PILE AND FOOTING IS NOT INCLUDED. (SOURCE: DIAMANT 1969)

FIGURE C3.8  GUIDEWAY CONSTRUCTION COST COMPARISON. (SOURCE: GENERAL ELECTRIC 1969)
Table C3.2 Comparison of Intercity and Suburban Guideway Costs
Double Track Guideway, "Average" Terrain

<table>
<thead>
<tr>
<th>Guideway Construction Method</th>
<th>80 pax intercity aero propulsion 160 mph cruise</th>
<th>50 seat suburban LIM - propulsion 100 mph cruise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevated 15 foot prestressed concrete pile footing</td>
<td>$640,000</td>
<td>$575,000</td>
</tr>
<tr>
<td>At grade, bitumen metallic guide rail</td>
<td>$550,000</td>
<td>$350,000</td>
</tr>
<tr>
<td>Extra cost of LIM rail</td>
<td>$200,000</td>
<td>$140,000</td>
</tr>
<tr>
<td>Vehicle Cost</td>
<td>$600,000</td>
<td>$160,000</td>
</tr>
</tbody>
</table>

In contrast to these figures, THL, on a contract from the U.S. OHSGT, completed an analysis of the effect of choice of section on guideway and vehicle costs for a 250 mph cruise vehicle, and their results are given in Table C3.3. The contrast between the quoted figures for the inverted T is rather striking. A third estimate for the inverted T, obtained by an independent group of consultants for the OHSGT is even higher: $1.86 \times 10^6$ (Parkinson, 1970, p. 237). Yet another contrast is provided by the TRW report, which quotes a figure of $480,000/route mile for a 250 mph trough section guideway. This assumes 75% of the guideway is at grade and includes fencing costs. (TRW, 1970, p.4-29). A very useful attempt was made by de Leuw, Cather (Parkinson, 1970) to rationalize the differences for the inverted T. It makes informative reading and shows the dangers inherent in simple comparisons and the need for explicit statement of the assumptions used in estimating procedures. The de Leuw, Cather estimate for Canadian conditions was $751,000 for an elevated guideway on piles.
Table C3.3 Comparison of Guideway and Vehicle Costs as Projected by THL. Cruise Speed = 250 m.p.h.  
Source Parkinson (1970)

<table>
<thead>
<tr>
<th>Guideway Type</th>
<th>Box</th>
<th>Inverted T</th>
<th>Trough</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guideway cost</td>
<td>$10^3$/route mile</td>
<td>1.100</td>
<td>1.563</td>
</tr>
<tr>
<td>100 seat vehicle cost 45 mph side-wind</td>
<td>.640</td>
<td>.494</td>
<td>.457</td>
</tr>
<tr>
<td>100 seat vehicle cost 60 mph side-wind</td>
<td>.690</td>
<td>.516</td>
<td>.457</td>
</tr>
</tbody>
</table>

In the final analysis it is the appropriately calculated system cost which is the criterion to be used for the selection of the guideway. Here, many additional factors enter; for example the extra cost of elevation of the guideway may be balanced by reduction in right of way acquisition costs. Also, elevation radically changes the cost of conventional rail construction, as is shown by Figure C3.8. Here, as for basic guideway costs, there seems to be discrepancies in available data. For example, the TRW report presents estimates of system costs for both the trough and the inverted T guideway. Their results, which are reproduced in Figure C3.9, show two interesting features, the existence of a definite optimum vehicle speed, and the lower costs of the trough section. These estimates may be contrasted with some given in the study by the Canadian Transport Commission (CTC) (Parkinson, 1970), which was based on data provided by THL and other groups. Their curves are reproduced in Figure C3.10, and show that the trough is the most expensive and the box the cheapest. As is noted in the CTC study, simple comparisons of this type are suspect, since different assumptions may be used by the sources generating the data employed in the analyses. Clearly, much more in the way of independent studies similar to that given by de Leuw, Cather is required.


VEHICLE CRUISING SPEED: 250 mph
DESIGN SIDE WIND: 45 mph
In general, it appears that if properly designed, the TACV could be less noisy than the equivalent conventional train. No published information on trials of TACVs is available at the present time. However, during a visit to the site of the Societe Aerotrain Orleans test site, one of us was told that the noise generated by the TACV and an electrically powered high speed train operated by the French Government Railways were compared at a distance of 200 ft from the tracks. The results showed that the TACV produced a perceived noise level some 8 pndB lower, or less than half the broad band noise intensity. If these figures are correct, then the LIM driven TACV is potentially capable of being very quiet, since the Bertin vehicle is powered by a shrouded propeller.

In spite of the lack of hard data for TACVs, it is possible to make some estimates of noise levels that might be experienced by the community. In this respect, some relevant formulae have been presented by Bender et al (1969), and these will be used here. For a LIM driven TACV, the two major sources of noise will be the suspension compressor and the jet noise associated with the air escaping from the cushions. The LIM itself will presumably generate some noise through magnetically induced vibrations, but this can safely be assumed to be unimportant. For the hypothetical vehicle, assume that the mean clearance is \( h = 0.1 \) inch, which implies that the compressor power is 610 HP and mass flow is 62 lb m/sec at 80% support area. The units in these calculations are standard; they are described in detail by Harris (1956). Power flux levels (PLW) are expressed in dB as \( 10 \log_{10}(\pi/10^{-12}) \) where \( \pi \) is the sound power in watts and the reference power level is \( 10^{-12} \) watts. The sound pressure levels (SPL) are expressed in dB as \( 10 \log_{10}(p^2/4 \times 10^{-6}) \), where \( (p^2)^{1/2} \) is the rms pressure fluctuation expressed in microbars, and the reference is 0.002 microbars or the approximate limit of audibility at 1 KHz. Although SPLs are used here as a measure of noise levels, the effect on humans must be expressed in terms of perceived noise decibels (pndB). The pndB is related to the SPL through corrections which are strongly dependent on the spectral distribution of the noise. For aircraft noise \( pndB = SPL + 10 \); presumably since aircraft and TACVs employ similar types of noise sources this estimate should apply to TACVs.

The broad band PLW radiated by the compressor inlet for the 80% support case is about 134 dB, with possibly another 6 dB to be added due to compressor whine. For the 40% support case, the PLW increases to 140 and 146 dB respectively or by a factor of about 2. Assuming that the observer is sufficiently far from the source to permit it to be treated as a point radiating in the upper half plane, the corresponding SPL at 100 ft would be about 96 dB. The suspension jet noise power (PLW) would be about 92 dB and the SPL at 100 ft. 62 dB. The approximate SPL at 100 ft from an electric train travelling at 100 mph would be about 95 dB, and this is almost entirely due to track noise. An SPL of 120 dB corresponds roughly to the threshold of physical discomfort, while conversational speech is typically 70-75 dB.

Some important conclusions can be drawn. Firstly, the noise associated with the cushion air escape is negligible compared to the other sources on a TACV. Consequently, contrary to the claims that are often made (Barthalon et al, 1969) the URBA type of vehicle possesses no particular advantage over the more "conventional" TACV in noise reduction. It is true that because the jet noise from the cushions is generated inside the suspension system, the effective cushion noise will be much less. But this is not the source of the problem; if anything,
lift fan noise on URBA vehicle might be worse because fans are generally noisier on the exit side. Secondly, in the interest of noise reduction it is desirable to have low cushion pressures and low clearances. Thirdly, at least in the 100 m.p.h. application, unless properly designed, a LIM driven TACV can easily be as noisy as a conventional electric train. A crucial difference however is that it is feasible to apply noise abatement techniques to the TACV in order to obtain improvements, whereas in contrast, it seems that little can be done to reduce the track noise of conventional trains. Typically, if the measurements made on the Paris Metro are any guide, trains running on pneumatic tires may be as noisy as those running on welded rails (qv Bender et al, 1969, p.154). For the hypothetical vehicle, if it is assumed that there are two circular intake ducts, each of cross section 4 ft$^2$, then the empirical formulae presented by Harris (1957, p.27-10) suggest that lining them with 5/8" Fibreglass will achieve an attenuation of about 1.3 dB/ft run. A 20 ft long entrance duct is feasible and this would allow reduction of the SPL at 100 ft to some 68 dB. Another approach is to use an appropriately designed constriction in the intake duct to reflect back compressor noise.

In conclusion, a brief comment on the noise level claims given by the Societe Aerotrain engineers for their vehicle can be made. The aerodynamic propulsion noise can be readily estimated by the formulae given by Bender et al (1969), since the shrouded fan is similar to a single stage compressor. The quoted cruise power of the Aerotrain vehicle is 700 HP (McLearly, 1969). Using this figure and some estimates of air volume flow, any errors in which should give higher noise levels, the estimated fan noise SPL was found to be about 80 dB, or some 15 dB on the estimated track noise of a conventional train. Jet noise from the power turbines has not been included in this estimate; it can easily be very high, but during an inspection of the vehicle it was noted that the exhausts were very thoroughly sound-proofed. Consequently, the claim made by the Aerotrain engineers was some 8 pdB less noisy than an electric trains seems reasonable. For urban applications, the noise level corresponding to full thrust at zero forward speed would be more relevant; an estimate of the peak SPL at 100 ft is at least 100 dB, giving a perceived noise of about 110 dB. This suggests that aerodynamic propulsion would be ruled out for applications type (ii).

C.5 THRUST, POWER AND BRAKING REQUIREMENTS

C.5.1 Drag and Thrust

The drag forces on a TACV travelling on level ground are composed of

1) aerodynamic body drag
2) momentum intake, or captation drag
3) structure contact drag

The aerodynamic drag depends in a complex way on both the vehicle and the guide-way shape as well as on vehicle and wind velocity, but for engineering computation purposes, it is useful to consider it as the sum of three components:

1.1) skin friction drag associated with fluid shear at the vehicle surface, and contributing about 5% to 15%.

1.2) form drag associated primarily with the suction created by the wake of the vehicle, and contributing 75 to 90%.
1.3) Air gap drag, which is an effective increase in the skin friction drag generated on the parts of the vehicle in close proximity to the guideway. This contributes about 3% to 10% to the aerodynamic drag.

The total aerodynamic drag scales approximately with the square of the vehicle speed. Formulae for computation of the various components of aerodynamic drag have been given by Giraud (1968). The momentum intake drag is the product of cushion air mass flow and speed, and is present because the cushion air has to be accelerated to vehicle speed. Little of this is regained because the air is directed primarily vertically downwards out of the cushion. The structure contact drag is present because some intermittent vehicle-guideway contact is inevitable. According to Giraud (1968) it is only a small component, adding a mean drag of perhaps 20 to 60 lbs to a vehicle of the size considered in this report.

Estimated values of drag and thrust requirements for our hypothetical vehicle operating on an inverted T guideway are given in Table C5.1. The aerodynamic drag estimates are based on the data presented by McCabe et al (1969). At 300 m.p.h., the total vehicle drag is nearly 19% of weight, whereas at 100 m.p.h. it is less than 3%. The penalty that has to be paid for insisting on operating at high speeds at sea level is graphically illustrated by computing the drag that would be generated at an altitude at which a 300 m.p.h. civil aircraft might fly, say 25,000 ft. Since this scales as atmospheric density, it would be approximately 4130 lbs, or less than half. The minimum thrust required for an acceleration of 0.15 g or a 5% grade climbing ability at reasonable speed has also been given in Table C5.1. It demonstrates that this factor will size thrust requirements for the 100 m.p.h. application, whereas high speed drag will size thrust requirements for the 300 m.p.h. application.

**Table C5.1**

<table>
<thead>
<tr>
<th>Drag Requirements at Sea Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
</tr>
<tr>
<td>Momentum Intake Drag</td>
</tr>
<tr>
<td>Aerodynamic Drag</td>
</tr>
<tr>
<td>Contact Drag</td>
</tr>
<tr>
<td>Total Drag</td>
</tr>
<tr>
<td>Minimum Acceleration Thrust</td>
</tr>
</tbody>
</table>

Figure C5.1 illustrates a decomposition of the power requirements for a ducted propeller driven vehicle of the Aerotrain configuration given by TRW (1970). Note that for a given payload, the power to achieve a given initial acceleration increases with increase in cruise speed, because vehicle weight is also increased.

FIGURE C5.2 PROPULSIVE EFFICIENCY OF TYPICAL AERODYNAMIC SYSTEMS AS A FUNCTION OF FORWARD SPEED. THE PROPULSIVE EFFICIENCY AT ZERO FORWARD SPEED IS IDENTICALLY ZERO.
For the high speed application, since aerodynamic drag sizes the vehicle thrust, it is obvious that careful attention has to be paid to this factor in selection of both vehicle and guideway shape. Streamlining at the rear will be especially important. Giraud (1969) claims that the guideway section can have a significant effect; and that the inverted T section gives a reduction to between 60% and 80% of the drag to be experienced on the original U.S. concept, which was an inverted double L. It would seem that, as for the side force problem, aerodynamic wind tunnel tests are required for new configurations, as these effects are not easily calculated.

C5.2 Propulsion Systems

Some of the alternatives available for TACV propulsion have been considered are:

- (i) turbo prop or turbo jet
- (ii) turbine driven alternator with linear induction motor (LIM)
- (iii) LIM with wayside power pickup
- (iv) electrically driven propeller with wayside power pickup
- (v) linear gas turbines with buckets in the guideway.

In general, attention has focussed in the literature on alternatives (i) and (iii). A detailed discussion of the merits of these is beyond the scope of this report; here we limit ourselves to some general comments and a review of the problems associated with aerodynamic propulsion. For more information, the reader should consult such reviews as the TRW report (1970).

A major disadvantage of LIM propulsion with wayside power pick up is that it can add considerably to guideway costs. The cost of electrification may increase effective guideway costs by as much as a factor of three (Bliss, 1970), but this factor would of course depend strongly on local conditions. Estimates of the cost of the reaction rail vary, but figures up to $200,000/track mile have been quoted (Parkinson, 1970, p 272). Furthermore LIM technology is very much in the process of evolution, and optimal designs have yet to emerge. Another complication for the 300 m.p.h. application is that there are problems associated with collecting the huge amounts of current required for the coil-on-vehicle LIM. In fact, the potential difficulties from this source are so severe that it has been described as "the key to electric propulsion of HSGT vehicles" (Uhler, 1969). The costs of a "coil-in-tracks" system are so astronomical that it can probably be ruled out for the 300 m.p.h. intercity application, although this would solve the collection problem.

The disadvantages of aerodynamic propulsion are:

- (i) noise and pollution
- (ii) mechanical complication
- (iii) undesirable effects on body shape
- (iv) unavoidable low efficiency at low speeds
- (v) unsuitability for multiple unit operation
The noise problem has been discussed previously. Aerodynamic propulsion is often criticized as an inherent polluter since the prime mover is usually a gas turbine (qv eg Bliss, 1970). However, to be fair, it must be noted, that if the electricity for a LIM driven vehicle is generated by a thermal station, then the pollution is not eliminated; the source is just relocated.

A primary advantage of the LIM is the inherent mechanical simplicity of the basic motor. It involves no moving parts at all, whereas aerodynamic propulsion involves gas turbines, mechanical transmissions, and reversible pitch propellers. However, this advantage becomes less obvious when it is remembered that certain auxiliary equipment is required to allow use of the LIM. Thus a separate suspension for the LIM may be necessary since its dynamical requirements are a small air gap as opposed to those of the vehicle, and the power conditioning equipment required for efficient flexible LIM operation may involve the use of rotating components.

Aerodynamic propulsion does have undesirable effects on the basic body shape. It will increase the size of any tunnels required, and any fan shroud will increase side forces and rolling moments caused by crosswinds. Apparently this can be a serious problem at high speeds; TRW (1970) has reported studies in which it is estimated that the addition of a duct to a propeller already mounted on top of the vehicle may increase rolling moments by as much as a factor of four.

Disadvantages (iv) and (v) are related to the basic nature of aerodynamic propulsion and are not easy to improve or circumvent. Aerodynamic propulsion acts by accelerating the air passing over the vehicle, and consequently dumps a fraction of the energy input into the kinetic energy of the jet stream. It is possible to define an aerodynamic propulsive efficiency, \( \eta \), which is given by

\[
\eta = \frac{TV}{P},
\]

where

\[
T = \text{developed thrust}
\]

\[
V = \text{vehicle forward speed}
\]

\[
P = \text{power dumped into propeller shaft}
\]

Idealized momentum theory, which although it gives an oversimplified picture, illustrates the source of the problem. This shows that

\[
\eta = \frac{2}{1 + \left(1 + \frac{2T}{\rho AV^2}\right)^{1/2}}
\]

where \( \rho = \text{atmospheric density and } A \text{ is the effective propeller actuator disc area.} \) This theory shows that propulsive efficiency increases with increase in \( V \) and with increase in \( A \). At zero, \( V \), \( \eta \) is identically zero. Some typical values of \( \eta \) are given in Figure C5.2. It can be seen that for the 300 m.p.h. vehicle, the attainable propulsive efficiencies are quite tolerable, perhaps greater than 60%. For the 100 m. p. h. application, however the efficiency is undesirably low, possibly not much greater than 25% or even as low as 15% if a 50 m. p. h. mean speed is typical. The crucial point highlighted by the actuator disc theory is that, since \( T \) and \( V \) are sized by system requirements, the only option open to the TACV is to increase \( A \). But although shrouding and, use of multiple stages and carefully contrived blade shapes may give some improvement, the dominant factor is \( A \) and it is hard to see how in practice this can be made any larger than the vehicle cross sectional area. The point of this discussion is
not that other propulsive systems do not waste energy at low speeds, an electric motor can dissipate energy through resistive heating in the stalled condition, and gas turbine also wastes energy when stalled. Rather the point is that other propulsive systems can be relatively easily matched to low speed operation whereas aerodynamic propulsion inherently cannot. For example, a rotary induction type AC motor can use a gear train and a LIM can have its coil spacing chosen to give maximum efficiency at design speeds.

The actuator disc effect also has implications for multiple unit operation. Power requirements for high speeds are such that for trains of TACVs, multiple power units will be required. If multiple fan propulsion is employed, second and subsequent fans will experience a fluid input velocity which will be greater than the vehicle velocity; for typical TACV geometries this increment can be as much as 50% of the previous fan slipstream velocity. This means that subsequent fans are acting partly as stages for previous fans, so that some of their effective disc area is lost. Furthermore, second and subsequent fans experience a turbulent eddying input. We are aware of an amphibious ACV which has two tandem propellers, and which experiences a serious loss from this effect. The front propeller, which is close to the front of the vehicle gives a thrust of perhaps 5 lbs/HP, whereas the rear propeller, which is close to the rear, but aligned with the slipstream, gives a thrust of only 2 lbs/HP. Aerodynamic propulsion is impractical for multiple unit operation.

There are other advantages associated with the use of LIMs. Since their peak thrust tends to occur near synchronous speed, whereas the peak thrust of an aerodynamic propulsion system occurs at zero speed relative to the wind, a LIM powered vehicle will have better acceleration characteristics and will be less affected by headwinds. This is shown in Figures C5.3 and C5.4, taken from Bliss (1970).

We sum up by observing that aerodynamic propulsion can be ruled out for the 100 m.p.h. application. For the 300 m.p.h. application aerodynamic propulsion will play a role until such time as traffic builds up to the point where electrification can be justified. This is illustrated by some costs of various alternatives calculated by TRW (1970) and reproduced in Figure C5.5. Note that the turboprop system in these results is the cheapest through the entire range of capacity examined. Hence the decision to change over to an electric system would be governed vehicle headway and other safety constraints. At one aerodynamically propelled vehicle every two minutes this would correspond to 3000/hr capacity.

C5.3) Braking and Safety Problems

Braking and acceleration of a TACV is not limited by wheel-rail adhesion as is the case for conventional trains but by human comfort and safety constraints. The TRW report (1970) suggests that for routine operation, deceleration should be limited to 0.07g, so that for high speed applications, the following procedure will probably be used:

1. Since aerodynamic drag can alone produce decelerations up to 0.2g, propulsion thrust will be first reduced at a controlled rate.

2. Below about 175 m.p.h. thrust reversal will be required to maintain the deceleration rate at 0.07g. This can be readily accomplished with either LIM or aerodynamic propulsion. Both can achieve the desired rate down to zero speed (see Figure C5.3). Aerodynamic thrust reversal
Figure C5.3: Variation of lim thrust and vehicle drag with speed for Aerotrain 180-44. (Source: D.S. Bliss - 1970).

Figure C5.4: Effect of headwind on track speed of Aerotrain 180-44 with linear motor propulsion. This is less marked than it would be with propeller propulsion. (Source: D.S. Bliss - 1970).
FIGURE C5.5 COMPARISON OF MAJOR TACV PROPULSION SYSTEM ALTERNATIVES. THE COST GIVEN DOES NOT INCLUDE MAINTENANCE, LAND ACQUISITION OR CREW.
(SOURCE: TRW 1970)
will require the use of reversible pitch propellers and LIM thrust reversal can be achieved either by feeding the station with DC current or interchange the connections of the three phase winding (plugging). The latter is the simpler, and apparently a routine operation is well within the overload capacity of the motor (TRW, 1970).

Finally at speeds below 50 m.p.h., frictional braking will be used to stop and position the vehicle in the station. For this operation, the TRW report (1970) suggest castered retractable wheels as desirable for accurate repeatable control, but the Aerotrain I-180 uses oaken shoes to clamp the guideway apparently quite successfully. The particular choice of this material for the braking shoes avoids significant wear on the guideway, it is claimed.

It is likely that special braking techniques will be required for emergencies, since figures up to 0.3g have been suggested as possible without incurring passenger injury. For single vehicle operation, parachutes appears to be one viable solution, and this technique has been employed on the Aerotrain I-180. For multiple vehicle trains, this technique cannot be used and other approaches, such as the use of retractable skids or allowing the rear cushions to drag on the guideway, have been suggested. In general there do not seem to be any serious obstacles to achieving satisfactory braking procedures, although some R & D is required to obtain information on such questions as friction coefficients at high speeds. The TRW calculations were based on data generated by the X-15 rocket plane programme, and these gave coefficients of sliding friction of about 0.3.

Safety problems which have to be considered include

(i) effect of total power failure
(ii) ice and snow accumulation
(iii) foreign objects on the guideway

The second of these three items is of special relevance to Canada.

A sudden complete power failure could present some serious problems at high speeds. The worst case corresponds to the vehicle immediately settling on the guideway, in which case the combined effects of frictional and aerodynamic drag could produce decelerations of about 0.5g. In addition, it has been speculated that small differences in sliding friction coefficients over the guideway-vehicle interface could induce dangerous and damaging vehicle oscillations. To avoid this possibility, the TRW report (1970) suggests incorporation of redundancy in the design, possibly including duplication of power collection apparatus. However, it seems that by careful attention to design the problem might be somewhat minimized. For example, design of the cushion levitation system to take account of the ram effect and fluid capacitances might be possible so the vehicle does not settle on the guideway immediately and only the aerodynamic drag is experienced at the very high speeds. This would ensure that deceleration remains below 0.3g through the critical high speed period and would allow time for implementation of appropriate procedures such as activation of standby emergency systems for lowering of wheels and brakes.

Consider now the possible effects of snow and ice. The box is fairly obviously the guideway section least likely to accumulate snow and this has been cited by THL (and others in responsible positions) as a sufficient reason for using this geometry in Canada. There are two objections to this approach, firstly it
could be a misleading suboptimization of system economics, and secondly there are
grounds for suggesting ice is technically a bigger problem than snow. In this
respect, all sections should be affected to much the same extent. An appropriate
analysis of the effect of snow on the inverted tee or the trough would have to
include expected frequency of snowfalls of sufficient magnitude to slow the TACV
by an unacceptable amount. No data on this is currently available, but it must
be remembered that the air cushions should have some snow clearance effect, so
that it is not reasonable to expect the vehicle to be significantly slowed by
small accumulations. Also, cost of snow removal has to be balanced against any
differentials incurred by choosing a guideway best suited to shedding snow.
Furthermore, it is reasonable to expect that in a developed TACV system, through
running between parts of Canada and the U.S.A. will become desirable, and there
is therefore strong reasons for following the U.S. lead in selection of guideway
section. Ice accumulation may likely be the more difficult problem, as it will
be more expensive to remove, and should have a more serious effect on cushion
performance, and linear electric motor propulsion. One possible answer is to
adopt amphibious ACV technology and use flexible skirts which could negotiate
irregularities up to 2 inches or more in size. This would mean that the ice could
be removed by relatively inexpensive means such as salting, instead of inbuilt
guideway heaters suggested in the TRW report (Ref. 12).

Foreign objects on the guideway could present a problem, especially
if cushion hard structure clearances are small; the TRW report (1970) envisages
this as a critical development area. Ability to detect objects ranging from
about 2 inches up to and including humans and animals at a distance of 2 to 3
miles including around curves has been cited as a design requirement. This would
seem to be a formidable and perhaps not quite necessary task; thus the use of
appropriately designed flexible skirts could allow objects as large as required
to be traversed. The maximum size chosen will clearly affect the economics,
but if say, objects as large as one foot high could be traversed, the detection
problem would be greatly simplified. At this point one could perhaps more easily
balance the cost of providing a detection system against the dangers inherent to
the vehicle and the probability of such an occurrence.

C.6) CONCLUSIONS AND RECOMMENDATIONS

The most striking feature that emerges from the discussions given
above is the confusion that appears to exist in the available literature on the
economic significance of the various design alternatives. The discussion on
guideway and system costs given in Section C5.3 is particularly interesting in
this respect. Now, clearly the extensive programs underway in Britain, France
and the U.S.A. on high speed TACVs indicate that a major Canadian program in this
field would be out of place. However, it is also clear that some independent
study and analysis will be required in order to generate information which will
enable a rational comparison relevant to the Canadian environment to be made
both with other competing alternatives to the TACV and of the various alterna-
tives facing the TACV designer. Also, there will no doubt be problems arising
from the peculiarities of Canadian weather conditions and transportation needs
that will require some R & D activity in order to allow the TACV to contribute
effectively. Furthermore it has been suggested that a programme aimed at develop-
ing the application to lower speed trains may usefully complement existing U.S.
activities. Using these guidelines we suggest some areas of investigation.

