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High Capacity Personal Rapid Transit System Developments

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***Abstract*—High capacity personal rapid transit (HCPRT) is a system concept which utilizes small, 4 to 6 passenger, vehicles at very short headways on exclusive guideway networks. The automatic operation of small vehicles at headways of 1 s or less presents a major technical problem which is amenable to a combination of design approaches. This paper explores the effect of basic parameters such as vehicle length, reaction time, emergency and failed vehicle deceleration rates, and emergency jerk rate on potential minimum operating headway. The results of this analysis are then discussed in the context of five HCPRT programs.**

I. INTRODUCTION

THE GROWTH of cities and the availability of the private automobile have resulted in the development of diverse, many-origin-to-many-destination travel patterns in urban areas. Such travel patterns, well served by the private automobile, present a difficult challenge for a public transportation system. Personal rapid transit (PRT) attempts to meet this challenge through a system concept which features relatively inexpensive guideways and offline stations combined with small computer-controlled vehicles. Low-cost guideway and station structures permit PRT networks to reach into low density areas with closely spaced stations improving access and modal split while automated operation reduces operating costs and provides the potential for nonstop origin to destination service [1]–[2].

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Automated small vehicle systems currently nearing service are characterized by relatively low passenger carrying capacities (3000–4000 passengers per lane per h). more passengers can be carried by using 12–15 passenger vehicles at higher frequencies (1200 vehicles per lane per h) or by using smaller vehicles (4–6 passengers) at very high frequencies (3600–18 000 vehicles per lane per h). Systems implementing the latter solution have been referred to as high capacity personal rapid transit (HCPRT) systems.

A small vehicle high capacity PRT system will provide a significant improvement in public transportation service, particularly during rush hours. Because of small vehicle size and automation, HCPRT vehicles can be operated effectively with 1–3 passenger loads. Thus most HCPRT vehicles will be occupied by passengers desiring service to one or two destinations permitting essentially nonstop service at all times. As a result, vehicle trip times will be reduced thus permitting increased vehicle utilization. High capacities will permit more revenue passengers to be carried by the system increasing the return on the quideway and station capital investments. With high passenger carrying capacity, HCPRT will be suitable for a densely populated as well as lightly populated urban sites.

The main disadvantages associated with HCPRT are related to the attainment of safe operation at short headways. The attainment of short headways will require technical innovations beyond those commonly associated with exclusive guideway transportation and substantial improvements in system reliability and maintainability.

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HCPRT may also lead to broader guideway deployment with associated environmental impacts which must be minimized by careful guideway and station design and route planning.

The achievement of very high vehicular frequencies implies operation at short headways. Thus the major attention of HCPRT system developers has focused on the technology required to achieve short headway operation. The following sections discuss and illustrate the factors which affect short headway operation and the approaches designers have adopted to achieve such operation.

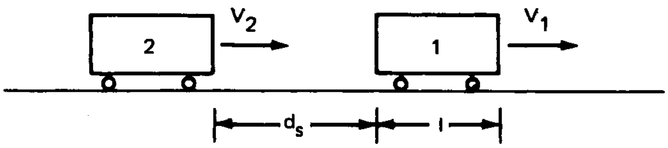

Fig. 1. Vehicle operating configuration.

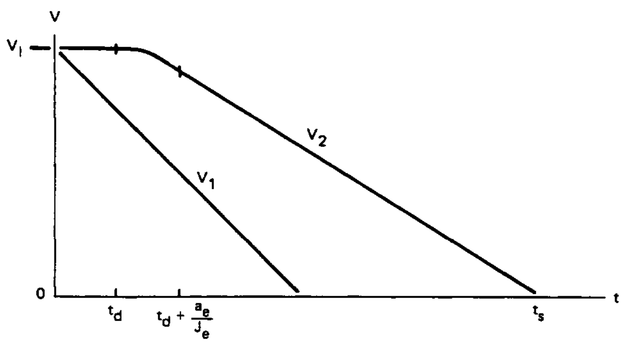

Fig. 2. Velocity profiles during emergency stop.

II. BASIC OPERATING LIMITATIONS

Consider the vehicles shown in Fig. 1. The vehicles are operating at a line speed V_l. The separation between the vehicles is d_s and the vehicle length is l. At time $t = 0$ a failure occurs in vehicle 1 which then decelerates at a constant rate a_f. The following vehicle detects the failure after t_d s. The emergency braking deceleration a_e is reached at a jerk rate j_e at time $t_d + (a_e/j_e)$. Once maximum emergency deceleration is achieved, the following vehicle continues to decelerate at a constant rate until a collision occurs or zero velocity is reached at time t_s as indicated in Fig. 2.

