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Overview of Some Problems in Ground Transportation

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Some problem areas in ground transportation systems, along with aerospace skill applications are surveyed. First, the ground transportation categories of line haul, network transit and local personal rapid transit are defined. System elements, phases and milestones are then identified. It is seen that surface transportation system development is characterized by activity which is conceptually similar to that in aerospace system development. Next, some technology areas are discussed: performance in the context of block speed relating to station spacing and passenger comfort, system capacity relating to vehicle size and headway, and power requirements as impacted by vehicle-guideway interaction; suspension dynamics in the context of ride quality and the trade between guideway roughness and suspension sophistication; propulsion and power in the context of electric systems for minimum on-line noise and pollution; guideways in the context of system cost sensitivity to configuration and stiffness requirements and interaction with other system elements; and control and communications in the context of high capacity, fail safe traffic control. It is concluded that new system development, systems integration and many technology areas can benefit from application of basic aerospace skills, but that other areas such as socio-political institutional constraints require considerable aerospace acclimation.

Introduction

THE purpose of this paper is to survey some problem areas in ground transportation systems and to illustrate the applicability of aerospace concepts and technology. The paper is directed toward the aerospace engineer with emerging interest in, but no special professional familiarity with, ground transportation.

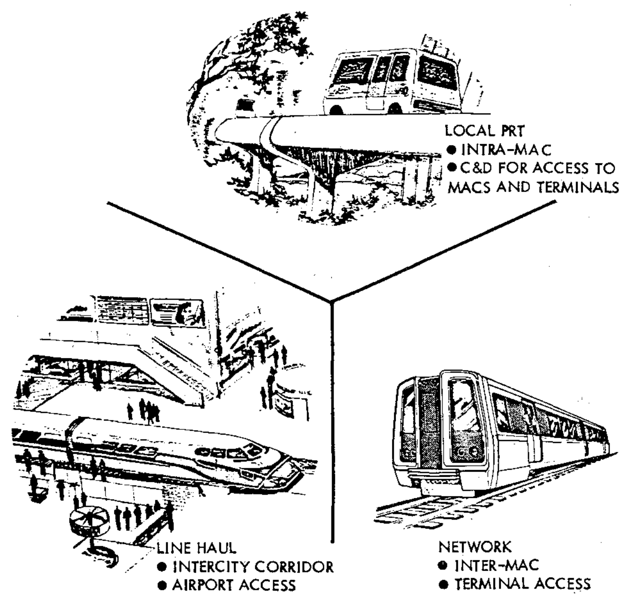

Fig. 1 Ground transportation system categories.

Surface transportation may be conveniently considered in three major categories: local Personal Rapid Transit (PRT); network transit; and line haul. Local PRT systems perform two major functions; to provide local transit within Major Activity Centers (MACs) such as airports, Central Business Districts (CBDs), college campuses, etc.; and to provide collection and distribution for MACs and access to terminals for connections to other categories of transportation. These systems are typified by relatively small serviced areas, closely spaced stations, and low peak speeds. Network transit systems serve to connect MACs within a metropolitan area and to provide access to terminals for other transit categories. Line haul systems provide high speed, long distance airport access and intercity corridor service. Figure 1 illustrates the three ground transportation categories, and Fig. 2 summarizes their applications and characteristics and identifies

CATEGORY	LINE HAUL	NETWORK	LOCAL PRT
APPLICATIONS	• AIRPORT ACCESS • INTERCITY CORRIDOR	• CONNECTING ACTIVITY CENTERS • LINE HAUL TERMINAL ACCESS	• C&D FOR NETWORK AND LINE HAUL SYSTEMS • LOCAL TRANSIT FOR CBD, CAMPUS AIRPORT, EXHIBITIONS, FAIRS, ETC.
TYPICAL CHARACTERISTICS	• HIGH SPEED (100-300 MPH) • STATION SPACING >5 MILES	• MODERATE SPEED (40-80MPH) • STATION SPACING > 1/2 MILE	• LOW SPEED (<50 MPH) • STATION SPACING ≈ 1-2000 FT
EXISTING CONCEPTS	• AUTOMOBILE • BUS • RAIL • TURBOTRAIN • NEW TOKAIDO LINE • TEE	• AUTOMOBILE • BUS • RAIL • NEW YORK SUBWAY • BART	• AUTOMOBILE • MINI-BUS
NEW CONCEPTS	• TACV • MAGNETIC LEVITATION • TUBE TRANSIT	• AUTOMATIC HIGHWAYS AND BUSWAYS • ADVANCED RAIL • DUAL MODE	• MOVING SIDEWALK • RUBBER TIRE • AIRCUSHION • MONORAIL • DUAL MODE

Fig. 2 The domain of ground transportation.

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Index category: Aerospace Technology Utilization.