These are:
1) Theoretical and experimental studies of existing and projected suspension - guideways designs to facilitate selection of optimal systems for the 100 m.p.h. application.

2) Evaluation of the effects of choice of guideway section on ice and snow accumulation.

3) Techno-economic studies of vehicle and guideway design to provide objective information leading to a rational choice of the most economic system for Canadian environments.

4) Investigation of methods such as the linear gas turbine of obtaining compact and efficient fluid mechanical propulsion of TACVs.
APPENDIX D: SUMMARY OF AVAILABLE DATA ON ACV COSTS

D1) First Costs

D1.1 Cost of Research  Data specifically related to the research costs associated with ACVs is not available. When these expenses are mentioned, they are lumped together with development costs. Generally it is difficult to predict research costs since the allocation of such expenses depends on the individual manufacturer's policy. Further a great deal of research is applicable to more than one craft; how should it be proportioned between them? One final consideration is the cost of research done at universities, research institutions, and government laboratories at fractional cost to the manufacturer, or at no cost at all. The assignment of research costs to a given vehicle is extremely difficult.

D1.2 Cost of Development and Prototype Testing  Included in this classification are: analysis, design, manufacture of the prototype, special tooling for its manufacture, and testing and evaluation costs. Due to the separation difficulties mentioned in section D1.1 research costs, in practice, will be buried in this grouping. Engine development costs will not be considered under the assumption that the engine chosen is already in production for some other use.

Reference 3 gives the following empirical formula for estimating development costs (not including research):

$$C_D = 16.4 W^{0.85} V^{0.6} n^{0.09} \times 10^3$$

Where:

$W$.......Gross Weight (AUW) - long ton
$V$.......Maximum Speed - kt
$n$.......Number of production

Reference 3 further breaks down the R & D costs as follows:

- Basic research, analysis, design or prototype (including stressing and aerodynamics) 45%
- Manufacture and tooling 40%
- Testing and evaluation 15%

Several references indicate that the R & D costs charged to any one vehicle should not exceed ten percent of the basic purchase price, if the total vehicle price is to be reasonable.

The table presented below is a compilation of all the information available to us concerning R & D costs.
<table>
<thead>
<tr>
<th>Company</th>
<th>Item</th>
<th>Amount</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BHC</td>
<td>Total R &amp; D spending</td>
<td>$15.6 Mil.</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Skirt R &amp; D</td>
<td>$3.0 Mil.</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>R &amp; D spending on SRN3</td>
<td>$2.6 Mil.</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Avg. R &amp; D spending per Ton (long) AUW</td>
<td>$65,000 to $75,000</td>
<td></td>
</tr>
<tr>
<td>Ministry of Technology</td>
<td>R &amp; D spending on SRN3</td>
<td>$5.2 Mil.</td>
<td>7</td>
</tr>
<tr>
<td>Cushioncraft</td>
<td>Total spending 1961-68</td>
<td>$400,000</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Development of CC-5</td>
<td>$96,000</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>Avg. Total spending per Ton (long) AUW</td>
<td>$45,000 to $50,000</td>
<td></td>
</tr>
<tr>
<td>Hovermarine</td>
<td>Total R &amp; D spending</td>
<td>$1.3 Mil.</td>
<td>7</td>
</tr>
<tr>
<td>Denny Bros.</td>
<td>R &amp; D spending on D2-002</td>
<td>$780,000</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Avg. R &amp; D spending per Ton (long) AUW</td>
<td>$26,000 to $31,000</td>
<td></td>
</tr>
<tr>
<td>Bell Aerosystems</td>
<td>Design and construction of SKMR-1 (contract price)</td>
<td>$2.05 Mil.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Avg. cost per Ton(Long)AUW</td>
<td>$60,000 to $75,000</td>
<td></td>
</tr>
<tr>
<td>U. S. Army</td>
<td>Research program 1962 (ACVs)</td>
<td>$439,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Research program 1963 (ACVs)</td>
<td>$563,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Research program 1964 (ACVs)</td>
<td>$643,000</td>
<td></td>
</tr>
</tbody>
</table>

The cost of extensive prototype testing can be prohibitive, especially in the case of large vehicles. For instance Ref. 10 indicates that testing of the SRN4 costs $1.3 Mil. per 1000 hours, and that about 4000 hours would be needed for complete testing. Obviously this is not economically feasible. It seems that in the face of such costs the manufacturer could complete sufficient testing as to guarantee at least, say, 80% reliability, and then turn the vehicle over to the operator for "operational" testing. The Manufacturer would then bear at least a portion, if not all, of the cost of subsequent modifications until the vehicle reaches 90-95% reliability, at which point the vehicle would be considered as developed to a satisfactory operational level and the manufacturer's liability ended.
Dl.3) Cost of Production Included under this heading are the costs of: preparations for production, basic hull structure and furnishing, skirt system, engine(s) and transmission(s), propeller(s) and fan(s), various control and environmental systems, navigational and communications equipment, and other miscellaneous equipment needed to make the vehicle operational. Note that it is possible that the navigational, communications, and miscellaneous equipment may be added by the buyer at a later date, rather than purchased in the basic vehicle package. This would be particularly true of charter operators, whose needs will vary throughout the life of the vehicle.

Reference 3 gives some indications of production costs for amphibious ACVs:

- Hull structure and furnishings: $10.5/lb.
- Systems and powerplant installation: $26.5/lb.
- Propellers, fans and transmissions: $44.0/lb.
- Over-all cost per lb. empty weight: $18.2/lb.

Note that these figures are per lbs. of the item in question, not of entire vehicle.

Some prices for engines are quoted in references 5 and 29.

Reference 3 also presents the following formula for computing production costs:

\[
C_{p,20} = 0.20 W_s^{0.85} + 0.34 W_o^{0.99} + 0.027(SHP)^{0.6} \frac{1}{5.18} ($\text{Mill.})
\]

where:
- \( C_{p,20} \) is the per unit cost of production for a batch of 20 ACVs
- \( W_s \) is the equipped structure weight in long tons
- \( W_o \) is the outfitting weight in long tons
- \( SHP \) is the installed shaft horse power of the lift and propulsion systems combined

The only breakdown of the components of an ACV available to us is a composite of references related to the SRN6 vehicle.
<table>
<thead>
<tr>
<th>Item</th>
<th>Price</th>
<th>Ref./Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic SK.6 (unpacked)</td>
<td>$350,000</td>
<td>15/probably higher than SRN.6 due to licensing costs</td>
</tr>
<tr>
<td>Interior trim, furnishing, radar and searchlight</td>
<td>$30,000</td>
<td>8</td>
</tr>
<tr>
<td>Cabin trim</td>
<td>$6,450</td>
<td></td>
</tr>
<tr>
<td>38 seats</td>
<td>$2,280</td>
<td></td>
</tr>
<tr>
<td>Radio</td>
<td>$2,580</td>
<td></td>
</tr>
<tr>
<td>Cabin heater</td>
<td>$3,200</td>
<td></td>
</tr>
<tr>
<td>Searchlight</td>
<td>$1,500</td>
<td></td>
</tr>
<tr>
<td>Pilot seat</td>
<td>$225</td>
<td></td>
</tr>
<tr>
<td>Screen wipers</td>
<td>$500</td>
<td></td>
</tr>
<tr>
<td>PA equipment</td>
<td>$570</td>
<td></td>
</tr>
<tr>
<td>Crew compartment partition</td>
<td>$1,095</td>
<td></td>
</tr>
<tr>
<td>New skirt</td>
<td>$18,000</td>
<td>29</td>
</tr>
</tbody>
</table>

It must be stressed that the above figures are only to indicate the order of magnitude of the production costs. It is difficult to set a vehicle price, even in the case of a well established one such as the SRN.6 due to large number of modifications that are available from the factory. It has been noted that the "basic" purchase price can vary as much as $50,000, depending on the "options".

D1.4) Cost of Manufacturer's Tests of the Vehicle There is no data available relating to this area yet. The reason is mainly due to the small numbers of vehicles produced so far. Each vehicle is virtually a prototype, and is treated as such. Manufacturer's trials are usually associated with a few hours testing on each vehicle of a large production run. The only comments that can be made then have already been discussed under prototype testing.

D1.5) Manufacturer's Profit It is far too early in the development of ACVs to establish profit margins. Particularly since there has been only one vehicle produced in large numbers, the SRN.6.

D1.6) Cost of Preparation for Service This cost includes: modifications to the vehicle after delivery (i.e., outfitting to the operator's specific need - as noted in section A1.3) which may be done at the factory and included in the purchase price), initial spares stock, and miscellaneous costs associated with the introduction of the vehicle, such as advertising the new or improved service.
Reference 3 presents the following guidelines:

<table>
<thead>
<tr>
<th>Type of ACV</th>
<th>8-10 ton ACV (1-2 engines)</th>
<th>100-150 ton ACV (multi-engined)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of units</td>
<td>2-3</td>
<td>3-4</td>
</tr>
<tr>
<td>After deliv. modif.</td>
<td>10%</td>
<td>5%</td>
</tr>
<tr>
<td>Initial spares</td>
<td>25%</td>
<td>20%</td>
</tr>
<tr>
<td>Cost</td>
<td>5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Total cost of vehicle per initial cost of vehicle</td>
<td>1.4</td>
<td>1.27</td>
</tr>
</tbody>
</table>

The percentages and fractions given above are based on the initial purchase price of the vehicle. The numbers are estimates for overwater operations based on airline experience with an allowance for the less complicated nature of ACV operations. These costs are strongly dependent upon the character of the operations, the vehicle, and the transportation need to be satisfied. For instance the various Canadian trials have indicated that for overland operations improved communications and navigational equipment will be needed, particularly more sensitive radars.

D1.7) Conclusions

Estimation of the total price of an ACV is important for the calculation of DOCs (Direct Operating Costs) because the Fixed DOCs - amortization, interest, and insurance - depend on the initial purchase price and the total price for the vehicle. Table D1.1 and Figure B2.1 (Appendix B) list and compare the prices and basic characteristics of ACVs to those of aircraft, helicopters, and hydrofoils.

If it is required to estimate the cost of a design vehicle for the purposes of an economic simulation of a transportation system the usual approach is to make a survey of all the existing vehicles and their costs, and with a careful prediction of the design vehicle's parameters and the length of the production run, use the survey to approximate the vehicle's price. However, as illustrated above in the earlier sections ACVs have not developed sufficiently to allow such ease of prediction.

D2) Direct Operating Costs

D2.1 Fixed DOCs

Fixed DOCs are composed of depreciation of invested capital, interest charges on borrowed capital, and insurance. It is obvious that these costs are determined by the price of the vehicle. A more detailed discussion of these factors now follows.

D2.1.1 Depreciation of Invested Capital

The amount of depreciation charged against each year's operations depends on the vehicle's expected lifetime, and its residual value at the end of its life. The following table is a compilation of depreciation data from several sources.
<table>
<thead>
<tr>
<th>VEHICLE</th>
<th>TOTAL UTILIZATION TIME</th>
<th>DIRECT OPERATING COST (DOC)</th>
<th>APPROXIMATE SELLING PRICE</th>
<th>BLOCK SPEED (MAXIMUM SPEED)</th>
<th>PAYLOAD</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HR</td>
<td>$/HR</td>
<td>$</td>
<td>KT</td>
<td>L.TON</td>
<td></td>
</tr>
<tr>
<td>SR. N6</td>
<td>2,000</td>
<td>82.0</td>
<td>310,000</td>
<td>45 (57)</td>
<td>3.0</td>
<td>17</td>
</tr>
<tr>
<td>SR. N6</td>
<td>2,000</td>
<td>130.0</td>
<td>312,000</td>
<td>46 (52)</td>
<td>3.0</td>
<td>25</td>
</tr>
<tr>
<td>SR. N4</td>
<td>2,000</td>
<td>770.0</td>
<td>4,550,000</td>
<td>55 (65)</td>
<td>44.0</td>
<td>17</td>
</tr>
<tr>
<td>HM 2</td>
<td>2,000</td>
<td>44.0</td>
<td>208,000</td>
<td>30 (35)</td>
<td>4.8</td>
<td>17</td>
</tr>
<tr>
<td>HM 2</td>
<td>2,000</td>
<td>70.0</td>
<td>240,000</td>
<td>32 (35)</td>
<td>6.0</td>
<td>25</td>
</tr>
<tr>
<td>VT 1</td>
<td>2,000</td>
<td>226.0</td>
<td>1,040,000</td>
<td>44 (48)</td>
<td>26.0</td>
<td>25</td>
</tr>
<tr>
<td>SK 5</td>
<td>2,000</td>
<td>160.6</td>
<td>-----</td>
<td>35</td>
<td>-----</td>
<td>19</td>
</tr>
<tr>
<td>SK 9</td>
<td>1,805</td>
<td>280.9</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>9</td>
</tr>
<tr>
<td>CC 7</td>
<td>1,000</td>
<td>26.0</td>
<td>117,000</td>
<td>(50)</td>
<td>1.0</td>
<td>29</td>
</tr>
<tr>
<td>N 300</td>
<td>2,000</td>
<td>287.0</td>
<td>1,180,000</td>
<td>(60)</td>
<td>13.0</td>
<td>29</td>
</tr>
<tr>
<td>N 102</td>
<td>2,000</td>
<td>45.0</td>
<td>110,000</td>
<td>(65)</td>
<td>0.9</td>
<td>29</td>
</tr>
<tr>
<td>HM 4</td>
<td>2,000</td>
<td>349.0</td>
<td>1,500,000</td>
<td>(45)</td>
<td>60.0</td>
<td>29</td>
</tr>
<tr>
<td>HOVERCAT</td>
<td>2,000</td>
<td>26.0</td>
<td>26,000</td>
<td>(30)</td>
<td>0.32</td>
<td>29</td>
</tr>
<tr>
<td>TERRAPLANE BC 7</td>
<td>2,000</td>
<td>20.0</td>
<td>60,000</td>
<td>(43)</td>
<td>2.40</td>
<td>29</td>
</tr>
<tr>
<td>TERRAPLANE BC 7 (10)</td>
<td>2,000</td>
<td>48.1</td>
<td>132,000</td>
<td>(43)</td>
<td>10.0</td>
<td>29</td>
</tr>
<tr>
<td>HYDROFOIL PT 20</td>
<td>2,000</td>
<td>78.0</td>
<td>355,000</td>
<td>(34)</td>
<td>7.0</td>
<td>17</td>
</tr>
<tr>
<td>HYDROFOIL PT 150</td>
<td>2,000</td>
<td>250.0</td>
<td>1,740,000</td>
<td>(39)</td>
<td>33.0</td>
<td>18</td>
</tr>
<tr>
<td>HELICOPTER BELL 204 D</td>
<td>254</td>
<td>205.0</td>
<td>-----</td>
<td>53</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>AIRCRAFT NORD 262 C</td>
<td>-----</td>
<td>196.0</td>
<td>940,000</td>
<td>(220)</td>
<td>3.6</td>
<td>34</td>
</tr>
<tr>
<td>FOREMOST TRACKED VEH.</td>
<td>287</td>
<td>34.1</td>
<td>-----</td>
<td>5</td>
<td>30.0</td>
<td>29</td>
</tr>
<tr>
<td>FOREMOST TRACKED VEH.</td>
<td>1,080</td>
<td>14.4</td>
<td>-----</td>
<td>5</td>
<td>8.0</td>
<td>29</td>
</tr>
</tbody>
</table>

**TABLE D1.1** SOME COST DATA.
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Depreciation Rate</th>
<th>Life of Vehicle</th>
<th>Residual Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>21.0% of DOC</td>
<td>10 years</td>
<td>10%</td>
<td>HM-2 used SF</td>
</tr>
<tr>
<td>17</td>
<td>18.2% of DOC</td>
<td>10 years</td>
<td>10%</td>
<td>SRN.6, used</td>
</tr>
<tr>
<td>17</td>
<td>26.5% of DOC</td>
<td>10 years</td>
<td>10%</td>
<td>SRN.4, used</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>10 years</td>
<td>10-15%</td>
<td>recommended</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>12 years</td>
<td>8%</td>
<td>HM-2, recom.</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>7.5 years</td>
<td>8%</td>
<td>SRN.4, recom.</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>10 years</td>
<td>10%</td>
<td>conventional ferry</td>
</tr>
<tr>
<td>35</td>
<td></td>
<td>5 years</td>
<td></td>
<td>Aerojet Gen. recommended overland ops.</td>
</tr>
</tbody>
</table>

From the above it is apparent that initially ACVs were treated as a conventional ferry by their operators in so far as depreciation is concerned. It can also be seen from the recommended values that complex amphibious ACVs may have to be depreciated at a faster rate, i.e., a much shorter life, and a smaller residual value. This will increase the Fixed DOCS per year. On the other hand the recommendation for the HM-2 is a decrease of about 10% in yearly depreciation. However, the most significant fact for the Canadian context is the recommendation of Aerojet General that their Valiant ACV, which is intended for overland operations on the Alaska North Slope, be depreciated over a five year period. This implies that overland operations will be more demanding and more expensive than the currently predominant overwater operations of Europe. Thus great care must be exercised in using data generated in the European operations for predicting Canadian usage of ACVs.

Finally, it is obvious that the lifetime of components such as engines, propellers, fans, etc. is considerably less than that of the vehicle as a whole. These costs should be treated as maintenance costs rather than included in the depreciated capital investment. If these components are depreciated then the spare parts on hand should also be included.

D2.1.2 Interest on Borrowed Capital Comparing all the data currently available it appears that the interest rates vary between 5% and 8%, with the majority clear to 5%. However, an important exception is the rate mentioned in Ref. 35 regarding the Alaska North Slope where it seems an interest rate of 8.5% can be expected.

D2.1.3 Insurance Rates Reference 3 presents the following:
<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Insurance Rates</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>conventional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ferry</td>
<td>1½ - 2%</td>
<td></td>
</tr>
<tr>
<td>conventional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ferry</td>
<td>5%</td>
<td>30% of operations in ice operations</td>
</tr>
<tr>
<td>aircraft</td>
<td>3%</td>
<td>overwater operations</td>
</tr>
<tr>
<td>ACV</td>
<td>3%</td>
<td></td>
</tr>
<tr>
<td>ACV</td>
<td>4%</td>
<td>coastal winter operations</td>
</tr>
</tbody>
</table>

These rates cover invested capital, and passenger and public liability. In most cases only a portion of the invested capital is insured - Ref. 18 quotes 75%, Ref. 9 quotes 50%. This results in some reduction in this portion of the Fixed DOCs.

In the one reference to overland operations (Ref. 35) we find the insurance rate very high relative to the above date - 15%.

D2.1.4 Conclusions  The Fixed DOC per year is the sum of the above three components (expressed on a yearly basis). They can be expressed as:

\[
\text{Deprec.} = \frac{(\text{Invested Capital} - \text{Residual Value})}{\text{Life of the Vehicle}}
\]

\[
\text{Int.} = (\text{Borrowed Capital}) \times (\text{Annual Interest Rate})
\]

\[
\text{Ins.} = (\text{Fraction of Total Investment Insured}) \times (\text{Total Investment}) \times (\text{Annual Insurance Rate})
\]

Now if H is taken as the annual number of operating hours, then the Fixed DOC per hour is:

\[
\text{FDOC (per hour)} = (\text{Deprec.} + \text{Int.} + \text{Ins.}) / H \text{ ($/hr.)}
\]

Or if we know the block speed of the operations \( V_{bl} \), the payload of the vehicle in tons \( P \), and the load factor \( L \), then

\[
\text{FDOC (per ton - n.m.)} = \frac{(\text{Deprec.} + \text{Int.} + \text{Ins.})}{H \times V_{bl} \times P \times L} \text{($/ton-n.m.)}
\]

Note that \( V_{bl} \), the block speed in knots, is the average speed of the trip from one point to another. It includes the time required for starting of the engines, loading of passengers, acceleration to cruise conditions, and the reverse procedure at the destination, as well as the time at cruising conditions. Given a particular vehicle its most efficient use requires a high utilization, i.e., high frequency of service, and high load factor.

Finally recall the earlier comments that suggest that overland operation will be considerably more expensive. This will require such operators to seek vehicles designed specifically to northern operations in order to provide efficient and profitable transportation.
D2.2) Variable DOCs  The variable portion of the direct operating costs is composed of crew salaries, fuel and oil expenses, and maintenance costs. The data available will be presented in tables with little comment owing to the great dependence of these costs on local factors not under the control of the vehicle designer.

D2.2.1 Crew Costs

<table>
<thead>
<tr>
<th>Reference</th>
<th>Crew Member</th>
<th>Salary</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>operator (pilot)</td>
<td>US$ 10,000/year</td>
</tr>
<tr>
<td></td>
<td>engineer</td>
<td>US$ 8,000/year</td>
</tr>
<tr>
<td></td>
<td>steward</td>
<td>US$ 6,000/year</td>
</tr>
<tr>
<td></td>
<td>complete SK-9 crew</td>
<td>US$ 26.7/block hour</td>
</tr>
<tr>
<td>19</td>
<td>operator (SK-5)</td>
<td>US$ 23.2/block hour</td>
</tr>
<tr>
<td></td>
<td>radar operator (navigator)</td>
<td>US$ 17.9/block hour</td>
</tr>
<tr>
<td>35</td>
<td>skilled labour on Alaska North Slope</td>
<td>US$ 25,000/year to US$ 30,000/year per man</td>
</tr>
</tbody>
</table>

Crew Requirements

<table>
<thead>
<tr>
<th>Factor</th>
<th>Details</th>
<th>Crew Required</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle size</td>
<td>for each 10-14 tons AUW</td>
<td>1 crew member</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>amphibious, up to 50 tons</td>
<td>2 crew members + steward, if passengers</td>
<td></td>
</tr>
<tr>
<td>Hours of Operation</td>
<td>600-1,400 hrs./yr./vehicle</td>
<td>1 complete crew</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1,200-2,600 hrs/yr/vehicle</td>
<td>2 complete crews</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2,400-3,600 hrs/yr/vehicle</td>
<td>3 complete crews</td>
<td></td>
</tr>
<tr>
<td>Trip distance</td>
<td>up to 50 naut. mi.</td>
<td>minimum 2 complete crews</td>
<td></td>
</tr>
<tr>
<td></td>
<td>over 50 naut. mi.</td>
<td>minimum 3 complete crews</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-assuming amphibious vehicle with up to 2000 hrs per year, add 1 crew per additional 800 hrs/year.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>wheeled ACV up to 50 n.m.</td>
<td>1 driver</td>
<td></td>
</tr>
<tr>
<td></td>
<td>wheeled ACV over 50 n.m.</td>
<td>2 drivers</td>
<td></td>
</tr>
</tbody>
</table>
For total maintenance costs expressed as a percentage of the DOCs the following guidelines are suggested:

skirted amphibious vehicles -
  up to 50 tons AUW: 45-55% of DOC
  50 to 200 tons: 35-45% of DOC

sidewall ACV - 20-30% of DOC

With regards to maintenance hours per operational hour:
  over water operations - 3 to 4.5 maint. hrs./op/hr.
  overland operations - 5.5 to 7 maint. hrs./op/hr.

Further information on DOCs for various vehicle is presented in Table D1.1 (Appendix D) and Figure B2.2 (Appendix B).

D2.2.4 Road or Track Preparation Costs For overland operation of ACVs it may be necessary, depending on local conditions, to prepare a road or track for them. This may involve merely the removal of large boulders and small brush, or it could go as far as setting grades and curves. The costs will vary greatly according to the local cost of labour, materials, construction equipment needed, etc. There is no cost data available yet.

There are two references which give information on the required track width. Reference 27 suggests a track width of 2.3 times the beam of the craft. On the other hand Ref. 36 suggests a track width of 0.9 times the craft beam. In this later case the track profile corresponds closely to that of the skirt cross-section.

Included in the track cost must also be the cost of marking it with radar reflectors, or some other navigational aid.

D2.3 DOCs: Conclusions

Table B2.1 (Appendix B) is a composite of all the available data on the DOCs for ACVs. It presents the individual breakdowns and indicates the proportion that each contributes to the total DOCs. The large scatter in the data is due to differing definitions of DOCs and of the various components of the DOCs.

Table D1.1 presents DOCs on a block hour basis for ACVs and other vehicles. The same data is also presented in Figure B2.2 (Appendix B).

The numbers tabulated should not be used for an economic simulation without checking the compatibility of the simulated and the reference operating conditions and definitions of values. Unfortunately, these conditions and definitions are often unclear or not stated. Perhaps the best compromise is to use the average values and assumptions from papers such as this one, or similarly Ref. 28.

D3. Indirect Operating Costs

IOC are extremely complex in nature and as a result they are generally stated as a percentage of the DOCs. The only data available comes from Ref. 26,
which suggests for ACV ferry operations:

IOCs of ferry operations, with terminal facilities - 40 to 55% of DOCs

IOCs of operations involving small amounts of local services - 15 to 20% of DOCs

D4. References on ACV Costs

1. J. R. Meyer
   M. J. Peck

2. M. L. Manheim
   Principles of Transport System Analysis (School of Engineering, Massachusetts Institute of Technology, January 1967, p.67-1)

3. Olle Ljungstrom
   Air Cushion Vehicles (ACV) in Water Transport (The Royal Institute of Technology, Stockholm, June, 1968, Me 35, UDC 629.1.039)

4. G. H. Elsley
   E. J. Deveraux

5. T. Ford
   International Hovercraft Conference. (Hovercraft and Hydrofoils, July 1968)

6. ACV Transport Potential (Canadian Aeronautical Journal, December 1965)

7. Where has all the money gone? (ACV Flight Supplement, July, 1968)

8. R. B. Stratton
   Commercial Viability of Hovercraft. (Canadian Aeronautical Journal, December 1965)

9. J. A. Cannon
   J. L. Wosser, Jr.
   Air Cushion Vehicle - San Francisco and Beyond (ACV - Textron's Bell Aerosystems Comp. Buffalo, N. Y.)

