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BRAKING SYSTEM INTEGRATION IN DUAL MODE SYSTEMS

Jeffrey J. Bowe

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16. Abstract

An optimal braking system for Dual Mode is a complex product of a vast number of multivariate, interdependent parameters that encompass on-guideway and off-guideway operation as well as normal and emergency braking.

Details of, and interrelations among on-guideway and off-guideway operations will be considered. The influences on the braking system of the digital or analog inputs from the command and control system will be analyzed. Included also will be a study of the interplay of headway, velocity, acceleration and jerk values, within passenger comfort limits, and the role of such interactions on the sizing and design of the brake mechanism, whether of drum, disc, skid, or other mechanical type; or of traction motor, LIM, or other electrical type. The actuation system, air or hydraulic, and its time constants are also factors. The impact of anti-skid devices and their servo aspects, upon the braking system will be presented. The problems and pay-offs of energy dissipation as direct heat, as heat from electrical resistive elements, or as electric power from a regenerative system will also be included as parameters of significance in a conceptual n-dimensional matrix.

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PREFACE

As a part of an overall consideration of the integration of vehicular functions, this report studies the integration of a braking function specifically into a dual-mode transportation system, in view of the particularities associated with such a system. The roles of economics, safety, energy considerations and pollution are analyzed in the establishment of the trade-offs among the factors operative in a braking function. The interactions of the command and control systems, the power and propulsion systems, and the parameters of motion are reviewed in the context of the dual-mode transportation system.

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1. INTRODUCTION

Dual mode transportation presents unique considerations for subsystem choice. This paper reviews those interrelationships of significance for integrating a braking system specifically into a dual mode operation. Some of these relationships arise from the interfaces of the braking system with the power and propulsion systems and with the command and control systems. Integration of a braking function in a dual mode system also necessitates consideration of the parameters of motion; the headway, velocity, deceleration and jerk requirements.

The criteria against which braking systems may be measured are those factors of safety, economics, energy management and environmental impact. Foremost must be the aspect of safety to the passengers, the transit operators and the citizens of the community. The economics of the braking system integrated into the dual mode operation and considered as a whole must occupy a major place in the considerations. In these days of energy shortages and crises, and interrelated with the economic aspects, a third significant criterion is that of energy management. This must be viewed from the operation of the entire system. The means for converting the kinetic energy of motion to other forms of energy, useful or unuseful, beneficial or harmful are of significance in the total utilization of energy.

A fourth criterion of importance to a transportation system or subsystem is its impact on the environment. Although a braking system per se has limited environmental impact, aside from possible pollution by friction materials and the production of unused heat, yet the energy management aspects of braking can have a large impact on the environment. This is then a joint function of the power and propulsion systems and the braking system.

A dual mode transportation system involves, in general, both an on-guideway and an off-guideway operation. The on-guideway portions offer personal rapid transit (PRT) amenities. The requirements on the system, or on the vehicle in particular, in reference to braking capabilities on the guideway are then similar to those

of personal rapid transit (PRT) vehicles. The off-guideway requirements for the braking system are similar to those of buses, trucks or automobiles.

In view of the dual mode of operation, the integration of the braking function must be essentially a compromise between on-guideway and off-guideway braking operations, a compromise made in view of the interface effects and the critiera for decision making. The compromise may be accomplished basically, by use of either different braking systems (on different vehicles as in pallet-pod operation or in the same vehicle) or by use of the same braking system suitable for on-and-off guideway operations.

By considering the system and subsystem performance criteria and the restrictions imposed upon the braking system by its interfaces, an orderly set of interrelations can be developed, specifically for a dual mode transportation system as an aid to useful integration of a braking function into a dual mode operation.

A schematic presentation of the major interrelations is shown in Figure 1. The braking system itself is not discussed in this paper. Present hardware is generally adequate to the requirements which arise from system limitations. Improvements are continually being made. In mechanical areas, development of disc brakes continues and anti-lock systems are being worked upon intensely.[1,2] Improvements in train braking appropriate to rapid transit are continuing.[3] Electrical braking systems are in a phase of rapid expansion and development.

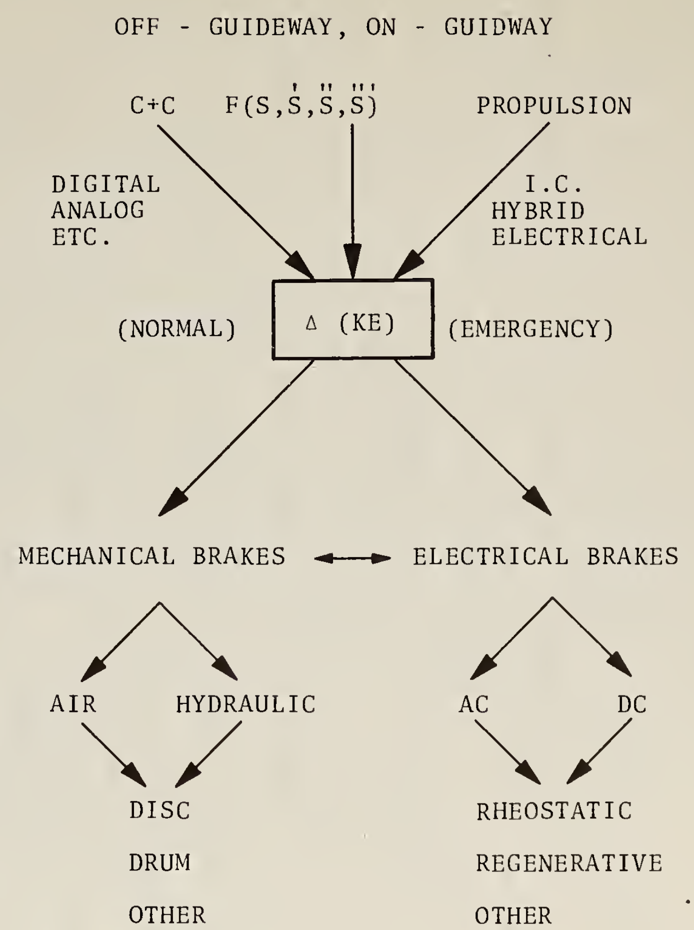

Figure 1. Braking System Integration in Dual Mode

2. INFLUENCES ON A BRAKING FUNCTION

There are many influences on the braking system as can be seen in Figure 1. The factors which must be considered initially for the integration of a braking function into a dual mode transportation system are the parameters of motion, requirements of headway, velocity, deceleration and jerk.