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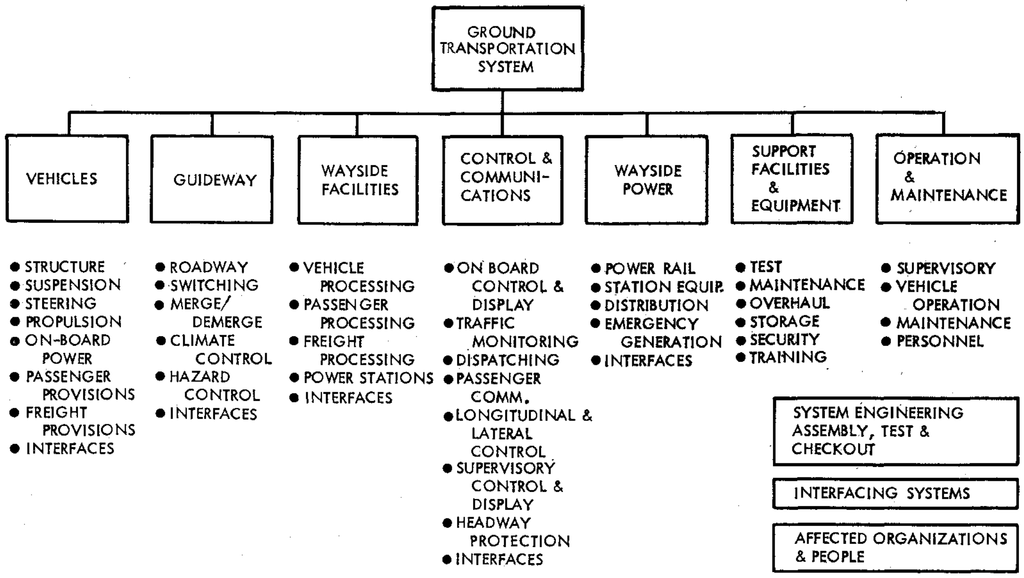


Fig. 3 System elements.

typical existing and new concepts. In the future, many line-haul requirements will be satisfied by the 60 to 100 passenger tracked air cushion vehicle (TACV) or the magnetically levitated vehicle (Mag Lev), powered by a relatively quiet and pollution-free linear electric motor, and traveling at speeds up to 300 mph on exclusive-use, elevated guideways. Many intraurban network needs will be served by rail vehicles, improved over present types by virtue of automated control and communications systems, light-weight, low-maintenance structures and mechanisms, and application of life-cycle operation and maintenance concepts. Local PRT systems, or "people movers," will typically involve small (6—30 passenger) capsules, rubber tired and airspring suspended, electrically powered and automatically controlled at speeds in the order at 25 mph, direct from origin to destination, e.g., from airport entrance station or parking lot direct to the individual airline gate. The three categories are not always mutually exclusive. For example, the ubiquitous automobile appears in virtually every application today. In order to minimize time delays associated with transfer between different transit systems and to maximize passenger origin to destination convenience, dual mode systems involving manual operation in the collection and distribution role and automatic guideway operation in the network role may be common in the future. Delays and congestion associated with intermodal and intercategory interfaces are among the most undesirable aspects of travel today. Dual mode transit and intermodal terminals will be key concepts in minimizing total

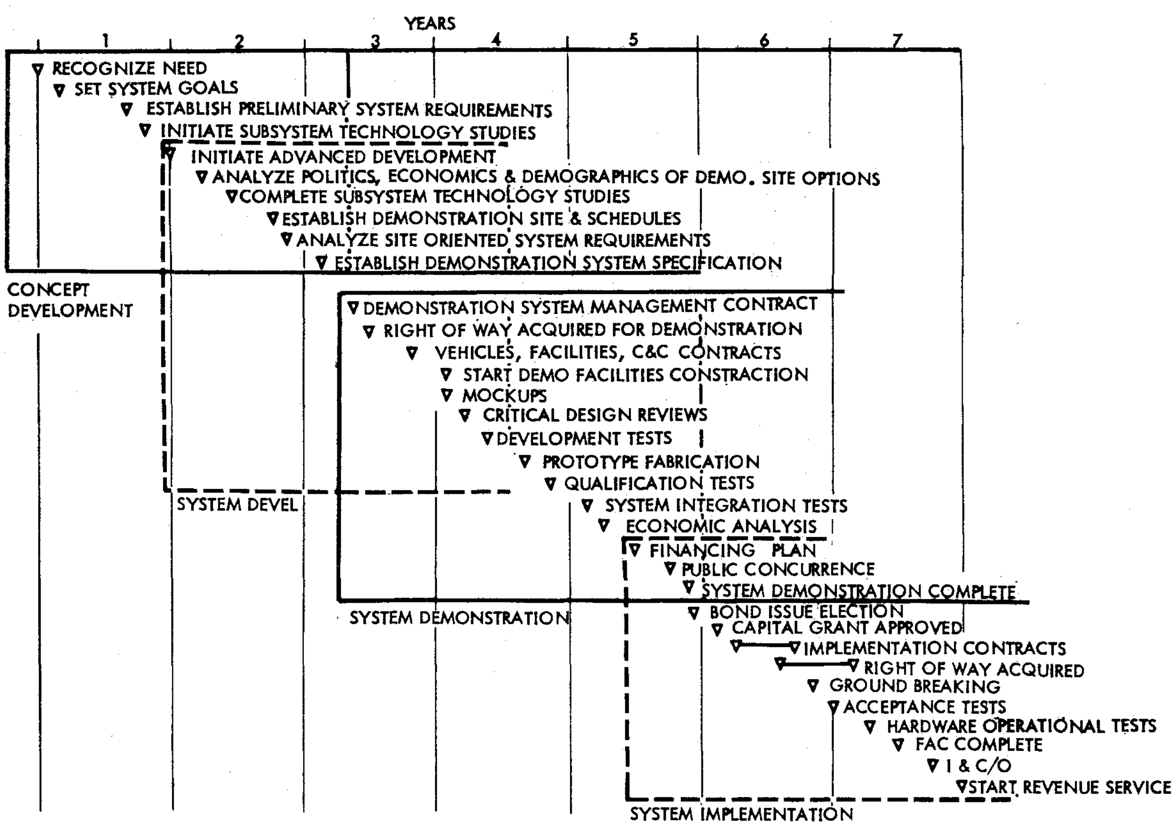


Fig. 4 System phases and milestones.

trip block time and assuring full system capacity utilization in the future.