10. A Crisis of Confidence (Hovercraft and Hydrofoils, Nov, 1969)

11. P. Winter
    Hovercraft of the Future (ACV Flight Supplement, Dec, 1968)

12. R. L. Trillo

13. J. Bentley
<table>
<thead>
<tr>
<th></th>
<th>Authors / Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.</td>
<td>Denny's Sidewall Hovercraft <em>(Hovercraft and Hydrofoils, May 1963)</em></td>
</tr>
<tr>
<td>15.</td>
<td>Big Canadian Deal Imminent <em>(ACV Flight Supplement, March 1969)</em></td>
</tr>
<tr>
<td>17.</td>
<td>A. F. Cornish <em>Some Commercial Aspects of High - Speed Marine Ferries, (Hovercraft and Hydrofoils, May, 1969)</em></td>
</tr>
<tr>
<td>18.</td>
<td>H. Muller <em>Commercial Aspects of ACV and Hydrofoils (Hovercraft and Hydrofoils, Dec, 1968)</em></td>
</tr>
<tr>
<td>20.</td>
<td>C. Clinton <em>Hovercraft Servicing and Maintenance (Hovercraft and Hydrofoils, Nov, 1966)</em></td>
</tr>
<tr>
<td>26.</td>
<td>Westland Counts Hovercraft Costs Within 5 pc. <em>(Hovercrafts and Hydrofoils, Feb, 1965)</em></td>
</tr>
<tr>
<td>27.</td>
<td>R. E. F. Lewis <em>Trials of an SK-5 Hovercraft for the Canadian Coast Guard</em></td>
</tr>
</tbody>
</table>


34. R. Miller
    D. Sawers
    The Technical Development of Modern Aviation

35. Improved Arctic ACVs: Project Valiant and An Air-Cushion Barge (Air Cushion Vehicles; Sept, 1970)

APPENDIX E: SCIENCE COUNCIL CRITERIA FOR MAJOR PROGRAMMES

1) The objective selected for each major programme must be of real importance to Canada, and perhaps even peculiar to Canada. Each should be such that the solutions would cope with problems posed by Canadian conditions - of climate, of organizational structure, or of availability of resources - and some of them should offer prospects of being more generally applicable in other areas of the world.

2) No major programme should duplicate work already under way in other developed nations. Rediscovering technology is expensive and pointless. If a problem for example is of great importance to another nation which has already set out to find a solution, Canada should attempt to learn from the other efforts by importing the technology being developed rather than squander much-needed resources by repeating work already done elsewhere.

3) There must be some demonstrable prospect of direct social or economic benefit which in an overall view would be commensurate with the resources invested. The concept of social needs can be extended to encompass Canada's obligation to contribute usefully to the progress of the world's developing nations.

4) The scientific and technological challenges must be fundamental and far-reaching enough, that they will not be quickly exhausted, and yet in general not so far-out that there is little hope of tangible progress with time spans of ten or twenty years. The challenge must stimulate genuine innovation, and it must be sustained consistently over a long enough period that manpower training sources respond and adapt, and new industries both come into being and get established on a viable footing.

5) The unpredictable quality of research and the openendedness of the future must be clearly recognized. The programmes should be regarded as campaigns to open up new opportunities. They should therefore challenge technologies over a broad, varied and open frontier rather than proceeding down a narrow and confining lane. Skills, capabilities, and organizations will thus be brought into existence in readiness to exploit breakthroughs and inventions, made in Canada or elsewhere, in the most opportune ways. Particular projects within the broad programme areas should be chosen more as stepping stones to future positions of advantage or readiness, than as fixed goals not subject to revision.

6) Not only does a programme need to be sufficiently sustained in time, if it is to be effective in building new industry and in supporting new ideas through the complete cycle to practical innovation, but it must be mounted on a sufficiently large financial scale that the various R & D groups formed to attack the special problems will be of above-critical or viable size, and will have reasonable prospects of a steady diet of challenging projects within their range of competence.

7) The choice of a programme should be based on a conjunction of need, and of scientific or technological opportunity. Thus a major programme to develop atomic energy for power generation would have been premature in 1920, where there was no felt shortage of power from hydro plants or coal, and before the necessary basic discoveries in nuclear physics had been made. Further, the potential innovative fertility of the programme area must be considered, since the benefits from the unexpected and unpredicted discoveries and opportunities may well exceed the benefits from those outcomes that could be predicted at the start.
NOTE ON LISTING: For ease of identification in the text of the report an alphabetical reference system has been used. The citation is usually the senior author, but, in cases where no author is given, the source agency or magazine name is used, for example, the report of the Trials of the SRN6 at Churchill, Manitoba is listed under Transport, Canadian Department.

Acres & Associates

"Mid Canada Development Corridor", Toronto, 1969.

Air Cushion Vehicles


(1962)

Air Cushion Vehicles


(1963)

Air Cushion Vehicles


(1968)

Air Cushion Vehicles


(1969)

Air Cushion Vehicles


(1970)

Andrews, E. J.


Arnold-Foster, M.


Barratt, M. J. et al


Barthalon, M. E.


Rechon, J. and

Watson, P.

Bender, E. K.


Dietrich, C. and

Franken, P. A.

Bentley, J.


Berthelot, J. M.


Bliss, D. S.

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Reference</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Author(s)</td>
<td>Reference</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Palm-Leis, A.</td>
<td>Private Communication</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
</tr>
</thead>
</table>
1) Preamble

This appendix presents a summary of the technical literature available to us which appears to have some R & D value. A brief description of the contents of each paper is given. The listing is in alphabetical order, of senior author. In cases where no author is given, the sponsoring agency or a first word in the title is used. A subject index is given in Section 3.
A.01 A PRELIMINARY DESIGN STUDY OF A TRACKED AIR CUSHION RESEARCH VEHICLE.  
VOLUME II: GUIDEWAY STUDY REPORT  
(Aero-Glyde Systems Inc., PB-183 320, December, 1968)  

Three guideway structure types: - inverted "Tee"  
- double L (Channel)  
- box (inverted channel)  

Loading criteria. Cost of construction. Design of the individual parts of the track, (stressing) properties of the sections, deflections. Cost breakdown of the track by individual parts with respect to the used material. Design tradeoff studies - the alternative cross sections (cost per mile as a function of the span of the track and material), track tolerance, switching and mutual evaluation of all three structures.

A.02 PERFORMANCE TESTING OF AN AIR CUSHION VEHICLE ON THE GREENLAND ICE CAP.  
ABELE, Gunars  

Tri-cell plenum ACV SK-3 "Carabao", Summer 1964. Problems and possibility of transport in polar regions. Description of the vehicle, climatic conditions and routes. Description and discussion of individual tests, their measured performances and characteristics. The following performances and data are presented:  
- braking distance as function of speed and direction, and speed of wind.  
- ditch crossing capability.  
- obstacle clearance.  
- skirt damage and maneuverability description.

A.03 A STUDY OF RADIAL-FLOW FANS FOR GEM PROPULSION SYSTEM APPLICATIONS.  
Aerophysics Co. Washington, D.C.  
(U.S. Army Transportation Research Command Fort Eustis, Virginia.  
TRECOM T.R. 64-33, July 1964)  

Overall results of a Rotating Diffuser Centrifugal fans (RD) for GEM study (Aerodynamics, structure, fabrication and design studies). Report consists of six phases:  
1. - General considerations on the fan-ducts matching problems of a GEM (GEM fan requirements, duct losses, etc).  
2. - Design problems of a RD fan suitable for GEM.  
3. - Theoretical analysis.  
4. - Experimental investigations (description of experimental rig, model and test results are presented. The following data are measured: $P_{tj}$ -total pressure rise of the fan and model system, total input power $SHP$, overall efficiency of the fan and model $\eta$, as a function of volume flow and delivery duct depth). Investigations were performed on a circular and an oval model.  
5. - Structure investigations.
6. Design studies. In appendices are presented: performance of RD wheel, internal flow requirements dictated by air cushion aerodynamics, and applied loads.

A.04 FORWARD SPEED EFFECTS ON ANNUAL JET CUSHION
ALEXANDER, A. J.

Introduction to the problems of calculating the effect of forward speed on hovercraft performance. Presentation of assumptions. Theoretical equations. Results are plotted in diagrams: change of plenum total pressure to free stream dynamic head ($\Delta H/q_\infty$) as a function of jet angle ($\theta$), pressure ratio at rear of the vehicle ($m = (\text{surface static pressure - free stream static pressure})/q_\infty$) and pressure ratio $k = (\text{rear cushion pressure - forward cushion pressure})/q_\infty$ for several $h/t$ ratios. Influence of upper surface lift coefficient on $\Delta H/q_\infty$ ratio for several values of $k$ as a function of $m$.

A.05 GEM CONTROL SYSTEM STUDY
ANDERSEN, B. V., BOYLE, R. V.

Description of a reference design vehicle and its control system. Introduction of reference design parameters, operating conditions, pitch equation components, roll and heave equation components, side slip and yaw eq. components. Assumed control system functions. Description of GEM control station design. Measured: - hoverheight and speed change (RPM) after step change in engine speed for 0,50 f.p.s. forward speed, as a function of time. - pitch angle, hoverheight and speed change after pitch command versus time for 0,20,40 f.p.s. forward speed. - natural roll and side motions versus time. - yaw angle and side velocity versus time for 50 and 100 f.p.s. forward speed. Response to command - acceleration and braking (change of pitch angle and forward speed change with thrust command versus time). Side motions (side velocity and roll angle versus time for 0 and 80 f.p.s. forward speed). Coordinated turns, side slip turns - equations and measured values of velocities and angles. Controllability and control modes - evaluation courses and results of controllability runs are presented. Simple course and simple turn course test runs, obstacle course test runs. Control system design considerations (control of roll, pitch and heave, fore, back and yaw motions) description of pneumatic control system. Conclusions and recommendations. In appendices: Linearization and simplifications of basic equations (pressure, flow, heave, roll, pitch), equations of motion. Particular equations for reference design GEM Peripheral jet and compartmentation jet flow equations, pressure and motion equations. Formulation of GEM six degree freedom body motions. Surface deflection and base pressure variations due to forward speed. Analog computer diagram.
A.06 NOTE ON PERIPHERAL JET GEM PROPELLED THROUGH FORWARD INCLINATION
ANDO, S.

Decrease in augmentation due to inclination - discussed with respect to ref.; for zero forward speed and in flight. Cushion power in terms of inclination angle - equations.

A.07 THE EXPERIMENTAL AERODYNAMICS OF HOVERCRAFT
ANDREWS, E. J.

Connection of the external aerodynamics and handling characteristics of the hovercraft. Presentation of the test programme of the hovercraft aerodynamics - this programme is divided into three phases. Some results are presented by individual phases: PHASE 1: parametric study of the effect of the hull shape; presentation of the basic model results: - external aerodynamics characteristics \( C_L, C_D, C_N, C_Y \) throughout the yaw angle at zero attitude in both pitch and roll - effect of the pitch attitude upon these coefficients. On the basis of the measured data some rough ideas about ideal aerodynamics characteristics are presented. Further data are presented:

- effect of the edge radii upon \( C_Y, C_N, C_D, C_L \), cross wind force, yawing moment, drag, and lift coefficients.
- effect of the side inclination upon \( C_Y, C_N, C_D, C_L \).
- effect of the foredeck length, on these coefficients.
- effect of superstructure height and edge of radii, and (or) side inclination and (or) foredeck length on lift.
- effect of skirt upon above mentioned coefficients.

Conclusions from these measurements for design and handling characteristics.

PHASE 2: effect of the efflux of cushion air on the external aerodynamics (effect of tunnel wind on cushion pressure, effect of cushion wind on \( C_L, C_D, C_N, C_M, C_Y, C_R \)).

PHASE 3: flow visualization.

A.08 THE AERODYNAMIC CHARACTERISTICS OF A FAMILY OF RELATED HOVERCRAFT SHAPES,
ANDREWS, E. J.
(The College of Aeronautics, Dept. of Aerodynamics, CoA Memo No. 133, Sept, 1967)

Description of the models and apparatus. Following results are presented in figures: effect of pitch angle, roll angle, effect of edge radii, side inclination, foredeck length, and effect of skirt on: \( C_Y, C_N, C_D \) coefficients. Effect of the edge radii, superstructure height, side inclination, and foredeck length on \( C_L \) coefficient. All test were measured for Reynolds Number \( N_R = 0.7 \times 10^6 \).
OPERATIONAL ANALYSIS OF THE USE OF AIR CUSHION VEHICLES IN SUPPORT OF THE ARMY'S OFF-ROAD LOGISTIC MISSION
ABEL, K.B.

Assumed mission and environment. Operation requirements on vehicle design. Description of the off-road deterministic model and general assumed design parameters. Engines data. Design criteria and application of wheeled acv (tire size, wheel sinkage or floatation, payload restraints, computer analysis and its discussion). Air cushion vehicle cost (cost methodology, initial cost-structure, powerplant, equipment, operating cost). Cost versus effectiveness-comparison with other terrain vehicles, helicopter, wheeled and skirted ACV with reciprocating and gas turbine.
B.01 THE WAVE DRAG OF THE HOVERCRAFT
BARRATT, M. J.

Introduction to the problem and presentation of the basic assumptions for analysis of the wave resistance and presentation of the wave resistance equations. Applications of these equations and analysis to the rectangular and elliptical cushion planforms (for deep and shallow water). Presentation of the results in graphic forms:

- wave drag of a rectangular planform: in deep water (various beam/length ratios) - in shallow water (various water depth/craft length ratios)
- wave drag of the elliptical planform - in deep water - in shallow water

All values of wave drag are plotted against Froude number.

B.02 LATERAL STABILITY AND CONTROL OF HOVERCRAFT
BARRATT, M. J.
(National Physical Laboratory, Hovercraft Rep. 3, January 1968)

Equations of motion of a rigid body. Analysis of Lateral Motion, external forces definition, equations for these forces. List of force components and their equations. Control forces expressions. Dynamic stability example is presented in an appendix.

B.03 THE MECHANISM OF SKIRT BOUNCE
BARRATT, M.J.
(National Physical Laboratory, Hovercraft T.M.21, July 1969)

Theory of bounce for a Continuous Loop Skirt, and an Open Loop Skirt. Equations of motion are presented (but too many assumptions are employed). In conclusion several further steps are suggested. Further progress depends on the measurement or calculation of many quantities to check theoretical work and to find the more important variables. No simple rule for bounce presentation is available and it isn't probable that it will be (bounce depends on number of parameters). At present fixed rigid model is considered adequate for further study (freedom of a hovercraft to heave will modify the bounce frequency slightly).

B.04 URBA IN BUSINESS. SOME COMMERCIAL ASPECT OF A SUCTION-SUSPENDED URBAN TRANSPORT SYSTEM.
BARTHALON, M.E., RECHOU, J., WATSON, P.
(Hovering Craft and Hydrofoil, May 1969)

Description of the URBA system (track, suspension, bogies). Essential features of URBA system for urban transport (low capital cost, low maintenance, low noise, etc). Present development position - URBA 8 description. Projected experimental line in Lyon - description and features. URBA with respect to existing transportation systems. Requirements of overhead transport (noise, aesthetics, cost). Flexibility of the installation, and the market for guided public transport systems are discussed. Merits and demerits of various transport systems. Appendices: characteristics of proposed URBA 30 and URBA 100 - comparative track cost for various transport systems - comparison of URBA and duo-rail capital cost, capacity of URBA 30.
B.05 ECONOMICS OF THE AEROTRAIN SYSTEMS
BERTHELOT, J. B.
(Hovering Craft and Hydrofoil, June 1969)
Description of Orleans intercity project (80 seat Aerotrain) and suburban full-scale project (44 seat Aerotrain). Operating cost - definition, assumptions and method of estimation of the operating cost; operating cost and basic data for intercity and suburban systems. Construction cost of guideway and vehicles for both systems. Market potential.

B.06 FRENCH AIR CUSHION VEHICLE DEVELOPMENT
BERTIN, J.
(Canadian Aeronautics and Space Institute Journal, Jan, 1968)

B.07 BIBLIOGRAPHY OF HIGH SPEED GROUND TRANSPORT
(Massachusetts Institute of Technology, Cambridge, Mass., PB-170 581, October, 1965)
Alphabetically arranged general bibliography and subject index with the following parts: vehicle aerodynamics and propulsion; vehicle - guideway dynamics; human factors; scheduling and network flow; control and communication; terminals; tunnelling; urban and population studies; general references.

B.08 DYNAMICS OF A MULTIPLE-SKIRT AIR CUSHION VEHICLE
BICKFORD, L. L., OLSON, G. K.
(Journal of Aircraft, Vol. 6, No.6, Nov-Dec, 1969, pp.564-565)
Presentation of the mathematical model of air cushion vehicle (supposed system is presented). Lumped parameter approach. Mathematical expressions for lift fan, skirt leakage, equation of motion in heave and in pitch. Initial assumptions. Analog computer simulation of the behaviour of multiple skirt system is briefly mentioned.

B.09 OVERLAND HOVERWAYS TRIALS
BLAKEY, G. G.
Tests over three hoverways; two wide of "Vee" cross section and one narrow. Presentation of the results of the trials for straight track and for curvatures. Evaluation of the results, presentation of the arising problems and difficulties. Comment on skirt and propeller wear, dust, etc. Narrow track seems to be most promising.
B.10 THE POTENTIAL FLOW SOLUTION OF THE PERIPHERAL JET OF AN AIR CUSHION VEHICLE. APPLICABLE TO ALL H/T RATIOS.

BLIGH, T. P.

Short review of existing theories and their assumptions, to date. Theory for complete flow solution for both deflected and split jet conditions are presented. This theory is for solution of inviscid and incompressible flow.

B.11 APPLICATION OF AIR CUSHIONS TO HIGH SPEED GUIDED LAND TRANSPORT

BLISS, D. S.
(Hovering Craft and Hydrofoil, November 1966)

Types of the air suspensions - basic characteristics and attempt to find relative merits. Track cross sections - some comments on merits. Second stage suspensions (Hovercraft Development Ltd) - Air Spring Hoverpad. Required clearance - (roughness, dynamic loads). Power requirements (fan power and propulsive power) - simple equations. Future development programme.

B.12 THE EVOLUTION OF TRACKED AIR CUSHION VEHICLE

BLISS, D. S.
(Hovering Craft and Hydrofoil, August and September, 1970)

Short review of various projects from beginning of TACV activity to present time: Ford Motor Company "Levacar" (suspension, track, comment on research, description of demonstration model and design studies, analysis of application). Hovercraft Development Ltd. and Tracked Hovercraft Ltd. (history, high-speed suspension problems, comment on advantages, disadvantages and propulsion, presentation of various concepts, Linear Induction Motor - LIM, some possible applications of TACV, review of track design studies and air cushion development, description of demonstration model of HDL TACV, proposed high speed test vehicle and site, recent development by THL - 100 seat, 250 mph TACV). French Aerotrain - (history, aerotrain concept description, Aerotrain 01, 02 description and some experimental results, Aerotrain 250-80 Orleans: description, characteristics, lay-out, track, propulsion, braking, performance, cost; Suburban Aerotrain 180 - 44: description, basic data, propulsion and braking, performance, lay-out, track, costs; comparison between LIM and air propelled vehicle). Comment on U.S. Government Sponsored Research, development programme and specifications of research vehicle. General Electric TACRV - proposal. Grumman TACRV proposals (basic characteristics and description of vehicles). LIM research, LIM test vehicle (Garrett-2500 hp LIM). URBA - principle, prototypes 1 and 2, experimental bogie URBA 3, first prototype vehicle URBA 4 and proposed URBA 8 (description and basic data), future projects. Transportation Technology Inc. - personal rapid transit system - description of proposed vehicle and system, cushion, vehicle design, future development. Research of air supported transport systems at the Cranfield Institute of Technology. Appendix: LIM - principle of operation, types, performance, control, power supply guidance.
INVESTIGATION OF LIGHTWEIGHT STRUCTURAL DESIGN TECHNIQUES FOR LIGHTWEIGHT FANS
BOEHLER, G. et al.
(U.S. Army Aviation Material Laboratories, Fort Eustis, Virginia, USAAVLABS T.R. 66-60, September 1966)

Consists of four phases:

1) - detailed stress analysis of a lightweight Rotating Diffuser (RD) impeller, computer program, lightweight material and techniques review.

2) - detailed design analysis of the aluminum fan proposed in phase 1 (64.5 ins diameter, lightweight RD fan) including drawings, analysis of fabrication problems, detailed stress analysis.

3) - two identical units of the design were fabricated under phase 2.

4) - the first unit was structurally tested, the following tests were conducted: - balancing
- brittle coating stress analysis
- strain gauge stress analysis
- proof test
- sound - excited vibration analysis

5) - comparison of calculated and measured stress levels. Weight of lightweight RD impellers.

In the appendix is presented a Fortran Computer Stress Program.

BIBLIOGRAPHY OF THE AIR CUSHION VEHICLE TECHNOLOGY WITH GUIDE FOR DESIGN AND ANALYTIC ENGINEERS.
BRATANOW, T.
(The University of Kansas, Lawrence, Kansas, Con Nonr-4201 (00) NR212-150).

Five parts: - Bibliography of general informations
- " of ACV Research
- " of Surface Effect Ships
- " of Hydrofoil Research
- " of Submarine Research

List of articles alphabetically by authors.

SRN.6 HOVERCRAFT, COLD WEATHER TRIALS IN SWEDEN, 17th FEBRUARY TO 26th MARCH, 1966.

Map of area of operations, daily record of temperatures, and abbreviated diary of events is presented. Results of trials by phase and their analysis: operation from calm water to smooth ice and vice versa, over smooth ice, rough ice, rough land, several long distance runs (20 to 100 miles). Evaluation of some parts of the vehicle: de-icing installations, engine air intake filters, cabin heating, windscreen heating, control system, radar, skirt wear, skirt behaviour at low temperatures, skirt freezing to surface. Results of de-icing system tests, vehicle's maintenance.
B.16 DEVELOPMENT OF IMPROVED FANS FOR THE BRITTEN NORMAN CC-2 001
CUSHIONCRAFT
BROTHERHOOD, P.
(Royal Aircraft Establishment, T. R. 66271, Aug, 1966)

Reasons for the model test programme on fans. Description of the fan test rig and the test procedure. Description of fans and fan requirements. Method of reduction of results. Determinations of the pressure rise across the fan are presented. Results are presented in graphic form:
- static and total pressure coefficient, efficiency factor and power coefficient as a function of volume flow coefficient for fans types: A, B, C, Cl, C2, D, G.
- comparison of efficiencies and power coefficients for fan types C, Cl, C2.
- fan type Cl efficiencies and pressure coefficients for various intake clearances.
- direction of flow, radial velocity distributions, pitot and static pressures distribution 0.5 in from trailing edge of fan types: A, B, Cl, C2, D, El, F, G for various values of flow coefficients.
- tests of fans fitted with diffuser were conducted: effect of vane angle (vane diffuser) on static efficiency, static pressure and power coefficient; effect of annular diffuser on static efficiency, effect of various diffusers on efficiency; effect of diffuser on flow radial velocity, pitot and static pressure distribution; effect of obstruction near the fan outlet on fan's efficiency for various positions of the obstacle.

B.17 AN EXPERIMENTAL STUDY ON THE DYNAMIC STABILITY OF A GROUND EFFECT MACHINE IN HEAVE, PITCH AND ROLL
VAN DEN BRUG, J. B., VAN STAVEREN,

Description of preliminary design of a GEM. Description of model GEM and experimental apparatus. Equations of motion in pitch, roll and heave. Experiments are divided into: static and forced oscillation tests. These experiments are conducted above ground without forward speed and over water with forward speed. Formulae for determination of coefficients of equations of motion are presented in tabulative form, their values are determined from experiments and are plotted in figures. All experiments were conducted with the model equipped with a flexible skirt (bag type skirt).

B.18 AIR CUSHION VEHICLES
BUCKLE, A. K.
(Hovering Craft and Hydrofoil, April 1968)

B.19 WIND-TUNNEL INVESTIGATION OF DTMB RECTANGULAR PLANFORM GEM MODEL 472
BURGAN, E. T.

Description of model and apparatus. Test procedure description. Following data were measured: - effect of height parameter \((S/hC)\) upon model characteristics (required power, lift, drag force and aerodynamics moments), - effect of pitch angle upon model characteristics, - pitching moment variation with forward speed, - effect of deflected side vanes on model characteristics (side vane deflection for thrust), - model characteristics at various angles of sideslip, - effect of removing of nacelle fairings.

B.20 NOTES ON THE HEAVE STIFFNESS OF HOVERCRAFT AT ZERO FORWARD SPEED OVER GROUND AND WATER
BURGESS, A. J.
(Royal Aircraft Establishment, Bedford, Naval Air Department NAD Note No. 122, May 1962)

Heave stiffness over ground and over water - equations. Relationship between hoverheight over ground and free water surface. Testing of several hovercraft of different sizes:
- Vehicles without flexibles, over ground: CC2 1/2 model, CC2 full scale
- Vehicles with flexibles, over ground: CC2 full scale, SRN.3 full scale, VA 3, and CC5 full scale
- Vehicle over water: CC5 model, CC5 full scale

Measured: Change of fan RPM function with hoverheight, non-dimensional heave stiffness. Comparative over ground/over water heave stiffness model results.

