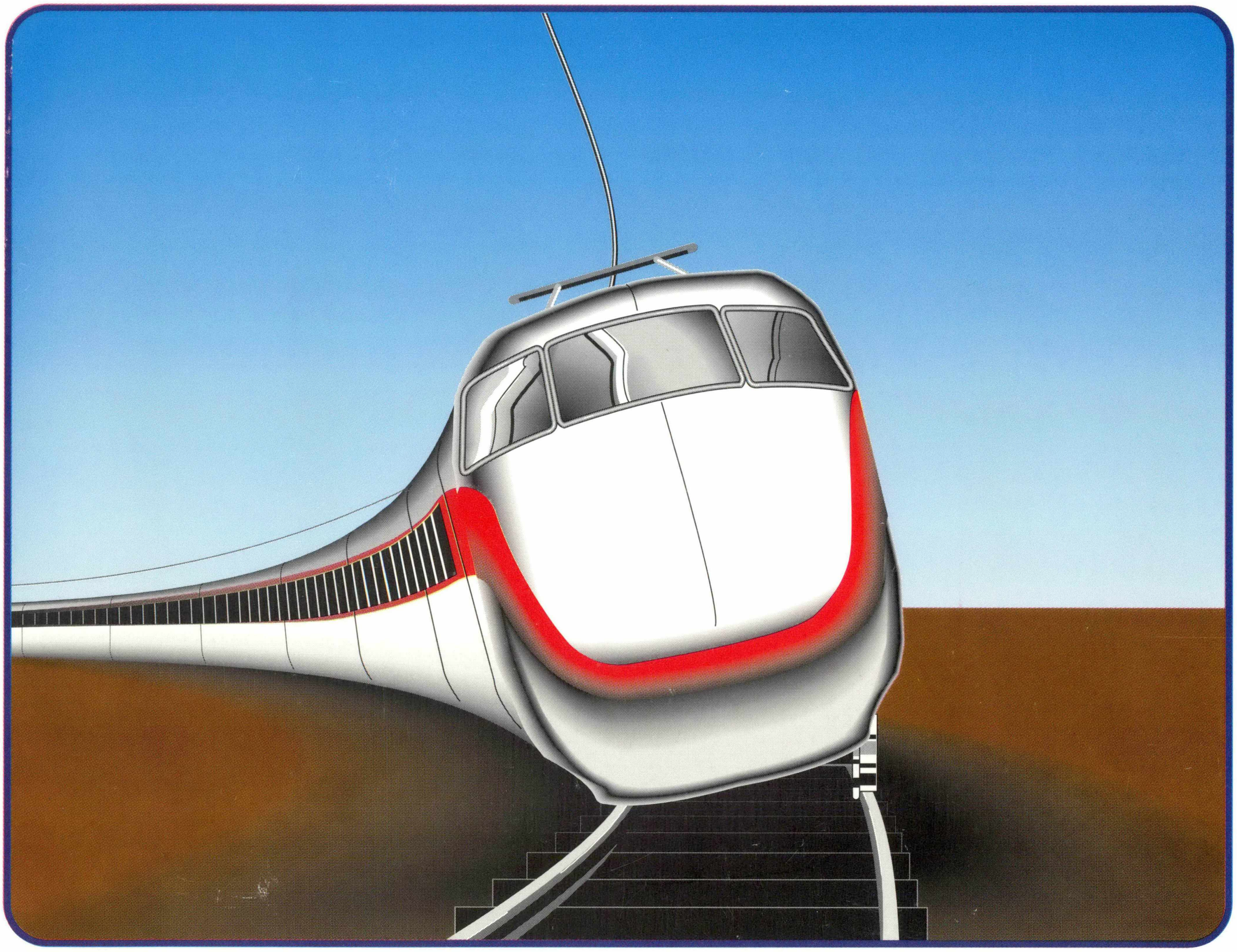
U. S. Department
of Transportation

**Federal Railroad
Administration**

Tilt Train Technology: A State of the Art Survey



Moving America
New Directions, New Opportunities

May 1992

NOTICE

In numerous places, this report discusses whether various aspects of the technology that is the subject of this report comply with Federal safety laws and regulations. Those discussions, which reflect the seasoned judgement of commentators qualified in their fields, do not constitute rulings by the Federal Railroad Administration's Office of Safety or its Office of Chief Counsel concerning compliance with the law.

FOREWORD

Many intercity high-speed train technologies have become an operating reality in recent years. Though mostly of foreign origin, these new trains offer the potential for immediate application in the United States. Each high-speed train was developed to meet the particular operating environment appropriate to the parent country's transportation policy. The resulting diversity in design concepts permits the consideration of a variety of systems in meeting various U.S. application requirements. One particular design concept, the tilt-train technology, offers opportunity for application over the existing rail infrastructure.

This executive summary and its companion report, one in a series of reports which describe new high-speed rail technologies, presents an overview of the state-of-the-art in tilt-train technology. It is intended to give the reader a better understanding of the unique features of this approach to train design and the variations that exist. Briefly described is the function of the tilting mechanism, whether passive or active, and its performance with respect to passenger ride quality, safety and trip times, which are all influential in passenger acceptance and modal choice. Two trains of the type described in this report, the Spanish Talgo *Pendular* and the Canadian LRC, were previously tested by Amtrak on the Northeast Corridor (NEC), though not used in revenue service. Currently being considered for test and revenue service in the NEC is the Swedish X2000, also covered in this report as well as in an earlier report on the Safety Relevant Observations on the X2000 Tilting Train.

A more comprehensive review of the state-of-the-art in tilt-train technology appears in the companion report which expands upon the technical relevance of the tilt-train technology and its proper perspective with respect to safety. This state-of-the-art report is not intended to be evaluative in nature, but rather to inform the reader of the considerations that may be appropriately directed to this form of high-speed rail.

Many Americans have had the opportunity to ride on the new families of high-speed trains operating in Europe and Japan, the TGV, the ICE, the X2000, the Pendelino, the Talgo, and the Shinkansen. Now, it is time to begin "Moving America" on high-speed, intercity, guided ground transportation. The future prospects have never looked better and the Intermodal Surface Transportation Efficiency Act of 1991 has laid the foundation with new opportunities for demonstration projects with federal support.

Gil Carmichael

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INTRODUCTION

This report presents a survey of the technical and operational features of existing and planned tilt-body rail passenger vehicles. It follows the general format of the December 1990 Federal Railroad Administration (FRA) Report entitled, "Safety Relevant Observations on the X2000 Tilting Train," (DOT/FRA/ORD-90/14; NTIS: PB 91-12-9668) but with a broader scope.

The most significant implications of tilt-body technologies are for the tradeoffs and compromises that have been, and continue to be made between the "best" track for freight operations and the "best" track for passenger operations or where space and/or economic constraints limit options for performance improvement.

This report presents and discusses basic concepts of railroad route selection, track geometry, the physics of curve negotiation, the rationale for body tilting, the advantages and disadvantages associated with body tilting, and the techniques used to achieve body tilt. An overview is provided of the development status and selected key characteristics of the tilt technologies examined in this survey. Issues associated with deployment and operation of tilt-body technologies in the United States are identified and discussed, including an overview of U.S. experience, areas of incompatibility with existing U.S. equipment and infrastructure, special maintenance procedures and skill requirements, and compliance with FRA and other regulations.

A detailed development of the physics of curve negotiation for conventional and tilting vehicles, a technical discussion of the principles of tilting and tilt control strategies and mechanisms, and descriptions and technical characterizations of each of the technologies are given in a companion to this report.[1]

In preparation of this report, information was drawn from public sources. Technical and illustrative material was also requested from the developers, suppliers, and operators of the different technologies. The variable level of detail in the technical descriptions and characterizations reflects differences in the availability of such information. The data in the public domain were identified through on-line searches of the National Technical Information Service (NTIS) and the Transportation Research Information Service (TRIS) databases, manual and on-line searches of holdings in the Canadian Institute of Guided Ground Transport (CIGGT), ENSCO, FRA, and National Research Council of Canada libraries, including recent (post-1980) periodicals and journals, and the files of senior researchers at CIGGT and ENSCO. This information was supplemented by materials provided by the FRA Offices of Research and Development and Railroad Development.

To ensure that the developers, suppliers and operators of tilt-body technologies worldwide had an opportunity to provide up-to-date information, requests for data were sent to Bombardier, Talgo Pendulentes S.A., SIG, FIAT Ferroviara, ABB, EB Strommens, and JR-RTRI as suppliers, and to VIA Rail Canada, RENFE (Spain), SBB (Switzerland), SJ (Sweden), FS (Italy), DB (Germany), NSB (Norway), OBB (Austria), and JR-SHIKOKU (Japan) as operators.

CURVING MECHANICS

The rationale for incorporating carbody tilting capability into a rail passenger vehicle is quite straightforward. Tilting permits maintenance of acceptable passenger ride quality with respect to the lateral acceleration (and the consequent lateral force) received by riders when a vehicle traverses curved track at a speed in excess of the *balance* speed built into the curve geometry. By tilting the body of a rail passenger vehicle relative to the plane of the track running surface during curve negotiation, it is possible to operate at speeds higher than might have been acceptable to passengers in a non-tilting vehicle, and thus reduce overall trip time. To understand the unique features of the tilt-body approach, it is important to establish the basic elements of railroad track geometry and the overall physics of curve negotiation.

Negotiating a Curve: Some Simple Physics

To compel any vehicle that is moving along a straight line at constant speed to change its direction of motion and follow a curved path, there must be some acceleration (and thus force) laterally inward toward the center of the curve, as illustrated in **Figure 1(a)**. In the case of a rail vehicle, the acceleration, and thus, the force comes from contact between the wheels and the rails. However, forces occur in pairs (the *equal and opposite reaction* of Newton's third law) so that there also appears to be a force acting laterally outwards. This force, which is what passengers are aware of during curving, is termed *centrifugal* force.