System Considerations

A typical ground transportation system includes the elements shown in Fig. 3. The building blocks of the vehicle system, the guideway, the system facilities, wayside power and the control and communications system are integrated by system engineering, assembly, test and checkout with due cognizance of interfacing systems and organizations to enable satisfactory system operation. The gestation of a system is characterized by the well-defined, though overlapping, phases of concept development, system development, system demonstration, and system operational implementation and their associated milestones as indicated in Fig. 4. The gestation period of a ground transportation system is seen to be comparable to that of an air or space transportation system and characterized by much conceptually similar activity.

The creation of an effective total transportation network requires that the characteristics of each new system are carefully matched to the particular application and that the new system is effectively integrated with already existing transportation modes and other interfacing systems such as intermodal terminals, baggage handling and parking. In addition, each new ground transportation system requires, for its successful implementation, due cognizance of such factors as: new system introduction aspects; integration, assembly, test and checkout; facilities design and construction management; multiple organizational and community involvement; training; logistics support; and commercial passenger vehicle experience. These factors are also crucial in the successful implementation of military, space and commercial airplane systems. Therefore, as indicated in Fig. 5, the capability base already developed within the aerospace field is very largely applicable to ground transportation. To detail this point, Fig. 6 summarizes some aerospace technology skills directly applicable to the problems associated with the ground transportation system elements. The classical aerospace skills of performance analysis, dynamics and loads, propulsion and power, electronics, design, and system analysis are matrixed against the ground transportation system elements of vehicle, guideway, wayside facilities, control and communications, support equipment, and systems planning, management, and integration.

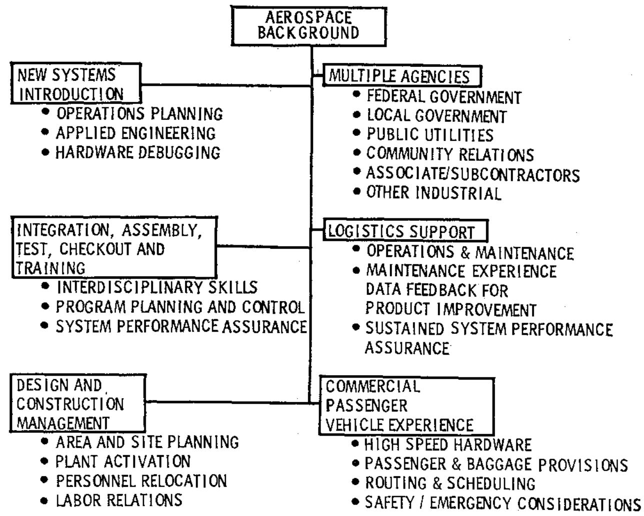


Fig. 5 Aerospace experience and transportation system capability.

The discussion thus far has served to define the domain of ground transportation, the types of systems likely for the future, and the technical problem areas of interest. The following discussion will examine some of these areas.

Performance

One of the first considerations in the definition of a transportation system is that of how much performance is appropriate to the mission. This is addressed in Fig. 7, which shows effective, or block speed as a function of maximum vehicle speed for different values of station spacing, and with passenger-imposed constraints of vehicle acceleration and station dwell time. From a passenger comfort standpoint, three mph/sec (just under 0.14g) is a commonly specified limit on normal operational acceleration and deceleration.[1] A station dwell time of 15 sec is also assumed in the figure. The numerical results are of course dependent upon these

SYSTEM ELEMENTS \ SKILLS	PERFORMANCE ANALYSIS	DYNAMICS & LOADS	PROPULSION POWER	ELECTRONICS	DESIGN	SYSTEM ANALYSIS
VEHICLE	• DRAG CHARACTERISTICS • PRIMARY POWER REQUIREMENTS • BRAKING	• DESIGN CRITERIA • RIDE QUALITY • SUSPENSION CHARACTERISTICS • RESPONSE SPECTRA • STABILITY	• PROPULSION • SUSPENSION POWER • POWER CONDITIONING • POWER PICKUP • AUXILIARY & EMERGENCY POWER	• OPERATIONAL CONTROL • COMMUNICATION • SWITCHING • ACTIVE SUSPENSION	• CAR • SUSPENSION • ON BOARD EQUIPMENT • PASSENGER & BAGGAGE PROVISIONS	• REQUIREMENTS & CONSTRAINTS SPECIFICATIONS • PERFORMANCE • SAFETY • RELIABILITY • MAINTENANCE • FUNCTIONAL ANALYSIS • CONCEPT TRADES
GUIDEWAY	• VEHICLE GUIDEWAY INTERACTION	• DESIGN CRITERIA • STIFFNESS REQUIREMENTS • SUSPENSION GUIDEWAY TRADES	• POWER DISTRIBUTION	• HEADWAY MONITORING • VEHICLE STATUS & VERIFICATION	• ROADWAY • PIERS • FOUNDATION	
WAYSIDE FACILITIES			• WAYSIDE POWER • PUBLIC UTILITY INTERFACE	• DISPLAYS • STATION MONITORING	• POWER STATIONS • PASSENGER STATIONS • BAGGAGE HANDLING • PARKING	
CONTROL & COMMUNICATIONS	• PERFORMANCE MONITORING		• PROPULSION & POWER MONITORING	• TRAFFIC SCHEDULING • VEH. STATION CONTROL • FAULT DIAGNOSIS & RECOVERY	• EQUIPMENT PROVISIONS	
SUPPORT EQUIPMENT			• EQUIPMENT POWER REQUIREMENTS	• SYSTEM SECURITY	• MAINTENANCE • REPAIR • STORAGE • SYSTEM ACCESS CONTROL	
SYSTEMS PLANNING MANAGEMENT & INTEGRATION	• OBJECTIVES • MASTER PLAN & SCHEDULE • CONTRACTING STRUCTURE & TEAM • CONFIGURATION & INTERFACE DEFINITION & CONTROL • VISIBILITY & ASSESSMENT • CUSTOMER COMMUNITY REGULATORY AGENCIES INTERFACE					

Fig. 6 Aerospace technology skills applicable to ground transportation.