B.21 A TWO DIMENSIONAL STATIC STABILITY THEORY FOR AN AIR CUSHION VEHICLE WITH A CENTRAL STABILITY JET
BURGESS, A. J.
(University of Southampton, Dept. of Aeronautics and Astronautics, A.A.S.U. Rep. No. 256, May 1964)

Choice of axes and jet terminology, choice of jet performance theory (Barratt and Elsley theory has been chosen). An extension of the Barratt and Elsley (Appendix) theory for underfed and split jet conditions. Definition of the flow types and their equations (except type C which is not treated). Two-dimensional stability theory is presented for two and three jet configurations. The agreement between theory and preliminary experiments for the two jet case was found to be poor - theory is unsuitable for two jet case, and suitable for limited range of three jet conditions. The dependence of the stability on the parameters \(h_z/l\) (hoverheight/length of the vehicle), \(h_z/t_1\) (hoverheight/jet thickness, \(\theta\) (edge jet angle), etc. is examined.

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B.22 AN INVESTIGATION OF THE INFLUENCE OF DUCT CONVERGENCE ON THE FLOW EXHAUSTING FROM THE EDGE JET OF AN AIR CUSHION VEHICLE
BURGESS, A. J.
(University of Southampton, Dept. of Aeronautics and Astronautics, A.A.S.U. Technical Note No. 258, June 1964)

Description of the model. The tests have been carried out at one ratio of hoverheight/jet thickness with the jet operating in split, deflected and underfed conditions. Measured: inner boundary static pressure distribution, distribution of pressure through jet for deflected jet and varying convergence distribution of total head through jet planes parallel to vehicle's base and normal to jet deflections. The same characteristics were measured for split and underfed jet. Split and underfed jet mass flow measured. Some comparison of theory and experiments.

B.23 THE PERFORMANCE OF FANS IN HOVERCRAFT - A METHOD OF REDUCING EXPERIMENTAL RESULTS
BURGESS, A. J.

Presentation of the assumptions - edge jet performance (pressure, volume flow), fan-duct configuration. Model: 1/3 scale half CC2-a rigid geometry, and a flexible skirt model. Following data were measured for the rigid geometry model: volume flow in the reduced form versus hoverheight for five model weights; fan flow coefficient and power coefficient versus hoverheight; fan RPM and power in reduced form versus hoverheight for five model weights. Flexible model: reduced form of the volume flow, the power and the fan RPM versus hoverheight, change of the fan flow and the power coefficients with hoverheight. All experiments were conducted for several model weights.

B.24 FRENCH MARINE AIR CUSHION VEHICLES.
BERTIN, J.

Brief review of ACV R & D activity in France. Development of the N-300, description of the vehicle and presentation of basic parameters, and testing of the N-300 Ol. Principle of the Naviplane (skirt system, independent supply of the cushions, passenger comfort, stability, power requirements). Discussion of the skirt reliability and vulnerability - some accidents are mentioned. Short term developments - N 102, N 500. Future trends (skirt/vehicle size limitations due to stress in a skirt). Future possibility of ACV in passenger and freight transport. Combination of multicell and side wall concepts.
B.25 APPLICATION OF COMPUTER METHODS IN AIR CUSHION VEHICLE RESEARCH
BRATANOW, T. and ECER, A.
(The University of Kansas, Centre for Research, Inc., Engineering Science Division Lawrence, Kansas, Appendix A to T.R. IV, AD 690 946, June 1969)

Description of the computer Fortran program used to simulate the motions of an Air Cushion Vehicle and to produce computer drawn movies representing the vehicle in motion. The experimental and operational data of the VA-3 test program is used as a guide for study. Presentation of important data of the VA-3 and parameters of the analysis. Effect of the parameter variations. Motions of ACV in flight over irregular land terrain and over waves, with and without crosswind and manoeuvres of the ACV. Computer program and time plots are presented. Discussion of the results.

B.26 MEASUREMENTS AND ESTIMATION OF THE LATERAL AND DIRECTIONAL STABILITY OF THE WESTLAND SRN.3 HOVERCRAFT
BROTHERHOOD, P.
(Royal Aircraft Establishment, Bedford Naval Air Department, NAD Note. No. 228, November 1968)

Description of the vehicle (skirt system, control, cockpit). Instrumentation. Dynamic stability tests: - lateral stability (roll stability time history), directional stability (pylon angle, rate of yaw, sideslip and angle of roll were recorded as a function of time). Variation of roll and pylon angles with sideslip on straight course at 45 kt airspeed. The variation of sideslip with steady rate of turn at various speeds. The variation of pylon angle with steady rate of turn at 47 kt. Theoretical estimation of stability (equations of motion, values of derivatives and control powers are presented) and its comparison with results of full scale tests. Control to trim for straight course and steady turns.
STATE OF THE ART SUMMARY. AIR CUSHION VEHICLE
CARMICHAEL, B. H.
(U. S. Army Transportation Research Command, Fort Eustis, Virginia, Publication No. U-926, June 1960)


HOVERING STATIC STABILITY AND PERFORMANCE EXPERIMENTS ON THREE-DIMENSIONAL ANNULAR JET MODELS
CARMICHAEL, B. H.
(U. S. Army Transportation Research Command Fort Eustis, Virginia, U-1443, November, 1961)

Test facility, model and instrumentation description. Experiments are divided in following groups:
static longitudinal stability - of simple peripheral jet model (centre of pressure shift is measured for various pitch angles and for various hoverheight/model length ratios (h/b), base and jet contribution to stability is measured separately), influence of jet angle on static longitudinal stability is measured - effect of base shape (convex, concave) is presented - effect of skirt and flap segmentation.
Lateral stability - the same conditions and variables as for longitudinal stability and same effects are investigated. Hovering performances are presented for the tested model and its modifications.

A PRELIMINARY DESIGN TECHNIQUE FOR ANNULAR - JET GROUND-EFFECT MACHINES (GEM's)
CHAPLIN, H. R.

Definition of "The Figure of Merit" (function of nozzle parameter, size parameter, jet discharge angle and efficiency factors). Definitions of limits of these parameters for practical design. Figures are presented for optimum nozzle configurations and figure of merit versus size parameter; and lift per horsepower versus wing loading for several figures of merit. Equations for mean total pressure, effective base pressure, mean jet exit velocity and jet momentum are presented as well. Discussion of Figure of Merit and efficiency factors.
C.04 GROUND EFFECT MACHINE RESEARCH AND DEVELOPMENT IN THE UNITED STATES

CHAPLIN, H. R.

Simplified ideal theory and figure of merit (performance expression) for simple air curtain, air curtain with skegs, integrated air curtain, water curtain plenum, ram wing and diffuser recirculation system.
Simplified engineering analysis of air curtain vehicle (cushion power, drag, curtain thrust, propulsion power). Comparison of simplified engineering calculations with experiments. Illustrative comparison of the ground cushion concepts.

C.05 DESIGN STUDY OF A 29-FOOT GEM

CHAPLIN, H. R.

Specifications and characteristics of designed vehicle are presented (payload - 1,200 lb., $V_{\text{max}} = 80$ kt, operating hoverheight - 3 ft, etc).

C.06 CURRENT STATUS AND PROBLEMS OF GEM RESEARCH

CHAPLIN, H. R.
(Lecture presented at the November 1961 Seminar of the University of Toronto, Institute of Aerophysics)

Basic principles of ACV and basic concepts. Brief survey of existing problems and some fundamental solutions, e.g., fundamental air curtain problems (jet reaction, cushion pressure, air flow), cushion contribution to stability, external aerodynamics, vehicle dynamics, hydrodynamics (over water problems), heave damping, pitch stability, etc.

C.07 SOME DESIGN PRINCIPLES OF GROUND EFFECT MACHINES SECTION A - INTRODUCTORY SURVEY

CHAPLIN, H. R., and FORD, A. G.,
(Dept. of Navy, David W. Taylor Model Basin, Washington, D. C. Rept.2121A, April, 1966)

Ground effect machines definition.
Simple plenum vehicle - description of principle, basic dimensions and characteristics, equations for cushion, propulsion, and total specific power. Ideal specific power as function of speed parameter, gap area ratio and total drag coefficient. Wavemaking drag of rectangular cushion as a function of speed/length ratio. Peripheral jet vehicle - comparison with plenum vehicle, basic principles.
Sidewall vehicle - description, propulsion power, wavemaking resistance.
C.08 SOME DESIGN PRINCIPLES OF GROUND EFFECT MACHINES SECTION B - AIR CUSHION MECHANICS
CHAPLIN, H. R., and FORD, A. C.

Thin jet theory (nozzle thickness parameter, discharge coefficients). Exponential theory. Plenum theory. Modified exponential theory. Performance characteristics of air cushion (total lift, cushion power, internal losses and efficiency factor for individual parts of air cushion system are discussed). Non-uniform nozzle parameters. Obstacle climbing. Two dimensional GEM in pitch. Flight over waves. Plenum - peripheral jet comparison. Some results are presented in figures: - air cushion pressure ratio as a function of nozzle thickness parameter; discharge coefficient and cushion power parameter as a function of nozzle thickness parameter and jet angle.

C.09 SOME DESIGN PRINCIPLES OF GROUND EFFECT MACHINES SECTION C - INTERNAL AERODYNAMICS
CHAPLIN, H. R., and FORD, A. C.

Illustrative compressor characteristics (pressure rise, power input, efficiency of the compressor) - theoretical analysis - equations - illustrative compressor charts. Duct losses, duct efficiency, overall internal efficiency. Some recommendations for design of the fan and ducts. Equations applicable to actual design are presented.

C.10 SOME DESIGN PRINCIPLES OF GROUND EFFECT MACHINES SECTION D - DRAG
CHAPLIN, H. R.

Wavemaking drag, hydrodynamic drag, skirt drag, external aerodynamic drag, ram or momentum drag. Drag summary. Breakdown of total drag of ACV, analysis of individual parts and equations for these parts of total drag. Propulsive power definition.

C.11 SOME DESIGN PRINCIPLES OF GROUND EFFECT MACHINES SECTION G - SEAKEEPING
CHAPLIN, H. R., and FORD, A. G.

Definition of seakeeping. Description of natural waves (simple wave, irregular wave - mathematical equations). Prediction of motions by linear superposition. Tests with Vickers VA-3 - description of the vehicle. Following results of the tests are presented: - vertical accelerations of VA-3 at bow for sea state 2 and 3 (definition of sea states is presented in tables) and for vehicle attitude to wave direction 0, 90, 180, 270° and various vehicle's speeds. - comparison of acceleration at bow and centre of gravity.
C.12 SOME DESIGN PRINCIPLES OF GROUND EFFECT MACHINES SECTION F - CUSHION CONTRIBUTION TO STABILITY

CHAPLIN, H. R.

Review of some more important elementary relationships which determine the influence of air cushion on the pitch, heave, roll stability of GEM for cases when vehicle is not in contact with surface.

Following analysis is presented:
- heave motion without water contact (heave stiffness, heave damping, wave excited heave motion, effect of wave length)
- pitch and roll motions without water contact (pitch stiffness, pitch damping, pitch natural frequency, roll stiffness, roll natural frequency).

Equations of these characteristics of motion are presented and some examples given.

C.13 THE DEVELOPMENT OF MULTICELL PLENUM CONCEPT

CHAPLIN, J. B.
(Bell Aerosystems Co., AIAA Paper No. 64-188, Wichita, Kansas, May, 1964)

Short review of the plenum concept history. Performance analysis: lift, equation for required HP is given, wave drag overall. Design: description of experimental vehicle SKMR 1, lift unit, propulsion unit, wheel system (and its contribution to directional stability, yaw control and sideforce), control system, skirt. Structural analysis: summary of loads and criteria, lift unit analysis. Description of development, first trials and demonstrations. Driving experience is mentioned.

C.14 GEM RESEARCH AT THE UNIVERSITY OF KANSAS

CHOLLASIMENOS, C. J.
(University of Kansas, Nonr - 4201 (00), December, 1965)

Description of GEM III research vehicle. Description of flight experience with GEM III. Presentation of tethered flight experiments - base pressure has been measured for various conditions (various obstacles, power of engines, two values of hoverheight) in the front part of base and the back part. Flight simulator development. Drift stabilizer development. Flexible understructure investigations:
- attempts to develop a flexible understructure for installation on GEM III
- search for new type of amphibious skirt (skirt system combined from rigid and flexible materials)
- theoretical investigations of common structural problems (static stability of flexible nozzle structures)

Theoretical investigations of low-speed overland turning manoeuvres of a GEM III.
C.15 HEAVE DYNAMICS OF FLEXIBLE - BASE FLUID SUSPENSIONS.
CAPTAIN, K. M., and RICHARDSON, H. H.

Introduction to flexible base (skirt) problems. Analysis of simple flexible skirt suspension - introduction of assumptions and basic equations. Static characteristics of flexible skirt plenum suspension (frequency of heave oscillation). Dynamic performance - transfer characteristics of vehicle and suspension (height, variation, passenger acceleration). Behaviour over deterministic irregularities and over random irregularities. Analysis of damped flexible skirt plenum:
- description and assumptions, heave motion analysis, effect of suspension parameters on vehicle acceleration and height variation, optimum dynamic performance. Transverse support pads:
- description, static behaviour, analysis of dynamic performance over sinusoidal and random irregularities. Experimental results:
  - description of dynamic test stand, tests and results presentation (dimensionless cushion pressure distribution, hoverheight as function of the dimensionless cushion pressure, flow per unit area as a function of cushion pressure, pumping power as a function of hoverheight and cushion pressure, dynamic stiffness and phase angle for various frequencies of rigid plenum and flexible skirt suspension).

C.16 STATIC AND DYNAMIC BEHAVIOUR OF A FLEXIBLE BASE FLUID SUSPENSION
CASEY, B. L.

Static and dynamic analysis of the air bearing - Analysis of float limit conditions. Experimental testing - description of experimental apparatus and tests. Experimental and theoretical parameters comparison. Following data were measured:
  - plenum pressure distribution, theoretical and experimental diaphragm shapes, floating height, unit load. The computer program is presented and its description.

C.17 POWERED LIFT MODEL TESTING FOR GROUND PROXIMITY EFFECTS
COLIN, P. E.
(Training Centre for Experimental Aerodynamics, Rhode - Saint Genese, Belgium, T.N. 14, October, 1963).

Experiments with single and double jet models representing VTOL configurations and an Air.Cushion Vehicle model. Model and apparatus descriptions (four models of simplified VTOL and one model of ACV). Experimental results are presented in figures (pendulum and wind tunnel tests). The following data are presented:
  - ground suction characteristics relative to jet coefficient $C_j$ and hoverheight/diameter of nozzle ratio for VTOL models.
  - centre of pressure position relative to jet coefficient and hoverheight/diameter ratio.
  - surface flow visualization
  - lifting force on base of ACV model with relative wind/static force on base of ACV ($L/L_s$) relative to jet coefficient and hoverheight/
ACV base diameter (h/Dg) for pendulum and wind tunnel.
- position of centre of pressure of ACV model relative to jet coefficient and h/Dg ratio
- visualization of the ground flow.

C.18 AIR CUSHION VEHICLES IN THE CANADIAN NORTH
COOPER, P. F.  
(Northern Co-ordination and Research Centre, Dept. of Northern Affairs and National Resources, Ottawa, August, 1965, NCRC-65-3)

Author's opinions on the ACV as ground transport vehicle in Canadian North. Analysis of climatic conditions (wind, temperatures, visibility, etc. in summer and winter) and roughness of the terrain and rivers, lakes, sea - general analysis by references. Author emphasizes a few design problems.

C.19 PROBLEMS ASSOCIATED WITH USE OF SKIRTS ON HOVERCRAFT
CRAGO, W. A.  
(Hovering Craft and Hydrofoil, Aug, 1968)

Reasons for the skirt and improvements achieved by use of the skirts. Problems connected to the use of skirts on hovercraft:  
The problem of internal pressure and running over water (Vehicle weight/bag pressure ratio). The problem of plough-in and overturning-definition of terms, analysis of plough-in (in two dimensions) and factors affecting plough-in and overturning, effect of deceleration on plough-in, plough-in under free running conditions, low speed overturning under constant speed conditions and under dynamic conditions - various data on these phenomena are presented in diagrams from theoretical and experimental investigations. The problem of skirt oscillation and wear - both - low and high frequency oscillation; and factors affecting delamination time are discussed.

C.20 THE BHC CONTRIBUTION TO HOVERCRAFT DEVELOPMENT
CREWE, P. R.  
(Hovering Craft and Hydrofoil, March 1969)

Survey of ACVs designed and constructed by BHC and specifications of individual types, comparison of DOC. Growth of ACV production in BHC. Technical contributions made by BHC (Twelve major technical contributions are cited: peripheral skirt improvements, flexible cushion compartmentation, skirt lifters, swivelling pylons, side ports, plenum feeding of the engine, fingers, large air propellers, antiplough compartmentation, etc). Discussion of individual improvements with particular emphasis on skirt improvements. Environmental trials and military activities - location, date, role, type of the vehicle. Operations in different parts of the world. Landmarks in the story of BHC vehicles. Analysis and prediction of future possibilities.
C.21 RESEARCH ON ANNULAR NOZZLE G.E.M. OPERATING OVER WATER. ANNULAR DISTRIBUTION OF JET MOMENTUM
CUMMING, J. D.
Experiments with an annular nozzle G.E.M. model over water. Description of the model and the test facilities. Theoretical equations for jet momentum, lift, drag (wave making resistance), and pitch moment are given. Wave making resistance versus Froude Number is measured for four values of hoverheight within 0.25 to 1.5 ins. Comparison of wave making resistance of the annular nozzle experimental results with Haverlock theory and square box tests by Abraham. Influence of the base pressure on wave making resistance. Pictures of the surface configuration of the water beneath the annular nozzle for different forward speeds of the model and various base pressures along the centreline of the G.E.M. model.

C.22 THE STATIC PERFORMANCE OF GROUND EFFECT MACHINES WITH ASPECT RATIOS OF 1/3, 2/3, 1-1/2 AND 3.
CURTIS, E. S. and CHODOFF, M. W.
(Hydronautics, Incorporated, T.R. 011-6, December, 1964)
Description of the models. The following data are measured:
- influence of pitch angle on the lift coefficient (variables: pitch angle ($\theta$), nondimensional height of the vehicle model above ground ($\bar{H} = H/t$), and the aspect ratio of model ($A$))
- influence of pitch angle on the pitching moment coefficient (variables: $\bar{H}$, $\theta$, $A$)
- influence of pitch angle on the centre of pressure location (variables: as above)
- influence of height on the moment curve slope at zero pitch
- comparison of experimental results and theoretical predictions for lift coefficient, pitch moment coefficient. (used theory: Thin Jet Theory - see Ref. 2 in report).

C.23 INVESTIGATION OF THE FREE FLIGHT CHARACTERISTICS AND HANDLING QUALITIES OF A GROUND EFFECT MACHINE
CARTER, A. W., and PERSON, L. H. Jr.,
(NASA TN-D 3885, April 1967)
Vehicle description. The following results of the experiments are presented: longitudinal and lateral stability characteristics (rolling and pitching moments as a function of roll and pitch angle). Time history of the response of the vehicle to a control longitudinal and lateral pulse disturbance. Time history of the response of the vehicle to a directional control step input during hovering. Time history traces of control movements and vehicle motions during hovering operation (pilot's first flight and after short period of familiarization). Effect of pitch and roll angle on hoverheight. Control system of the given vehicle is classified as poor. Deceleration and acceleration of the vehicle are not considered as acceptable. The vehicle is judged as not suitable for overwater operations.
D.01 STATIC FORCE OF SEVERAL ANNULAR JET CONFIGURATIONS IN PROXIMITY TO SMOOTH AND IRREGULAR GROUND
DAVENPORT, E. E., KUHN, R. E. and SHERMAN, I. R.

Description of model and apparatus. The following data were measured:
- thrust in ground proximity to thrust of free jet (ground plate removed) versus h/D ratio (height above ground/diameter of annulus) for several values of Aj/Ab ratio (jet flow area/nozzle base plate area) for circular and elliptical configurations.
- Tm/Tc (thrust measured/thrust calculated) versus h/D ratio for various configurations of circular shape.
- Tm/Tc of circular annular jet over edge of a cliff.
All measurements were done at zero forward speed.

D.02 EFFECT OF GEOMETRIC VARIATIONS ON LIFT AUGMENTATION OF SIMPLE PLENUM CHAMBER G.E.M.
DAVENPORT, E.E.

Investigation of effect of some variations in plenum chamber geometry on lift augmentation. These variations are:
- ratio of plenum chamber depth to plenum chamber diameter (optimum between 10 and 15% of D)
- ratio of inlet diameter to plenum chamber diameter (optimum about 15%)
- effect of multiple inlet on lift augmentation
- effect of flared inlet and turning vane assembly on lift augmentation

Description of model and apparatus.
E.01 BASIC PRINCIPLES OF THE STABILITY OF PERIPHERAL JET GROUND EFFECT MACHINES
EAMES, M. C.
(IAS Paper No. 61-71, Jan, 1961)

Initial assumptions, and description of basic model. Unbalanced jet operation (overfed and underfed conditions), heave and pitch equations, equations of motion (dynamic equations), forced oscillations, non-linear effects, effect of a central jet, effect of double jets, momentum variation and jet thickness.

E.02 HOVERCRAFT DESIGN AND CONSTRUCTION
ELSLEY, G. H., and DEVEREUX, A. J.

Guide to design of ACV. Basic principles and equations. Book is divided into following sections: cushion performance, internal aerodynamics (ducts, fans, compressors), drag, propulsion, performance criteria, control and stability, hovercraft economics, basic requirements of structural design, weight and its reduction, materials, design of transmission, skirt design, vibration, systems testing, design of structure for vehicle's overall strength and for internal loads. Two design cases are presented as well.

E.03 A VISCOUS FLOW ANALYSIS FOR THE QUASI-STATIC PRESSURE-FLOW-DISPLACEMENT CHARACTERISTICS OF PERIPHERAL JET FLUID SUSPENSIONS ERCAN,Y., and RICHARDSON, H. H.

Introduction to problems of peripheral jet system. Comparison between inviscid theories and experiments for equilibrium and unbalanced peripheral jet, definition of flow conditions. Inviscid velocity distribution theory for balanced (equilibrium) and unbalanced (overfed, underfed) jet - basic equations, and analysis of the flow. Viscous theory for the balanced jet - relations for a submerged and a semicontained wall jet. Application of submerged jet and wall jet relations to peripheral jet analysis - momentum balance for viscous peripheral jet. Viscous theory for overfed and underfed jet. Presentation of analytical procedures and computed results for viscous theory (dimensionless cushion pressure versus hoverheight, dimensionless cushion flow versus cushion pressure for various hoverheight/jet thickness ratios and jet angles; flow-pressure sensitivity for peripheral jets and flow-height sensitivity). Experiment correlated with theoretical results. The computer program for the complete wall jet solution is presented.
E.04 EXPERIMENTS ON THE SKIRTED HOVERCRAFT RUNNING AT ANGLES OF YAW WITH SPECIAL ATTENTION TO WAVE DRAG
EVEREST, J. T., and WILLIS, R. C.
(National Physical Laboratory, Ship Division, Ship Rep. 119, Nov, 1969)

Towing tests of a skirted hovercraft model running at various angles of yaw. Wave making resistance, forces and moments acting on the model and hoverheight were measured. Description of model. Two model weight, fan speed, yaw angle in the range 0° to 60° and Froude Numbers from 0.4 to 0.8. Comparison of experiments and theory. Wave drag is presented in figures as a function of Froude number, yaw angle, weight of model and fan RPM. Side force, yaw moment, roll angle, trim angle are presented in figures as a function of yaw angle, Froude number, model weight and fan RPM, as well.

E.05 THE POTENTIAL OF AN AIR CUSHION LANDING GEAR IN CIVIL AIR TRANSPORT
EARL, T. D.
(Canadian Aeronautics and Space Journal, Nov, 1968)

Description of the concept. Experience with the LA-4 with an Air Cushion Landing Gear; description of the installation. Scaling on the base of LA-4. Effect of ACLG on operations (rough runway, water, cross wind), transport efficiency of the aircraft, field length, payload, and profit.
F.01 EXPERIMENTAL INVESTIGATION OF THE EFFECT OF STABILIZING NOZZLE WIDTH ON THE HOVERING STABILITY AND PERFORMANCE OF A CIRCULAR GEM MODEL
FINK, M. D.

Model (circular, annular jet GEM) and test procedure description. The following results are presented:
- effect of secondary nozzle (compartmentation and inner annulus nozzle) width on pitch stability for various hoverheights (up to that height at which the model was unstable in any attitude).
- effect of pitch angle on model height (various widths of secondary nozzle).
- variations of the ratio of cushion loading to total pressure with diameter/height ratio and width of secondary nozzle ratio.
- variation of base pressure/total pressure ratio with nozzle width/height ratio (comparison with theory)
- effect of secondary nozzle width on required power

F.02 THREE NOTES ON PROPULSION AND BRAKING OF TUBEFLIGHT VEHICLES
FOA, J. V.
(Rensselaer Polytechnic Institute, Troy, N. Y., March, 1968, PB 177 520)

Note TR AE 6707: Tubeflight Propulsion by Bladeless Fan

The principles of bladeless propulsion. An analytical model. Analysis of the interaction. Power requirements. Some results of analytical calculations are presented in graphic form (secondary mass flow/primary mass flow for various values of spin angle and density ratios; power input factor for bladeless fan as a function of spin angle, density ratio, etc.)