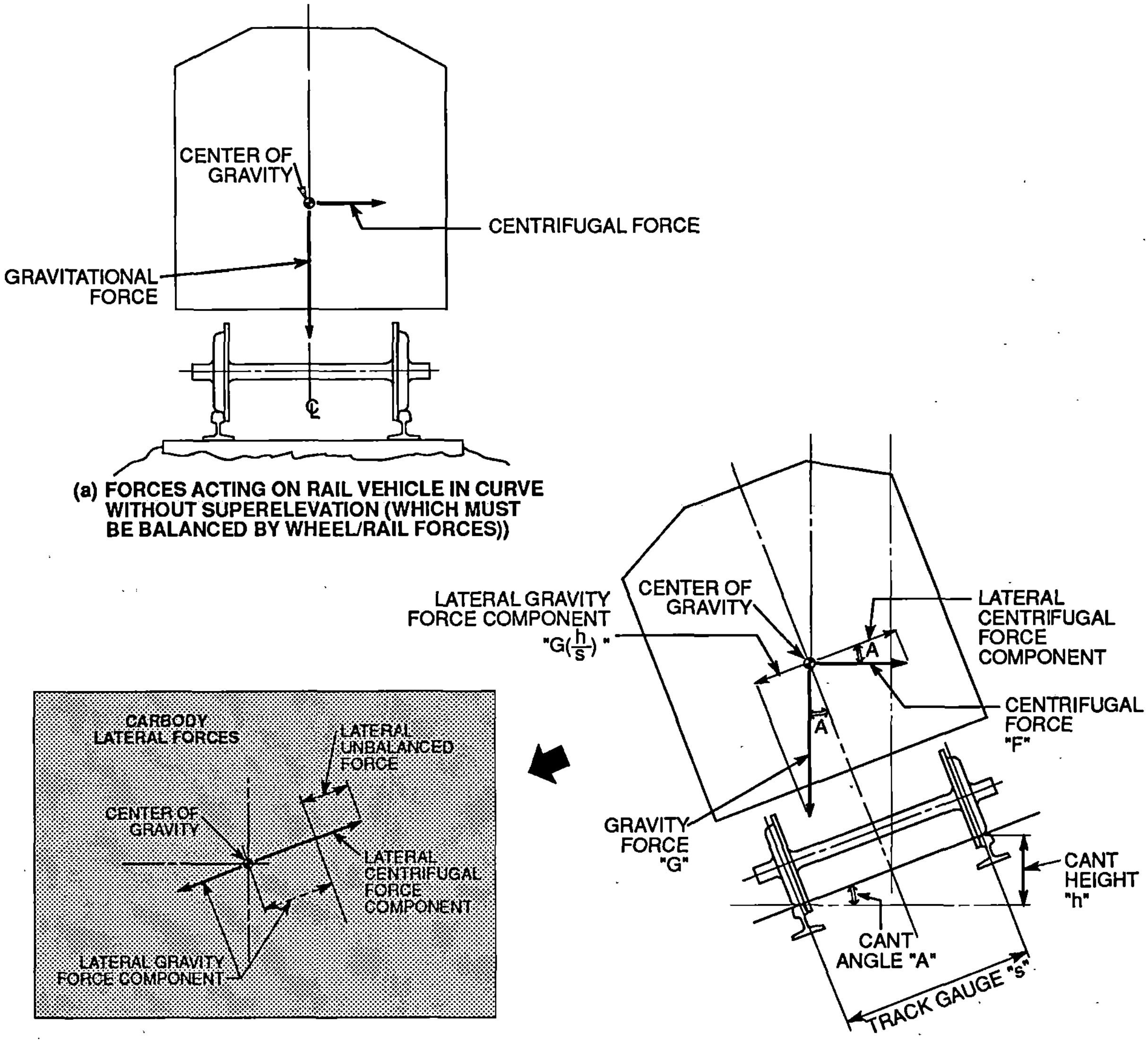
The magnitude of this lateral force increases proportionally, for a given forward speed, as the degree of curvature increases (that is, as the curve radius decreases) and, for a given curvature, as the square of the forward speed. As with all track, tangent or curved, gravity continues to exert a downward force on the vehicle and its contents.

At low-speed, or with gentle curves, the lateral force would not cause much discomfort, even if the curve were not banked (superelevated or canted), as in **Figure 1(a)**. However, as speed increases, or curves become tighter, the force level increases, until eventually passengers no longer find the ride acceptable. Passenger railroad designers and operators worldwide have established that this occurs once the perceived lateral force exceeds about 10% of the passenger's weight.[2]

These expectations of travellers, with respect to comfort, are the basis for most geometric limits. These limits are the levels of lateral and vertical acceleration, expressed as a proportion of gravitational acceleration (g), that have been shown to be acceptable to the majority of passengers - 0.08g to 0.10g for lateral and downward vertical accelerations, 0.05g for upward accelerations. Most passengers cannot detect accelerations of less than 0.04g.[3]

Quite apart from passenger comfort is another important aspect of increased vehicle speed in curves, that of safety. As the required lateral guidance force (between wheel and rail) to negotiate the curve increases, the margin of safety from derailment (loss of guidance) may also be reduced. The ratio of lateral and vertical forces (L/V ratio) at the wheels is a critical determinant of curving safety.

In an effort to reduce the effect of centrifugal force on railway vehicle



(a) FORCES ACTING ON RAIL VEHICLE IN CURVE WITHOUT SUPERELEVATION (WHICH MUST BE BALANCED BY WHEEL/RAIL FORCES))

(b) FORCES ACTING ON RAIL VEHICLE IN CURVE WITH SUPERELEVATION (WHICH MUST BE BALANCED BY WHEEL/RAIL FORCES)

Figure 1: Accelerations and Forces Acting During Curving

passengers and to maintain a good safety margin from derailment, railroad track in curves is not flat; rather, it is banked (*superelevated* or *canted*) with the outside rail raised relative to the inner rail. The amount of superelevation can be expressed in terms of either the difference in rail heights (in length units) or (as in a maglev guideway or the pavement of a highway) the size of the angle between the plane of the tops of the rails and the horizontal. Superelevation can reduce or eliminate the effect of centrifugal force on railway vehicle passengers by compensating this force with the lateral component of the gravitational force acting on the passenger, in the opposite direction to the perceived centrifugal force, as shown in **Figure 1(b).**

By banking the track, the centrifugal force acting on the passengers is cancelled out, at least in part, by a component of the force of gravity.

Since the centrifugal force which a passenger perceives while traversing a given curve is a function of vehicle speed, it follows from **Figure 1** that at some speed, the lateral components of the centrifugal and gravitational forces acting on a passenger will exactly cancel one another. In other words, for any given curve and track superelevation, there will be a single speed for which the lateral component of the centrifugal force will be exactly compensated by the corresponding component of the gravitational force.

This speed is referred to as the *balance* or equilibrium speed for a particular combination of curve radius, superelevation, and vehicle characteristics. For virtually all curves in railroad track, it is common practice to set the balance speed (and thus, the amount of superelevation or cant built into the curve) to accommodate the least stable freight car (in the U.S. and Canada, this might be a tri-level automobile carrier, which has a high center of gravity and large surface area susceptible to wind forces) under worst-case conditions (i.e., stopped on the curve with a strong cross-wind acting on the side of the vehicle on the outside of the curve).

The traversing of a curve at speeds either higher or lower than the balance speed results in an imbalance between the lateral component of gravity and the centrifugal force induced by operation through the curve, as shown in **Figure 1(b).** It is common railroad practice to speak in terms of "cant deficiency or excess" or "inches of unbalance" when there is a difference between the actual operational speed through a curve and the balance speed of the curve.

If there were no premium on speed, the curve geometry could be set for the most restrictive class of traffic and all trains would operate at that speed. Since speed is always at a premium for passenger service, and increasingly for freight service as well, the curve geometry (and thus balance speed) becomes a compromise between the maximum that can be tolerated by the slowest, least stable trains and the minimum that can be accepted by the fastest trains. This means that the majority of trains may well operate at other than the balance speed for a given curve, but always within the limits of the safety envelope for track forces and train stability.

Cant deficiency is defined as the difference between the actual superelevation (cant) in a given curve and the amount of superelevation which would be required to exactly balance the lateral (centrifugal) force acting on the train when it traverses the curve at a higher or lower speed. Cant deficiency is a particularly convenient measure of unbalanced speed operation in this context, insofar as it relates directly to the amount of vehicle carbody tilting which would be required to balance the forces acting on passengers and thus, maintain acceptable passenger comfort.