A collision will not occur if the initial value of d_s is sufficiently large. The minimum "no collision" value for d_s is given by the expression

$$d_{sm} = \max_{0 \leq t < \infty} \int_0^t (V_2(\alpha) - V_1(\alpha))\, d\alpha. \tag{1}$$

The resulting value of d_{sm} will depend on the relative vehicle velocities and deceleration rates, the emergency jerk rate, and delay time as well as initial vehicle state errors, variations in braking characteristics, measurement errors, and the effects of grade changes and wind as indicated in [3] and [4]. The following discussion will ignore the latter five effects to focus attention on the role of the fundamental parameters t_d, a_e, j_e, a_f, l, and v_l.

If the value of a_f is always greater than or equal to V_l/t_s and $V_l \geq a_e^2/2j_e$ the solution of (1) may be written

$$d_{sm} = V_l^2\left(\frac{1}{2a_e} - \frac{1}{2a_f}\right) + V_l\left(t_d + \frac{a_e}{2j_e}\right) - \frac{1}{24}\frac{a_e^3}{i_e^2} \tag{2}$$

$$= d_e - d_f \tag{3}$$

where d_e is the emergency stopping distance and d_f is the stopping distance of the failed vehicle. This equation is valid in most practical cases.

Operation of the vehicles at separations less than d_{sm} implies that a collision will occur. The relative impact velocity V_c now becomes a design parameter which specifies the time of collision t_c

$$V_c = V_2(t_c) - V_1(t_c). \tag{4}$$

The permissible operating separation d_{sc} is then given by the equation

$$d_{sc} \quad \max_{0 \leq t \leq t_c} \int_0^t (V_2(\alpha) - V_1(\alpha))\, d\alpha. \tag{5}$$

The resulting reduction in separation is

$$\Delta d_s = d_{sm} - d_{sc} \tag{6}$$

or the minimum permissible operating separation becomes

$$d_s \geq d_{sm} - \Delta d_s. \tag{7}$$

III. SHORT HEADWAY OPERATION

The headway h of a transportation system is determined by the operating separation d_s, the vehicle length l, and the line speed V_l

$$h = \frac{d_s + l}{V_l}. \tag{8}$$

Substituting d_s from (7) in (8) yields an equation of the form

$$h \geq c_1 V_l + c_2 + \frac{c_3}{V_l} \tag{9}$$

where

$$c_1 = \frac{1}{2a_e} - \frac{1}{2a_f} \tag{10}$$

$$c_2 = t_d + \frac{a_f}{2j_e} \tag{11}$$

$$c_3 = l - \frac{a_e^3}{24j_e^2} - \Delta d_s. \tag{12}$$

The function $h(V_l)$ is thus constructed of three components as indicated in Fig. 3.

Designers of short headway high capacity PRT systems have approached the attainment of short headways in a

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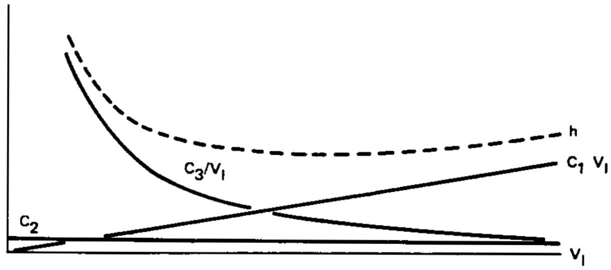

Fig. 3. Headway versus line speed, function components.

number of different ways:

a) decrease c_1 by increasing a_e and/or decreasing a_f;
b) decrease c_2 by decreasing t_d and/or increasing j_e;
c) decrease c_3 by decreasing l or by permitting collision ($V_c > 0$).

Increasing a_e presents a number of difficulties. Reliable traction braking is limited to approximately 0.2–0.4g as a result of variations in the guideway coefficient of friction. Achievement of higher rates implies some form of nontraction braking. Higher braking rates demand heavier braking devices and stronger vehicle structures to accommodate the braking forces. Very high emergency deceleration rates will also require passenger restraint systems.