Control of the vehicle to suitable ranges of value of these parameters under a variety of conditions such as gradients, wind velocities, and temperatures are the function ultimately of the braking system and penultimately of the command and control system. Both may be incorporated into a braking function.

Of the four criteria discussed above, the chief concern from a system view point in these initial considerations is that of safety, although economic aspects related to throughput arise in connection with headway and velocity.[4,5] Jerk and deceleration limitations come from passenger safety and comfort requirements.[6,7] Maximum values of .7g deceleration with standees in the event of emergency braking failure or .35g for emergency braking and of .15g for service braking are imposed from safety aspects for seated and standing passengers. Higher maxima are allowed when there are not standees in the vehicle. In this case, the values are increased by 50%. In a similar manner from passenger safety and comfort considerations, upper limits on values of jerk are obtained. These are .35g/s for emergency braking and .15g/s for service braking, when there may be standees. When no standees may be present in the vehicle, the maxima are raised by 50%.

A physical limitation on the degree of deceleration obtainable is the contact between the vehicle and the running surface. The value of the coefficient of friction (μ) is a highly variable number, depending upon the conditions of the two contacting surfaces - that of the vehicle and that of the running surface.[8] The first concern is the coefficient of friction for one surface rolling upon another surface. For a rubber truck tire rolling on concrete, this coefficient varies from about .45 (for smooth, wet and oily concrete) to .75 (for smooth dry concrete). Figure 2 shows values of μ under

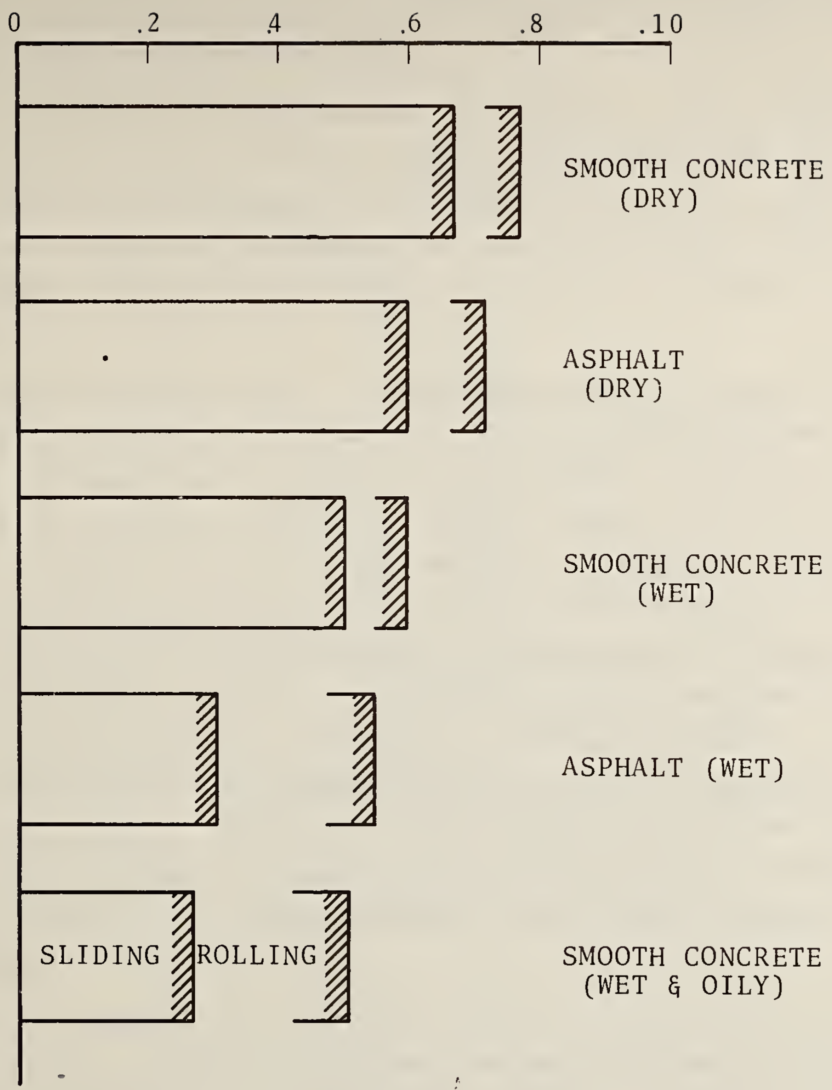

Figure 2. Truck-Tire to Pavement Friction Coefficient (μ)

various conditions. The second concern in regard to coefficient of friction is that of sliding friction. Any braking forces which raise the frictional force requirements beyond that which the braking surfaces can provide as influenced by the coefficient of rolling friction will move into the regime of sliding friction, and lowered frictional retardation forces as indicated by the lower coefficient associated with sliding friction.

The transition is illustrated in Figure 3. The coefficient (μ) does not have two discrete values, the coefficient of rolling friction and the coefficient of sliding friction but rather has a continuum of values as a function of percent of wheel slip. This is of importance for anti-skid or anti-slide considerations, discussed separately.

It should be noted that in degradation of braking from the causes above or from the failure of the emergency braking system, the final condition may be that of one surface sliding up on another surface if the failure results in either locked wheels or mechanical breadkown leading to parts of the vehicle sliding on a surface. On the other hand, should the failure result, for example, in freely rolling wheels there would be little retardation. Designs are such as to make the latter highly improbable so that emergency braking failure is more likely to result in a sliding situation. A sliding braking may be achieved deliberately for emergency braking by the use of skids. Even then, the braking can not be assumed "safe". The existence of the second braking system affords only a lowered probability of total braking failure with reduced braking performance.