Note TR AE 6802: Power Demands of Tubeflight Vehicles

A review of references related to power demands of tubeflight vehicles. Operating conditions and dimensions of vehicle and test data considered in analysis. Drag of the body (unchoked body) - frictional drag, pressure drag. Total parasite drag of unchoked and choked flow. Drag due to flow. Required power. Results of calculations of the drag of the body and the required power are presented in graphic form.

Note TN FT 6801: Preliminary Evaluation of the Braking Capabilities of Tubeflight Vehicles.

Equation of the braking force; the increment of braking force due to flow separation. Maximum initial braking force.
F.03 AIR CUSHION MONORAIL DEVELOPMENT
FORD, T.
(Hovering Craft and Hydrofoil, June 1968)

Introduction of the URBA principle. Propulsion of URBA. Description of the URBA 4 experimental vehicle. Future plans with URBA (URBA 20, URBA 100)

F.04 A STUDY OF WINDS AND BLOWING SNOW IN THE CANADIAN ARCTIC
FRASER, W. C.
(Department of Transport, Meteorological Branch, 315 Bloor St, W., Toronto 5, Ont. CIR-4162, TEC-548, Dec, 1964)

Location of 15 arctic weather stations (latitude, longitude and height above MSL) on which all data have been measured. Definition of the terms (blowing snow, wind, etc). Frequency of blowing snow. Relation of wind speed and direction to the occurrence of blowing snow. Visibility. Summaries of individual stations. Measured data are presented in figures:
- percentage frequency of blowing snow, by months (January - peak of blowing snow)
- percentage frequency of winds by directions and by specified speed groups
- percentage frequency of winds in specified speed classes which cause blowing snow
- percentage frequency of visibility 6 mi. or less
- percentage frequency of specified visibilities in blowing snow for three wind speed groups
G.01 EFFECT OF GROUND BOARD BOUNDARY LAYER ON AIR CUSHION VEHICLE WIND TUNNEL TESTS
GARAY, E. K.
(Institute for Aerospace Studies, University of Toronto, UTIAS T. N. No.100)

Description of the model and the test facility. Measured:
- lift coefficient ($C_L$) as a function of tunnel dynamic pressure/jet dynamic pressure ratio ($q/q_j$), angle of attack ($\alpha$), nondimensional hoverheight parameter ($h/D_{eq}$).
- comparison of measured lift with theory (Boehler), and light line tethered tests of the same model
- lift components of a complete ACV
- augmentation factor measured for various hoverheights
- comparison of ACV lift measured with and without a ground board boundary layer
- lift coefficient as a function of the jet momentum coefficient
- pitching moment coefficient ($C_m$) for various angles of attack and hoverheights as a function of $q/q_j$
- horizontal force coefficient ($C_x$) for various angles of attack of hoverheight as a function of $x/q_j$ (Drag).

In appendices: dimensions and characteristics of the model; and notes on the use of model aircraft engines for wind tunnel testing.

G.02 STUDIES OF GROUND EFFECT ON AN INWARDLY INCLINED ANNULAR JET.
PART I: APPARATUS AND METHOD OF TESTING: EFFECT OF ASPECT RATIO AND PRESSURE RATIO
GARLAND, D. B.
(Institute of Aerophysics, University of Toronto, UTIAS Tech. Note No.37, August, 1960)

Test of a $\theta = -60^\circ$ inwardly inclined annular jet over a wide range of jet exit areas, pressure ratios and heights above ground. Presentation of non-viscous theory of the annular jet, close to the ground, for thin and thick, high and low aspect ratio annular jet - presentation of the basic equations (augmentation ratio, thrust). Description of the test facility, the apparatus and the methods of testing. The following data are presented:
- effect of nozzle pressure ratio on the augmentation ratio for various nozzle aspect ratios and heights above ground
- effect of ground proximity on the augmentation ratio for several nozzle pressure aspect ratios (a comparison with theory)
- effect of jet thickness parameter and aspect ratio on the augmentation ratio for several values of nozzle aspect ratio and nozzle pressure ratio
- augmentation ratio for focussed and unfocussed annular jet
- flow patterns.
G.03 A CRUDE THEORY OF HOVERCRAFT PERFORMANCE AT ZERO TILT
GATES, S. B.
(Royal Aircraft Establishment, T. N. No. Aero 2800, No. 1961)

Assumptions of crude model flow. Two-dimensional circular jet approximations - presentation of several simplified solutions and their discussion. Results for unit length of the jet annulus (thrust, mass flow, momentum drag, power required). Performance estimate - lift, drag, lift/drag ratio, power required, mass flow, and jet velocity. Discussion of power, geometric, and aerodynamic parameters. Optimum P/WV (Total Power Required/Weight x Forward speed) parameter, and the effect of $p_o/q$ (mean pressure over the outer surface of jet/dynamic pressure) ratio upon this parameter. Examples of performance estimates - design for minimum power and off design performance (speed variation at the design height, height variation at the design speed).

G.04 WIND - TUNNEL TESTS OF SEVERAL DUCTED PROPELLERS IN NON-AXIAL FLOW
GILL, W. J.

Description of models, test apparatus and procedure (four 2 ft. diameter duct shapes and three different sets of contra-rotating propellers were tested). The following measured characteristics are presented:
- variation of ducted propeller static force and power coefficients with blade angle ($\beta$) for various settings of RPM and variation of these coefficients with tilt angle
- variation of ducted propeller power coefficient and efficiency with tilt angle ($\alpha$) and variation of ducted propeller force and moment coefficients with tilt angle (for various $\beta$ settings)
- variation of ducted propeller force and moment coefficients with advanced ratio ($\lambda$) for various $\alpha$ and $\beta$ settings
- variation of duct force and moment coefficient with tilt angle ($\alpha$) for various $\beta$ and $\lambda$ (Variation of $\alpha$ within 0 to 90°).

G.05 THE AEROTRAIN SYSTEM: AIR CUSHION GUIDED GROUND TRANSPORTATION: DESCRIPTION AND PERFORMANCE OF THE EXPERIMENTAL VEHICLE.
GIRAUD, F. L.
(Aeroglyde Systems Incorporated, N. Y., 1968, pB 178 961)

Description of the experimental vehicle, its performance (max. speed with rocket booster 215 mph) - deceleration, and acceleration. Curves for various means of propulsion. Vertical and transverse accelerations for different suspensions, and propulsion systems. The vehicle's behaviour at high speed and in curves (i.e., the vehicle's response to impulses in the vertical and transverse directions). Breakdown of the vehicle's drag (air gap, friction, and form drag) and power requirements. Suspension and guidance of TACV (feeding system, load factors and stiffness for suspension and guidance, behaviour of air cushion suspension). Limiting speed (theory and experiment). Noise level of air cushion. Track characteristics - general description, track-vehicle interactions, track specifications and tolerances. Techno-economic model of the system cost functions, vehicle characteristics, and transportation service characteristics.
A comparative study of alternative designs of the guideway -
functional comparison of cross sections (inverted T, double L, and box),
economic comparison of guideway cross sections. Functional comparison
of three alternative suspensions, description, and transfer functions.
The problem of suspension and the merit of an active suspension - ob­
jectives of their design, optimization, the need for an active system,
the means of activation (i.e., control of an activated suspended lip)
and the suspension response to signals. Functional comparison
of the propulsion means - general evaluation of requirements, types of
propulsion, noise level evaluation, and general evaluation of braking
system capacities. Design study for the recommended track and vehicle -
specification and performance of experimental vehicle and suspension
(basic parameters of the recommended vehicle). Specification and cost
estimate of the guideway.

Lift augmentation characteristics have been measured for various jet
area/total area ratios, and jet pressure/base pressure ratios.
Augmentation increases as the area ratio is reduced to 0.10. The
effect of the pressure ratio on lift is negligible. Pitching moment
characteristics have been determined through an angle of attack range
(the vehicle was unstable at ratios of hoverheight/nozzle diameter
about 0.10). The effect of angle of attack on lift and drag, plots
of total pressure/atmospheric pressure ratio versus height above
ground/nozzle diameter and annular jet area/total area are presented.
The nondimensional lift parameter (L/mV) is plotted against the
same variables as well. The lift per air horsepower at the exit as
a function of area ratio, and hoverheight ratio, the effect of the
centre jet's size on lift augmentation, the effect of the centre jet
and the inner annulus on static aerodynamic characteristics (pitching
mom., drag, and lift) for various angles of attack (variables: centre
jet configuration and dimensions, angle of attack) and the effect of
hoverheight ratio and angle of attack on pressure variation across
base are given.

Description of the model (GETOL) - construction, specifications and
performance - model calibrations (pressure rise across fan, RPM, inlet
mass flow, propulsion duct thrust and mass flow, exit jet mass and
momentum flow and fan efficiency). Augmentation curve for the model.
Comparison of the augmentation as a function of height above ground/
equivalent diameter of circular model ratio \((h/D_e)\), for four models with theory. Curves of pitching moment versus angle of pitch for several models and several values of \(h/D_e\) ratio. Static thrust versus angle of pitch. Pitch angle versus time (frame number) for several \(h/D_e\) and several runs - comparison of experimental results and analogue solutions. In appendices are presented: model data and derivation of augmentation factor for inviscid 3 dimensional thick-jet flow.

G.09 LARGE-SCALE WIND-TUNNEL TESTS OF A CIRCULAR PLANFORM AIRCRAFT WITH A PERIPHERAL JET FOR LIFT, THRUST AND CONTROL
GREIF, R. K., and TOLHURST, W. H. Jr.,

Description of the model and the apparatus. The following data were measured: \(C_L, C_D, C_m\) coefficients at the maximum and minimum test heights (power off)
- \(C_L, C_D, C_m\) as a function of jet momentum coefficient and free stream dynamic pressure
- \(C_L, C_D, C_m\) of the hover configuration for various ground heights and longitudinal control positions and jet momentums
- effect of ground height upon \(C_L, C_D, C_m\)
- \(C_L, C_D, C_m\) of the transition configuration (various transition control positions and jet momentum coefficients)
- \(C_L, C_D, C_m\) of the cruise flight configuration at various ground heights and jet momentum coefficient
- \(C_L, C_D, C_m\) of the cruise flight configuration without trail and with flaps on the control vanes (various \(C_j\))
- effect of angle of attack on \(C_L, C_y\) (side force coefficient) and \(C_n\) (yawing moment coefficient) for various \(C_j\) and transition control positions, with and without rotor intake guide vanes
- effect of lateral control position

G.10 GROUND EFFECT MACHINES (GEM), VOLUME I
(Defence Documentation Centre, Alexandria, Virginia, April 1970, AD-704 800)

Bibliography covering the years 1960 to Sept, 1969. Individual parts of the report present:
- list of reports by date of issue with a short review
- corporate author index
- subject index
- title index
- personal author index

G.11 AERODYNAMIC CHARACTERISTICS OF VEHICLE BODIES AT CROSSWIND CONDITIONS IN GROUND PROXIMITY
GRUNWALD, K. J.

Description of the models (cross sections: circular, square, triangular, half circle, half circle with short and long extended sides) and the test apparatus. Testing over a moving ground plane a fixed ground belt, and image model testing. The following tests were conducted with a moving
ground plane: - the effect of cross section shape, angle of sideslip (β), and effective height above simulated track, on: pitching moment, yawing mom, drag, lift and side force coefficients (zero angle of attack α)

- stability derivatives (C_L/α, C_m/α, ΔC_L/Δα ) as a function of cross section, β, effective height. The effect of ground simulation (moving belt, stopped belt and image model) on C_L, C_D, C_Y, C_m, C_n of circular, square and half circle model configurations for several values of effective height, with α = 0°. The effect of ground height on the aerodynamic characteristics of circular, square, triangular and half circle configurations with moving and stopped ground belt (α = 0°). The effect of angle of attack on the aerodynamic characteristics of circular, square, triangular and half circle configurations with moving and stopped ground belt. The effect of the height on the aerodynamic characteristics of circular, square, triangular and half circle configurations by use of the image model ground simulation technique.

G.12 AERODYNAMIC CHARACTERISTICS OF AIR CUSHION MODELS AT VERY LOW GROUND CLEARANCES AND AT FREE - STREAM DYNAMIC PRESSURES EXCEEDING CUSHION PRESSURE
GRUNWALD, K. J., and JOHNSON, W. G. Jr.,
(NASA TN D-6011, Oct, 1970)

Wind tunnel investigations of peripheral jet and plenum cushions of circular, rectangular and side-by-side rectangular planform models. Description of the above mentioned models and the test facility. Comparison of cushion effectiveness (p_c/H) of all three models with exponential theory at zero forward speed, effect of various model configurations. The following results are presented: - effect of forward speed on the aerodynamic characteristics of the circular model (peripheral jet and modified plenum) lift, drag, pitching moment, cavity and plenum.
- effect of the moving, and stopped belts resp.,
- effect of hoverheight and angle of attack
- effect of forward speed on the aerodynamic characteristics of the rectangular model (peripheral jet, modified plenum)
- pressure coefficient, along centreline of cushion
- effect of sideslip (roll, yaw, side force)
- effect of the moving belt
- effect of forward speed on the aerodynamic characteristics of the side-by-side model (flat bottom and contoured channel configurations)
- effect of angle of attack, sideslip, etc.

Comparison of longitudinal aerodynamic characteristics of a powered air cushion with an unpowered cushion. Discussion of the results.
H.01 SOME TESTS ON A CIRCULAR GROUND EFFECT MACHINE WITH FORWARD SPEED
HARRIS, T. M., DAVIES, J. H. and ALEXANDER, A. J.
(The College of Aeronautics, Cranfield, Co. A Note 133, October 1962)

Model and experimental method description. The following data were measured:
- variation of lift augmentation with height and forward speed (wind speed)
- variation of jet thrust with height and windspeed
- variation of lift augmentation with momentum coefficient
- variation of base static pressure with wind speed
- variation of base static pressure with angle of incidence
- flow visualization for V from 0 up to 200 fps. All experiments were conducted in a wind tunnel.

H.02 SOME EXPERIMENTAL MEASUREMENTS OF PITCH AND HEAVE MOTIONS OF DTMB GEM MODEL 463 IN FLIGHT OVER REGULAR FOLLOWING WAVES
HARRY, C. W., and MAGUIRE, W. B.

Description of the model and the apparatus. The following results are presented:
- pitch and heave amplitude ratios versus excitation frequency ratio for wave heights of 2 in. and nominal model altitudes of 8, 6, and 4 in. and for wave lengths 10, 15, 20 and 28 ft.

H.03 A LITERATURE SURVEY ON THE AERODYNAMICS OF ACV
HARTING, A.

Classification of ACVs - basic principles described. Annular jet principle analysis; augmentation ratio definitions. Theories for the calculation of base pressure, total lift and augmentation ratio (two-dimensional non-viscous approximate theories; the thin non-viscous curved jet theories; the thick non-viscous curved jet theories; two-dimensional non-viscous exact theory; two-dimensional viscous approximate theory; two-dimensional viscous exact theory). Mutual comparison of the two-dimensional theories. Three-dimensional non-viscous approximate theories, and three-dimensional viscous approximate and exact theories). Experimental investigations on the influence of primary parameters are presented in figures (hoverheight, pressure ratio at the nozzle exit, jet angle, jet thickness).
Theoretical and experimental investigations on the influence of some secondary parameters are presented as well (planform, jet segmentation, special nozzle configurations, duct convergence). Non-horizontal hovering flight overland and forward flight overland - some equations, and some experimental and theoretical results are presented in figures. Hovering and forward flight over water - equations and some results in figures. Flexible jet extension, skirt, - basic principles and types. Stability - basic principles. Plenum chamber - basic principles and equations. Labyrinth seals sidewall, ram wing, and diffuser are mentioned. Large list of references.
H.04 HOVERING CRAFT OVER WATER
HOGG, N.
(National Physical Laboratory, Ship Division, SHIP T.M. 119, April 1966)

Review of existing ACV principles and their definition. Calm water behaviour of the vehicle - air pressure on water surface - wavemaking - shallow water wavemaking - wave resistance equations and theoretical diagrams - wave elevation equations - measured and computed wave profiles. Peripheral jet equations, jet profile over solid surfaces, water, and influence of forward speed. Skirt of the vehicle. Propulsion system efficiency.

Rough water behaviour - basic dynamics (and basic definition of terminology - heave, surge, sway, etc). Equations of heave motion. Rough water performance. Plots of wave height as function of place and wind speed. Comparison of hovercraft and hydrofoils.

H.05 ANALYSIS OF HIGH-SPEED PERIPHERAL JET FOR ACV APPLICATIONS
HOPE-GILL, C. D.

Reasons for higher cushion pressure are mentioned - it means, increasing peripheral jet speed. Description of the theoretical model. Analysis and presentation of the basic equations for compressible flow through a nozzle. Variation of jet thickness ratio with Mach number and hoverheight/nozzle width ratio. Variation of jet thickness on the ground with jet angle and hoverheight/nozzle width ratio. First and second power coefficients - their definition and variation with jet thickness, jet Mach number (on ground) and height/jet thickness ratio. The effect of jet Mach number and flow angle on power coefficients is discussed. Pressure recovery; the effect of Mach number, and jet angle, - comparison of the theoretical results with experiments.

H.06 ON THE FLEXIBLE FLAP DAMPER FOR AIR CUSHION VEHICLES
HSU, C. C.
(Hydronautics Incorporated, T.R. 347-1, May 1964)

Approximate analysis of the general dynamic characteristics of a two-dimensional air cushion craft with hinged flexible flaps. Mathematical analysis is performed and the equation for dimensionless heave response is presented as a function of seven essential variables (mass ratio per unit length, damping coefficient, forced frequency ratio, natural frequency ratio, dimensionless radius of gyration and dimensionless parameters $r_1, r_2$). Several figures of heave response as function of the above mentioned variables are presented.

H.07 EFFECT OF REYNOLDS NUMBER ON OVERALL PERFORMANCE OF A 6-INCH RADIAL BLADED CENTRIFUGAL COMPRESSOR
HEIDELBERG, L. J., BALL, C. L., and WEIGEL, C.
(NASA TN. D-5761, April 1970)

Testing of a 6-inch diameter, radial bladed centrifugal fan over an inlet pressure range 1.5 to 8.6 psia (Reynolds Number range - $0.32 \times 10^6$ to $1.8 \times 10^6$). The design parameter of the compressor are presented for argon and air as a working fluid. Description of the test apparatus and
and the test facility. The following results are presented: - adiabatic efficiency, compressor work, total pressure ratio as a function of the equivalent weight flow for the mentioned inlet pressure range. - Variation of maximum efficiency, flow efficiency and losses with Re. No. Comparison of total pressure and fan work coefficient for various Re. Nos. The method of correlation and a comparison of air-argon overall performance is presented.

H.08 THE DESIGN OF AIR CUSHION VEHICLE AUTOMATIC AND SEMI-AUTOMATIC CONTROLS (FINAL REPORT)
HANNINGAN, F. J.
(R & D Dept, General Dynamic Corp., Electric Boat Division, Groton, Connecticut, AD 620 144, July 1965)

Design of automatic and semi-automatic controls for the following ACV configurations: - propeller fore and aft of the c.g.; - propeller located behind the c.g.; - rudders located behind the propeller behind the c.g. Development of a mathematical model (equations of motion, five degrees of freedom - heave is omitted). Computer simulation of the vehicle dynamics and the controls. Design of automatic controls. The effect of wind on the automatic system. Vehicle equations of motion for a linearized model are presented in Appendix A. ACV computer computer program (for SKIP-l). Block diagrams of the automatic and semi-automatic controls. Analog computer data are presented.

H.09 THE DESIGN OF SINGLE-PROPELLER AIR CUSHION CONTROL CONFIGURATION
HANNINGAN, F. J.

Final report on a study of maneuvering control systems of an ACV with a single thrust propeller. Presentation of the mathematical model and computer simulation (as a model vehicle, General Dynamics experimental vehicle SKIP-l has been taken). The method of determination of necessary forces and moments is given. The following control configurations have been considered: hydrodynamic surface, rotatable rudder, rotatable propeller pylon - small variable pitch propeller, additional rotatable propeller, roll control, rockets, side jets, peripheral jet deflection, water jets. These configurations are discussed and some of them evaluated by analog computer. Comparison of single propeller and two-propeller ACVs. The following data are presented in appendices: data for the vehicle model, analog computer programs, mathematical representation of control configuration, computer results.
Definition of the primitive (or most basic) vehicle suspension, its analysis and performance (suspension is assumed to be in point contact with the two dimensional guideway). Externally fed fluid suspension-fundamental mechanics. Analysis includes: feeding system characteristics, pressure-flow displacement, characteristics of the sealing mechanism, flexible base or skirt behaviour. A flexible base fluid suspension is selected for detailed study of suspension performance and dynamics. Performed experiments and their results are presented. Recommendations for further research are summarized.
I.01 TECHNO-ECONOMIC ASPECTS OF HOVERCRAFT

IGGLESDEN, M. G.
(National Physical Laboratory, Hovercraft Report 6, January 1969)

A short history of ACV and their basic comparison with displacement and planing ship. Operational capabilities - speed, payload and range. The status of present technology - air cushion systems, structures, propulsion, engines, equipment. Status of present economics - breakdown of DOC (SRN6-$105 per hour - it is about 7-8¢ per seat n. mile; HM-2 $45 per hour - it is about 2.5¢ per seat n.mile). Indirect operating cost. The potential improvement in economics. An elementary analysis of DOC - analysis of present cost estimates (cost breakdown for SRN6, SRN4, HM-2). Effect of major vehicle parameters on DOC. The prospect for improved economics (equipped hull cost - less engines, and skirt, but including all systems - $35,000 BHC; this includes cost of material - aluminum - $2,500/ton).
J.01 THEORY AND EXPERIMENTS ON AIR CUSHION VEHICLES AT ZERO SPEED
JAUMOTTE, A., and KIEDRZYNSKI, A.
(Hovering Craft and Hydrofoil, Aug, 1965)

Short survey of existing air cushion configurations. Lift without forward speed for the plenum chamber, calculations of lift, augmentation ratio. Improvement of the plenum chamber (Bertin). Study of the lift of the peripheral jet without forward speed, thin jet theory (cushion pressure, nozzle pressure, augmentation ratio, analysis of the influence of hoverheight and jet inclination angle, required power, influence of the jet thickness). Theory of the thick jet. Theory with the consideration of viscous fluid (Chaplin theory - presentation of assumptions, computation of lift, augmentation ratio, etc; Shan-Fu Shen theory). Comparison of theories. Description of experimental rig and model (circular planform) and presentation of results, influence of the jet inclination angle, nozzle width, planform shape, ground pressure distribution, base pressure. Experimental methods (fixed ground and turning arm methods). Influence of forward speed on lift. Required power for lift and momentum drag (comparison of peripheral jet and plenum chamber by required power for lift). The effect of the use of flexible skirt. Preliminary design of an ACV (weight breakdown, planform, hoverheight, Stanton-Jones rules, cushion pressure and fan selection, total pressure requirement-design equations).

J.02 VEHICLE EXPERIMENTAL A COUSSIN D'AIR PV-1.
ESSAY E VOL SUR L'EAU
JAUMOTTE A., and KIEDRZYNSKI, A.
(University of Bruxelles, Rep. No. 6, DRME: No. 79-65, 1967)

A study of the flight over water of the experimental ACV PV-1. Drag versus speed is presented and its breakdown. Pictures of the vehicle travelling over water are presented for various forward speeds, but unfortunately copies of these pictures are very bad. Vehicle description and weight breakdown.

J.03 VEHICLE EXPERIMENTAL A COUSSIN D'AIR PV-1.
REPPORT DE SYNTHESE
JAUMOTTE A., and KIEDRZYNSKI, A.
(University of Bruxelles, DRME: No. 79-65, Rapp. No. 7, 1967)

Summary and guide of experiments on the PV-1 experimental vehicle of the University of Bruxelles. The vehicle's components and characteristics; evaluation and analysis.
J.04 STUDY OF THE POTENTIAL OF HOVAIR FOR HIGH-SPEED GROUND TRANSPORTATION, FINAL REPORT.
JINDRA, F.
(Research Laboratory, General Motors Corporation, Warren, Michigan, 48090, PB 177 523, March 1968)

Hovair pad description. Performance characteristics of the low speed Hovair air bearing (stationary and moving hovair, mass flow, load capacity and vertical stability). Pressure distribution for Hovair with rigid-rectangular, rigid-curved profile and flexible diaphragm and flow-minimum gap characteristics for these, were measured experimentally. Performance of the high-speed hovair bearing - flow equations (inertia terms are considered), estimation of velocity, pressure and performance corrections for the high speed Hovair. Pressure profile for the rigid-rectangular and the rigid-curved pad are computed for various speeds (0 to 300 m.p.h.). Ride comfort analysis.

J.05 RESULTS OF GEM III TETHERED TESTS
JOHNSON, A. E., and CHAPLIN, H. R.

Static tests of hovering performance, pitch and roll stability, and control effectiveness. Vehicle, test rig, and apparatus description. Test conditions. Measured data:
- performance: effect of roll and pitch angle on hoverheight
- stability: pitch and roll moments
- propulsion, braking and steering control: propulsive and braking thrust of variable chamber vanes as a function of deflection. Yawing moment produced by differential vane deflection.
- pitch and roll control: four dump valves allowing air to escape from all four parts of cushion - ineffective
- simulated jet spoiler test: effect on rolling moment and hoverheight

J.06 WIND TUNNEL INVESTIGATIONS OF THE DAVID W. TAYLOR MODEL BASIN GROUND EFFECT MACHINE MODEL 448
JOHNSON, A. E., and CHAPLIN, H. R.