However, the geometry of the track and the speed of a vehicle or train are not the only elements affecting curving behavior and the effective angular inclination of a carbody. The situation can be complicated by the behavior of the vehicle suspension when operating above or below the balance speed. With some rail vehicle secondary suspension designs, the unbalanced lateral force acting on the vehicle at the center of gravity can tend to further tilt the vehicle in the direction of the unbalanced force by compressing the suspension springs on the outside of the curve. This would increase the magnitude of the unbalanced force, as shown in **Figure 2**. In this instance, the "softer" the vehicle suspension, the greater

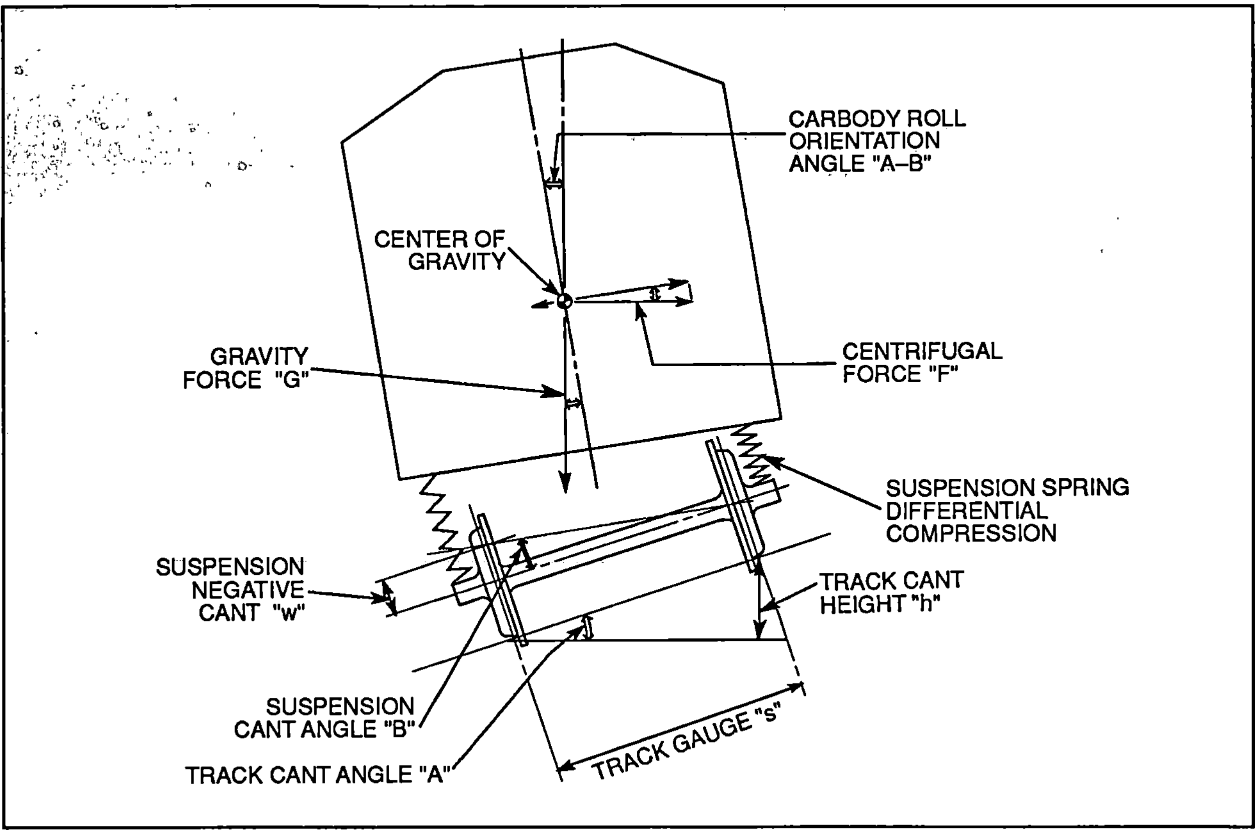


Figure 2: Effect of Suspension Compression on Forces Acting on Passengers During Curving

the amplification of the unbalanced force would be, just as some automobiles will "roll" uncomfortably when making a turn at relatively high speed. Many suspension systems, however, are designed to limit this effect using roll torsion bars or lateral links.

This effect is sufficiently important that it must be accounted for when designing or assessing the performance of vehicle-tilting systems. The outward roll due to suspension compression for some suspension designs would have the same effect, with respect to passenger ride comfort, as reducing the superelevation in a curve by the amount of the differential compression (labelled "w" in **Figure 2**).

Finally, by intentionally tilting the body of a passenger rail vehicle, it is possible to reduce or eliminate the unbalanced lateral force acting on passengers, as shown in **Figure 3.** Intentional tilting affects passenger ride comfort as though the superelevation of the track in a curve was increased by the amount of deliberate banking, relative to the horizontal plane.

By incorporating the effects of differential suspension compression and deliberate body tilting into the expression for balance speed, a complete picture of the forces acting on rail vehicles, and, equally important, on passengers, is obtained. This allows passenger service operators to assess how tilt-body equipment would alter the time required for a particular trip. This information is essential in making an informed trade-off between the additional cost of acquiring and operating tilting equipment and the revenues to be gained from reduced trip time. A companion to this report[1] provides a more detailed discussion of the physics of curve negotiation, including a step-by-step development of the complete unbalance force equation.

Why Tilt the Vehicle? Why Not Change the Superelevation?

The objective of carbody tilting while curving at a speed above the *balance speed* (discussed above) is to achieve an acceptable ride quality with respect to the lateral force perceived by the passenger, without being forced to invest large sums of money to build a dedicated passenger track with very large radius (very gentle) curves, or alternatively, to reconfigure the geometry of existing curved track to the point where safe freight operations would be compromised. By tilting the train, existing curves can be traversed at higher speeds without compromising passenger ride quality and without risking instability during freight operations should the track superelevation otherwise be increased.

However, tilting the carbody does not reduce forces at the level of the track; increasing speed increases the lateral inertial force as the square of speed. Thus, increasing the curving speed without considering the effect of higher speed on the dynamic wheel/rail forces during curving, will result in a greater exposure to accident risk because the safety margin on curving forces can be reduced. This is the principal reason why tilt-body technologies with relatively high top speeds (above 160 km/h [100mph]) also incorporate other features, such as low axle loads, low

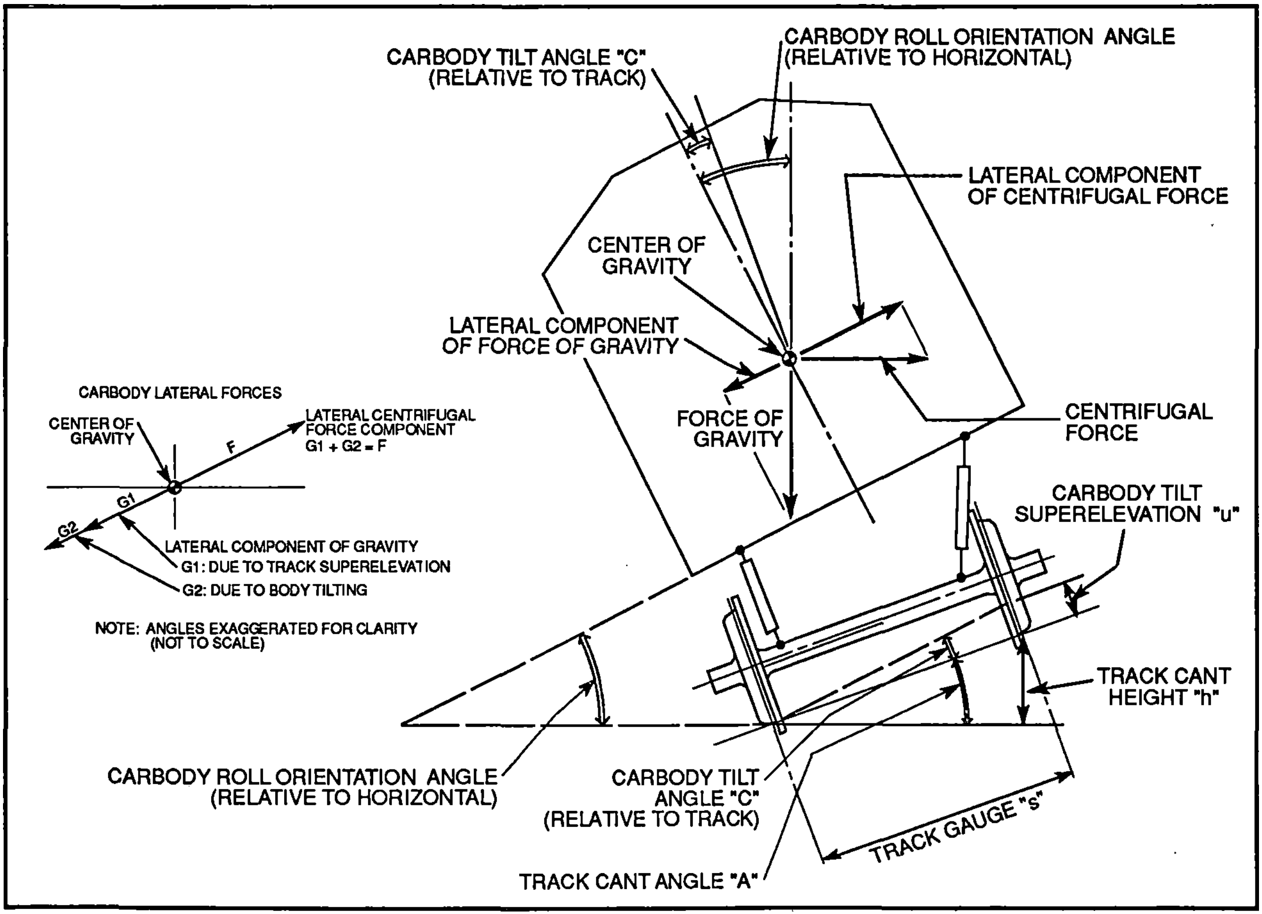


Figure 3: Effect of Deliberate Body Tilting on Forces Acting on Passengers

unsprung masses, steerable trucks, and/or active suspensions, to reduce track forces and improve or maintain operating safety margins, as well as body tilting to maintain passenger comfort.