Once the values of the coefficient of friction are determined for the specific physical interface between the dual mode vehicle and running surfaces, the achievable limits of braking deceleration can be delineated. These will, except under abnormal conditions of ice or oil-water mixtures on the surface exceed the limits imposed by safety and comfort. A typical deceleration curve is shown in Figure 4. The rate of change of deceleration, the jerk, also is limited by human safety and comfort. Figure 5 depicts limits of

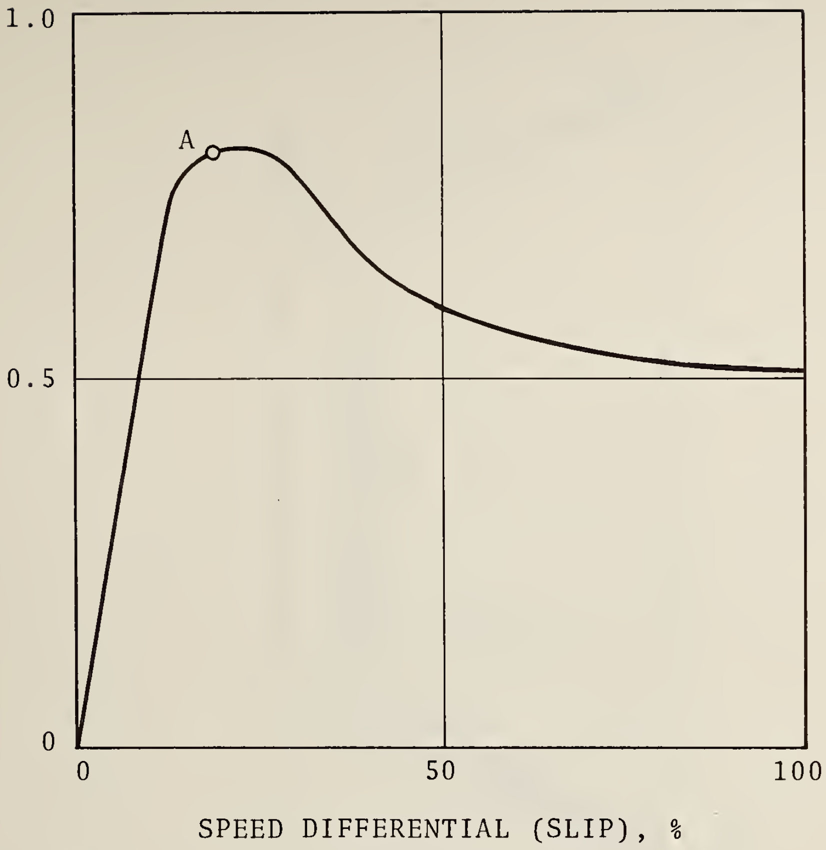

Figure 3. Coefficient of Friction as a Function of Slip

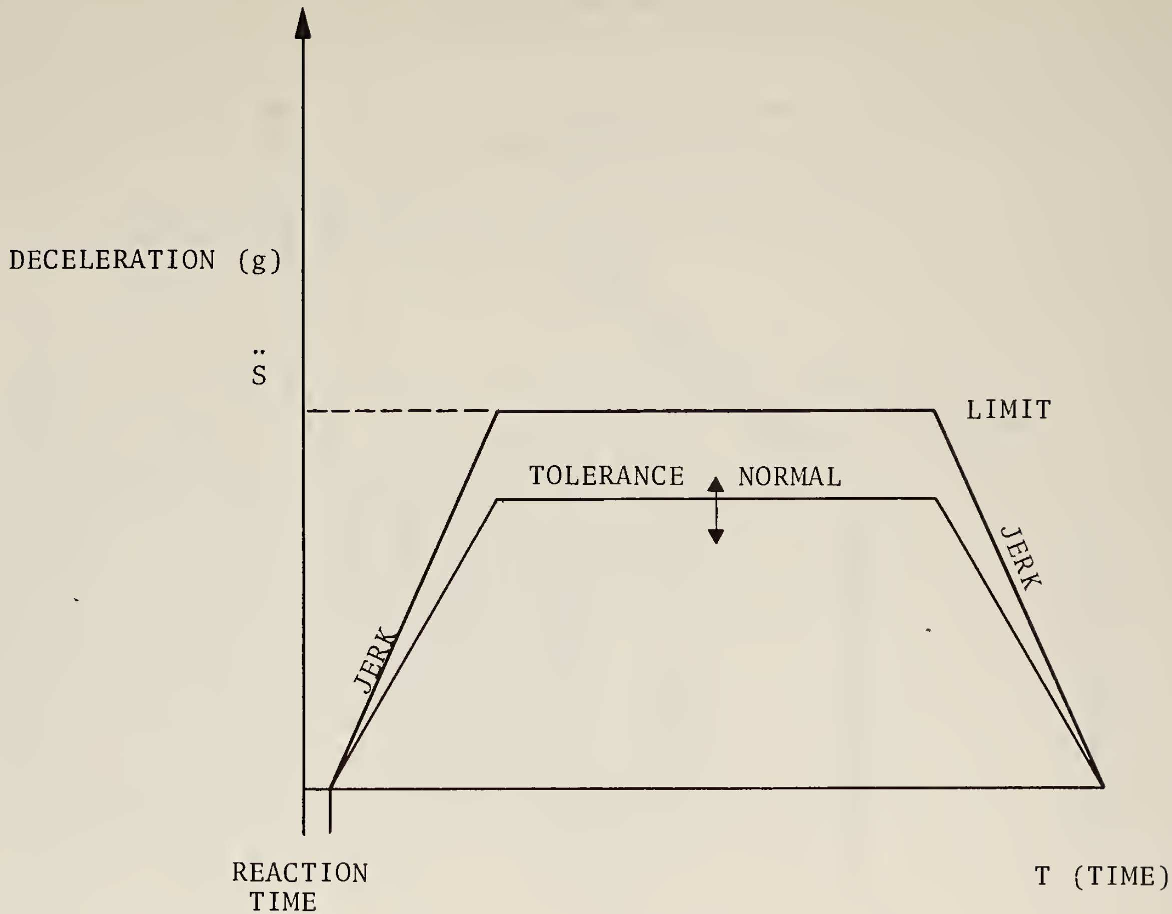

Figure 4. A Typical Deceleration Curve

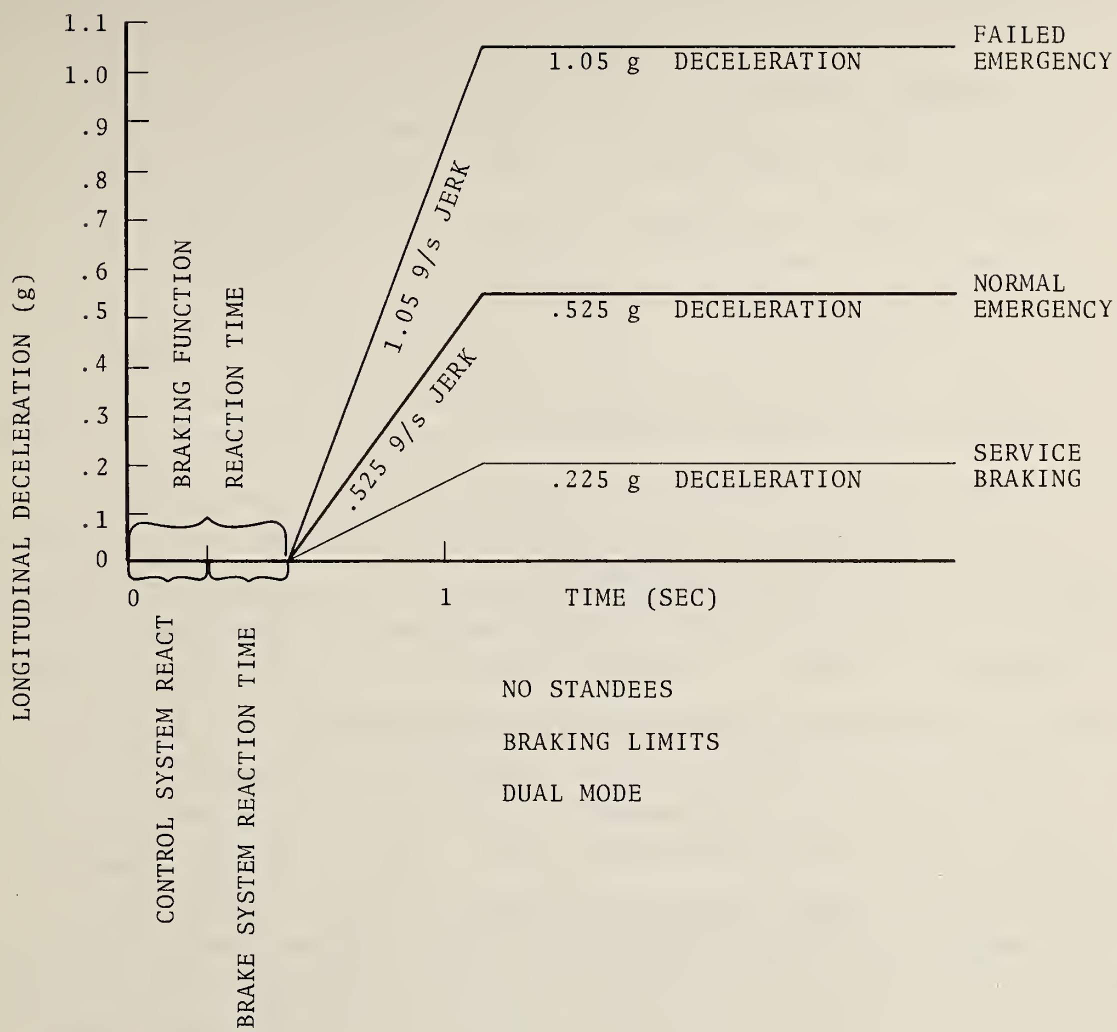

Figure 5. Typical Values of Deceleration and Jerk On-Guideway

values of deceleration and jerk typical of on-guideway operations. The off-guideway braking conditions are those of FMVSS-121. Although not so specified, these conditions require braking deceleration values up to about 0.5g (service deceleration from 60 mph in 245 feet, with up to 0.25 second brake actuation time) assuming a constant rate of deceleration. Of course, were the deceleration not constant, even higher values of deceleration would be required at some periods of the braking.

It should be carefully noted that the so-called emergency braking system, off-guideway, lacks the stopping capability of the service brake and is therefore not the emergency system required for on-guideway operation. A complete emergency braking system performs two functions. It provides, in addition to a working service braking system, a second heavier braking effort, with reduced comfort. It also provides in place of a failed service braking system, a backup less effective braking effort. The off-guideway or bus-braking system provides the second function only.

A single, dual-purpose braking system in dual mode would be required to meet both sets of limitations for on-guideway and off-guideway operation. This approach has merit if the conditions for on-guideway and off-guideway operation are similar, as when the guideway surface design is similar to that of a road or highway.