Seat belts, shoulder harnesses, and air-bags are the most common proposed restraint systems. Seat belts alone allow the upper torso and the lower limbs to pivot about the waist. The resultant displacements permit parts of the body to impact with each other or with interior components of the vehicle. Most serious of fatal injuries occur from these latter impacts. Shoulder harnesses further improve safety by restraining upper torso motion. Air-bags provide levels of protection comparable to the lap and shoulder harness. The airbag requires no action on the part of the passenger to achieve protection; however, the complexity of airbag systems increases costs and creates reliability problems. Airbags require about 1/20 s for deployment and must therefore be integrated with a rapid failure management system to assure effectiveness.

Aft facing seats are a particularly effective method to safely permit high levels of deceleration. With head support, rear facing seats could limit the accelerations of all body components to approximately the maximum deceleration experienced by the vehicle. Aft facing seats permit very high, 1.5–2.0g, emergency braking levels and short headway operation at values of d_s greater than the emergency stopping distance.

Assurance of low-failed vehicle deceleration rates is an approach which has been adopted in several HCPRT system designs. A finite failed vehicle deceleration must be established as an engineering design goal and all potential anomalies in deceleration behavior carefully studied. A prolonged test program is required to establish that the design goal has been achieved. Most HCPRT designers have attempted to minimize vehicle length to reduce minimum headways.

System design to accommodate collisions presents a number of difficult technical problems. If $a_f \simeq a_e$ and c_2 is sufficiently small the relative velocity between two vehicles will always be quite small during an emergency stop maneuver. As a result the collision energy can be absorbed by relatively simple bumpers without danger of passenger injury. Collision management at higher relative velocities requires a much more sophisticated approach incorporating collision resistant vehicle structures, complicated bumpers, and passenger restraints.

IV. EXAMPLE

These concepts may be illustated by a simple example. Consider a 10-ft long, 6 seat HCPRT vehicle. The nominal vehicle emergency braking rate a_e is 0.35g and the reaction time t_d is 0.1 s.

The effect of increasing a_e on minimum online headway and capacity is illustrated in Fig. 4. Headway can be reduced by increasing a_e, however, the maximum reduction is limited by the emergency jerk limitation. Values are shown for emergency jerk limitations of 0.35g/s (solid lines) and 3.5g/s (dotted lines).

Fig. 5 shows the minimum operating headway and capacity as a function of line speed for various values of a_f. The solid and dotted lines represent results for j_e equal to 0.35 and 3.5g/s, respectively. Note that a_e must be approximately equal to a_f before substantial reductions in headway can be achieved. Thus a reasonable design goal for a_f is $a_f = a_e$. This is particularly true if failures result in closed loop emergency brake actuation. Decreasing t_d results in a uniform decrease in headway as indicated in Fig. 3. Increasing j_e has a similar effect as shown in Figs. 3 and 5.

Equipping vehicles to survive collisions permits further reductions in headway as indicated in Fig. 6. A collision velocity of 3.5 m/s can be absorbed by a 0.61-m stroke bumper without exceeding a 1.0g average deceleration level.

Fig. 7 shows the relative velocity at collision as a function of initial separation for various values of a_f. Note that if the peak collision velocity is less than the design value, the minimum headway reduces to

$$h = \frac{l}{V_l}. \tag{13}$$

If a_f is equal to a_e the collision velocity is essentially independent of d_s for values of separation less than d_{sm}. In this case the collision velocity is primarily determined by time delay t_d and the emergency jerk data j_e.

V. HIGH-CAPACITY PRT PROJECTS

Five significant short headway system concepts have been developed. These systems are

a) Cabtrack (United Kingdom) [5], [6]
b) Aerospace (U.S.A) [7]–[9]
c) MBB-Demag "Cabintaxi" (Germany) [10], [11]