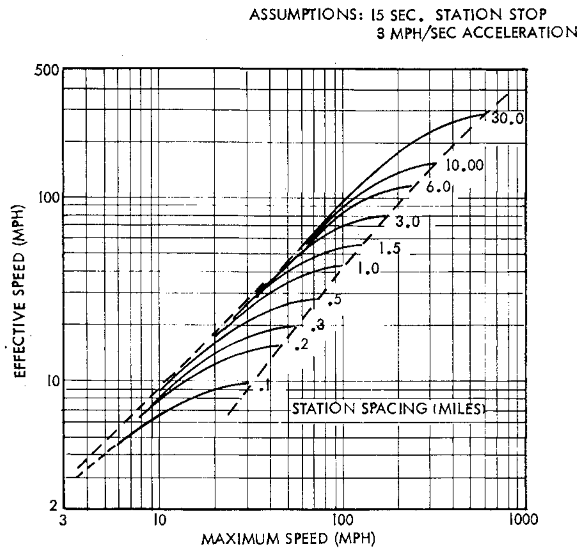


Fig. 7 Effective vs maximum speed for various station spacings.

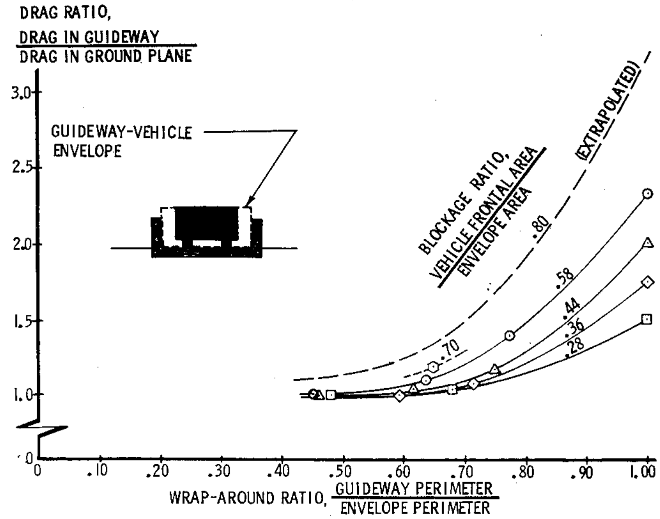


Fig. 9 Vehicle-trough guideway interaction drag.

assumptions. If the vehicle continuously cruised at constant speed without stopping, then the effective speed would equal the maximum speed, and this would correspond to the 45° sloped dashed line asymptote on the left in the figure. The effects of station stops and associated accelerations are manifested as dropoffs to the right of and below this asymptote. The horizontal asymptotes on the right for each station spacing indicate the maximum usable vehicle speed. For example, a "people mover" with stops every half mile, can't really use a maximum speed capability of more than about 70 mph, which corresponds to an effective speed of just under 30 mph. Indeed, a maximum speed capability of 30 mph and an associated effective speed of just over 20 mph might be more appropriate. On the other hand, a line-haul vehicle with stops only every ten miles can make use of a maximum speed capability of 300 mph, which corresponds to an effective speed of about 150 mph. Here again, though, a maximum speed capability of 200 mph yields an effective speed of just under 150 mph, and may be a better design point.

System capacity is addressed in Fig. 8, which shows capacity in passengers per hour as a function of vehicle separation time, or headway, for different size vehicles. High capacity can be achieved by either: a) using relatively few large vehicles or vehicle trains at relatively long headways, which is the approach common for high-speed line-haul systems; or b) using many small vehicles at quite short headways, which is a logical approach for local PRT systems with adequate automatic close headway control and direct origin to destination service.

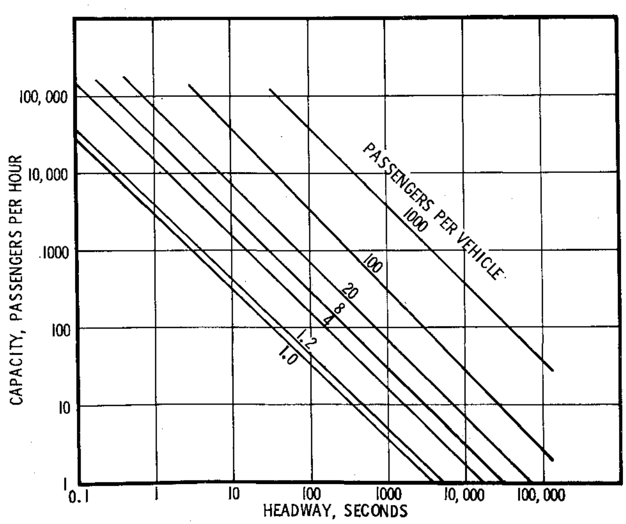


Fig. 8 Headway/capacity relations.

Vehicle-guideway interaction is of crucial importance for high speed ground transportation. One aspect of this interaction is treated in Fig. 9 which is based on water tank test data from Ref. 2. The figure shows the ratio of vehicle drag in the presence of the guideway to the vehicle drag in the presence of the ground plane only, as a function of: a) the fraction of the vehicle frontal perimeter taken up by the guideway, and b) how tightly the guideway cross section hugs the vehicle frontal envelope. The limiting case of the free vehicle on the ground plane corresponds to the unity ordinate value. The opposite limiting case of the guideway completely and tightly wrapping around the vehicle like a cylinder around a piston is upward and to the right in the figure. Wind-tunnel test facilities such as the moving belt facility at NASA-Langley Research Center, can also be used to obtain insight into the aerodynamic aspects of high-speed ground travel.[3] It is plainly indicated that vehicle-guideway interaction can substantially increase the vehicle power requirements.