The power and propulsion system interfaces the braking system giving rise to mutual limitations. The possible practical propulsion systems may be divided for convenience into electrical, hybrid and mechanical types. The electrical are of course either AC or DC in nature. The DC propulsion systems subdivide into series, shunt or compound motors while the AC types may be subdivided into synchronous and induction motors. The latter may be of either rotary or linear (LIM) design.

More detailed consideration may be given to specific propulsion system applications. The operating details of such systems are not of significance here but their outputs and interfaces which may influence proposed braking systems are pertinent.

The internal combustion engine as found in an automobile or truck may, for example, be utilized as the primary power and propulsion system in a dual mode vehicle. A source of electrical energy such as a storage battery, is required for auxilliary functions and electronic subsystems. This may also power an electrical secondary propulsion system.

A braking system compatible with this may be basically mechanical with electronic controls. Braking systems of pneumatic or hydraulic type are discussed in many places.[9,10] In order to meet FMVSS-1, an automatic electronic anti-lock subsystem is desirable, although not specified. This subsystem can provide, with proper design, the automatic braking required for on-guideway operations. Anti-lock systems are considered separately in detail.

Such a braking arrangement has many merits. It is to be noted that this study is not primarily concerned with the choice of propulsion system, but only with the compatibility of the chosen system and the braking system and the performance of the latter. The braking system can be designed to afford the deceleration required within the jerk limitations, provided the guideway conditions are sufficiently good to maintain a high enough coefficient of friction. The same system is adaptable to both on-guideway and off-guideway operations. Brake system impact on the environment is directly limited to friction materials dissipated into the air.

Indirectly there is adverse impact on the environment from the lack of management of the kinetic energy converted into heat, except for such heat as is utilized either to provide warmth for the vehicles or the stations.