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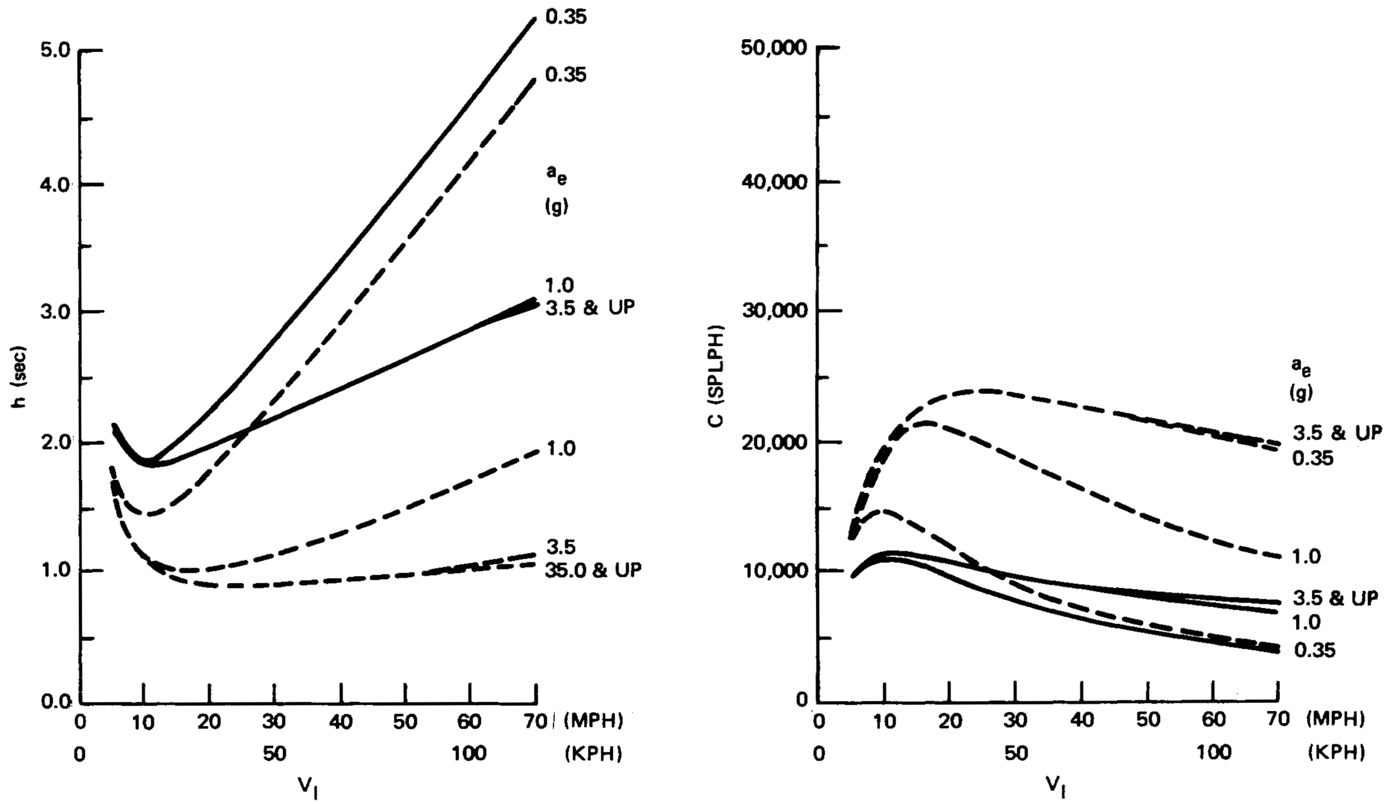

Fig. 4. Headway and capacity versus line speed for various emergency braking rates ($a_f = \infty$).