Suspension

The prime functions of the vehicle suspension system are to deliver adequate stability and passenger ride comfort, with the latter function being the more difficult. The suspension system is largely designed on the basis of the twin inputs of passenger ride comfort requirements and guideway irregularities, as indicated in Fig. 10. In the upper left of the figure is the ride comfort requirement, expressed as allowable acceleration at the passenger seat as a function of frequency (e.g., Ref. 4). In the upper right of the figure is one mode of expressing guideway roughness; irregularity amplitude as a function of wavelength for different qualities of roadway surface.[5,6] Curve 2, "good runway," is also indicative of the track alignment maintained for the Japanese New Tokaido Line.[7] Indicated on Curve 1, "welded track," is a point at 0.1 in. irregularity in 100 ft of length which is typical of the current state of the art in post-tensioned, close-tolerance concrete beam guideway design and construction. For elevated guideways there is the additional factor of the resonant rfequency of the guideway between supports. The twin inputs of comfort requirements and guideway irregularities can be combined to yield envelopes of allowable suspension system transfer function, i.e., allowable suspension system

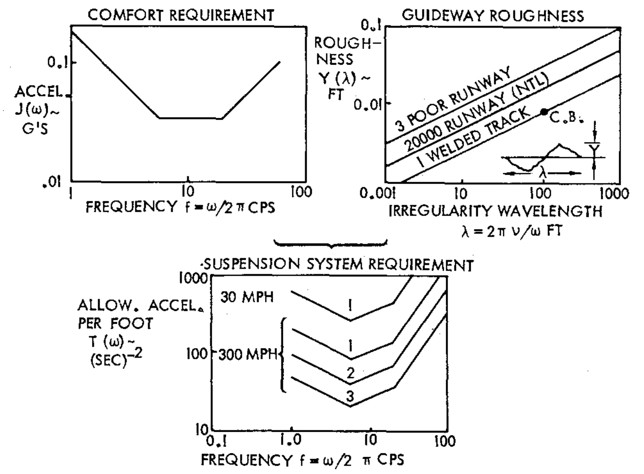


Fig. 10 Ride quality requirements vs guideway roughness.

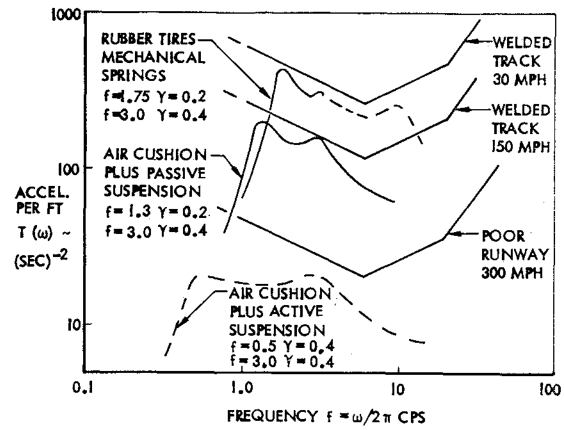


Fig. 11 Suspension system influence on ride quality.

output acceleration per foot of guideway roughness as a function of frequency, as shown in the bottom portion of Fig. 10.[8] As indicated in the figure, the demands on the suspension system increase markedly with increasing speed and degrading guideway surface. Figure 11 from Ref. 8 depicts allowable suspension system transfer functions for several combinations of guideway surface quality and speed for the same specified ride comfort requirements, with an overlay of illustrative expected characteristics of several types of suspension concepts. The data in the figure, while not definitive, suggest several conclusions: 1) at low speeds, on good quality track, the demands on the suspension system are modest and a conventional rubber tire, mechanical (or pneumatic) spring approach should be quite adequate; 2) at high speeds in the neighborhood of 150 mph, this approach is probably inadequate to satisfy stringent ride quality criteria, and a more viable approach would be to use air cushion pads in conjunction with a secondary mechanical or pneumatic suspension; and 3) at very high speeds in the neighborhood of 300 mph on a relatively poor quality guideway surface, it is probably necessary to employ active sensing and automatic wide-band width control in the secondary suspension. Reference 9 presents a very good discussion of suspension system influence upon ride quality at high speeds.

Air cushion pads, as indicated previously, hold great promise as vital components of high-speed surface vehicles, and appear attractive for some low-speed vehicles as well. The most common basic types of air cushion pads are: a) open plenum, in which air is distributed throughout the planform area of the pad; b) peripheral jet, in which the addition of a center disk causes the air to exit only around the periphery of the pad planform area; and c) thin-passage bearing, in which the center-fed air is distributed in the very thin gap between the pad surface and the guideway. The practical air cushion pad has to satisfy many requirements, including: optimum performance throughout the vehicle design speed regime; minimum noise levels; minimum guideway obstruction susceptibility and moderate allowable guideway tolerances; minimum airflow and power requirements; and minimum pad wear. To satisfy these requirements, advanced concepts incorporating variable geometry, variable flow, and flexible pads, as indicated in Fig. 12, are appropriate.[10]