Outside the Northeast Corridor (NEC), both the alignment geometry and track geometry of existing North American railway tracks have been modified over the years[4] to meet the requirements of current freight operations. This means that the balance speed and degree of superelevation in a given curve will be appropriate for relatively slow (65 to 100 km/h [40 to 60 mph]) freight trains made up of vehicles with relatively high centers of gravity (compared to modern passenger equipment). At best, where freight and passenger operations share track, superelevation may be increased slightly above the ideal level for freight. However, safety considerations arising from freight vehicle instability under certain conditions, and also the increased forces imposed on the lower (inside) rail in a curve by the much heavier freight cars and locomotives, when traversing the curve at speeds below the balance speed, force any track geometry compromise towards the freight optimum. Imposition of heavier forces on the lower rail increases the risk of rail failure through fracture or overturning, and thus of derailment, and also causes greater rail (and wheel) wear, and thus increased maintenance costs.

Outside North America, the emphasis tends to be on railroads as passenger carriers, rather than as movers of freight. Freight cars are limited to a 22 tonne (24.2 ton) axle load, and trains are shorter, lighter, and often much faster.[5] However, in Japan and in many European countries, there are extensive mountainous areas served by secondary and even main lines with curvature that restricts achievable speed below the safety limit, due to passenger comfort considerations. Even where regional purpose-built high-speed lines exist to remove this comfort restriction (e.g., the *Direttisma* in a mountainous region of Italy), there may be advantages to tilting technologies if train service extends through the rest of the national network or onto international routes where non-purpose-built track may be used. In addition, the emphasis on passenger operations, environmental concerns and stringent approvals processes, especially in European countries, provide an on-going incentive to seek service improvement opportunities that are not limited to extensive new infrastructure development.

In essence, tilt-body technologies represent a potentially effective approach for improving achievable service speed for passenger equipment on existing tracks, without altering the geometry of curves and thus affecting the cost and safe operation of freight equipment, and without requiring investment in new dedicated high-speed infrastructure. For lines where passenger traffic density (and thus potential revenue) is low, this *equipment-oriented* strategy offers a cost-effective means for significant service improvement, and one that can be implemented incrementally, so as to ease the effect of financial limitations.

The Trade–offs of Tilting Trainsets

The intentional tilting of railroad passenger carbodies has the advantage of allowing a significant increase in the speeds at which existing track curves can be traversed, relative to those for non-tilting vehicles, with an equivalent level of passenger comfort. There are very substantial financial benefits that can arise from achieving higher average speeds (and thus, reduced trip times) on existing tracks, insofar as the required investment for tilt-body vehicles is quite modest compared to that needed for infrastructure improvements.

Clearly, the magnitude of such benefits will be very much a function of the number and total degrees of curvature on any given route. Higher average speed achieved through reduction or elimination of speed restrictions on curves that have been imposed for reasons of passenger comfort may permit improved equipment utilization. This should result in reduced requirements for capital investment in equipment and in increased passenger ridership in response to the reduced travelling time.

The introduction of body tilting alone will not affect speed limits imposed for reasons of safety (i.e., to ensure that track forces and especially the lateral force exerted during curving does not exceed acceptable limits). The Swedish X2000, for example, has a maximum axle load of 17.6 tonnes (19.3 tons), with frame-hung traction motors to reduce unsprung mass, and radial-steering trucks, all of which combine to help keep track forces within acceptable limits even with a substantial increase in speed.[6]

ACHIEVING DELIBERATE BODY TILT

There are two basic approaches to deliberately tilting the body of a rail passenger vehicle.

Passive-Tilting

Passive-tilting is based on the pendulum effect provided by centrifugal and gravity forces when the carbody roll center is located well above the center of gravity (c.g.). In effect, the carbody behaves as though suspended from pivots located at or near the top of the car, so that the body can swing laterally about its long axis, as shown in **Figure 4**.

Passive-tilting technologies have the advantage of technical simplicity and lower weight for the tilting components, but the outward lateral displacement of the c.g.

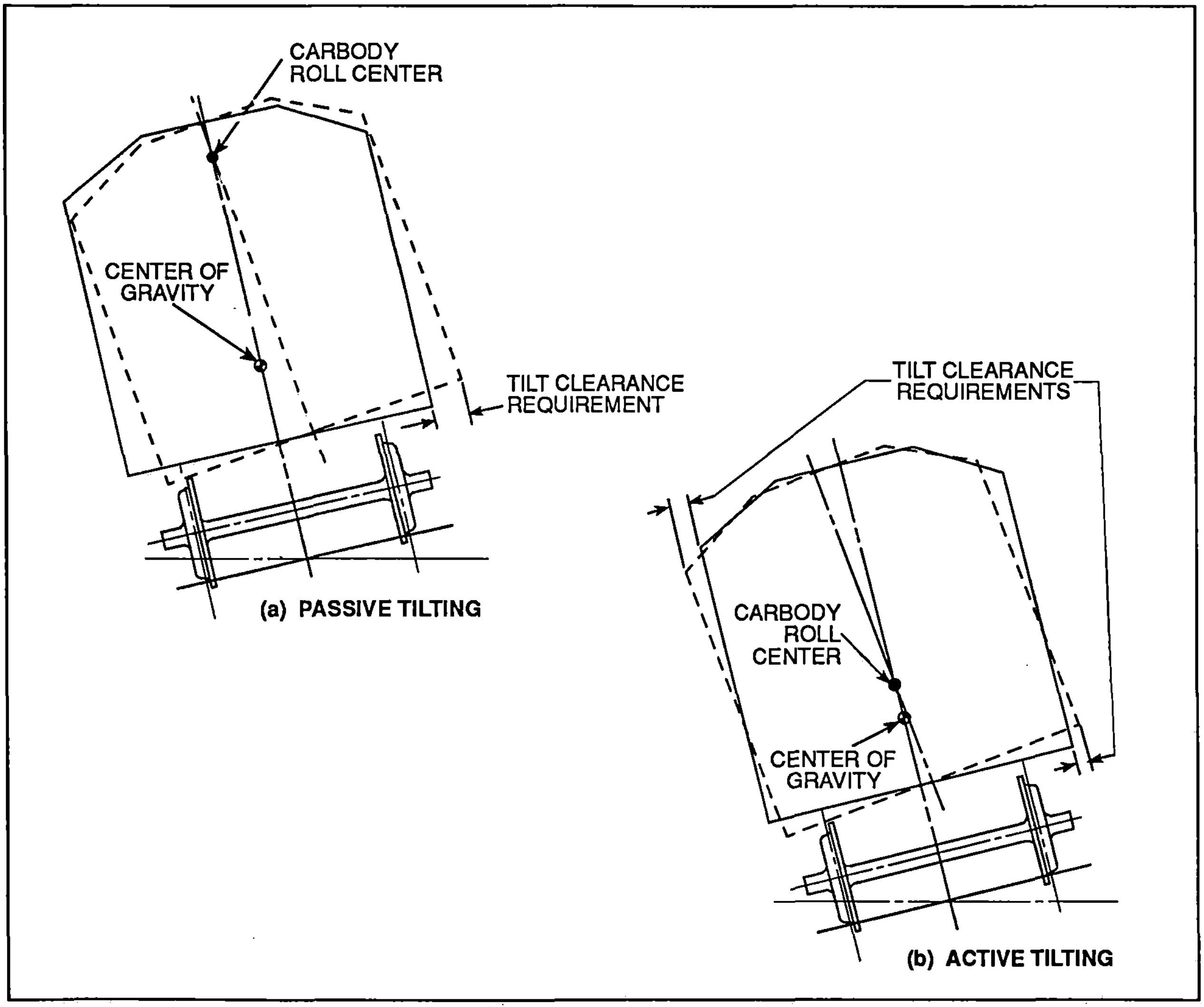


Figure 4: Location of Carbody Roll Center and Center of Gravity for Passive and Active Body Tilting

while tilting means a potential reduction in the margin of safety for vehicle overturning. Technologies based on this principle include the Spanish Talgo *Pendular*, the JR Series 381 Electric Multiple-Unit trainset (EMU), and the United Aircraft (UAC) *Turbotrain*. The latter, since retired, was used by Amtrak in the early 1970s and by CN and VIA Rail Canada in the 1970s and early 1980s.

The Swiss consortium SIG has developed a truck-based passive-tilt mechanism known as *Neiko* for use with their unpowered high-speed truck; the truck can also be equipped with forced radial steering.

The potential increased risk of overturning, at least in curves, can be offset by designing the vehicle to have a very low center of gravity, thereby lowering the lateral inertial overturning moment (the vehicle roll moment induced by the lateral inertial force acting at the c.g. and reacted at the rail is a function of the height of the c.g. above the rail). The Spanish Talgo passive tilting coaches (**Figure 5**) are notable in this regard. The lightweight carbodies are carried between the bogies, rather than on top of them so the center of gravity is very close to the track.

In contrast, the other operational passive tilting technology, the Japanese Railways-Shokaku Series 381 electric multiple-unit trainset (**Figure 6**), has the carbody located on top of the trucks, so that the center of gravity is relatively high. The effect of this high center of gravity on overturning safety margin is exacerbated by the fact that this equipment operates on narrow-gauge (1 meter) track. However, these trainsets operate at relatively low-speeds (less than 120 km/h [75 mph]), and there have not been any serious incidents during its 18 years of service.