Model and apparatus description. Equations for estimation of required shaft horsepower ($P_s$), total drag force/total lift force ratio ($D/L$) are presented and their results are compared with the experimental results. Corrections for the transfer of model results to the full scale vehicle are presented. The following effects were investigated: effect of compressor blade angle, hoverheight, variation of front and rear motor frequency, variation of front and rear vane deflection, pitch, side slip and roll angle, effect of variation of right or left vane deflection, and effect of variation of right or left motor frequency on: $P_s; D/L; M/L_b$ (Pitch moment/lift x length of base); $L_x V_0/P_s$. Lift and drag coefficients are measured for power-off with external flow simulation. Variation of internal flow with speed,
variation of individual motor power and RPM with speed. Example of the application of corrections to wind tunnel data to obtain performance of a hypothetical vehicle. Distribution of power between cushion and propulsion systems.


Description of the model and the test/apparatus. The following experimental data are presented in graphic form: - hovering performance (figure of merit) as a function of hoverheight parameter, - hovering static stability (pitching moment) as a function of pitch angle, hoverheight parameter and jet angle, - cruising performance (drag/lift ratio, lift and pitching moment) as a function of lift coefficient, jet angle, pitch angle, fan blade angle and hoverheight, - the effect of fan blade angle on cruising performance. A circular model with compartmentation.


Short review of the state-of-the-art of plenum chamber concept. Theory of overland operation (two dimensional phenomena). Theory of overwater operation. Discussion of the experimental investigations of overland and overwater performance. Some typical test measurements are presented. Alternative solution for overwater performance and the shape of the deformed water surface are presented in appendices.
K.01 HOVERCRAFT RESEARCH AT ROYAL AIRCRAFT ESTABLISHMENT, BEDFORD
KEILLER, I. L.
(Hovering Craft and Hydrofoil, September 1967)

Summary of research work: - The development of improved fans, performance of the fans in hovercraft, hovering efficiency - some results are presented in figures for two types of fans installed in the CC2 001 hovercraft. Cushion aerodynamics - examination of the lift performance of a variety of flexible skirt designs on a CC2 model and full scale on CC2 002. Static stability of various ACV types. The forward performance of hovercraft. Fan intake investigations. Selected experiments and their results are presented in figures.

K.02 INVESTIGATION OF THE INTERNAL AERODYNAMICS OF A MODEL HOVERCRAFT
KEILLER, J. L.
(Royal Aircraft Establishment, T. R. 68098, May 1968)

Investigation of the effect of various factors on hovering performance of an ACV. Tests have been made with a rigid jet model, but the results are shown also to be relevant to a skirted hovercraft. The model (Cushioncraft CC-2) and the test facility are described. The following tests have been done:
- effect of obstructions in the airflow on the internal aerodynamic efficiency of the model (influence of obstructions on; hoverheight (h), volume flow (Q), fan rpm and fan power ($P_f$))
- effect of plenum leaks on h, Q, rpm, $P_f$
- effect of closed stability jets on h, Q, rpm, $P_f$
- effect of fan design E1 and G1 on h, Q, rpm, $P_f$
- effect of corner blockage on h, Q, rpm, $P_f$

Some suggestions for hovercraft design with respect to internal losses are presented. Measuring of hovering, aerodynamic, and pumping efficiency for various configurations of the model.

K.03 AN INVESTIGATION OF FLEXIBLE SKIRT FOR GROUND EFFECT VEHICLES
KELLETT AIRCRAFT CORP, WILLOW GROVE, PENNSYLVANIA.
(U. S. Army Transportation Research Command, Fort Eustis, Virginia, TRECICLEM T.R. 64-18, May 1964)

Evaluation of skirt materials, skirt section shapes, various skirt arrangements and skirt types. Investigation of skirt configurations, establishing of criteria, material evaluation, and two-dimensional section tests (description of apparatus, model; results presented - obstacle forces on skirt, and deflection of skirt). Full-scale GEM skirt tests - description of apparatus and tests, results presented - acceleration, deflection of skirt (fingers), and stability of vehicle. Analysis of the performance of the vehicle with a finger skirt, and analysis of the vehicle's dynamics.
K.04 AERODYNAMIC CHARACTERISTICS OF ANNULAR JET FLOW OVER SCREEN

KHANZHONKOV, V. I.

Six nozzle devices were tested (jet angles: 0°, 30°, 45° nozzle widths: 8, 20, 25 mm). Layouts of investigated devices and experimental rig and their description. The method of processing test results is presented. The effect of Reynolds Number on pressure and flow rate coefficients (no Re. No. effects due to changes of the jet velocity within the limits 5 to 35 m/sec. on pressure and flow rate). Measured the influence of nozzle width/hoverheight ratio (b/h) on pressure and flow rate coefficients; distribution of pressure over the bottom of an annular nozzle (variables: b/h angle of incidence (α), jet angle (θ), nozzle width/base diameter (b/Db)). An increase in the inclination angle of the nozzle leads to a noticeable pressure rise in the central part of the bottom and to some degree a pressure reduction on the periphery. Distribution of pressure over the screen is presented (variables: b/h, θ, b/Db).

K.05 CALCULATED PARAMETERS OF AIR CUSHION DEVICES WITH NOZZLE DEVICE AT HOVERING CONDITIONS

KHANZHONKOV, V. I.

Proposed a method of calculating parameters for an Air Cushion Vehicle with a double-jet arrangement, in the free hovering regime: power in the airstream, the required shaft fan horse power; lift coefficient; pressure coefficients, flow coefficients of the inner and outer nozzles. Comparisons of theoretical and experimental results are given for pressure, flow and lift coefficients.

K.06 SUPPLEMENTARY LIFT FOR AIR CUSHIONED VEHICLES, VOLUME II OF III. DATA ANALYSIS.

KIRCHBAUM, N., and HELGESEN, J.

A wind tunnel study of supplementary lift for ACVs. Model described (airfoil cross-section; rectangular planform). Test program presented. Required SHP presentation, breakdown, and equations. Basic aerodynamic data for models with aspect ratios 0.83 and 1.25 are presented (C_L, C_m, C_D). The following data were obtained by tests: lift coefficient (C_L) and free stream velocity/velocity of the jet at the nozzle exit when expanded to atmospheric pressure (V/Vjo) as a function of the blowing coefficient (C = mVjo/qS; where m = mass flow) for a number of configurations. Hover lift/Shaft HP versus base loading for various configurations of model geometries and hoverheights. Mass flow distribution with different nozzle thicknesses; the effect of different mass flows in acceleration and deceleration.
A short survey of experimental techniques. Description of the experimental apparatus and model development. Reduction of film data and film analysis are presented. Development of the equations of motion of the vehicle and estimation of cable effects on the vehicle's. Air reactions and ground effect impacts. Derivative extraction technique is presented.

In appendices:
- general equations of motion
- theoretical evaluation of some aerodynamic derivatives
- scaled analogue equations of motion

In Tables:
- the nondimensional system
- experimentally extracted derivatives

Experimental results are presented and their comparisons with computer simulation. Comparison of the derivatives of motion by experiments and simulations.
L.01 HEAVE RESPONSE OF A PLENUM AIR CUSHION INCLUDING PASSIVE AND
ACTIVE CONTROL CONCEPTS
LEATHERWOOD, J. D., and DIXON, G. V.

An analytical and experimental investigation of the heave response
caracteristics of a open-plenum air cushion suspension to simulated
guideway inputs. Experimental apparatus described. Mathematical
analysis of the heave response of a simple plenum air cushion to
simulated guideway irregularities. The equations of motion are
presented. An analog computer is used for solving heave response
and for control analysis. Passive and active control devices;
introduction and analysis. Analytical and experimental steady-
state displacement response characteristics of the air cushion
to small disturbances, and to large disturbances.

L.02 OPERATIONAL ENGINEERING PROBLEMS CONNECTED WITH COMMERCIAL
HOVERCRAFT OPERATIONS
LEFAUX, J., M.
(Air Cushion Vehicles, The International Hovercraft Journal,
September, 1970)

Experience with the operations of the SRN4. Lists important events
in hovercraft history. Reliability of service (SRN6, SRN4). Problem
of the skirt and its material - major tear of the skirt. Jacking
system. Engines (salt water problem - turbine blades). Structure
(reinforcing of bow and stern). Airscrews (blade protection problem-
every two or three weeks change of erosion strips). Controls.
Problems and solutions (heating and ventilation, noise-rattling
doors and fittings). Workshop support. Engineering staff.

L.03 A NOTE ON SOME STATIC TESTS OF FLEXIBLE SKIRT FOR HOVERCRAFT
LESTER, W.G.S., and KIERNAN, F. T.
(Ministry of Technology, Aeronautical Research Council Current
Papers, C.P. No. 990, London 1968)

Description of the test rig and skirts. Static tests were conducted
with various types of skirts and various modifications. Comparison
of theory and experiments - \( \frac{p_c}{H} \) ratio was measured for various \( h/t \)
ratios of three basic types of skirts (parallel nozzle card skirt,
Investigation of the influence of cut back in the inner wall of
the skirt, - cushion pressure versus horsepower curves. Comparison
of the main types of skirts (p, versus horsepower/sq. ft. exit area).
Comparison of the performance of the same fabric skirt and two different
hull configurations. Important results of the experiments: power
per unit exit area is directly proportional to the cushion pressure:
\( p_c = \lambda \left( \frac{P}{1h} \right) \), where l is jet length, h height of the nozzle above
ground, \( \lambda \) depends on nozzle - skirt - hull configuration.
L.04 TRIALS OF SK-5 HOVERCRAFT FOR CANADIAN COAST GUARD
LEWIS, R. E. F., and STORR, J. W.
(DRML Rep. No. 667, April 1967)

Trials of SK-5 hovercraft in October and November 1966 in Lake Ontario. Tests of towing, transfers, firefighting, man rescue, barking, and loading of the vehicle aboard a ship. Four long runs (more than 100 miles). Description of night, day, blind and rough water operations. Fuel consumption, noise level, speed and stopping distance have been measured. Recommendations for vehicle modifications and improvements; additional equipment for CCG operations. All in respect to overwater operations. No troubles with the skirt, one engine failure.

L.05 A PARAMETER FOR COMPARING GROUND EFFECT VEHICLES
LIBERATORE, E. K.
(Aero-Space Engineering, October 1959, pp.33-36)

Description of basic ground effect configurations. Introduction of "Factor of Merit" as a new parameter for hovering performance. Definition of this factor for plenum chamber and annular jet configurations. Design of ACV with respect to "Factor of Merit" is discussed. Factor of Merit as a possible base for comparison of plenum and peripheral jet ACVs.

L.06 A FACILITY FOR DYNAMIC TESTING OF MODELS OF AIRBORNE VEHICLES WITH GROUND EFFECT
LILIVA, J.
(Institute of Aerophysics, University of Toronto, UTIA, T. N. No.53, October 1961)

Test track, flight recording, centre post and model (GETOL) description. Model harnessing characteristics (cable tension, cable drag, coefficient and cable derivatives) are presented. Comparison of the vehicle's aerodynamic and cable derivatives. The following data were measured:
- height above ground (measured at three reference points) for flight along track with no ramp installed, for nacelle slots open and forward speed 26.5 and 27 f.p.s.
- height above track and angle of pitch for flight in the plenum chamber configuration over a 0.50 inch ramp in the track
- height above track and angle of pitch for flight in the annular jet configuration over 0.125, 0.25, 0.50 inch ramps in the track
- drag coefficient as a function of Reynolds number for two dimensional flow around a cylinder (cable drag)
An analysis of the influence of the cable on model testing, and the measured results are presented.
L.07 AIR CUSHION VEHICLES (ACV) IN WATER TRANSPORT
LJUNGSTROM, O.
(The Royal Institute of Technology, Stockholm, Sweden, 1968, ME 35)
A survey of existing and planned ACVs, their basic characteristics. Influence of weather and vehicle's dimensions on performance and maneuverability. Navigation. ACV transport system model. Analysis of the size of an ACV for Sweden. Passenger comfort. Economic analysis, operating costs, and profitability. Estimation of development costs and purchase price of ACVs, depreciation, interest, insurance, etc. Maintenance costs of ACV operations. ACV ferry service example.

L.08 PERIPHERAL JETS: EFFECT OF EXIT GEOMETRY
LOWENSTEIN, A., BERRY, P., and DUFFY, R. E.
(Journal of Aircraft, November/December 1969, Vol.6, No.6, pp.558-563)
An introduction to peripheral jets and their problems. Description of the test apparatus, and a list of test conditions. The following data were measured: base pressure/plenum pressure versus h/t \((\cos \theta + l)\) for several \(R^*\); and comparison of the results with theory; base pressure and ground pressure distribution for various \(h\), and \(t\); the influence of base extension (or overhang); the influence of mass flow and the shape of the peripheral jet exit on base pressure/plenum pressure ratio.

* - Reynold's Number based on nozzle exit conditions = \(\rho j V j t / \mu\) \((\mu - viscosity)\).

L.09 GEM CONTROL SYSTEM STUDY
NORGEN, W. M.
(Garrett, Airsearch Manufacturing Co., Phoenix, Arizona, August 1965, AD 620 964)
GEM simulator - its description. The simulator consists of the following parts: analog computer, master control console, visual generator, pilot - operator's control station. The analog computer program (for a generalized ACV), the master control console, and other parts of the simulator are described individually. Description of wave generator system is included.
L.10 ANALOG ANALYSIS OF THE HEAVE RESPONSE AND CONTROL OF A PLENUM-TYPE AIR-CUSHION VEHICLE.
LEATHERWOOD, J. D.
(Langley Research Center, NASA TN D-6257, April 1971)

An analytical investigation was conducted to determine the basic heave response characteristics of a plenum-type tracked air-cushion vehicle, as a function of vehicle operating parameters. In addition to determining basic characteristics, the effect of an active lip control system on the vehicle's dynamic response was investigated. Nonlinear equations describing the dynamic and thermodynamic state of the air-cushion system were derived, and the response of the system to sinusoidal perturbations of the guideway was obtained with the use of an analog computer. Results are presented in terms of vehicle-to-guideway motions and vehicle accelerations experienced during fundamental and subharmonic oscillations.

L.11 HEAVE DYNAMICS OF TRACKED AIR-CUSHION VEHICLES.
LEATHERWOOD, J. D.
(AIAA - Technical Information Service)

This paper presents the results of an analytical investigation to determine the basic heave response characteristics of a TACV as a function of parametric variations of vehicle operating parameters. Results are also presented to demonstrate the feasibility of controlling vehicle heave response by the use of an active lip control system. Nonlinear equations describing the dynamics and the thermodynamic state of the air cushion system are derived and solved with the use of an analog computer. Results indicate that the air cushion vehicle responses are highly nonlinear and depend upon such parameters as equilibrium hover height, air cushion support pressure, supply flow characteristics, cushion dead volume, and input disturbance amplitudes. They further indicate that vehicle-guideway contact may readily occur for small input disturbances and the active control lip is very effective in eliminating the possibility of contact and in reducing undesirable vehicle responses.
M.01 SOME DESIGN ASPECTS OF AIR CUSHION CRAFT
MANTLE, P. J.
(International Congress of Subsonic Aeronautics, New York, N.Y. April 1967)

General introduction. Approximate equations for the vehicle's range, Lift/Drag ratio, and some additional economic measures (ton-miles per lb of fuel, i.e., transportation productivity). Comparison with current vehicles on the basis of transport efficiency, power, size, and load carrying capacity. Power requirements - definition of a non-dimensional power coefficient, Froude number, pressure number, Figure of Merit, cushion pressure and flow, lift power requirement, aerodynamic drag power requirement, and wave drag power requirement. Stability considerations in a sea state (heave motion damping). Aerodynamic air cushion craft (ram wing) - lift coefficient, L/D ratio. Second generation craft: air cushion, hull, variable geometry ACV.

M.02 EFFECT OF GEOMETRIC PARAMETERS ON THE STATIC PERFORMANCE OF AN ANNULAR NOZZLE WITH A CONCAVE CENTRAL BASE
MERCER, Ch.E., and SIMONSON, A. J.

Models, methods and apparatus description. Three series of convergent nozzles with concave central bases were tested. The following data were measured:
- base pressure distribution: for series A, B, C nozzles; the effect of base and nozzle geometry on base pressure was investigated; base pressure distributions across the base were measured for several values of jet angle (θ), nozzle width/base radius ratio (g/R), nozzle width/distance from nozzle exit plane to concave base ratio (g/l), and primary jet total pressure/ambient static pressure ratio (p_tj/p_a).
- Base thrust: measured as function of p_tj/p_a ratio and for the same geometric characteristics as nozzles series A,B,C. The highest thrust ratio corresponded to the greatest nozzle width/base radius ratio.

M.03 CUSHIONCRAFT CC-7 PERFORMANCE TRIALS 2-4 JUNE 1969
MILES, M.
(National Research Council, Canada, Ottawa, Division of Mechanical Engineering, LTR-SH-97, September 1969)

Evaluation of the performance of the CC-7 as a marine vehicle. The speed and measured fuel consumption are presented (block and maximum speed) for runs with full load and half load. Climatic and technical conditions are presented. Also measured: emergency stopping, turns; the conditions of these runs are also mentioned. Handling characteristics and maneuverability of the vehicle are evaluated. Description of the vehicle.
Description of the test facility, models and instrumentation. Objectives of the program: to determine whether a moving ground plane simulation is necessary for valid TACV wind tunnel test results; to determine the aerodynamic characteristics of air cushions; and to determine the aerodynamic characteristics of TACV bodies. Appendices: a brief review of previous work regarding relative motion of ground plane and air cushion; a summary of air cushion theoretical aerodynamic relations; an ideal minimum power condition for exponential theory; and the effect of nozzle losses on peripheral jet performance. Design of air-exhaust channels for parallel elongated cushions. Theoretical estimates of the mean cavity pressure for the circular model at forward speed; delineation of vertical forces acting on the air cushion; and some analytic considerations of the bottom flow for peripheral jet air cushions (Reynolds number definition). The following characteristics were measured: the air cushion mean pressure parameter as a function of plenum chamber total pressure; and horsepower as functions of the height at constant lift for various cushion and body configurations, including comparison with theory; the effect of cushion length/width ratio; the complete vehicle (cushion and body) and air cushion aerodynamics characteristics as functions of a forward speed parameter; and the base pressure distribution.

Vehicle configuration (rudders in propeller slipstream). The following design approaches of a decoupler are presented: mathematical model (equations are presented, disadvantages are discussed); rudder side-load cells; control cable load cells. An analog computer study evaluated the mentioned approaches. The computer program and the results are presented. The rudder side-load cells concept has been selected on the base of the computer study. Detailed design of the side-load cells concept, description of the system (the load cells, and the decoupler computer). Decoupler testing; description of the testing methods; presentation of the results. The equations of motion, the ACV computer program and some additional data on the decoupler are presented in appendices.
MC.01 TRACKED AIR CUSHION VEHICLE DEVELOPMENT. A STATUS REPORT
McCabe, W., Swanston, C. G., and Tang, K. K.

HSGT technical requirements, TACV advantages, and uncertainties. Factors affecting the design, performance and cost of TACV. Discussion of several factors (minimum cushion pressure, crosswind, vehicle-guideway configurations, propulsion, LIM problems). NASA/TRW wind tunnel test program: - body shape and cushion investigations - presentation of the results to date (body shape wind-tunnel tests, effect of crosswind and ground proximity on the aerodynamic characteristics of TACV body shapes). Air cushion wind tunnel tests - description and presentation of the basic results (the effect of free stream pressure being higher than the cushion pressure on cushion forces, moments and pressure distribution). Basic technology studies. MIT fluid suspension studies, and MIT vehicle suspension studies. The Bertin Aerotrain - results of aerotrain investigations. NASA Langley dynamics studies. Research vehicle requirements.

MC.02 AMERICAN TRACKED HOVERCRAFT CONCEPT
McCabe, W. L., Swanston, C. G., and Tang, K. K.
(Air Cushion Vehicles, Flight Supplement, Jan-Feb, 1969)

Advantages of TACV. Technical uncertainties (cushion at high speed; ride quality; vehicle response to long wavelength guideway irregularity, crosswind and curves). Minimum pressure constraint, effect of crosswind, vehicle - guideway configurations, propulsion. NASA/TRW wind-tunnel tests - body shape wind-tunnel tests (some results are presented) air cushion wind-tunnel tests, MIT fluid suspension studies. NASA Langley dynamic studies. The Bertin Aerotrain - description of experimental vehicle, results of aerotrain investigations - air cushion (suspended lip), suspension system - guideway interaction, secondary lift control, propulsion, research guideway.

MC.03 THE EFFICIENCY OF JET CURTAINS
McDaid, J. W. C.
(Hovercraft and Hydrofoils, Aug-Sept, 1964)

Research on the peripheral jet at the Queens University of Belfast. Description of the test rig. The following tests were conducted: a cushion or support pressure measurement (the effect of jet angle and base height). The pressure distribution along the ground - oil flow patterns. Total head traverses across the jet at exit. Proposed research programme for the jet curtain test rig. Theoretical analysis of the jet curtain for various jet conditions (underfed, and overfed jets).
MC.04 STATIC TESTS OF FLEXIBLE SKIRTS WITH VARIOUS INLET AND OUTLET GEOMETRIES
McDAID, J.W.C.
(Royal Aircraft Establishment, Bedford, Naval Air Department NAD Note No. 152, April 1967)

Description of the test rig. Experimental skirt model description.
The following data were measured:
- variation of power with cushion pressure for 2", 4" and 10" opening at inlet and 2", 4", 6", 8", 10" cutback at outlet
- comparison of skirt performance (cushion pressure/input power) with different inlet and outlet geometries
- skirt internal flow pattern for 2", 4", 6", 8", 10" cutback.

MC.05 AN ANALYSIS OF SKILL REQUIREMENTS FOR OPERATORS OF AMPHIBIOUS AIR CUSHION VEHICLES (ACV's)
McKNIGHT, A. J., BUTLER, P.J., and BEHRINGER, R. D.
(Human Resources Research Organization, Alexandria, Virginia, TR 69-18, AD 698 458, November 1969)

Analysis of the ACV system, - control of vertical motion, longitudinal control, lateral control, yaw control, pitch and roll control. - analysis of various control devices, their efficiency and requirements on skill. ACV operating requirements, - manoeuvering (response characteristics, maneuver restrictions, control coordination, and control alternatives). Navigation. Maintenance. Effect on the environment on control characteristics (water-surf, waves, wind) and effect of the surface conditions (grades, obstacles). Personnel and training implications (fundamental control, basic manoeuvring, environmental operation, crew training, and unit training). ACV simulator study (requirements of various control systems on skill, simulator-display, motion system, and response characteristics). Results of the simulations.
NATIONAL PHYSICAL LABORATORY
(National Physical Laboratory, Hovercraft Unit Report 10, Sept, 1969)

A note on scaling laws (definition of Reynolds, Froude, Weber, and cavitation numbers; cushion loading and dynamic head coefficients). Lift power for calm water and waves (equations for volume flow and fan horsepower). Drag: aerodynamic, momentum, trim, induced wave drag, skirt contact drag, sidewall drag and appendage drag, and rough water drag - definitions and equations. Propulsion: air propeller and centrifugal fan thrust, ducted fan and cushion thrust and water propulsion. Total power requirement. Sample calculations are presented in appendices for an air propelled amphibious vehicle and a water propelled sidewall vehicle. Presentation of air propeller performance curves, drag curves for vehicle over calm, shallow and deep water.

N.02  A PRELIMINARY STUDY OF THE POWER REQUIRED TO HOVER WITH A PARTICULAR REFERENCE TO ANNULAR JET VEHICLES
NEWMAN, B. G.
(Canadian Armament Research and Development Establishment, CARDE Tech. Memo. AB-55, Nov, 1959)

Introduction of the annular jet principle. Dimensional analysis of the power required to hover (definition of "The Figure of Merit"). Figure of Merit for some simple machines unshrouded propeller, ducted fan, annular jet near the ground). Figure of Merit for annular jet is defined on the basis of certain assumptions which simplified this problem considerably (incompressible flow, 100% efficiency of the fan, irrotational jet flow). Simple momentum theory for a ducted fan and a note on the performance of the SRN1 are presented in appendices. The ideal figure of merit of an annular jet vehicle is presented in figures as a function of h/R (height of base above ground/radius of base), b/R (b-width of annular nozzle at jet exit), and θ (jet angle). The power required to hover for a particular annular jet vehicle (various hoverheights and nozzle width) is presented in figures as well.

N.03  THEORETICAL ANALYSIS OF AN INTERNALLY-BRACED TWO-DIMENSIONAL AIR STRUT WHICH IS PARTIALLY BRACED
NEWMAN, B.G., and JONES, D.
(The Aeronautical Quarterly, February 1968)

Theoretical analysis of a two-dimensional air strut with walls consisting of thin membranes which are joined by inextensible strings. Deflection of the strut throughout large angles. Numerical solutions are obtained for two cases: in particular the resultant force on each of the solid plates, which form the ends of the strut, is determined.
N.04 GROUND EFFECT MACHINE PROPULSION SYSTEM DESIGN CONSIDERATION
NORMAN, L. W.

Description of the individual parts of an ACV propulsion system; analysis of their advantages and disadvantages. Component analysis. Internal air duct design. Fan duct system design technique. Fan efficiency equations, momentum per horsepower at fan exit. Coupling systems - gear drives (spur and bevel gears, gearbox) - air drives; propulsion efficiency of the propeller. Propulsion system computations.

N.05 NORTH SLOPE PROBLEMS.
LAST YEAR'S EXPERIENCE.
IMPROVED ARCTIC ACV'S.
(Air Cushion Vehicles, The International Hovercraft Journal September, 1970)

Description of North Slope climatic, terrain and weather conditions and arising problems (tundra, thaw, tracked vehicles, aircraft, helicopter - S 64 Skycrane cost of operation: $2,000/hr, possibility of ACV).
Experience with three modified SRN6 owned by Pacific Hovercraft Ltd. of Vancouver: overload, trip from McKenzie Delta to Alaska North Slope, Vehicle damage, and seismic survey. Project Valiant - its compatibility with C-130, dimensions, power, performance, description of the design (hull, cargo space, and side thrusters), cost analysis (operating cost per hour), cost of seismic operation. The Air Cushion Drilling Barge project - basic design and characteristics, propulsion, cost of drilling.