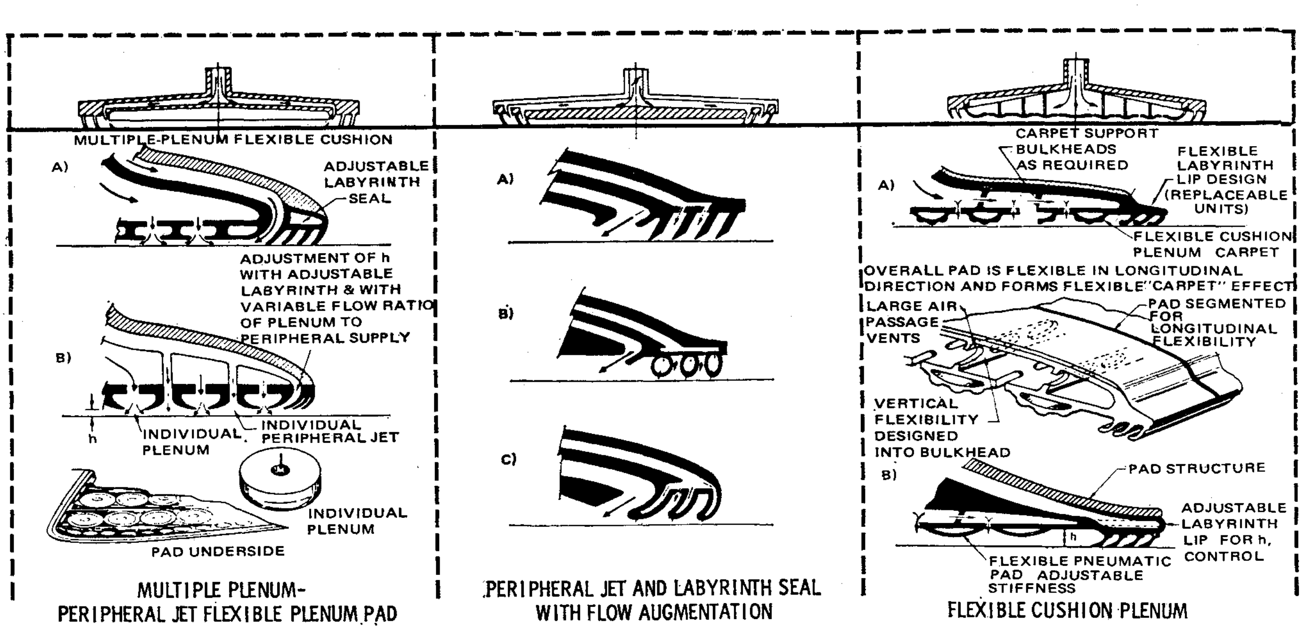


Fig. 12 Advanced air pad design concepts: variable geometry—adjustable labyrinth seal provides for pad clearance control to accommodate requirements as speed changes; variable flow—pads have ability to increase flow rate in peripheral supply to seal aerodynamically, at speed; flexible pad or "carpet" design increased compliance of pads—higher efficiences better ride and less wear.

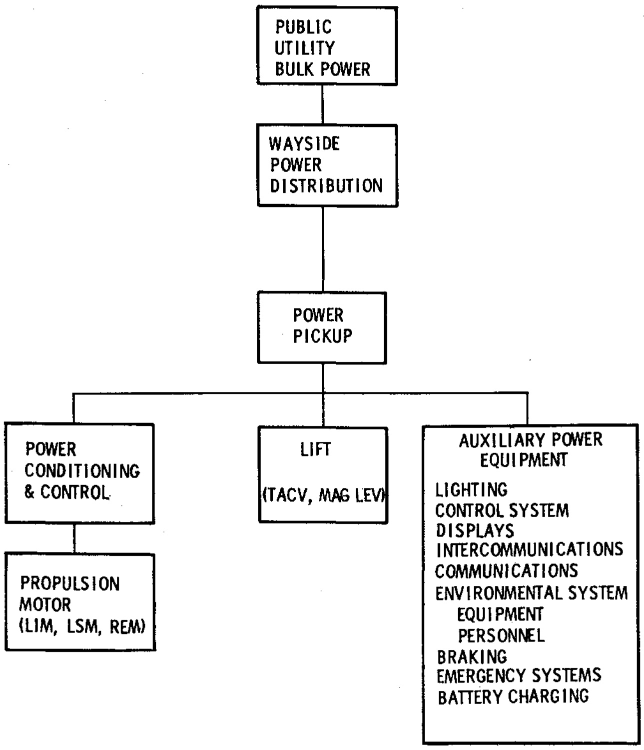
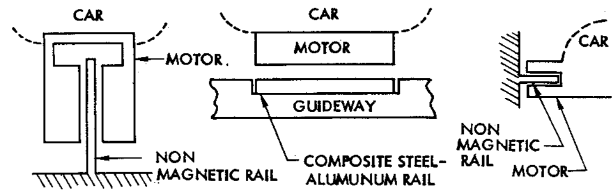


Fig. 13 Electric propulsion and power.

Propulsion and Power

In order to satisfy requirements for minimum on-line noise and pollution, many ground transportation systems will employ electric propulsion, using such items as linear induction motors, linear synchronous motors, or rotary motors. The system elements are in two main categories as depicted in Fig. 13: 1) wayside power, including the public utility interface, power station equipment, and power distribution to the guideway; and 2) propulsion and on-board power, including power collection from wayside to vehicle, power conditioning, the motor and its associated reaction rail (for linear induction motors), and suspension, auxiliary, and emergency power. The linear induction motor is attractive, not only from the noise and pollution standpoints, but also as part of a tracked air cushion vehicle or a magnetically suspended vehicle, with no direct mechanical contact between the vehicle and the guideway in order to assure minimum drag and maximum ride comfort. Some configurations under current study are shown in Fig. 14. It can be appreciated that there is considerable configuation interaction between the motor, the vehicle, and the guideway. Some areas requiring further research are: dynamically adequate noncontact, high-speed power pickup; light-weight, high-power factor on-board power conditioning equipment; motor configurations compatible with passive track switching; low-cost power distribution; and active vehicle vs active guideway cost trades.