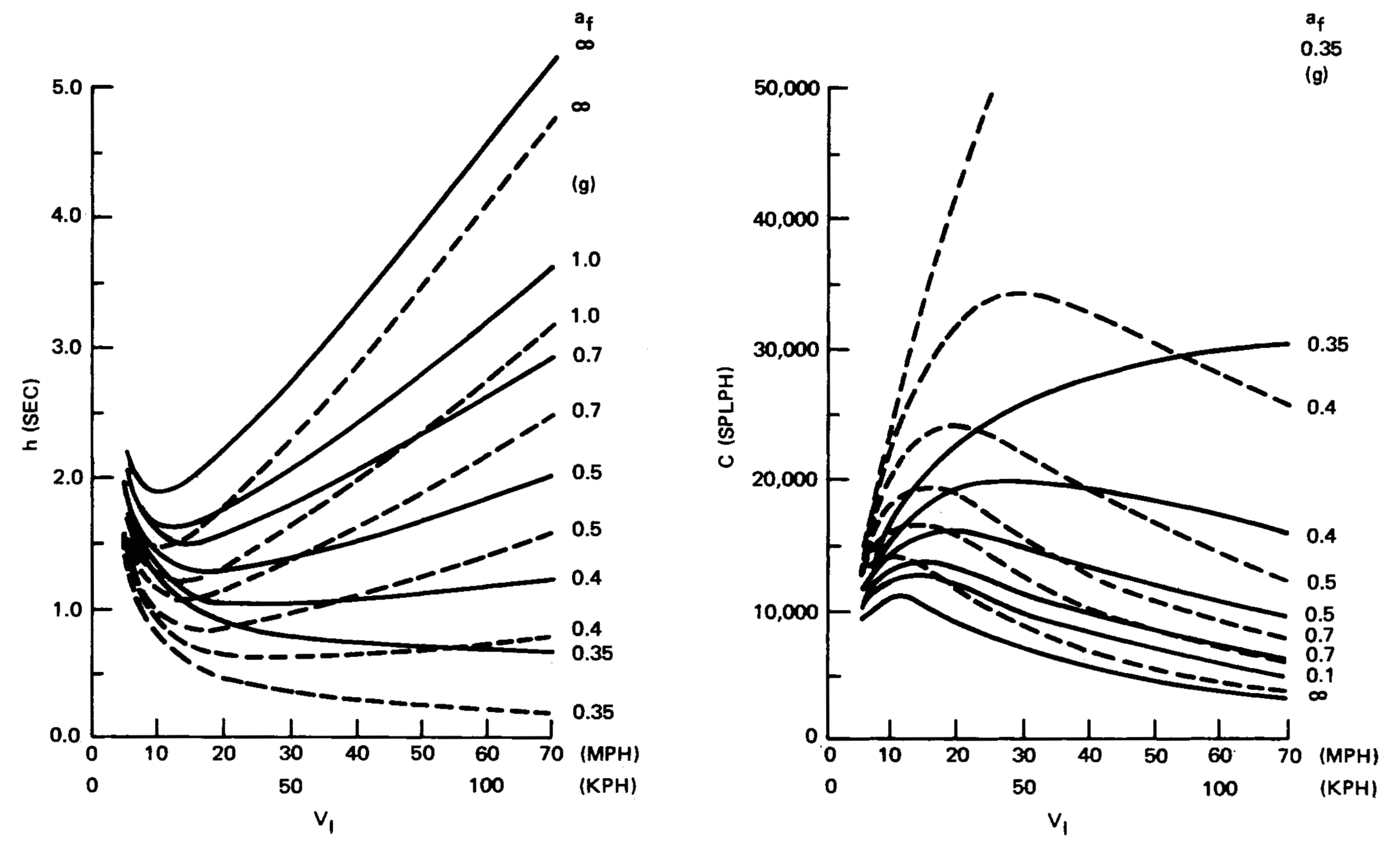

Fig. 5. Headway and capacity versus line speed for various failed vehicle deceleration rates ($a_e = 0.35g$).