Another example, a hybrid power source, is that of a mechanical-electrical power system. Power for the electrical equipment can either be generated on board (e.g. by a gas turbine generator) or be collected from the wayside during the on-guideway portion of travel. With such a hybrid power source, the brake system interfaces are with the electric power subsystem and the trade-off considerations become essentially those of an all-electric power and propulsion system and are a function of the type of electrical power and propulsion systems.

To consider interface of a braking system with electrical power and propulsion systems, two general categories are significant: rotary and linear systems. Electric rotary motors may be used for braking purposes in a dynamic braking system with the generated power dumped into resistors for conversion to heat energy, but such a conversion technique requires bulky components (the resistors) which must be exposed to aid dissipation of heat and which are thus more vulnerable to accidental failures. Such a conversion system is useful on a large vehicle like a rapid transit car, but is not efficient on a small vehicle because of the more severe weight and space requirements.

There are two manners in which electric propulsion systems may be utilized in dual mode systems; the power generated in braking with a rotary electric motor can be fed back into the power sources or, in a linear motor, the motor may be "plugged", that is essentially operated in reverse in a controlled way so that the vehicle is effectively braked to a stop. The first method requires special provisions for feeding back the power. The second method necessitates careful control to bring the vehicle to a smooth and precise stop; staying within the deceleration and jerk limits. In the case of a linear induction motor, the service braking is essentially independent of vehicle-to-running-surface friction but rather depends upon the electro-magnetic interaction between the primary and the secondary. The inter-relationships among the power and propulsion systems and the braking system are shown in Figure 6.

The command and control systems also interface with the braking system. Off-guideway the command and control system is the driver, assisted by aids such as indicators, speedometers, warning lights and control subsystems (brake boosters, anti-lock devices, etc.) . On-guideway the command and control system is an electronic system communicating to the braking system. The electronic parts of the braking system must be made immune to electrical interference and should be composed of highly reliable components for safe braking operations. A part of the control function is the monitoring aspect in which critical component functions are automatically self-checked and required to give status indications on a continuous or sampling

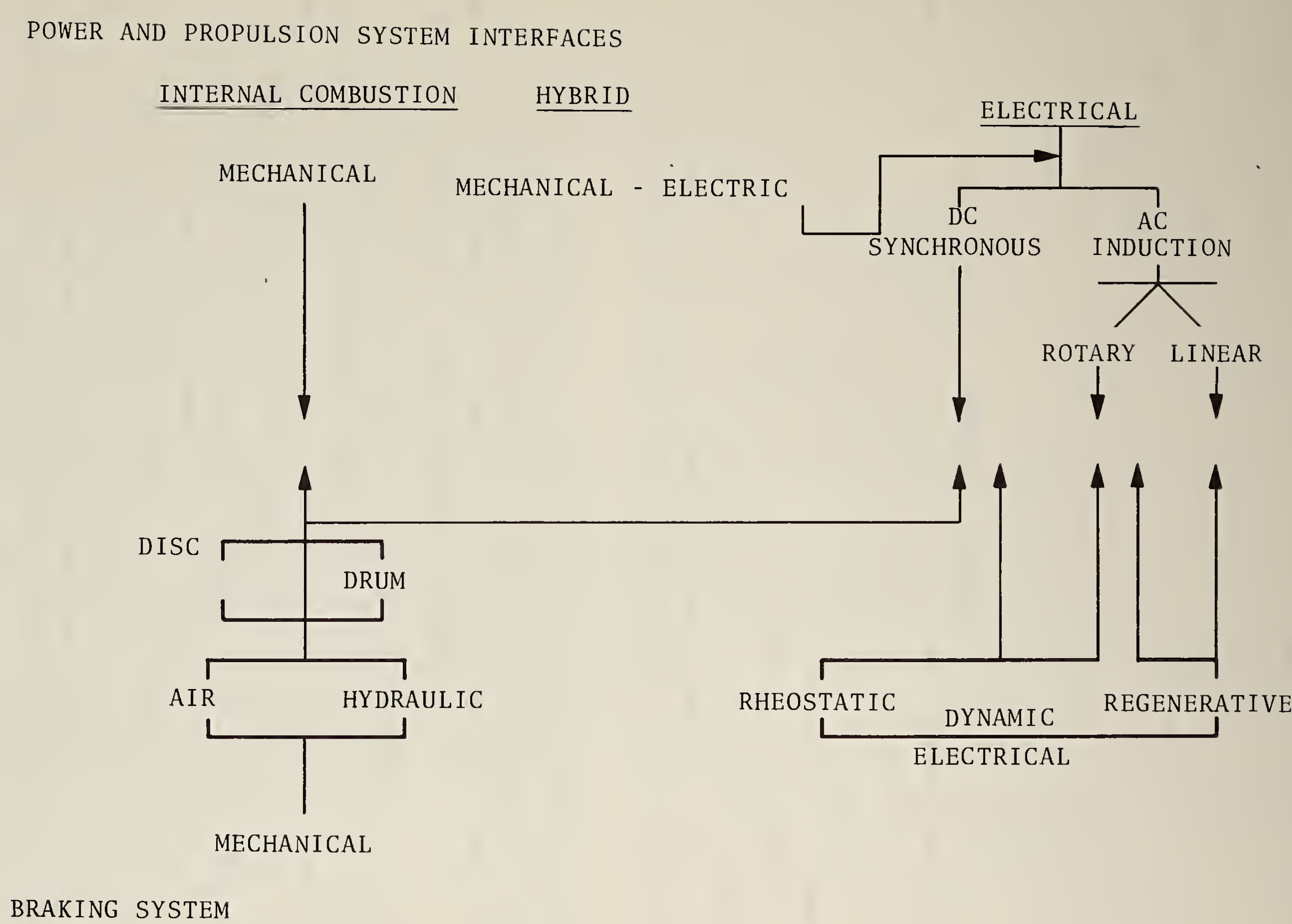

Figure 6. Interrelations Among Power and Propulsion Systems and the Braking Systems

basis. The control unit supplies information to the braking system basically setting the deceleration level and the jerk value. For service braking, the data are fed to the service brakes or to the propulsion system in those cases in which that is used for braking. Emergency braking data is fed directly to the emergency brake system. Emergency braking signals are also received by this system from five sensors including door-open indicators, passenger stop-button operation, etc. The signals arrive at the braking system generally by hard wiring either from the on-board vehicle control unit which receives the commands ultimately from the vehicle communication transceiver, or directly from the on-board emergency indicators. Precision stopping in stations is generally initiated by signals from fixed markers on the guideway in response to commands from the local controller. A safety system, an element of the controller, either separate or integrated, is generally operated independently of other control functions. Its interface with the braking system through the communications channels is the initiation of emergency braking should any predetermined safety conditions be violated.