NUMBER REQUIRED	ONE	ONE	TWO (ONE ON EACH SIDE OF THE CAR)
LENGTH	12' TO 15' SECTIONS	ANY LENGTH	12' TO 15' SECTIONS
TURNING	RESTRICTED	UNRESTRICTED	RESTRICTED
CONTROL TOLERANCE	±1/16"	±1/4"	±1/4"
MAGNETIC ATTRACTION TO RAIL	NONE	YES	NONE
AIR GAP	1.75"	VARIABLE	1.75"

THRUST VARIES INVERSELY AS THE AIR GAP SPACING

Fig. 14 Linear motor configurations.

Guideway

The guideway is by far the largest single cost element in a typical ground transportation system: the guideway and associated items can account for 50–90% of the total system cost. There is thus considerable motivation to identify the guideway cost drivers and to develop minimum cost configurations and fabrication and assembly techniques. Figure 15 summarizes the guideway elements: requirements, environment, characteristics, construction and maintenance.

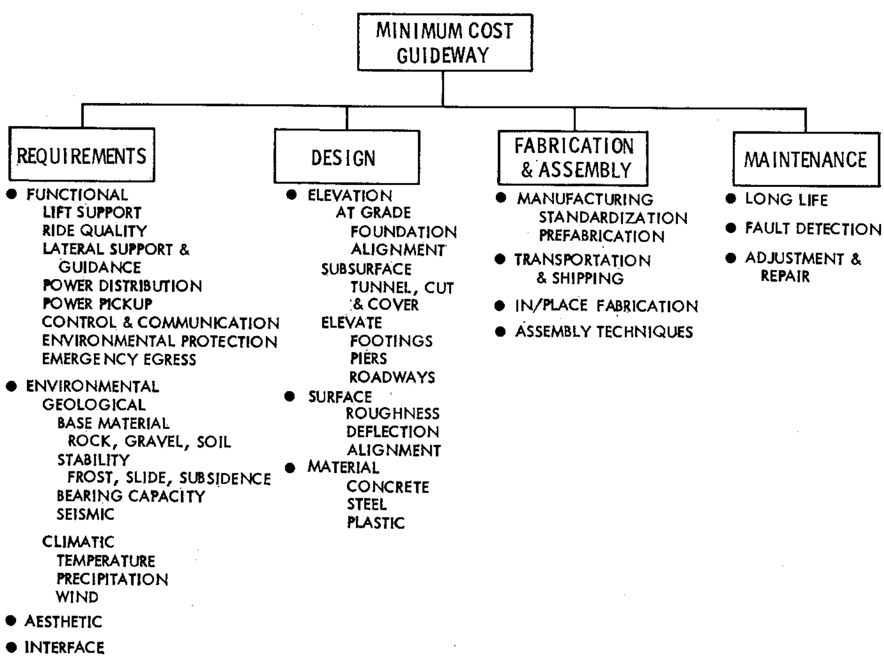
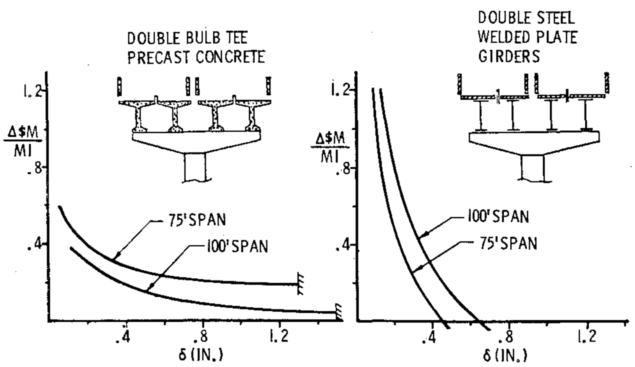


Fig. 15 Guideway elements.



• DEAD LOAD DEFLECTION COMPENSATION AND CAMBER PROVIDED BY PRE-FAB AND/OR CONSTRUCTION TECHNIQUES
• PRECAST CONCRETE $300/YD^3 (7.5¢/# STEEL 25¢/# ERECTED) INSTALLED

Fig. 16 Guideway cost sensitivity.

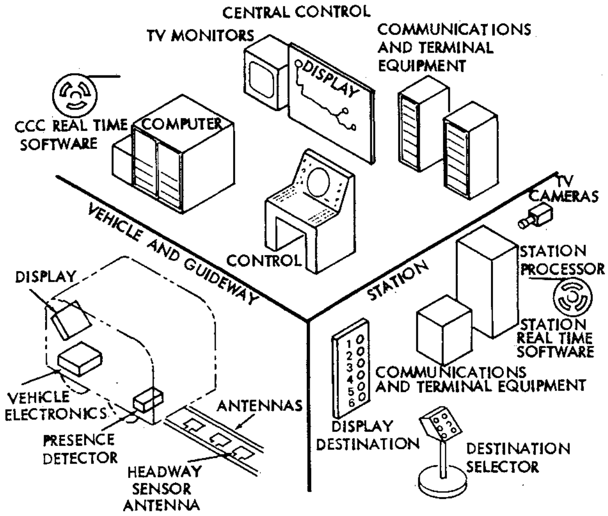


Fig. 17 Control and communications system.