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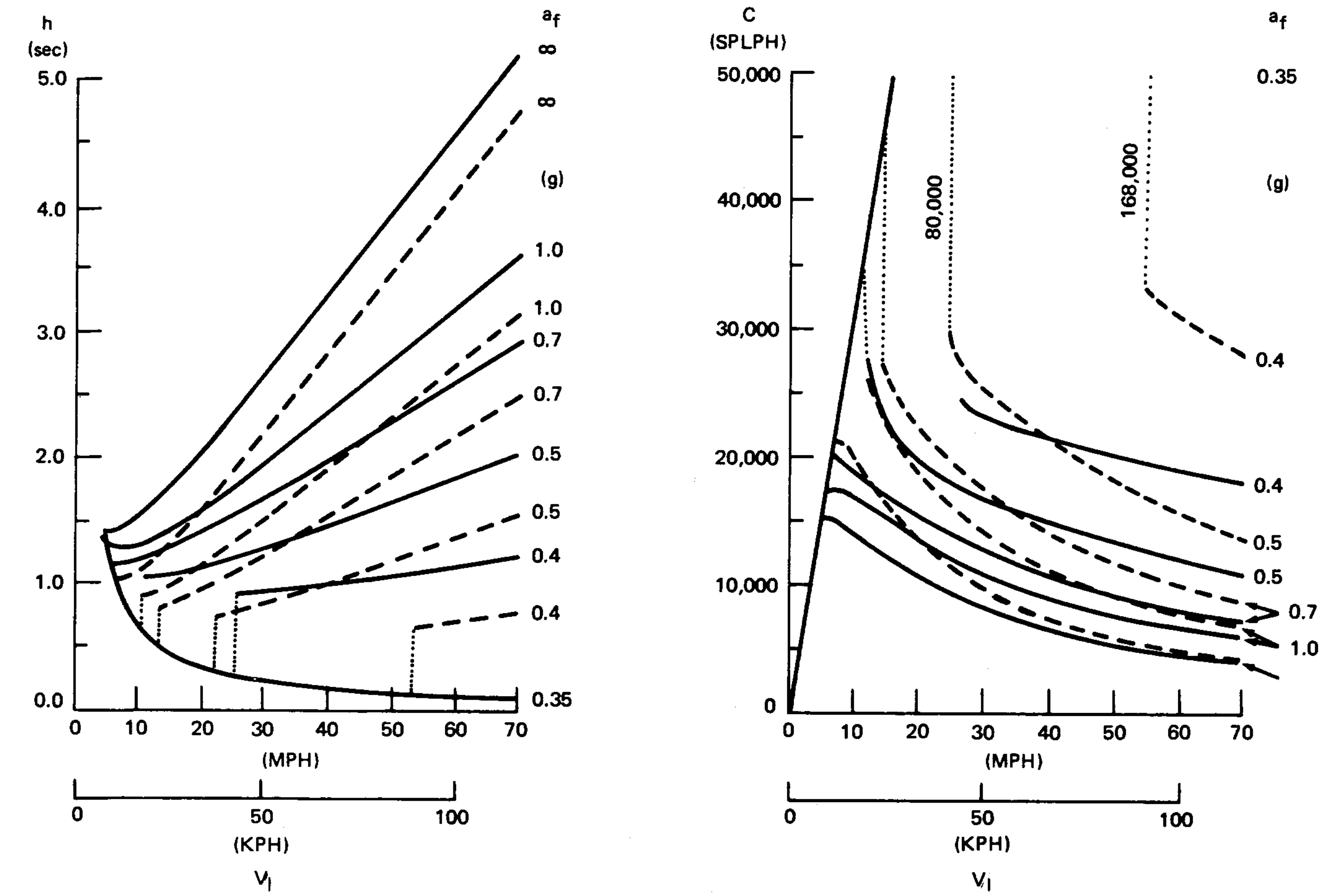

Fig. 6. Headway and capacity versus line speed for various failure deceleration rates with collision velocities up to 3.5 m/s ($a_e = 0.35g$).

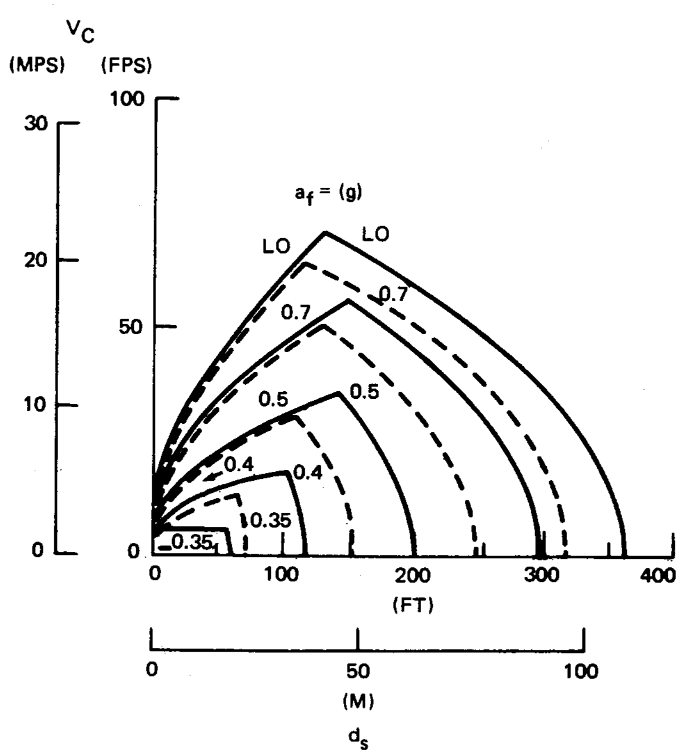

Fig. 7. Collision velocity versus initial vehicle separation for various failed vehicle deceleration rates ($a_e = 0.35g$).

d) CVS "Controlled Vehicle System" (Japan) [12]
e) Matra "Aramis" (France) [13].

The first two systems have been developed to the conceptual stage with hardware development and test confined to the component level. The latter three systems have been developed beyond the conceptual phase to the prototype fabrication and test state.