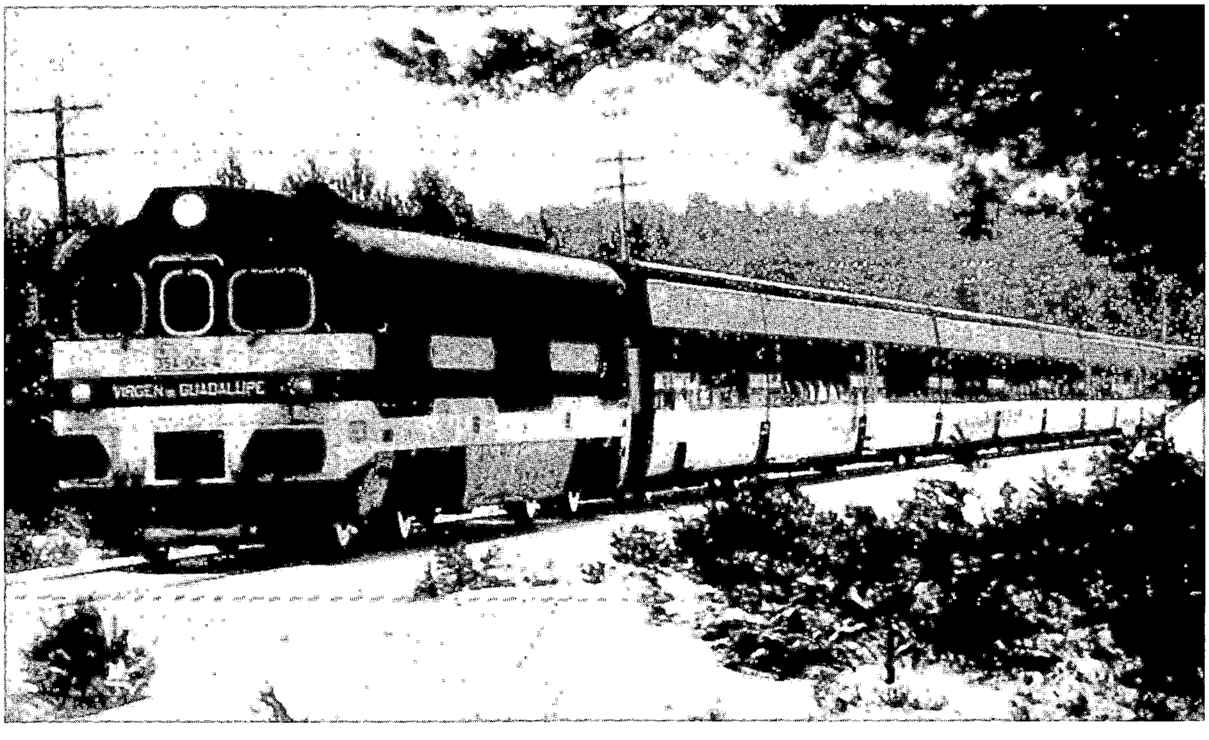
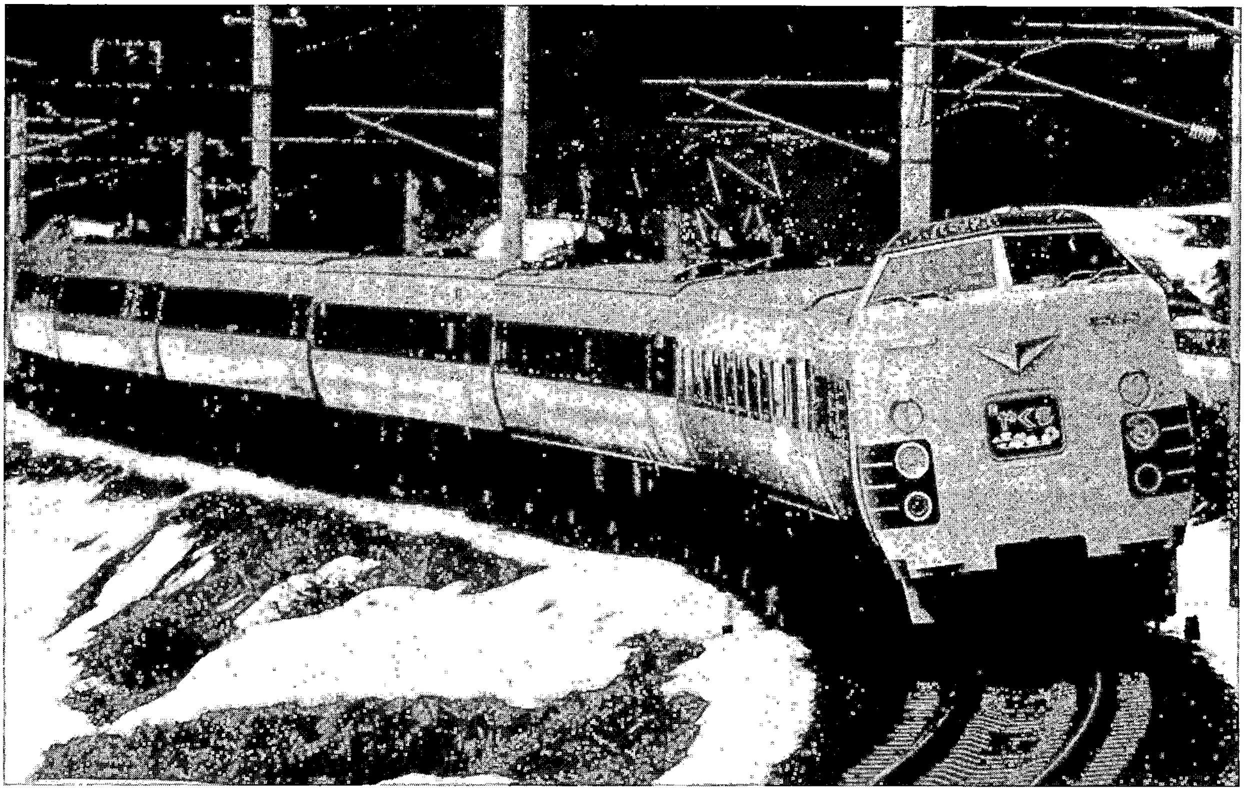


Figure 5: The Talgo Passive-Tilt Coach



(Source: Japanese Railway Engineering, Dec. 1986)

Figure 6: The JR-Shokaku Series 381 Passive-Tilting Narrow-Gauge EMU

Active–Tilting

The other tilting technique uses hydraulic, electromechanical, or pneumatic actuators in combination with a tilt control system to provide *active* body tilting. Active-tilt mechanisms also incorporate mechanical linkages to keep the carbody roll center close to or below the carbody center of gravity, as in **Figure 4(b)**. These linkages effectively eliminate any adverse effect on the safety margin for vehicle overturning, and have the additional practical advantage of minimizing the clearance envelope for the vehicle at maximum tilt, also shown in **Figure 4**. This approach also reduces the force exerted on passengers during tilting, in that the center of rotation typically tends to be near the passenger seat cushion level.

The principal disadvantages of active-tilt mechanisms stem from the complexity and added weight of the tilt actuators and the difficulty in defining optimum control strategies, given the nature of the track geometry and passenger comfort. An inability to achieve reliable detection of curve onset and exit and acceptable timing of tilt actuation led to the cancellation of the British Rail Advanced Passenger Train (APT) of the 1970's. However, part of the problem stemmed from the inadequate data processing capability available during the late 1970's and early 1980's.

The MLW/Bombardier LRC coaches operated by VIA Rail Canada have also been affected by problems with curve detection and reliability of tilt operation, especially during their first half-decade of operation. Bombardier redesigned the control system during 1986-1988 and retrofitted the VIA fleet (**Figure 7**). The equipment tested on the NEC as part of the CONEG Task Force Program (see page 24) had been so modified. As a consequence of this aggressive program and the extensive training of operating and maintenance personnel, VIA now employs active tilting on the Ontario-Quebec corridor.

Despite the problems encountered by some active tilt technologies, the successful Fiat ETR 450 EMU (**Figure 8**), the ABB X2000 (**Figure 9**), and the LRC show that these challenges can be overcome.

Curve Detection and Tilt Actuation

While body tilting can maintain ride quality at higher speeds in curves, it is essential that the amount of body tilt, and the rate at which tilt is increased, closely match the increase in lateral acceleration (force) that arises as the vehicle moves from tangent track onto the run-in spiral and then onto the section of track with a uniform radius of curvature.

Similarly, the tilted carbody must be returned to its normal position as the vehicle moves over the run-out transition spiral.

This careful control of both magnitude and rate of tilting requires reliable detection of the onset of a change in track curvature. However, the mechanism must not be so sensitive as to overreact to irregularities in track geometry.

The curve detection and tilt control mechanisms incorporated in the

Figure 7: The LRC as Produced for VIA Rail Canada, Inc.

technologies considered in this report depend on one or more of the following techniques:

- Continuous measurement of lateral acceleration of the vehicle,
- Continuous measurement of the carbody roll angle relative to the plane of the truck (bogie),
- Continuous measurement of track superelevation, and
- Continuous monitoring of vehicle location on the track relative to the known location of each transition and curve on the route.

Lateral acceleration on the vehicle is detected by accelerometers mounted on the carbody and/or the trucks. All but one of the actively-tilting technologies summarized below and detailed in the companion report depend on measurement of lateral acceleration. Suitable acceleration sensors are commercially available.

A number of the active-tilt technologies also measure the angle of the carbody relative to that of the truck. This measurement requires sensors that detect the difference in the position of the two sides of the carbody. Such sensors (typically differential transformers) are also commercially available.