Figure 7 schematically illustrates the basic interrelationships between the command and control systems and the braking systems. The signalling mode is a function of the individual command and control system and of the propulsion system.

The braking systems above are discussed in terms of one of the solutions to the compromises required by dual mode transportation; that of implementing braking functions for both on-guideway and off-guideway operations in the same vehicle either in one common braking system or in two separate systems. The other compromise is the use of an off-guideway set of brakes on a vehicle for off-guideway operation and similarly an on-guideway braking system on an on-guideway vehicle. The interfaces of each braking system are similar of course to the corresponding functions in the single vehicle with dual braking functions. For integrating a braking function, this approach to dual mode reduces to the former case.

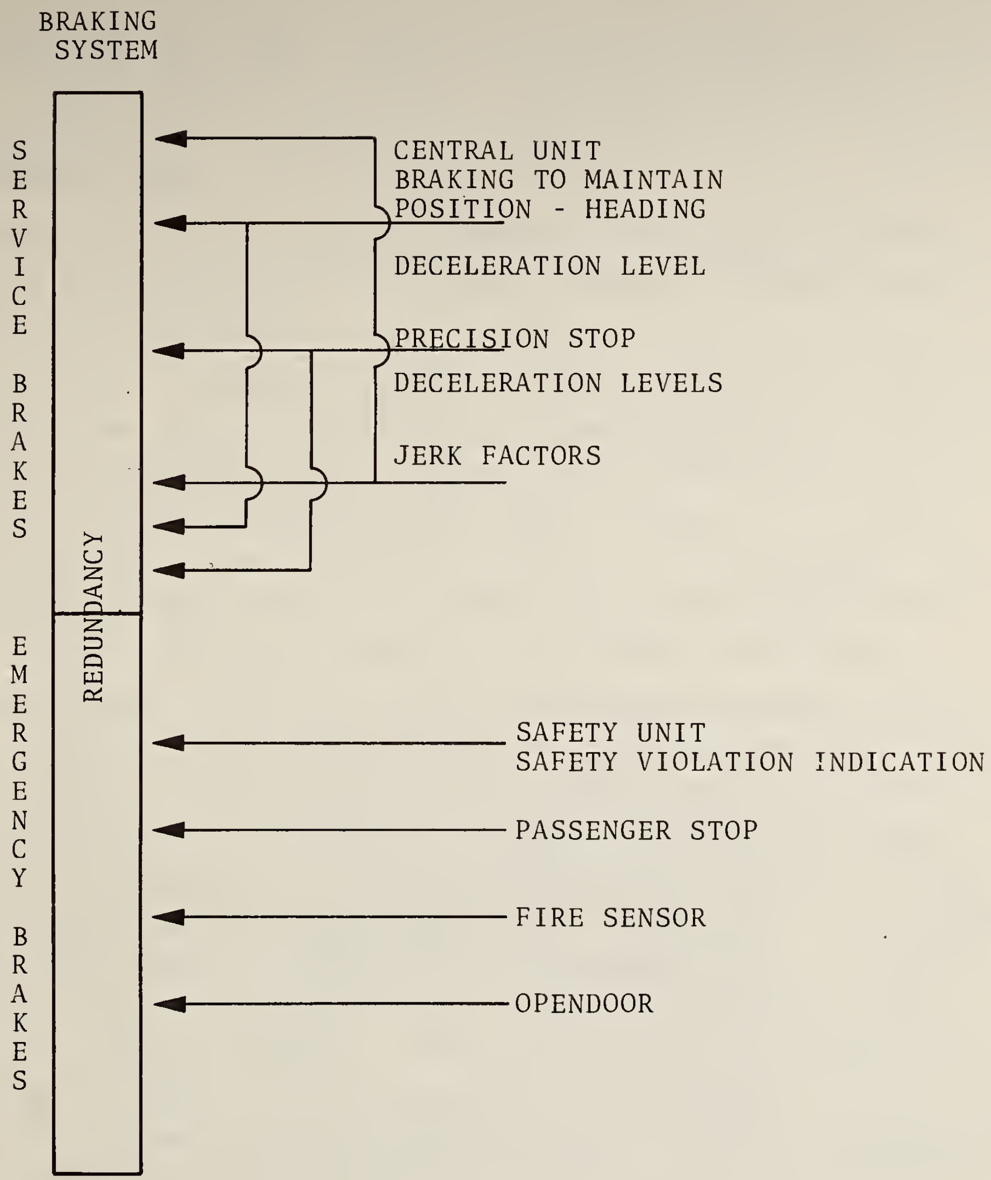

Figure 7. Interrelationships Among Command and Control Systems and the Braking Systems

3. OTHER CONSIDERATIONS

There are some other aspects of special significance in dual mode. The off-guideway need for an anti-lock device and the on-guideway need for a longitudinal control system can be jointly met by a common unit.

The necessity for reliable operation of a complex braking function indicates the need for self-testing or monitoring of significant subfunctions.

Operation at shorter headways requires reduction of equipment-reaction times and utilization of all possible means to permit safe stopping in lessened time. The improved crashworthiness of vehicles includes a bumper mechanism which permits contact of vehicles without damage to the vehicles or injury to the passengers at speeds up to some value (e.g. 5 mph). This additional margin must be utilized in some manner in the braking functions.

An extremely important aspect of a braking function today is an anti-lock subsystem.[11] This is usually considered a part of the overall braking function, but might also be conceived as an on-board part of the control systems. Indeed the braking function can be seen to be incorporating more and more of those control functions previously considered separately. The incorporation of the braking controls into the braking system is all the more necessary for transportation systems operating at higher speeds or shorter headways. The chief function of an anti-lock subsystem of course is the detection of an incipient skid or lock condition in time to reduce braking force. This is accomplished in a variety of ways which reduce basically to determining that wheel deceleration is too high (that is, wheel speed is too slow). The determination is made either directly by measurement of deceleration or indirectly by computation based on wheel speed measurements.