Vehicle-guideway dynamic interaction must be duly accounted for in design.[11] One of the parameters strongly influencing guideway cost is the allowable live load deflection. This is illustrated in Fig. 16 which shows incremental guideway cost, in millions of dollars per mile as a function of allowable deflection, for concrete and for steel construction, and for two different span lengths between piers. The markings at the right hand portions of the curves applicable to concrete correspond to allowable deflections of 1/800 of the span, which is a value often used for conventional highway bridge design. The data in the figure suggest that guideway cost can substantially increase as allowable deflection is reduced below conventional civil engineering practice, and steel construction cost is more sensitive to allowable deflection than is concrete construction. In addition to material selection and allowable deflection, guideway cost is also affected by the cross sectional shape, the number of separate pieces which need to be handled during assembly, and required maintenance.

There is also intimate configuration interaction between the guideway, the vehicle and the motor configurations. There have been three major types of TACV guideway identified thus far.[12] The French Aerotrain uses an inverted tee-shaped guideway in which the center vertical member acts as a reaction rail for the double-sided linear motor and also as a base for the vehicle lateral support air cushion pads. Tracked Hovercraft Limited in Great Britain has developed a rectangular box-beam guideway, allowing a flat-bottomed passenger compartment to ride close to the flat upper face of the box. The vehicle lateral support air cushion pads are below the passenger compartment and glide along the vertical faces of the box. The Tracked Air Cushion Research Vehicle will feature a trough-shaped guideway with a protruding vertical center member as the LIM reaction rail. The lateral-support air cushion pads will glide along the inside vertical sides of the trough.[13] None of these shapes especially facilitates vehicle switching. It is not yet apparent which TACV guideway configuration is optimum.

Control and Communications

This system comprises: 1) vehicle on-board operational control on the guideway and in the station; 2) vehicle and system traffic control and monitoring; 3) passenger, in-car and operational communications; and 4) control system safety. Implementation of the system requires, as indicated in Fig. 17, components located on the vehicle, the guideway, each of the stations on the route, and at central control. Among the crucial decision and trade study areas are those involving: a) system traffic allocation and balance for optimum distribution of vehicles along the system route (including guideway, stations, servicing, and storage) to maximize vehicle utilization and minimize passenger wait time; b) off-nominal and emergency operation to minimize interference of disabled vehicles with traffic flow, to execute remedial action, and to assure passenger safety; c) optimum degree of control system centralization to allow maximum flexibility for system growth consistent with low initial cost; d) lateral control and switching; and e) especially important for local PRT systems using many small vehicles, adequate control of minimum headway between vehicles consistent with vehicle and passenger safety and backup system adequacy. The control and communications system interacts strongly with the other major system elements. For example, the headway control concept will dictate minimum safe headway, which will in turn influence vehicle size in order to maintain a specified system capacity (Fig. 8). As another example, selection of a scheme of synchronous velocity commands to all vehicles is consistent with off-line, rather than on-line stations on the system route.

Conclusion

The preceding discussion has identified some key problem areas associated with ground transportation systems. These include systems problems such as systems integration and new system implementation; and technology problems such as vehicle-guideway interaction, ride quality, propulsion and power collection, and high capacity, fail-safe traffic control. These are areas which can benefit from application of basic aerospace skills. To be sure, there are other problem areas in ground transportation which require considerable aerospace acclimation. Institutional constraints, involving delays which impede adoption of new technology and approaches, is one such area. The following quote from Ref. 14 hints at the scope of the problem: ". . . approval of proposed construction was required from several local, state and federal agencies. Approval of the route location was first obtained from the Director of Parks, the Director of Works, the Port Authority, and the Board of Commissioners of Allegheny County. Approval was then obtained from the Water Power and Resources Board for the four structure crossings over Catfish Run. The State Art Commission also approved the general structural arrangement. Finally, approval was obtained from the Federal Housing and Home Finance Agency."

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Total In-Flight Simulator (TIFS)—A New Aircraft Design Tool

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TIFS is a newly developed, variable stability C-131 aircraft with the unique capability to vary its flying qualities in all six degrees of freedom. It also surpasses the utility of past variable stability aircraft through the realism possible in its separate, new evaluation cockpit. The capabilities and features of this in-flight simulator considerably broaden the ability of the designer to deal with difficult trade-offs in flying qualities problems. This paper describes the aircraft and its potential as a design tool. Physical characteristics as determined in flight and examples of simulation planning are given. Flight test records of model-following performance are included.

Nomenclature

C_L = lift coefficient
$C_{L\alpha}$ = lift curve slope
$C_{Y\beta}$ = sideforce curve slope
SHP = shaft horsepower
V = true airspeed
V_e = equivalent airspeed
W/S = wing loading
i_c = cockpit mounting incidence
n_y = side acceleration, g, positive right
n_z = normal acceleration, g, positive down
$\bar{q}$ = dynamic pressure
α_{FRL} = angle of attack of fuselage reference line
β = sideslip angle
γ = flight path angle in vertical plane
δ_F = Fowler flap deflection
δ_r = rudder deflection
δ_y = side force surface deflection, positive TE left
δ_z = direct lift flap deflection, positive TE down
θ = pitch angle
χ = flight path angle in horizontal plane
$(\ )_M$ = model motion variable or parameter
$(\ )_{EXT}$ = extremal value
$(\ )_{KTS}$ = quantity in knots
$(\ )_{DEG}$ = quantity in degrees

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Introduction

THE idea of applying the principles of automatic flight control to the development of variable stability airplanes has been established for more than twenty years. The concept has progressed from elementary variations in stability and control characteristics for research purposes to full simulation of the flight characteristics of all kinds of aircraft. The usefulness of the variable stability airplane for advancing knowledge and understanding in the areas of handling qualities and flight control is exemplified by the variable stability T-33, which has been engaged in research flying for over ten years. The Air Force Flight Dynamics Laboratory has now