Measurement of track superelevation forms part of the basis for curve detection and tilt control on the Fiat ETR 450 active-tilt

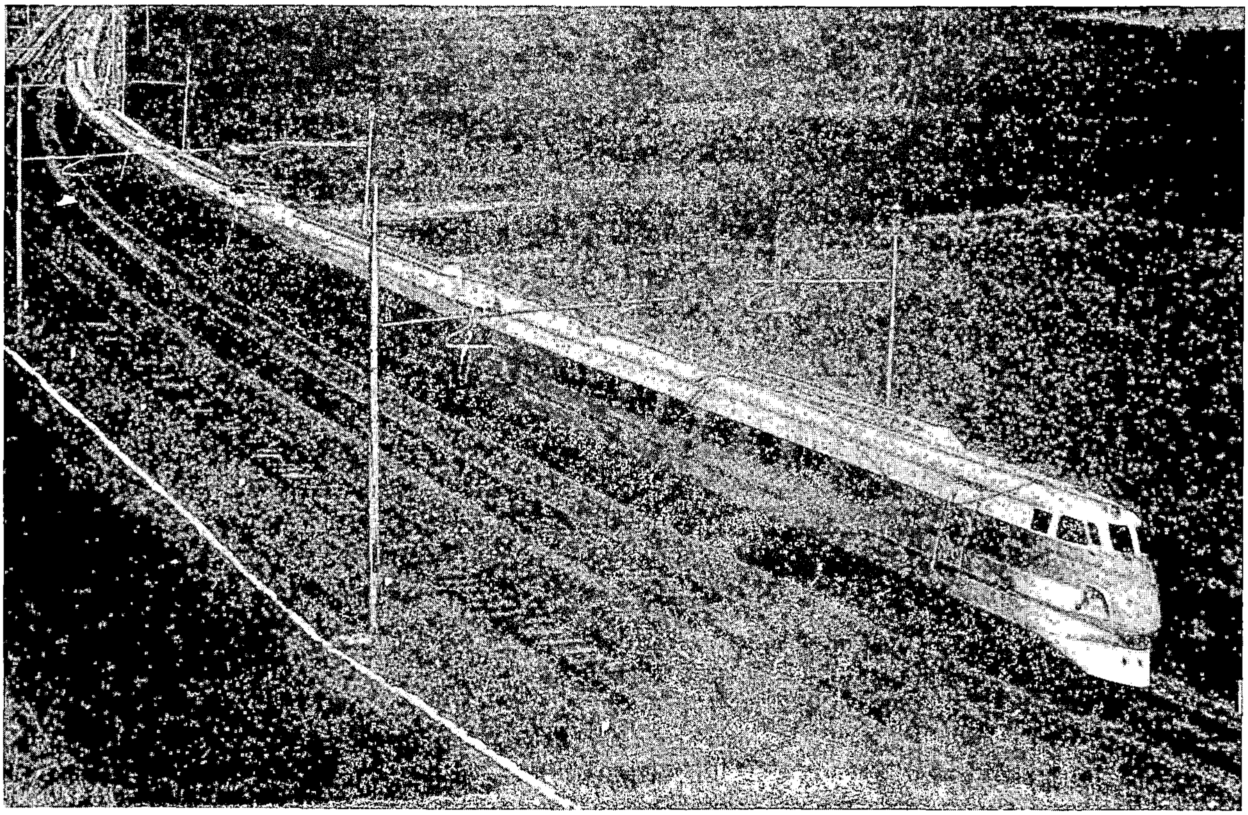


Figure 8: The Fiat Ferroviara ETR 450 Active-Tilt EMU Trainset

equipment. Gyroscopes mounted on a truck of the vehicle at either end of the train provide an absolute horizontal reference against which the roll position of the truck can be measured. This information, which is instantly available, is used to supplement the lateral acceleration data, which tends to lag slightly behind the onset of curving due to the filtering of the acceleration signal to remove the false inputs caused by random variations in track geometry.

The three curve-detection techniques summarized above depend on measurement of acceleration, carbody and/or truck positions, and, as such, are generalized techniques that allow a vehicle to operate over any route. In contrast, the final technique listed above depends on access to complete information about the exact absolute location and geometry of each transition spiral and constant-radius curve on the line over which the vehicle is operating, and a mechanism, such as wayside transponders, that allows detection of the exact position of the vehicle with respect to the next transition.

This technique, which was developed as part of a retrofit package for the Series 381 EMU and has since been used in the TSE-2000 DMU equipment for JR-Shikoku, is essentially a programmable control system that causes the vehicle to "follow" the lateral track geometry, banking the correct amount, in the correct direction, at the proper rate based on vehicle speed, just as the wheel-rail forces cause the vehicle to follow the longitudinal and vertical alignment geometry.

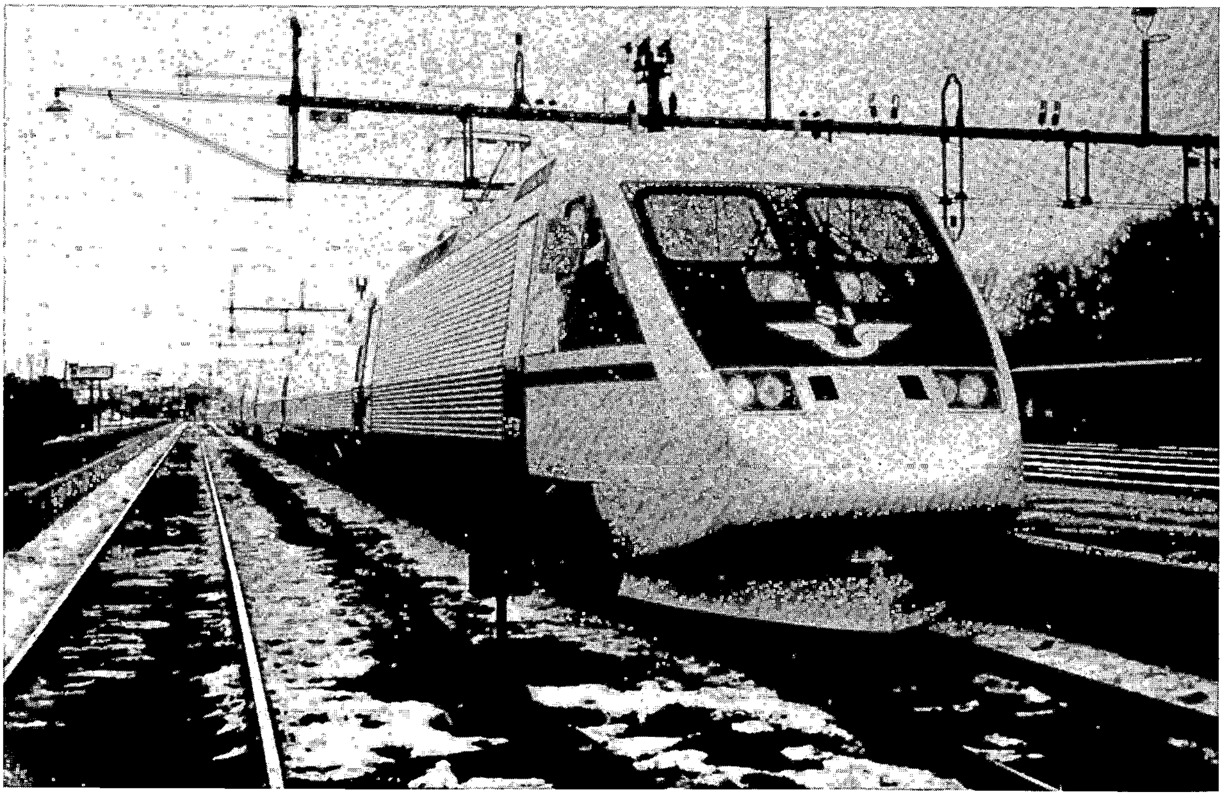


Figure 9: The ABB X2000 Active-Tilting Trainset

This approach offers several advantages in terms of overall simplicity and reliability, and in its avoidance of real-time (reactive) curve detection, the practicality of which is strongly affected by train speed. However, the need for continuously updated speed information and accurate vehicle "locators" at each curve may offset the advantages somewhat. This technique could be of value to maglev, should tilt be required to adapt to the geometric constraints of existing rights-of-way.

Another important consideration in the design of active-tilt controls is the location of the sensor mechanism(s) that provide the input data to trigger the onset of tilting. Basically, there are two alternative sensor locations that are used in conjunction with the generalized techniques, as shown schematically in **Figure 10**:

- On the car or vehicle immediately *ahead* of a given car, or
- On the trucks of a given car.

The "car-ahead" sensor location allows sufficient time for the control system to process the input data and "anticipate" the onset of curving, so that tilting of the vehicle can be timed to coincide with the onset of lateral acceleration. This provides superior acceleration compensation provided both rate and magnitude of tilt correspond exactly to the changes in track superelevation and the radius of curvature at each point in the transition.

This approach also permits detection of entry to and exit from the constant-radius portion of the curve, so that tilting can be halted and reversed without apparent discontinuities. However, the use of "car-ahead" sensors does impose the minor requirement for transmission of sensor data and/or tilt control signals between cars or vehicles in a train.