Figure 8 shows a generic schematic of an anti-lock system: It is clear that the wheel deceleration control for anti-lock purposes is also essentially that control required for automatic operation of service braking and by extension for emergency braking. Up-grading is of course necessary for the control system to be adequate to the total braking requirements.

As the complexity of the braking function vastly increases, the need for reliability and especially reliability of the electronic components rises at least proportionally and probably at a faster rate. Reliability must be achieved by two means simultaneously. The one is the use of components of higher reliability initially. The second is the use of self-testing or monitoring of the more significant portions of the braking function.

In the braking function, there are many possible test or monitoring points. These of course vary with the specific braking and control system.

Another factor which may be included as a part of the braking system is that of crashworthiness. At least, those equipments such as improved bumpers which permit controlled contacts of vehicles up to five (5) or more miles per hour without damage to the vehicle or danger of injury to the passengers, must be considered to provide a stopping or braking function in an emergency. The kinetic energy of motion of a failed vehicle is in this case transmitted to the leading vehicle or at least to its bumper mechanism. The controlled contact should be included in braking considerations for back-up to a failed emergency stopping system and as a tolerance factor in normal emergency stopping. This can lead to economies in both the braking function itself and the dual mode system overall.

Fail-safe concepts and misconcepts constitute another area for serious consideration for integration of a braking function into dual model transportation. At the most, the fail-safe concept implies the detection of a failure of one mode (of braking, in this case) will institute a backup mode which in general have a lower probability of failure. The combination of braking modes will have

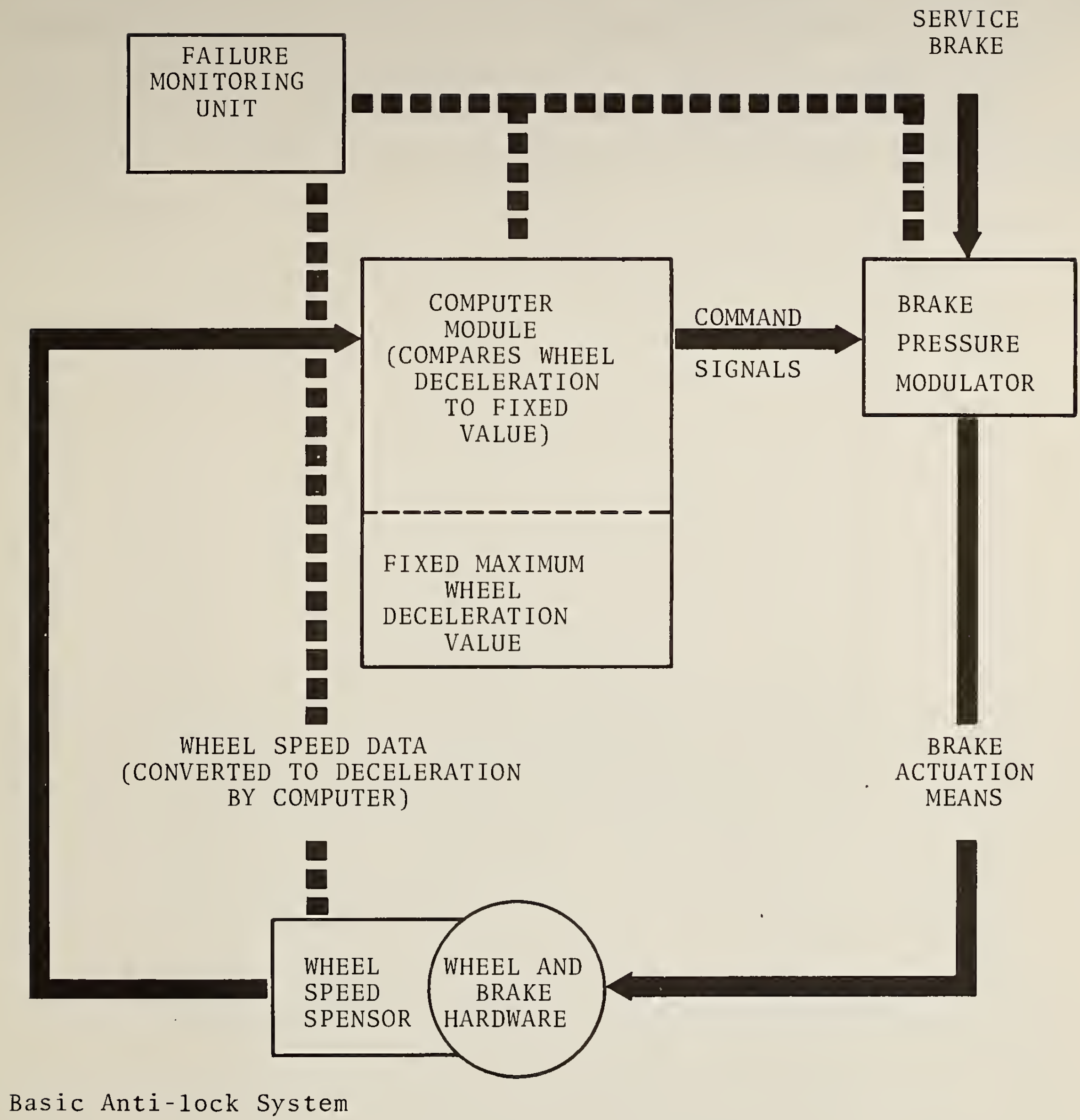

Figure 8. Generic Schematic of Anti-Lock Systems

a lower probability of failure. The fail-safe concept as traditionally understood since its inception in the 1880's implies a reversion "to a state which is known to be safe." The National Transportation Safety Board recommends abandonment of the fail-safe concept and the institution of an organized disciplined approach.[12] Fault tree analysis is suggested as an alternative. Fault tree analysis considers the impact of single failures and multiple failures in a graphic presentation which isolates the truly critical components.