N.06 AIR CUSHION VEHICLES. THEIR POTENTIAL FOR CANADA
(National Research Council of Canada, Catalogue No. NRCC 10820, December 1966)

Special needs for Canadian transportation. Canadian environment. Present transportation system. ACV technology (history, types of ACV). Canadian ACV operations (Government trials - Tuktoyaktuk, Fort Churchill, etc., Commercial operations - SRN6 Expo 1967) - winter problems, commercial potential, SRN6 maintenance. Selected ACV ferry applications - route simulations, analysis. Arctic lightering - present method, considerations for ACV lightering, ACV lighter concept, lightering market estimate summary. Off-road selected ACV applications, design requirements, simulations, market estimate. Utility - selected ACV applications - comparison of projected and available utility ACV's and existing utility vehicles, market estimate. Sport, recreation ACV, miscellaneous ACV applications. Defence considerations. The manufacturers of ACV in Canada. Considerations for the future research and development. In Appendices are presented: ACV study team, Companies and Government Departments connected, methods of study, Canadian ferry services, state-of-the-art, charging rates of various modes of transportation, performance and economy data, survey of existing ACVs, bibliography.
Description of the model and the apparatus. Investigations of the ground-effect characteristics of a circular annular jet model at forward speeds up to 100 ft/sec. At zero angle of attack there is a rapid increase in lift augmentation with forward speed, relatively independent of the height/diameter ratio. Low angles of attack had little effect on lift augmentation at low velocity ratios. Inlet momentum drag was a large part of the relatively large drag forces measured at the higher velocity ratios. Large angles of attack had a considerable effect on the nondimensional drag parameter at the higher velocity ratios. Measured: Nondimensional Lift \( \frac{L}{M_d V_j} \), Drag \( \frac{D}{m_d V_j} \), Pitching Moment \( \frac{M}{L_d} \), mass rate of the jet flow \( m_d \), average exit velocity of the annular jet \( V_j \), average increment of the jet total pressure \( p_t \), average increment of the base plate pressure \( p_b \) as a function of the velocity ratio \( \frac{V}{V_j} \), height/diameter ratio, and rpm of the fan (propeller). Photographs of tufts showing flow patterns at the ground plane for various velocity ratios, angles of attack and height/diameter ratios are presented.
P.01 OSCILLATION OF AN ELASTIC PLATE IN A FLUID
PAVITSKIY, A. S.
(Air Force System Command, Foreign Technology Division WP-AFB, Ohio, FTD-HT-66-790, August 1967)

The two dimensional problem of an oscillating elastic plate (either of a constant or variable thickness) in contact with the free surface of an ideal liquid. Only free natural frequencies are considered, especially the first mode of oscillation.

P.02 THE MULTI-SKIRT "NAVIPLANE N 300" MARINE HOVERCRAFT. THEIR PRINCIPLE, CONCEPTION AND CONSTRUCTION
PONT, D.

A short review of hovercraft development and the ACV industry in France. Power comparison of multiple skirt and peripheral jet systems. Discussion of other criteria for comparisons. Discussion of the design problems of the N 300: the problems of stability, improvement in performance, the technological aspect of the components. Description of conception and construction of the N 300 (general arrangement, structure, skirt, propulsion and transmission, controls, electrical and safety equipment, and systems). Characteristics (performance, dimensions, and weights) of the N 300 are presented in appendix.

P.03 PRELIMINARY DESIGN STUDY OF A LINEAR INDUCTION MOTOR WITH AN ALUMINUM BONDED TO STEEL REACTION RAIL
(Westinghouse Electric Corporation, Transportation Division, East Pittsburgh, Pa., August 1969, PB 186 231)

Purpose of the study: to determine, if a steel - aluminum bonded reaction rail could be used to guide and support the LIM as well as guide the vehicle. Design tasks of the reaction rail for the expected LIM characteristics. Review of bonding techniques. Evaluation of LIM. LIM performance model. Magnetic unbalance. Air cushion and steel wheel guidance of the LIM. In appendices: Analysis of Rail Deflection, for guidance and support. LIM configurations and considerations. Equations for the LIM performance model (thrust, efficiency, power). LIM performance computer model. Magnetic unbalance pressure model for bonded steel, iron composite reaction rail. Air cushion analysis for guidance and support of the LIM and guidance of the vehicle. Steel wheel guidance of the LIM. An interesting conclusion has been reached: air cushion guidance is impractical for the aluminum bonded steel rail due to the large amounts of power required for the air cushions.
PROCEEDINGS OF THE NATIONAL MEETING ON HYDROFOILS AND AIR CUSHION VEHICLES
(U.S.A. Dept. of the Navy, Washington, D.C. September 1962)

Contains the following papers:
Y. Senoo: Considerations of the lifting fan-duct systems of ground effect machines.
N. K. Walker: Some notes on lift and drag of ground effect machines.
K. R. Cossairt: A recirculation concept.
B. F. Holcombe: Materials and fabrication techniques in Air Cushion Vehicles.
R. E. Stark: Structural load criteria for navy hydroskimmer.
D. H. Winter: Air Cushion Vehicle.
S. Rethorst: VRC surface effect ship Columbia.

ON THE AERODYNAMIC DESIGN OF PROPELLERS AND DUCT SYSTEMS FOR GROUND EFFECT VEHICLES
PRUYN, R. R., and PERLMUTTER, A. A.
(Kellet Aircraft, Report No. 208 A 90-1, January 1962)

This final report is divided into four sections. First: Theoretical analysis of propeller thrust and power, duct efficiency, the effect of an inlet ring, and the effect of the nozzle velocity distribution. Second: Test results analysis - overall performance (straight, curved duct), the effect of geometric modifications on the performance of various ducts, propeller thrust and power coefficient, etc. Third: Correlation of the analytical method and the test results. Fourth: A method of design for propeller and duct systems. A description of tested configurations and instrumentation, and a discussion of the test results are presented in appendix.
R.01 A TWO-DIMENSIONAL FLUID-SUSPENSION APPARATUS FOR INVESTIGATION OF PRESSURE RATIO, MACH NUMBER AND REYNOLDS NUMBER EFFECTS
RIBICH, W. A., and RICHARDSON, H. H.

Presentation of the objectives of the two-dimensional test apparatus (investigations of Re. No. and M effects on suspension behaviour, observation of flow patterns, influence of forward speed, etc). Dimensional analysis, geometrical scaling. Apparatus design-parameter ranges, instrumentation, flow visualization, data reduction techniques. Presentation of the results of preliminary experiments - dimensionless cushion pressure versus jet exit Reynolds Number and hoverheight/jet thickness ratio; dimensionless mass flow and pumping power versus Reynolds Number and pressure ratio. Comparisons of the experimental and theoretical results.

R.02 DYNAMIC ANALYSIS OF HEAVE MOTION FOR A TRANSPORT VEHICLE FLUID SUSPENSION
RIBICH, W. A., and RICHARDSON, H. H.

Four basic types of fluid suspensions; brief discussion of the state-of-the-art with respect to high speed vehicle fluid suspension. Presentation of lumped parameter heave model, description of general configuration (vehicle-guideway suspension system, model for heave dynamics of fluid suspension), assumptions and governing relationships, linearized relationships and influence coefficients, form of the suspension transfer functions, data required for formulation of the lumped model. Analysis of the simple suspensions: rigid simple plenum, rigid simple plenum with compressor, rigid peripheral jet supplied by constant pressure source, and flexible base plenum suspension supplied by constant pressure source.

R.03 AN ANALYSIS OF THE EFFECT OF FINITE FLUID-SUSPENSION PAD LENGTH ON THE DYNAMICS OF THE VEHICLE ON AN IRREGULAR GUIDEWAY
RIBICH, W. A., CAPTAIN, K. M., and RICHARDSON, H. H.

Presentation of the linearized lumped parameter approach to the analysis of fluid suspension operating in the heave mode over general guideway irregularity profiles. Analysis of the rigid edged plenum suspension over simple sinusoidal irregularities; displacement, acceleration as a function of pad length/irregularity wavelength ratio, dimensionless frequency. Simple step response (simple step in guideway) -displacement, acceleration, and frequency. Response to a general guideway profile. Analysis of the rigid peripheral jet configurations. Application of the results to suspension design criteria.
R.04 DYNAMICS OF SIMPLE AIR-SUPPORTED-VEHICLES OPERATING OVER IRREGULAR GUIDEWAYS
RICHARDSON, H. H., CAPTAIN, K. M., and RIBICH, W. A.
02139, Rep. DSR 76110-4, June 1967)

Description of an idealized model of the vehicle-suspension system, presentation of assumptions, and characterization of guideways and irregularities. The transfer characteristics of the fluid suspension and of the vehicle and suspension (relations between vehicle heave motion and guideway irregularities). Passenger comfort criteria. One dimensional suspension analysis - behaviour over sinusoidal irregularities of constant wavelength and amplitude (equations for the dimensionless relative displacement and acceleration) - behaviour over sinusoidal irregularities having amplitude proportional to wavelength, and over a sinusoidal guideway with randomly distributed irregularity amplitudes. Performance of a vehicle supported by simple plenum operating over an irregular guideway - basic relationships (static stiffness, flow pressure coefficients, power and mass flow for a suspension pad). Design procedure and performance of a typical vehicle.

R.05 SIMPLIFIED STATIC PERFORMANCE CHARACTERISTICS OF LOW-PRESSURE PLENUM AND PERIPHERAL JET FLUID SUSPENSIONS
RICHARDSON, H. H., and CAPTAIN, K. M.
02139, Rep. DSR-76110-8, January 1968)

Definition and listing of the design system parameters of a fluid suspension. Performance of a simple plenum (basic assumptions and equations, single-pad gravity-loaded suspension performance, performance of opposed transverse suspension, examples, modifications of the equations and results from both a constant pressure supply and a fluctuating pressure supply). Performance of the peripheral jet (basic assumptions and equations, single-pad gravity-loaded suspension, opposed transverse suspension - examples). Theoretical comparison of the plenum and peripheral jet suspensions - diagrams are presented. Comparison between inviscid theories and experimental results for peripheral jet static performance (exponential, Barratt, thin-jet and potential flow theories).

R.06 PRESSURE-FLOW-DISPLACEMENT CHARACTERISTICS OF A PERIPHERAL JET FLUID SUSPENSION
RICHARDSON, H. H., RIBICH, W. A., and ERCAN, Y.
Rep. DSR 76110-7, June 1968)

Description of the experimental apparatus. Summary of conducted tests. Test results presented are: dimensionless cushion pressure versus jet exit Reynolds Number for several h/t (hoverheight/jet thickness) ratios, jet thicknesses and ambient pressures - comparison of theory and experimental results; dimensionless mass flow versus jet exit Reynolds Number for various h/t ratios, jet thicknesses and ambient pressures; dimensionless pumping power versus jet exit Reynolds Number for conditions as above; dimensionless pumping power
and mass flow versus nozzle pressure ratio for several h/t ratios; dimensionless cushion flow versus dimensionless cushion pressure for several Reynolds Numbers, h/t ratios, jet thicknesses, ambient pressures and cushion depths (characteristics of overfed and underfed unbalanced regions); dimensionless mass flow versus dimensionless cushion pressure comparison of experimental results with Barratt theory (mass flow, pumping power versus cushion pressure-geometric sealing criteria).

R.07 STUDY OF AN ELECTRICALLY PROPELLED, HIGH SPEED AIR CUSHION AMPHIBIAN
ROESLER, D.J.
(U. S. Army Mobility Equipment Research and Development Center Fort Belvoir, Virginia, Rep. 1949, May 1969)

Design study of an ACV amphibian capable of carrying a 20 ton container and/or bulk cargo. Electrical propulsion (free shaft gas turbine driving two 400 hz generators). List of the vehicle's basic data and supposed performances and modes of operation. General description of the vehicle's layout, powerplant and controls. Analog and digital computer simulations were performed in order to meet the design requirements. (Computer program is presented in appendix). Results of the computer simulations are presented. Detailed description and analysis of components (powerplant, alternator, turbine and alternator control). Equations used for the vehicle's simulation are presented.

R.08 EJECTOR POWERED RECIRCULATION LIFT SYSTEM FOR AIR CUSHION VEHICLES
ROSENBURG, M. H., and FULLER, F. L.
(Grumman Aircraft Engineering Corporation, Research Dept. Res. Memo RM-202, April 1962)

Description of the model (and its configurations) and the apparatus. Test procedure and the data reduction method are presented, along with the calibration of the ejector nozzle (local jet thickness and local pressure along nozzle span). The following data are presented: pressure coefficient distribution for various hoverheights and configurations; lift as a function of ejector total pressure and hoverheight; pressure distribution for small hoverheights; lifting efficiency versus hoverheight (comparison between the peripheral jet and recirculation configurations); comparison of the peripheral jet theories and experiments.

R.09 BIBLIOGRAPHY ON HOVERCRAFT (ACV)
RUSSELL, H. G.
(Ministry of Technology, TIL/BIB/101, September 1968)

This bibliography is divided into the following chapters: State of the Art, Design, Dynamics, Stability, Lift, Propulsion, Control, Skirt, Noise, Structure, Jets and Nozzles, Research and Development, Trials, and Performance. Each part contains several titles and a short review. A list of authors is presented.
R.10 INVESTIGATION OF SEAL MATERIALS AND CONFIGURATIONS FOR HIGH SPEED AIR CUSHION VEHICLES
REYNOLDS, H. J. Jr.,
(Dept. of Transportation, Office of High Speed Ground Transportation, October 1969, PB-186 414)

Air cushion seals for TACV—metal and rubber as single and multiple skirts. Description of the test apparatus and tested model's configurations. Two types of the skirt material have been tested: 1/8 in. thick metal boiler plate, and 1/4 in. and 1/2 in. thick fabric reinforced rubber sheet. Rectangular 6 in. by 24 in. straight pieces of the skirt material have been tested. The following data are presented: effect of skirt flexibility and thickness (discharge coefficient through daylight clearance gap, versus clearance ratio and Reynolds number); determination of the most effective skirt configuration; effect of the spacing between multiple skirt elements and hoverheight on discharge coefficient; effect of ventilation holes on the discharge coefficient; effect of track roughness. Calculation of the efficiency of the multiple and single skirt configurations on an actual plenum. Calculation of flow and power requirements for various configurations. Concludes that a multiple skirt is more efficient than a single one, and that rubber is a more efficient material than metal for the skirt.

R.11 A STUDY OF AIR CUSHION LANDING SYSTEMS FOR SPACE SHUTTLE VEHICLES.
RYKEN, J. M.
(NASA CR-111803, December 1970, N71-13097)

Description of the Air Cushion Landing System (ACLS) and its development status. The comparison of the conventional landing system and ACLS. Discussion of the merits, typical structure and arrangement of the ACLS. Some experience with ACLS on LA-4 amphibian are mentioned and results are briefly discussed. Booster configuration study. Orbiter configuration study. Approximate pressure and air flow requirements. Air supply systems, their alternatives and comparison. Trunks (bags) description, attachment and thermal protection, materials, structure, weight, retraction and extension. Trunk flutter. Braking system description and comparison of alternatives. Brake tread wear. Effect of ACLS on vehicle structure, aerodynamics and stability.

R.12 A SCALING TECHNIQUE FOR HOVERCRAFT MODELS.
RICHARDSON, J. R.
(National Physical Laboratory, Hovercraft Unit, Report No.13 July 1970)

The scaling laws for hovercraft models are examined with the object of introducing correct elastic effects. It is shown that the correct Froude Number needs to be maintained, but that if this is done by scaling the gravity field instead of the speed, then the correct elastic scaling can be achieved. It is then shown that by using a whirling arm facility for providing forward speed to a model, centrifugal accelerations are created of sufficient magnitude to simulate a high gravity field. The model would operate on the inside face of a cylindrical wall.
R.13 A MECHANISM OF ROUGH WATER DRAG.
RICHARDSON, J. R.
(National Physical Laboratory, Hovercraft Unit, Report No. 14, January, 1971)

An explanation of the rough water drag of a hovercraft is proposed which depends upon the action of the air suspension system instead of contact with the water. The theory is developed in the first instance for regular waves, but it is shown that the drag in an irregular sea can be found by adding the drag caused by its separate wave components. Suggestions for interpreting data from model tests are given, based on the significant parameters defined by the theory. In principle such a drag must occur on any vehicle with a suspension which can absorb energy.

R.14 SUPPLEMENT TO SURVEY OF TECHNOLOGY IN FLUID SUSPENSIONS: PATENT SEARCH AND EFFECT OF FORWARD SPEED.
RICHARDSON, H. H., RIBICH, W. A.
(Massachusetts Institute of Technology, Cambridge, Rep. No. DSR 76110-1, Nov 1966)

Discusses some potential advantages of fluid suspensions. Gives a description the basic types of fluid suspensions, including a survey of the patent literature from very early patents (yrs 1876) to recent ones (yr 1966). Also a table of the principal U.S. patents on fluid suspension and fluid suspension vehicles - since 1962. Influence of the vehicle forward speed on the suspension performance. Some results of the experiments performed are presented and discussed together with the experimental techniques. A list of the test facilities used for forward speed effects is presented herein.
S.01 AIR CUSHION CRAFT PROPULSION
SHEETS, H. E., and MANTLE, P. J.

Classification of propulsive devices. Definitions of overall propulsive efficiency, and a comparison of the efficiencies of various propulsive devices. Ideal propulsive (Froude) efficiency. Waterscrews as an ACV propulsive device; presentation of propulsive efficiency versus thrust coefficient for a water-screw and its design charts. The air propellers (the same characteristics are presented and predesign charts). The water jet (efficiency equation). The air jet (thrust coefficient equation and drag parameter for air screw and airjet. The turbofan. Propulsive system weight: a comparative figure of engine specific weight versus horsepower rating for several types of engines.

S.02 AERODYNAMIC DESIGN OF AXIAL LIFT FANS
SHIPWAY, J. C.
(National Physical Laboratory, Hovercraft Rep. 4, July 1968)

Preliminary design, Detail Design (detail design is divided on: prerotor design, rotor design, straightener design), and "Off Design" Characteristics: A method for axial lift fan aerodynamic design is presented in guide form. Tables and diagrams are presented for computation and estimation of individual design steps.

S.03 A REVIEW OF HOVERCRAFT RESEARCH IN BRITAIN
SILVERLEAF, A.
(The Aeronautical Journal of the Royal Aeronautical Society, Vol. 72, December 1968, pp. 1019-1028)

A short review of ACV activities in U. K. with particular attention to research: research on marine hovercraft hydrodynamics (calm water drag, stability and control in calm water behaviour in waves), research on the aerodynamics of ACVs (internal, and external aerodynamics), structure (rigid, inflated, flexible), propulsion (air and water propulsion systems). Research vehicles (HD 1, HD 2, CC 2). Tracked hovercraft. Industrial applications. Future research (objectives of research; typical problems for research; and some tasks are pointed out).

S.04 THE HEAVE STABILITY OF AN AIR CUSHION VEHICLE WITH A FLEXIBLE PERIPHERAL SKIRT
SPILLMAN, J.

General analysis of the heave motion of skirted ACVs. An increase in heave stability can be achieved if the heave motion is such that the skirt is never fully clear of the supporting surface - i.e., most of the skirt rubbing the surface. A new type of skirt is presented composed of rigid segments. An analysis of heave stability
and the equations of heave motion for a vehicle fitted with this skirt are presented.

3.05 SOME DESIGN PROBLEMS OF HOVERCRAFT
STANION-JONES, R.
(IAS Paper No. 61-45, January 1961)

Basic theory - cushion pressure, required power, optimum jet thickness, optimum cruising speed, optimum L/D ratio. Practical GEM's performance - practical power/weight ratio vs. forward speed, practical lift/drag ratio vs. forward speed, optimum cruise speed vs. hoverheight/effective diameter, effect of jet thickness and jet angle on lift/drag ratio. Design study on a family of GEMs - structural requirements, optimum cushion pressure, positioning of propulsive thrust, lateral control, separated and integrated propulsion. Static stability - basic equations. Dynamic stability (natural period in heave). Dynamic stability over waves (equation of motion). Economics of GEMs, capital cost.

3.06 INVISID-INCOMPRESSIBLE FLOW THEORY OF STATIC PERIPHERAL JETS IN PROXIMITY TO THE GROUND
STRAND, T.

First exact theory of peripheral jets applicable to all jet thickness/hoverheight ratios. Definition of lift and power coefficients (equations) and lift augmentations. Solutions and data are plotted in diagrams (lift augmentation, lift coefficient, base pressure, velocity across the jet, etc).

3.07 SURVEY OF TECHNOLOGY FOR HIGH SPEED GROUND TRANSPORT
(Massachusetts Institute of Technology, Cambridge, Mass. June 1965, PB 168 648)

speed Tokaydo line. Highway system in HSGT.

S.08 SNATCH-TEARING OF FABRICS. COMPARISON OF SIX FABRICS
SWALLOW, J. E., and MIKOLAJEWSKI, E.
(Royal Aircraft Establishment, T. R. No. 66299, September 1966)

Comparison of the tearing behaviour of six fabrics. Description of the apparatus and methods of testing. Properties of the fabrics used are tabulated. An equation for length of tear is presented for weftwise or warpwise tension. Results of the tests (length of tear) are presented in tables as a function of the direction of tension (horizontal-weftwise, vertical-warpwise), energy input at impact and nail diameter. A summary of the results for significant factors and analysis of errors is presented as well.

S.09 HIGH SPEED ABRASION OF TEXTILE CORDAGE ON AN ASPHALT SURFACE
SWALLOW, J. E., and WEBB, M. W.
(Royal Aircraft Establishment, T. R. No. 67023, January 1967)

Two sets of experiments: (1) the effect of cordage type, relative velocity between the cordage and the asphalt surface, inertial tension in the cordage, time of abrasion on the residual breaking strength, residual strain energy, heat production and temperature rise, and (2) the effect of cordage type, relative velocity and internal tension on the time to cause failure (results given in tables). Equations for the total frictional work and the heat produced are given. Materials and apparatus are presented in Appendix. Relationships between residual breaking strength and surface to cordage relative velocity, internal tension of cordage are given in figures. Average failure time as a function of type of cordage and relative velocity are given in figure as well.

S.10 PLANFORM CHARACTERISTICS OF PERIPHERAL JET WINGS
SWEENEY, T. E., and NIXON, W. B.
(Dept. of Aeronautical Engineering, Princeton University, Rep. No. 524, December 1961)

Description of the model and the test apparatus. Seven models were tested: four rectangular with aspect ratios 1, 2, 3, 4, one 30° swept wing, one 60° delta wing, and one taper wing planform (A-3.0). The following data were measured:
- augmentation ratio as a function of height from base to ground plane/mean aerodynamic chord ratio (h/m.a.c.) and height from the base to ground plane/diameter of circle of equivalent area (h/d) for jet angle 0° and area of peripheral nozzle total wing area ratio (S₁/S) = 0.063.
- pitching moment coefficient (Cₚ) as a function of h/m.a.c. and angle of attack (α) for all planforms.
- rolling moment coefficient as a function of h/m.a.c. and angle of roll (ψ)
- effect of asymmetric slot width on the centre of pressure location for rectangular and taper wing planforms - effect on longitudinal and lateral stability.

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- effect of compartmentation slots on performance, longitudinal and lateral stability of the 60° delta planform.
- effect of stability holes on longitudinal and lateral static stability of the 60° delta planform.
- longitudinal and lateral static stability characteristics \((C_m, C_1')\) as a function of jet velocity distribution (for the rectangular planforms).

S.11 PROMISING APPLICATIONS OF THE AIR CUSHION VEHICLE
SWEENEY, T.E., and NIXON, W. B.
(ASME Publication, ASME 67-de-36, March 1967)

General analysis of the nonmilitary application of ACVs: rescue vehicle, ACV pallet, general transportation (for use in highly developed and underdeveloped countries), and agricultural vehicle. Description of agricultural operations, experience to date, economies of the agricultural concept, evaluation of agricultural operations, design tasks, and comparison with agricultural aircraft.
AN INTRODUCTION TO SIDEWALL HOVERCRAFT
TATTERSALL, E. G.
(Canadian Aeronautical and Space Institute Journal, November, 1967)

Size of the vehicle (relationships between vehicle length, capacity, and ferry route length, from comfort considerations). Speed (useful speed spectrum versus stage length). Power requirements (comparison of displacement vessels, hydrofoils, and sidewall hovercrafts). Operating cost (typical breakdown of DOC for sidewall hovercraft). Particular vehicle examples: HM2, HM4, HM5 - description, basic dimensions and performance.

TECHNICAL BACKGROUND ON LINEAR INDUCTION MOTORS IN TRANSPORTATION
(Office of High Speed Ground Transportation, Federal Railway Administration, U.S. Dept. of Transportation, June 1970)

Report contains seven parts:

1 - Linear-Motion Electrical Machines - survey and principles of various linear motors, history, applications, LIM most suitable for transportation, design problems.

2 - Linear Induction Motor Research in USA - background and reasons for research, description of linear motor, LIM performance, comparison with other modes of propulsion, history of LIM in USA, cost considerations, prototype of LIM, test vehicle.

3 - Application of LIM to High Speed Transport System - primary secondary location, double sided motors, track layout, track member economy, special features of sheet rotor machines, designing for large air gaps, power supply and control, operation on fixed and variable frequency, method of braking, choice of plate section and material, future developments.

4 - Application of Linear Motor to Transport - loading gauge restrictions, air gap, reaction plate, guidance, braking, starting performance, efficiency and power factor, energy consumption, adhesion, locomotive and maintenance cost.