Location of the sensor array on a given car simplifies requirements for data and/or control transmission, but imposes a lag between detection of a curve and the onset of tilting. This lag makes it more difficult

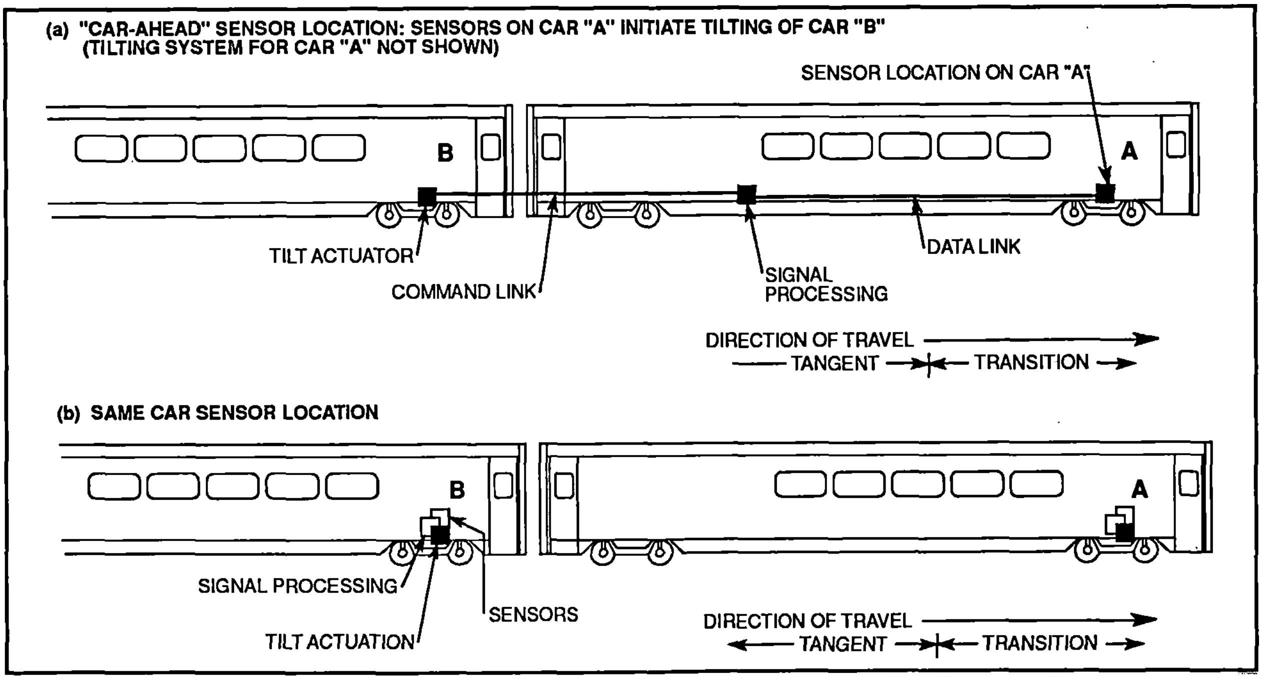


Figure 10: Alternative Sensor Locations for Active Body Tilt Control Systems

to match rate and magnitude of tilt so as to exactly cancel out lateral acceleration. Mismatches between body tilt and curve geometry may result in a higher level of passenger discomfort (in the form of acceleration peaks or acceleration reversals) than would traversing the curve without body tilting.

Fail-safe and Fault-tolerant design

An important consideration in the design of either active or passive tilting mechanisms is the requirement that the mechanisms be fault-tolerant and ultimately "fail-safe"; should some component fail, the system must continue to operate safely. In the event the mechanism does not operate properly, the carbody must return to its untilted (neutral) position, be automatically or manually locked in that position, and the vehicle speed in curves be restricted to that approved for conventional (non-tilting) equipment. Each step is important, insofar as the vehicle requires minimum clearance when untilted. Passenger comfort and safety would be adversely affected if the carbody were allowed to swing freely, and the ride quality would exceed acceptable limits if curves were taken at the higher speed used with a functioning tilt mechanism. It is clear from review of the technical literature that each manufacturer has considered this requirement.

Reliability and Maintainability

As noted above, passive and especially active tilt mechanisms and the features that reduce or control track forces, add complexity to the design of passenger rail vehicles. This added complexity translates into a greater potential for failure with consequent additional requirements for maintenance, relative to a conventional (non-tilting) vehicle. Suppliers of tilt-body equipment have gone to considerable effort to ensure that their designs are as reliable as possible and also to facilitate the additional maintenance activities that are required.

In terms of reliability enhancement, tilt-train designs emphasize fault-tolerant subsystems with redundancy of critical components and sophisticated self-test and diagnostic capabilities. This strategy minimizes disruption of revenue service and facilitiates subsequent maintenance activities, but demands an aggressive and disciplined preventive maintenance program.

Fault-tolerant design for critical components and subsystems differs somewhat from, although does not obviate, the traditional "fail-safe" standards of the U.S. railroad industry; reconciliation of these two approaches is already occurring in some areas, notably train control, signaling, and interlocking devices. However, this process may need to be expanded to deal with the key design elements for tilt technologies.

To enhance maintainability, there is an emphasis on programmed preventive maintenance in purpose-designed facilities. Much effort has been made to ensure ease of access to important subsystems and components, and the modularization of major components and subsystems to permit rapid interchange so that repair or servicing need not immobilize a vehicle or complete trainset.

Cost versus Performance: How Tilting Affects This Fundamental Tradeoff

Tilt-body technologies have the capability to offer improvements to trip time on routes with frequent curves of sufficiently small radius to warrant the imposition of speed restrictions for reasons of passenger comfort. (If speed restrictions are imposed because of other reasons, such as excessive wheel/rail forces, other design modifications such as the use of radial-type trucks must also be incorporated). Improvements which are achieved by raising the *average* speed on a particular route through reduction or elimination of deceleration/acceleration cycles on some curves may be significant, in terms of enabling the service operator to offer a more competitive transportation product. However, the effect on service competitiveness, and ultimately, on ridership and revenue is very dependent on the characteristics of each specific market.

The major potential benefit from body tilting is higher average speed without major investment in new infrastructure. Tilt-body equipment may, under the right conditions, offer a much more cost-effective way to improve performance using existing rights-of-way and tracks.

Tilt-body technologies will permit speed increases in curves only to the extent that existing speed limits are imposed for reasons of passenger comfort. The use of body tilting does not alter the acceptable levels of lateral and vertical force that can be imposed on the track structure during curving, so that the effects of operating at a higher speed must be assessed for safety on a curve-by-curve basis. The most important element in controlling the magnitude of the forces imposed on the track structure at any given speed is minimization of the weight of the rail vehicle and especially what is termed its *unsprung mass* (the portion of vehicle weight that is located between the track and the first set of springs [primary suspension]) in the vehicle suspension, as illustrated in **Figure 11.**

In North American locomotives, the unsprung mass comprises the wheelsets and axle-mounted traction motors. European and Japanese designs typically suspend the traction motor from the carbody or mount it on the truck frame above the primary suspension, with power being delivered to the wheels though a flexible driveshaft. This greatly reduces the unsprung mass (and also moves the traction motor out of a very dirty and demanding operating environment). **Table 1** summarizes unsprung mass and axle load for some typical North American and foreign locomotives. As an illustration, the

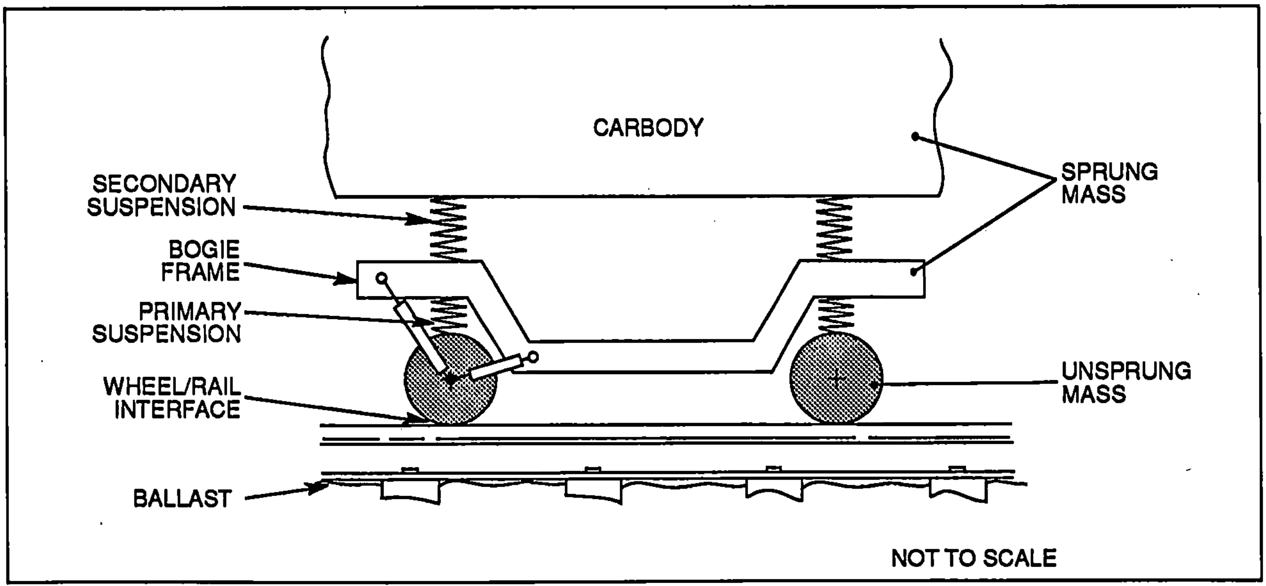


Figure 11: Vehicle Suspension Configuration

TABLE 1
COMPARISON OF MAXIMUM AXLE LOAD AND UNSPRUNG MASS

Technology	Propulsion Type	Static Axle Load Tonnes (Tons)/Axle	Unsprung Mass Tonnes (Tons)/Axle
LRC	Medium-Speed Diesel	28.5 (31.4)	4.0 (4.4)
X2000	Overhead Electric	15.0 (16.5)	1.9 (2.1)
ETR 450	Overhead Electric	12.5 (13.8)	1.5 (1.6)
F40PH	Medium-Speed Diesel	29.0 (32.0)	3.6 (4.0)
HST	High-Speed Diesel	17.5 (19.3)	2.2 (2.4)

unsprung mass of the Bombardier LRC locomotive is over 3990 kg (8,800 lb), similar to that of a typical four-axle freight locomotive; that of the diesel-powered HST used by British Rail is less than 2000 kg (4,400 lb). The axle load and unsprung mass of the X2000 power car (locomotive) which draws electric power from overhead catenary is even lower and the X2000 power car has trucks equipped with radial steering. None of these locomotives tilt.

The ETR-450 electric multiple-unit vehicles, which also draw power from overhead catenary, have smaller, lighter traction motors mounted on the body structure of each car; the axle load and unsprung mass are even lower. All ETR-450 vehicles tilt.