Table I summarizes the variables which affect system capacity. The vehicle utilization may be gauged in terms of maximum seat—kms per vehicle per h as indicated. Vehicle utilization is improved by increasing line speed thus reducing travel time. The ratio of the separation d_s to the emergency stopping distance d_e (K-factor) is also shown. Systems featuring K-factors less than 1 must rely on finite failed vehicle deceleration rates and shock absorbing bumpers to achieve safe operation. The indicated headways have been demonstrated experimentally.

The following subsections discuss the physical characteristics of the HCPRT systems identified. Included in this discussion are

a) vehicle parameters,
b) suspension, propulsion, and braking,
c) lateral guidance and switching,
d) vehicle control,

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TABLE I
SYSTEM PARAMETERS

SYSTEM	VEHICLE CAPACITY (SEATS)	MINIMUM HEADWAY	MAXIMUM CAPACITY (SEATS PER LANE PER HOUR)	VEHICLE UTILIZATION (SEAT-KMS PER VEHICLE PER HOUR)	APPROXIMATE K FACTOR
CABTRACK	4	0.6 SECONDS AT 36 KPH (22.5 MPH)	24,000	144 (90)*	0.15
AEROSPACE	6	0.5 SECONDS AT 32 KPH (20 MPH)	28,800	192 (120)	0.10
CABINTAXI	3	0.7 SECONDS AT 35 KPH (21 MPH)	15,428	105 (66)	0.20
CVS	4	1.0 SECONDS AT 80 KPH (50 MPH)	14,400	320 (200)	1.10
ARAMIS	4	0.183 SECONDS AT 50 KPH (31.2 MPH)	78,688 (14,000)**	200 (124)	0.01

* SEAT MILES PER VEHICLE PER HOUR
** WITH PLATOONING

e) vehicle management,
f) safety features.

A. *Vehicle Parameters*

HCPRT vehicles are small, 2.0–3.3 m (6.5–10.8 ft) long, 2–6 seated passenger vehicles; roughly the size of a small automobile. The cost per seated passenger is expected to be higher than that associated with other modes as a result of sophisticated automation. The vehicle parameters are summarized in Table II.

TABLE II
VEHICLE PARAMETERS

SYSTEM	LENGTH	WIDTH	HEIGHT	CAPACITY (SEATS)	EMPTY WEIGHT	WEIGHT PER SEAT
CABTRACT	3.0M	1.5M	1.7M	4	600kg	150kg
AEROSPACE	3.0M	1.8M	1.7M	6	1,090kg	181kg
CABINTAXI	2.0M	1.6M	1.6M	2	700kg	350kg
CVS	3.3M	1.6M	1.6M	4	980kg	245kg
ARAMIS	2.3M	1.3M	1.9M	4	650kg	162kg
BUS	12.2M	2.5M	3.1M	53	11,500kg	217kg
RAPID RAIL*	22.8M	3.1M	3.3M	81	32,700kg	404kg
MORGANTOWN	4.7M	1.8M	2.7M	8	3,930kg	490kg

* WASHINGTON METRO

B. *Suspension, Propulsion, and Braking*

The Cabtrack system utilizes four rubber tires in a conventional dual rail supported arrangement. A secondary suspension is provided to assure ride comfort. Propulsion is achieved by a hydrostatic drive. A constant speed ac motor drives a hydraulic pump which in turn drives separate hydraulic motors in each driving wheel. Propulsion thrust reversal is used for service braking. Friction brakes. mounted in the support wheels, are used for emergency stops.

The Aerospace system utilizes a channel shaped monorail guideway. The vehicle is supported on two tandem mounted wheels. Lateral support is provided by horizontally mounted guidewheels. A linear dc motor provides propulsion and emergency braking forces. A backup friction braking system is also provided for emergency use.

The Cabintaxi vehicle is supported or suspended by four rubber tires (two different vehicle designs). A dual rail steel guideway configuration is used. A linear induction motor provides service thrust and braking forces. Emergency braking is achieved by a combination of wheel mounted friction brakes and propulsion thrust reversal producing a deceleration rate of $0.5g$.

The CVS system utilizes a conventional traction motor-gearbox-differential-drive wheels configuration. Each vehicle is supported on four rubber tires on a dual rail guideway. Propulsion thrust reversal provides service braking levels while a friction jaw brake acting directly on guideway mounted rails generates the required $2.0g$ emergency braking rate.