4. BRAKING IN THREE DUAL-MODE SYSTEMS

Thus far, we have reviewed the criteria and the significant interrelationships which influence the considerations for integrating a brake function into a dual mode transit system. An application, of rather general nature, of these principles will be made to three dual mode systems: those of TTI, Rohr and GMC.

The TTI system is that of a pallet-pod operation. On-guideway a "Transporter" is used. Two single sided linear induction motors (LIM) provide the propulsion. Fourteen HOVAIR air cushion pads support the on-guideway vehicle. The emergency braking is provided by brake skids, and normal braking by LIM plugging. Off-guideway, a close-to-standard van is used, with standard bus braking. A Mercedes Benz 0309D passenger bus is presently the choice. (Incidently, the Mercedes Benz 0307 overland bus has recently been awarded the Grand Prix Louis Bolandard in tests ranging from seating comfort to driving precision.[12]

The Rohr system utilizes one vehicle for on-and-off guideway. Off-guideway the power and propulsion system consists of a gas turbine operation in an electric system composed of an alternator, rectifier, inverter and three phase rotary induction motor. On-guideway, the power is received from way-side. Braking is achieved by airpowered dual wedge drum type brakes (like Transbus) and has anti-skid control meeting FMVSS121. The anti-skid control, upgraded, is used for automatic electronic control on-guideway.

The General Motors dual mode system utilizes, essentially, a GMC Motor Home on-and-off-guideway. Braking is provided by two disc front brakes and two drum rear brakes which provide 244cm^2 of braking area in the rear. The vehicle is provided with a dual split master cylinder which is vacuum boosted.

The primary braking system incorporates four hydraulic-actuated multi-disc brakes located on the front driving axle as an integral part of the electric motor assembly. The master cylinder is split for a dual system and has an electric power assist to minimize braking effort requirements.

The vehicle will be equipped with anti-lock braking control to meet FMVSS105. Major components of the system are speed sensors mounted on the wheels, brake pressure control valves, and control circuitry integrated into the electronic control system equipment.

Emergency braking capability is provided in two ways. The dual application system reduces the probability of a complete loss of primary brakes. Secondly, when a loss of application pressure is sensed in either side of the system, the secondary propulsion electric drive motors will be energized, generating reverse torque. The resultant drag assists in decelerating the vehicle.

The primary braking system and the emergency braking system will be continuously monitored and controlled while the vehicle is operating in the automatic mode on the guideway.

The Longitudinal Control System includes the employment of an accelerometer to help provide smooth service braking and emergency braking through coordinated throttle and brake actuators.

The parking brake is actuated through a conventional lever which applies the pressure pods on the disc front and intermediate axle brakes.

With this brief review of the chief characteristics of the braking system and their interfacing systems, some aspects of the integration may now be considered. The braking systems, summarized are:

1) LIM braking and skids; standard bus,

2) Drum,

3) Disc and drum.

It is clear that the latter two are not very esoteric. They are nevertheless adequate to the task. A bus driver can control these with precision. The possible problems with such braking systems are then in the automatic control section. It should be carefully noted that the more severe limitations of FMVSS-121 is on the service braking (not on the "emergency" braking.) On-guideway the emergency braking must control the design. These differences should be reconciled by making the emergency braking

sufficient for the on-guideway travel; it will then exceed the requirements of FMVSS-121, and indeed should do so. As another consideration, it should be noted that care should be given to ascertaining that precision stopping (e.g. in stations) will be achieved with the automatic control system in conjunction with the latter two braking systems.

The first dual-mode system, off-guideway utilizes a standard braking system which should meet FMVSS-121. On-guideway if reverse thrust is inadequate to the slowing or stopping requirement, the pallet-pod is lowered to permit skid braking. Care must be exercised that a sufficiently safe system is worked out for such an event. Lift by air cushion pods must be positively cut-off, and adequate safeguards for quick detection of lack of plugging of the LIM installed. Consideration must be given to the skid design such that proper emergency braking will be achieved. Should the skids land unevenly, or should the frictional coefficients between the running surface and the skid vary from part to part, lateral or tumbling forces could result.

In terms of the general concepts of integration of a braking system into a dual-mode vehicle, each of the dual-mode vehicles incorporates a braking system which meets its interfaces well (and each meets a different set of interfaces). Judgements must then be made, not on the individual braking system, but on the overall complex of power and propulsion systems, command and control systems and braking systems.

5. SUMMARY

There are many interrelationships of significance for properly integrating a braking function specifically into a dual mode transportation system.

Factors shaping the characteristics of the braking system are its interfaces with other vehicle systems. The braking system must be compatible with the power and propulsion systems and with the command and control functions. The operational parameters of motion the headway, velocity, deceleration and jerk limits constitute, of course, another set of determining factors.

A dual mode transportation system involves, in general, both an on-guideway and an off-guideway operation. The on-guideway portion offers essentially personal rapid transit amenities. The requirements in the vehicle in reference to braking capabilities on the guideway are then similar to those of personal rapid transit (PRT) vehicles. The off-guideway braking system requirements are similar to those of buses, trucks or automobiles. The integration of a braking function into a dual mode system must be basically a compromise among on-guideway and off-guideway braking operations. In general, the compromise may be accomplished by use of either different braking systems (on different vehicles as in a pallet-pod operation, or in the same vehicle) or by use of the same braking system suitable for on-and-off guideway operations.

Criteria against which braking systems may be measured are those factors of safety, economics, energy management and environmental impact. By considering these criteria, and the limitations set by the braking system's interfaces, an organized set of matrix of interrelations is developed, from which desirable and undesirable aspects of integration of braking functions into a dual mode system can be determined.

The significance of the interfaces is such that these become the controlling factors. The actual braking hardware now available, with proper design and application, is adequate for tasks of stopping dual mode vehicles. The braking function of necessity includes

its controls, especially as headway is lowered to tenths of seconds on-guideway, where the limitations are the more restrictive. Off-guideway, service braking is the more restrictive, and "emergency" braking can be considered as back-up braking. Fail-safe braking is possible only when all interrelationships are properly evaluated. Fail-safe, here and in general, can mean only that under a failed mode, the function is put into a back-up mode with reduced probability of failure.

A safety analysis such as fault-tree analysis is preferable to reliance on fail-safe concepts.

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