5 - Linear Induction Motor for High Speed Tracked Vehicle - description of LIM, electric design of LIM, theoretical analysis electric design considerations, application problems, design problems and considerations.

6 - Electric Propulsion System for LIM Test Vehicle - description of test vehicle and test program, LIM design and performance, selection of air gap, static and dynamic testing.

7 - Control and Instrumentation for a High Speed Rail Vehicle Propelled by LIM
T.03 COMPARISON OF EXPERIMENTAL AND THEORETICAL DESIGN PARAMETERS OF A 6-INCH DIAMETER JET MODEL WITH A JET ANGLE OF 45° HOVERING IN PROXIMITY TO THE GROUND AND EXPERIMENTAL RESULTS FOR FORWARD FLIGHT AT ZERO ANGLE OF ATTACK
TINAJERO, A. A.

Model and apparatus description. Two phases of tests: static and dynamic. Equations for lift and augmentation, definition of parameters for the annular jet model. Results are presented in graphic form: - effect of altitude (h/r) on lift augmentation factor for various jet pressure ratios, for static conditions and for various dynamics pressures. (q = 5, 10, 20, 30, 40, lb/sq.ft), - effect of altitude ratio on ground pressure distribution for various jet pressure ratios, in static conditions, - variation of lift, drag, jet momentum, pitching moment coefficients with altitude ratio, jet pressure ratios and dynamic pressures, - variation of $C_{L0}$, $C_{D0}$, $C_{mo}$, (coefficients for zero jet momentum coefficient - no flow through nozzles) with dynamic pressure and altitude - comparison of augmentation factors by theory and by experiments, - effect of altitude on lift augmentation (for various jet momentum coefficients and dynamic pressures), - effect of dynamic pressure on lift augmentation (for various jet pressure ratios and altitudes), - effect of dynamic pressure on $\Delta C_L/Qu(Cu$-jet momentum coefficient)
for various jet pressure ratios and various altitudes.

T.04 PRELIMINARY INVESTIGATION OF PLANFORM EFFECT ON AUGMENTATION PARAMETER FOR PERIPHERAL JET GEM
TINAJERO, A.A.

Investigations have been conducted with four basic planforms. Report contains description of models and test facilities. One model circular and three oblong with various width/length ratios. Augmentation factors have been measured as a function of ground proximity factor ($4S_b/hC$) for all these planforms with variable air supply pressure (50 to 90 psi) and for variable propulsion thrust/jet momentum ratio. Propulsion thrust has been simulated by tangential deflection of peripheral jet (20° to 45°). Circular planform has highest augmentation factor but oblong planform has better propulsion thrust/jet momentum ratio ($T/j$ increased with increasing length/width ratio of oblong planform). Losses of augmentation have been estimated with increase of propulsive thrust factor. Highest values of these losses has circular planform, lowest oblong planform with highest length/width ratio.
T.05 STATIC BEHAVIOUR OF A SPECIAL PLANFORM GEM MODEL UTILIZING AN INTEGRATED SYSTEM FOR LIFT AND PROPULSIVE THRUST
TINAJERO, A.A.

Description of model and test facility. Special planform GEM. Tests divided into two parts: the hovering tests (zero propulsive thrust), the propulsive thrust tests. Results are presented in graphic form:
- augmentation factor as a function of ground proximity parameter \( \frac{4S_b}{hC} \) for various jet tangential deflections \( 0^\circ, 10^\circ, 20^\circ, 33^\circ \) and therefore for variable propulsive thrust
- effect of jet discharge angle on augmentation for various setting of tangential jet deflection
- variation of efficiency ratio with nozzle thickness for variable propulsive thrust factor \( T/J \)
- variation of propulsive thrust factor with tangential jet deflection
- loss in augmentation versus gain in propulsive thrust for various ground proximity parameters and propulsive thrust parameters.

T.06 STATIC BEHAVIOUR OF RECTANGULAR PLANFORM GEM MODEL UTILIZING AN INTEGRATED SYSTEM FOR LIFT AND PROPULSIVE THRUST
TINAJERO, A.A.

Description of model and test facility. Rectangular planform GEM. Two types of tests: hovering tests (zero propulsive thrust), and propulsive thrust tests. Tests were conducted for jet discharge angles: \(-15^\circ, -30^\circ, -40^\circ, -53^\circ\). The following data were measured and presented in the report in graphic form:
- augmentation factor as a function of ground proximity factor \( \frac{4S_b}{hC} \) and propulsional thrust factor \( T/J \) for various jet discharge angles.
- efficiency ratio \( \frac{\eta_A}{\eta_J} \) - augmentation efficiency factor/jet momentum efficiency factor as a function of nozzle width/hoverheight ratio \( G/h \) for various \( T/J \) factors and discharge angles
- effect of discharge angle on augmentation factor.

T.07 A BRIEF SUMMARY OF THE EFFECT OF PLANFORM ON AUGMENTATION OF GEM WITH AN INTEGRATED SYSTEM FOR LIFT AND PROPULSIVE THRUST
TINAJERO, A.A.

Summary of previous experiments with various planforms. Measurements of augmentation factor as function of ground proximity parameter \( \frac{4S_b}{hC} \) and forward propulsion for circular, rectangular and oblong planforms. A special planform is presented. Losses in augmentation with an increase in propulsive thrust factor
are presented as well for various ground proximity parameters.

T.08 A PRELIMINARY DESIGN TECHNIQUE FOR PLENUM - CHAMBER GROUND EFFECT MACHINE (GEM's)
TINAUERO, A.A.

Hovering performance is expressed by the dimensionless parameter "Figure of Merit-M". Simplified method of solution of hovering performance (assumption: no losses exist). Detailed solution - equations of total lift, cushion power and pressure, fan efficiency, figure of merit, etc. are presented. Cruising performance - simplified and detailed solution. Illustrative examples for performance computations are presented. Stability and control - principles. The following data are presented in figures: the efficiency ratio (fan efficiency factor duct efficiency factor/empirical fan efficiency factor) as a function of escape area/fan area, fan blade tangential velocity/average escape velocity and dynamic pressure lost in the duct, the variation of the figure of merit for a range of parameters cushion area/escape area, fan area/cushion area, escape area/fan area and internal efficiency, duct efficiency, plenum fan efficiency, and lift for HP versus wing loading for several figures of merit.

T.09 NRC TRIALS OF HM2 HOVERCRAFT
TOTHELL, J. T.
(National Research Council, Canada, Ottawa, Division of Mechanical Engineering, LTR-SH-96, September 1969)

Measured: maximum speed for full and half load, and several values of RPM; wind conditions are given, results of each run are given in tables and figures. Block speed-half and full load, conditions are described, results given in table and figure. Stopping distance - conditions described, results in tables. Turning circles - 90°, 180° and 360°; results in tables. Bollard pull. Analysis of the results is presented. Evaluation of steering characteristics, accelerations, and shallow water effects. The vehicle's basic dimensions and characteristics are given.

T.10 TRACKED AIR CUSHION RESEARCH VEHICLE. DEVELOPMENT PLAN STUDY REPORT
(General Electric, Transportation Systems Division, Philadelphia, Pa. March 1969, PB 183 177)

Description of the vehicle (configuration and alternate modes). Subsystem design and development plan (critical problems - aerodynamic design, secondary suspension, etc). Description of development tests. Fabrication plan, vehicle final assembly, tool, facility, manufacturing schedule. Qualification plan: test program, test equipment. Scheduling: work breakdown, manpower profiles.
T.11 TRACKED AIR CUSHION RESEARCH VEHICLE. RESEARCH PROGRAM STUDY REPORT
(General Electric, Transportation System Division, Philadelphia, Pa. March, 1969, PB 183 178)

Research requirements. Desirable TACV capability (speed, safety, ride comfort, aesthetic, etc). State-of-the-art. Research objectives and approach. Example of research - air cushion. Research areas and instrumentation, vehicle experiments, vehicle-guide-way interactions, vehicle-environment interactions, air cushion and duct experiments, secondary suspension requirements and types, noise experiments and other research areas. Vehicle utilization plan, development test, test facilities, typical research program.

T.12 TRACKED AIR CUSHION RESEARCH VEHICLE: PRELIMINARY DESIGN STUDY REPORT

Research vehicle description and characteristics. Development requirements. Vehicle requirements (noise, speed, accelerations, etc). Vehicle's dimensions; description of the vehicle's parts. Performance data: acceleration, weight, thrust, deceleration, maximum speed, air cushion daylight clearance, effect of speed on guideway clearance. Propulsion (4 turbofan engines, LIM) - engine characteristics, and installed engine characteristics. Noise - maximum, minimum, spectra, possible means of noise reduction. Weight and its distribution (weight breakdown for essential parts of the structure. Suspension system and ride quality: air cushion (peripheral jet), secondary suspension (air spring), passive and active suspensions. Design analysis of the secondary suspension. Ride quality analysis. Vehicle structure: design and load criteria. Vehicle systems and subsystems, personnel compartment. Operational safety. Guideway (requirements, safety, cost). Ground support equipment. All parts of report, as mentioned above, are analyzed with respect to the research programme and its requirements.

T.13 TRACKED AIR CUSHION RESEARCH VEHICLE. FINAL REPORT. VOLUME I.
RESEARCH VEHICLE PRELIMINARY DESIGN
(Grumman Aircraft Engineering Corporation, Bethpage, N.Y. March, 1969, PB 183 172)

T.14 TRACKED AIR CUSHION RESEARCH VEHICLE, VOLUME II. RESEARCH VEHICLE DEVELOPMENT PLAN. PLAN I. TECHNICAL PLANS.
(Grumman Aircraft Engineering Corporation, Bethpage, N.Y. March 1969, PB 183 173)

General arrangement of Grumman TACV ("U" shape guideway, vehicle body inside guideway, and support cushions on the top of guideway).

Project development schedule. Systems development, subsystems development, vehicle design (subsystem development, air cushion control valve, friction and wear data for friction brake, flexible peripheral jet material). Vehicle design: powerplant/propulsion system, structural design, mechanical systems, instrumentation/communications, dynamics, loads, stress, aerodynamics, safety.

Manufacturing plan (vehicle manufacturing breakdown, manufacturing schedule, facilities, materials). Qualification plan.

T.15 LOW SPEED WIND TUNNEL TESTS ON A 1/6th SCALE MODEL OF AN AIR CUSHION VEHICLE (BRITTEN-NORMAN CUSHIONCRAFT CC2)
TREBBLE, W.J.G.
(Royal Aircraft Establishment, T.R. 66383, December 1966)

Investigation of the effect of mainstream speed on the performance and stability of an ACV. Large intake momentum drag (biggest part of the total drag). Large nose-up momentum at forward speed close to maximum. Model description. The following characteristics have been measured:
- aerodynamic characteristics \( (C_L, C_D, C_m) \) of the basic model; intakes and exits sealed, with and without fins.
- total head and velocity of peripheral jet at nozzle at various positions of the periphery as a function of the dynamic pressure.
- effect of hoverheight on lift, and cushion pressure.
- effect of intake lip shape.
- effect of height and mainstream speed at zero incidence on \( L, D, m \).
- effect of incidence on \( L, D, m \) for various \( h/t \) and \( q_o/p_{co} \) ratios.
- effect of mainstream speed on pitch stability.
- pressure distribution along the centreline of the undersurface of vehicle with and without stability jets for various angles of incidence and mainstream speed.
- yawing and rolling moment, and sideforce.
- effect of the lifting system on lateral stability.
- effect of blade angle and mainstream speed on thrust coefficient and power requirements.
- effect of propellers on lift, drag and pitch moment.
- effect of stopping of one propulsion engine on directional and lateral stability.
- tailplane contribution to pitching moment.
- effect of sealing front peripheral jet.
- external lift to air curtain lift ratio.
T.16 TRIALS OF AN SRN6 HOVERCRAFT AT CHURCHILL, MANITOBA, JAN-MARCH, 1968
(Department of Transport, Ottawa, Ontario)


T.17 TRIALS OF A CC7 AIR CUSHION VEHICLE IN CANADA, MAY-AUGUST, 1969
(Department of Transport, Ottawa, Canada, December 1969)


T.18 AN EMPIRICAL STUDY OF HOVERCRAFT NOISE
TRILLO, R. L.

T.19 TRACKED AIR CUSHION RESEARCH VEHICLE. FINAL REPORT. VOLUME 3.
RESEARCH VEHICLE RESEARCH PLAN
(Grumman Aircraft Engineering Corporation, Bethpage, N.Y.
March 1969, PB 183 174)

Research program goal (test data on ride comfort, performance, efficiency and noise level in operation). List of variables which must be examined. Recommended test program. Test logic. Test support equipment (guideway with special test sections, instrumentation, gust simulator, auxiliary cushions). Facilities and support (repair and maintenance area, control and data areas, fuel storage and transfer areas). Operational personnel. Cost factors: Instrumentation, gust rocket. Operational cost. Summary of test objectives are presented in Appendix A (Performance, aerodynamics, acceleration deceleration, ride quality, acoustics, safety, thermal, maintainability, costing, reliability, subsystems, etc). Primary research objectives are presented in Appendix B (dynamics and ride quality, air cushion dynamics, aerodynamics, guideway dynamics, noise control, LIM system, etc). Test measurements are presented in Appendix C.

T.20 TRACKED AIR CUSHION VEHICLE SYSTEMS.
(Office of High-Speed Ground Transportation, Dept. of Transportation, Washington, D.C. May 1970, PB 195 030)

Place of TACV in HSGT system. Description of basic configurations (guideway, cushion, propulsion). Cost of the system (research work, development, testing, manufacturing, guideway cost - breakdowns for 50, 100, 150 pax and 150, 250, 350 mph vehicles). Critical development - suspension, LIM, power pick-up, obstacle detection. Requirements and constraints. Ride comfort, community acceptability. Description of vehicles (150, 250, 350 mph): weight analysis; structure; vehicle coupling; vehicle aerodynamics (basic formulae for lift, drag, sideforce, pitching, rolling and yawing moment coefficients, bottom drag, tunnel effect, passing of the vehicles). Propulsion: forces and moments, requirements, alternatives, cost and weight comparisons, performance comparisons. LIM performance, concept and requirements analysis. Braking requirements and limitations, braking techniques. Suspension requirement and general criteria, air cushion characteristics (plenum, peripheral jet), guidance cushions, power requirements, roughness effect. Primary and secondary suspension analysis. Compressor design. Guideway design approach, physical characteristics, switching, construction techniques, comparison of various cross sections, cost (effect of dimensions, shape). Power and control (guideway and vehicle installed equipment). Terminal design and criteria. TACV system study.
The aerodynamics of the Tinajero ground effect machine and its two-dimensional counterpart were investigated under various flight conditions. Tests of the full scale machine included external aerodynamics, control effectiveness, stability and the effect of changing the vertical centre of gravity. Tests were conducted in the University of Maryland Subsonic Wind Tunnel diffuser section and on a ground board set up in the open air. The machine was found to be basically unstable in yaw and the controls were ineffective. The two-dimensional model, with several nose shapes was tested in a twenty four inch subsonic wind tunnel to obtain flow patterns and pressure distributions. It was found that nose shape had no real effect on the cushion under the vehicle, but did effect the basic external aerodynamics characteristics. Significant changes in flow patterns were observed as forward speed increased.
W.01 THE INFLUENCE OF FAN AND DUCTING CHARACTERISTICS ON THE STABILITY AND PERFORMANCE OF GROUND EFFECT MACHINE
WALKER, N. K.
(N. K. Walker Associates, Bethesda, Maryland. AIAA Paper No. 64-185, Wichita, Kansas. May 1964)

Historical survey of GEM stability references: Tulin-heave Eames-heave and pitch, Manhut and Paine, Cross, Strand, Walker, etc. Stability of plenum chamber with arbitrary fan characteristics - heave equation, estimation of static stability derivative, damping derivative and ratio. Discussion of results for simple cases. Stability of annular jet GEM - estimation of the static stability derivative, undamped natural frequency, damping derivative for underfed and overfed jets and estimation of damping ratios. Discussion of results for simple cases. Comparison with experiments.

W.02 THE PROPERTIES OF FLEXIBLE CONICAL LIFTING CELLS FOR AIR CUSHION VEHICLES. FINAL REPORT
WALKER, N. K., and BONSALL, D. E.
(U. S. Army Mobility Equipment, Research and Development Center, Fort Belvoir, Virginia, December 1969, AD 700 020)

Comparison of British and French skirt concepts. Description of ACV model and cells. Presentation of test procedure. Simple theoretical analysis of lift over a horizontal surface, clear of, and with contact with the ground. Skirt instabilities (failure of lift, partial lift, venting, buckling, suck in and buzz - skirt buzzes at the edges). Presentation of the experimental results for the following angles of skirt cones: 5, 10, 16, 20, 30° - lift as a function of skirt height. Comparison of simple theory with measured lift. Limiting C.G. height.

W.03 EFFECT OF FORWARD SPEED ON A TWO-DIMENSIONAL GROUND-EFFECT MACHINE
WEST, A.A.
(Hovering Craft and Hydrofoil, Aug-Sept, 1964)

Flow around a two-dimensional ACV at forward speed (subcritical, critical, supercritical - i.e., in the subcritical regime, the front part of the jet is split on the ground; critical - it is deflected under vehicle; and supercritical - the free stream passes under the vehicle). Description of the model and facilities. The following results are presented: total lift versus free stream dynamic pressure, aerodynamic lift coefficient versus forward speed parameter for several $p_{\text{d}}/P_0$ ratios, drag versus free stream dynamic pressure, thrust recovery coefficient versus forward speed/jet velocity ratio.
ON THE PERFORMANCE OF THE HOVERCRAFT SINGLE-WALL SKIRT

WEST, A.A.
(The Aeronautical Quarterly, November 1967)

Simple analysis of the air flow and nozzle power requirements of a hovercraft with a "single wall" skirt (peripheral jet is blown along inner skirt face). This analysis is applicable to the equilibrium jet state. A comparison of the air flow and nozzle requirements of a plenum chamber vehicle and a vehicle with twin wall skirt. It is concluded that at the same conditions (clearance, terrain, operation) the order of merit is: twin wall, single wall, plenum chamber.

TWO-DIMENSIONAL AIR CUSHION VEHICLE CRITICAL FORWARD SPEED

WEST, A.A.
(University College of Swansea, Swansea, Wales, Reprinted from Journal of Aircraft, 1967)

Analysis of the critical forward speed for a peripheral jet.

HOVERCRAFT RANGE

WEST, A.A.

Equations for hovercraft range computations and initial assumptions are presented (constant hoverheight, wavedrag, etc).

THE INFLUENCE OF PLENUM CHAMBER OBSTRUCTIONS ON THE PERFORMANCE OF A HOVERCRAFT LIFT FAN

WILSON, G., MYLES, D. J., and GALLACHER, G.
(Canadian Aeronautics and Space Journal, April 1969, pp.132-134)

Description of test facility, fan parameters and dimensions. Total pressure and total efficiency of impeller, unobstructed impeller plenum system and hovercraft configuration were measured as a function of flow rate. The effect of an obstruction plate in impeller plenum chamber combination on the total efficiency was examined.

THE DOMINANT AERODYNAMICS CHARACTERISTICS OF A SHAPED GROUND EFFECT MACHINE

WOJCIECHOWICZ, A.F.
(U. S. Army Transportation Research Command, Fort Eustis, Virginia, TRECOM T. R. 64-45, Sept, 1964)

General analysis of GEM's lift and its breakdown into components. Lift equations. Effect of aerodynamic lift upon performance, and required power for forward flight (equation for required power and components are presented). Drag analysis and its breakdown, equations are presented. Pitching moment. Wind tunnel tests - description of tested configurations. Test results for individual configurations are presented (CL, Cp, Cm angle of attack) in figures. Full-scale tests - description of configurations, flight test instrumentation, flight test results presentation (hoverheight vs.
BHP, velocity; variation of $C_L$ with non-dimensional height parameter ($h/D$); variation of augmentation factor with speed and $h/D$ parameter).

**THE EFFECT OF CONFIGURATION ON THE LIFT AUGMENTATION RATIO OF A TWO DIMENSIONAL OPEN PLENUM GROUND EFFECT MACHINE**

WRIGHT, D. E.

Description of model and apparatus, model characteristics. Theoretical analysis (jet exit velocity, jet thrust and lift augmentation equations are quoted). The following data were measured for all model configurations: base pressure (various models have various nozzle area/base area ratios, side depth and side angle), influence of various hoverheights, and angle of incidence of model relative to ground base. Lift augmentation for various model configurations versus hoverheight/base length ratio; effect of side incidence, nozzle area/base area ratio, model incidence relative to the ground board, flow variation and diversion on augmentation. Comparison of experiments and theoretical values of lift augmentation.

**HEAVE SUSPENSION CHARACTERISTICS AND POWER REQUIREMENTS OF A PLENUM AIR CUSHION**

WHEATLEY, J. H. W.
(National Physical Laboratory, Hovercraft Unit, Report No.9, December 1969).

Assumptions of the heave motion analysis. Derivation of the cushion equations and the equation of motion in heave. Suspension configuration and characteristics are presented. The heave response and acceleration for short and long waves. The cushion power requirements for static or calm water conditions and dynamic or over wave conditions (short, intermediate, long waves). The heave stiffness and damping. Discussion of the limitations of the theory. The derivation of cushion pressure change parameters for small motions and surface forcing factor in heave are presented in the appendices.
Y.01 PATTERNS OF FLOW UNDER A TWO DIMENSIONAL GEM
YEN, Ben-Chie.
(Iowa Institute of Hydraulic Research, State University of Iowa, Iowa City, Office of Naval Research, Nonr 1509(03), January, 1962)

Definition of basic notations, description of experimental apparatus. The following data were measured: \( \frac{p_b}{p_o} \) ratio (pressure at base/total pressure at nozzle) on base plate (pressure distribution on base plate) as a function of jet thickness and jet discharge angle, velocity and pressure distribution at nozzle exit, augmentation factor as a function of jet discharge angle and jet thickness, force on the base plate per unit length as a function of jet thickness and jet angle, flow patterns and pressures across the base for various annular jet configurations.
3. **SUBJECT INDEX**

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**Active Suspension:**  G.06, R.02, S.07, T.12, T.20

**Aerodynamics:**  A.07, A.08, C.10, C.22, G.07, G.08, G.09, G.11, G.12,

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**Air Cushion Landing Gear:**  C.01, E.05, G.08, L.06, R.11

**Air Cushion Principles:**  B.18, C.06, C.07, E.02, H.03, I.01, N.02, N.06, P.04

**Amphibious Vehicle:**  A.02, A.09, B.06, B.15, B.18, B.24, C.14, C.20, H.04

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**Analysis of Operating Cost:**  A.09, I.01, L.07, N.06, S.07, T.01, S.07, T.20

**Angle of Attack:**  A.07, A.08, B.19, C.22, C.23, G.08, G.09, G.11, G.12,

H.01, J.06, J.07, 0.01, S.10, T.15, T.20, V.01, W.08

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O.01, S.06, S.10, T.03, T.04, T.05, T.06, T.07, V.01, W.08, W.09

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**Axial Fan**  S.02

**Bag Pressure:**  C.09, R.11

**Base Pressure:**  C.01, C.14, F.01, G.07, H.01, J.01, K.04, L.08, M.02,

M.04, R.11, V.01, W.09, Y.01

**Bibliography:**  B.07, B.14, H.03, N.06, R.09, S.07

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Turns: A.05, C.14, M.03, M.02, L.09, T.09, T.16, T.20

Underfed Jet: B.10, B.21, B.22, E.01, E.03, H.03, Mc.03, R.06, W.01, W.03

University Research: B.22, C.14, C.15, C.16, C.17, E.03, G.01, G.02, G.08, H.01, J.02, J.03, K.07, L.06, Mc.01, Mc.03, R.01, R.04, R.05, R.06, S.04, S.07, S.10, U.01, W.09

URBA: B.04, B.12, F.03


Vehicle - Suspension System: B.04, B.12, C.15, F.03, G.05, G.06, M.01, M.02, R.02, R.04, S.07, T.11, T.12, T.20


Volume Flow: A.03, B.16, B.23, H.03, K.02, K.04, N.01, 0.01

Water Jet: N.01, S.01

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Water Screw: N.01, S.01, S.03
Wave Drag: B.01, C.01, C.10, C.13, C.21, E.04, H.03, H.04, J.02, M.01, N.01, R.13, S.03
Wave Elevation: C.11, H.02, H.04, W.10
Wave Profile: C.11, C.12, C.21, H.02, H.04, J.08
Wave Simulation: C.11, L.09
Wavemaking: B.01, C.07, C.08, C.10, C.11, C.19, C.21, E.04, H.03, H.04, J.02, M.01, M.05, N.01, R.13, S.03
Waviness: C.11, C.12, H.02, H.04, R.04
Weight Breakdown: C.05, E.02, J.01, J.02, P.02, R.11, T.12, T.13, T.20
Wind Effect: A.02, F.04, G.11, H.04, H.07, T.09, T.16
Winter Trials: A.02, B.15, F.04, N.06, T.16
Yaw Angle: A.05, A.07, B.26, E.04, G.12, H.08, L.09, M.05, T.20, U.01, V.01
This review attempts to present a basis for discussion of research and development requirements for effective exploitation of air cushion technology in Canada. Detailed reviews of the status of two important applications, namely amphibious air cushion vehicles (ACV) or Hovercraft and tracked ACVs or Hovertrains, are given. An examination of the relationship of R & D to transportation vehicles is also included to provide a basis for taking an adequate perspective of needs in this new technology. Some recommendations on the form of an appropriate R & D programme are also made in the light of trends in other fields. A summary of available information on amphibious ACV costs, and an annotated bibliography of the research literature together with a subject index, completes the review.

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