The Matra "Aramis" system utilizes two dc motors which drive each rear wheel independently thus eliminating the differential and providing redundancy. Propulsion thrust reversal is used for emergency braking. Backup friction braking is used in the event of power failure.

C. *Lateral Guidance and Switching*

All five systems utilize rubber guidewheels for normal lateral guidance. The Cabtrack, Cabintaxi, CVS, and Aramis systems utilize onboard-switching devices which manipulate the guidewheels in association with appropriate guideway-mounted steering rails. The Aerospace system utilizes an off-board electromagnetic switch to provide lateral steering forces on the vehicle.

D. *Vehicle Control*

The Cabintaxi and Aramis systems exploit "vehicle follower" autopilots to control the relative position of vehicles in the system. Each vehicle "looks" down the guideway to detect the range to the nearest vehicle ahead. If the range is large the autopilot maintains some nominal value of line speed. At closer separations the autopilot adjusts vehicle range to satisfy some safety criterion. Vehicle follower systems may be implemented to perform all maneuvers at constant K-factor thus preserving a uniform safety margin. The Cabintaxi and Aramis systems provide continuous monitoring of lead vehicle dynamic

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behavior. Thus response to failures affecting lead vehicle dynamics is essentially instantaneous.

Autopilots proposed for the Cabtrack, Aerospace, and CVS systems operate on the point-follower principle. Each vehicle is assigned an electronically generated point which it follows along the guideway. Adjacent points are separated in time by the system headway. The distance between points is called the slot length. The point follower autopilot adjusts vehicle speed to minimize the position error between the vehicle and the moving point. The proposed point follower systems provide functions such as "slot-slipping" to resolve merge conflicts. In a "slot-slipping" maneuver a vehicle drops back one or more slot lengths before locking onto a new point.

E. Vehicle Management

The Cabtrack and Aerospace system designers both propose a quasi-synchronous vehicle management scheme. Each vehicle remains electronically locked to a moving point online. In the vicinity of merges local computers command through vehicles to "slip-slots" creating openings for merging vehicles if necessary. Routing is also handled on a local basis. Each switch is controlled by a local computer which generates a switching decision based on vehicle destination and an overall average routing policy produced by a centralized authority. The finite probability of "missed merges" with quasi-synchronous control imposes geometrical constraints on guideway topology which could result in deployment problems.

The Cabintaxi system utilizes a similar local vehicle management approach. Merging is achieved in the case of a vehicle follower by utilizing the elasticity of the moving stream of through vehicles to create gaps for merging cars. Average link flow levels are controlled, as above, by local switching decisions guided by a centrally generated flow policy.

The vehicle management strategy proposed by the CVS developers is based on synchronous longitudinal control. Each vehicle is assigned a reserved slot between its origin and destination thus eliminating merge conflicts.

The Aramis system arranges vehicles into platoons which are operated at 50-s headways. The platoons are construced dynamically online. As a result the Aramis vehicle management is similar to that of a rapid-rail system. The long interplatoon headways permit online as well as offline stations. Level crossings could also be used with such a system.

F. Safety Features

A detailed safety study was not performed on the Cabtrack system. The designers adopted traction emergency braking indicating that safe operation would be achieved with relatively low emergency braking rates. Aerospace has proposed passenger restraints, a strong vehicle structure, and energy absorbing bumpers to achieve safety. The MBB-Demag Cabintaxi incorporates energy absorbing bumpers and vehicle structures although no passenger restraints are used. The CVS system, operating at K-factors greater than 1, does not require shock absorbing bumpers. It does, however, require a fairly strong vehicle structure because of the high, 2.0g, emergency deceleration rates. Aft facing seats are proposed to protect the passenger from injury during emergency maneuvers.

VI. CONCLUSIONS

The automatic operation of small vehicles at fractional-second headways may be accomplished by applying different design philosophies. Rapid failure detection and management have been used by all developers to date. The assumption of guaranteed finite failed vehicle deceleration can permit short headway operation, however, the failed vehicle deceleration must be well bounded through careful design and prolonged testing. High emergency braking rates, which may also be used to reduce headways, pose safety problems which must be addressed in the design of the vehicle interior and passenger restraint systems. Permitting low-velocity controlled collisions does not substantially reduce headways although a vehicle design capable of withstanding such impacts is desirable.

VII. ACKNOWLEDGMENT

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