Adherence to the U.S. standards for carbody strength (CFR Title 49 Part 229.141) instead of those specified by UIC Code 566 may affect both the axle load and unsprung mass of the vehicle.[7] The wheels and axles are sized in proportion to the mass which must be carried, so that as the static mass of the locomotive increases, as it must to provide the additional compressive strength in a cost-effective fashion, the unsprung mass must also increase (the static axle load of the LRC, which does meet U.S. standards, is 28.5 tonnes [31.4 tons]; that of the HST just 17.5 tonnes [19.3 tons]). Due to these high axle loads, the ability to maintain passenger comfort at higher speeds through curves by means of carbody tilting may be curtailed by the track forces imposed by locomotives, compatible with U.S. standards.

Summary of Safety Considerations: What Tilting Does and Does Not Affect

As noted above, body tilting is a technical solution to the problem of maintaining acceptable ride quality while increasing speed through curves, without modifying the geometry of the curve. However, **body tilting alone does not improve the safety margin for operating through a given curve.** In fact, depending on how well a given tilt design positions and moves the c.g., it is possible that use of a tilting technology could reduce the margin of safety, even at the same speed. Since the objective is to increase speed, the margin of safety with respect to imposed track forces could be decreased, unless the axle load and unsprung mass of the locomotive used to propel the tilting cars is reduced, so that the track forces remain unchanged. Finally, because tilting the carbodies may increase the amount of clearance needed to ensure that the tilted vehicles will not impinge on tunnels, bridges, buildings, or trains on an adjacent track, some investment may be necessary to provide the added clearance space.

It is important to recognize that most tilt-body technologies incorporate other design features for high-speed operation, such as lower axle loads and reduced unsprung mass, steerable trucks to reduce lateral forces during curving, and improved traction and braking control, that have the potential to improve safety relative to the conventional technologies in use in the United States. The systematic application of preventative maintenance practices for both vehicles and infrastructure also contributes to enhancement of safe operations through emphasis on event avoidance, rather than on event survivability.

Most operational tilt-body technologies are not aimed at *very high-speed* operation (200 to 320 km/h). The ETR 450 with a 250 km/h (156 mph) service maximum, is the fastest revenue tilting train. The X2000 has a 200 km/h (125 mph) design speed, and has begun operating at that speed on portions of selected routes in Sweden; it reached 250 km/h (156 mph) during running trials on German high-speed track. The production LRC has been limited to 155 km/h (95 mph) or less during its service with VIA Rail Canada, primarily because that is the maximum speed Canadian federal regulations permit on track with at-grade road crossings. A much lighter prototype locomotive and coach was operated in test at 200 km/h (125 mph) at Pueblo, Colorado, and two trainsets leased to Amtrak operated at lower speed on segments of the Northeast Corridor between New York and Boston (this equipment was returned to Bombardier in July 1981 at the expiration of the lease period since Amtrak's limited budget would not allow purchase of the trains[8]).

In part, these relatively modest speeds reflect an inherent conflict between the characteristics of trucks capable of stable (safe) operation at very high-speed on purpose-built track, and the characteristics of trucks designed to run on existing tracks. Simply put, high-speed trucks are very rigid to resist hunting; trucks for existing track must be quite flexible, even if not steerable. The advanced truck designs proposed for high-speed tilt trains like the Fiat "AVRIL" incorporate independent wheels, active lateral and vertical suspensions, and a variety of unusual propulsion configurations to help address the challenge posed by this divergence.

OVERVIEW OF TILT-BODY TECHNOLOGIES

Tables 2, 3 and 4 provide an overview of the tilt-body technologies that were examined. **Table 2** summarizes technologies employing active body tilting that are either operational or under construction. For completeness, the ABB X2000 is included, although that technology was assessed in some detail in the December 1990 FRA report cited earlier. **Table 3** summarizes advanced active-tilt technologies at the conceptual design stage.

Table 4 summarizes passive-tilt equipment in service or under current development.

This report does not address two tilt-body technologies that are primarily of historical interest:

- The United Aircraft Turbotrain, equipped with passive tilting, which was operated with varying degrees of technical success and market acceptance both by Amtrak in the U.S. and by Canadian National Railways and VIA Rail Canada, in the late 1960's, 1970's, and early 1980's, but has since been replaced. The passive-tilt aspects of the Turbotrain, with low c.g., were favorable. Lack of information on any current development precluded further review.

- The British Rail Advanced Passenger Train (APT), an electrified, 250 km/h (156 mph) active-tilt articulated trainset which was developed and tested in prototype in the 1970's and early 1980's, but which failed to perform reliably and was subsequently scrapped.

TABLE 2
ACTIVE TILT TECHNOLOGIES

STATUS: **In Service**	TECHNOLOGY TYPE	MAXIMUM SPEED	TILT CONTROL	TILT ACTUATION	DESIGN STANDARD	OPERATOR/ FLEET SIZE	SERVICE EXPERIENCE	FIRST USED	COMMENTS
LRC	Tilting Coaches; Non-tilting diesel locomotive	155 km/h (95 mph) service; 200 km/h (125 mph) design	Same-car accelerometer	Hydraulic; 10° maximum tilt	FRA/ AAR/ TC	VIA Rail Canada; 100 coaches, 32 locomotives	Tilting coaches in service; 10 locomotives in service	1981	Tilt extensively used, Ontario-Quebec corridor
ETR 450	Electric MU; all cars tilt	250 km/h (156 mph)	Lead car gyro and accelerometers	Electro-hydraulic; 10° max but limited to 8° for passenger comfort	UIC	Italian State Railways; 82 2-car powered units plus 14 trailers	Quite successful; additional order placed 1991	1987	Forms backbone of FS high-speed services
X2000	Tilting coaches and driving trailer; non-tilting electric locomotive	200 km/h (125 mph) service; has reached 250 km/h (156 mph) in test	Lead vehicle (locomotive or DT) accelerometer; differential transformer on each tilt truck	Hydraulic; 8° maximum tilt, 6.5° effective tilt angle	UIC	Swedish State Railway; 20 1-5-DT sets in service or construction	Successful but limited by small (as yet) fleet	Sept 1990	Being tested in Germany and Switzerland; a candidate for U.S. testing
TSE-2000	Narrow-gauge 3-car diesel MU	120 km/h (75 mph)	Look-ahead controller based on geometric data file, wayside transponders	Pneumatic; 5° maximum tilt	UIC	JR-Shikoku; 38 3-car sets (Nov '91)	Successful; may see other applications	1989	Tilt controller could have potential for HSR, maglev in U.S., elsewhere
E7 Coach	Coach	200 km/h (125 mph) design; 160 km/h (100 mph) service	Locomotive-mounted gyro and accelerometers	Hydraulic; 7° maximum tilt	UIC	Norwegian State Railway; NSB standard coach	Successful, but with tilt locked out	1985	Coaches built post '86 have tilting trucks, but feature not used
STATUS: **In Production**									
VT-610	Two-car diesel MU	160 km/h (100 mph)	Same as ETR-450, but without sequenced tilting	Same as ETR 450; 8° maximum tilt	UIC	German Federal Railway; 20 2-car units	Delivery of first unit due December 1991	1992?	An interesting export success for Fiat
Series 4012	3-car electric MU	200 km/h (125 mph)	Same as ETR-450	Same as above	UIC	Austrian Federal Railways; 3 6-car sets (2x3)	First delivery 1994	1994/ 1995?	AC induction motors and EM rail brakes

TABLE 3
ACTIVE TILT TECHNOLOGIES - CONCEPTUAL DESIGNS

TECHNOLOGY	TECHNOLOGY TYPE	MAXIMUM SPEED	TILT CONTROL	TILT ACTUATION	DESIGN STANDARD	PROGRAM SCHEDULE	OTHER FEATURES	COMMENTS
Fiat "AVRIL"	Electric MU, 4-car traction unit	320 km/h (200 mph)	Based on ETR-450 system	Not stated	UIC	Announced Nov 1990	Independent-wheel truck	Could be affected by FS decision to proceed with ETR-500 procurement
RTRI 250X	Narrow-gauge Articulated EMU	250 km/h (156 mph)	Based on TSE-2000 system ?	Not stated	JR/UIC	Announced April 1991	Independent-wheel single-axle truck with ac hub motors and active suspension	Will require use of advanced materials and very sophisticated on-board control system (an "intelligent train"); will have to be able to draw power from third rail and catenary

PASSIVE

STATUS: <u>In Service</u>	TECHNOLOGY TYPE	MAXIMUM SPEED	TILT LIMITS
Talgo Pendular	Coach	200 km/h (125 mph) design, 180 km/h (112.5 mph) service	3.5°
JR Series 381	Narrow-gauge EMU	130 km/h (81 mph) design, 120 km/h (75 mph) service	5°

STATUS: <u>Under Development</u>	TECHNOLOGY TYPE	MAXIMUM SPEED	TILT LIMITS
Talgo 250	Coach	250 to 300 km/h (156-187.5 mph)	Unstated
SIG Truck with "Neiko"	Truck only	230 km/h (144 mph) design	about 3°

TABLE 4
TILT TECHNOLOGIES

DESIGN STANDARD	OPERATOR/ FLEET SIZE	SERVICE EXPERIENCE	FIRST USED	OTHER FEATURES/ COMMENTS
UIC	RENFE; 428 cars as of 1989; additional cars under construction	Excellent; market acceptance and performance has led to expansion of services	1980	The backbone of RENFE international services; automated gauge change between Spain/ France; has been tested on NEC, in Germany, Austria; ran at 288 km/h (180 mph) on DB
JR/UIC	JNR to 1987; JR-Shikoku thereafter	Still in service, but many problems with tilt nausea, braking	1973	Retrofit active-tilt package developed due to tilt nausea problem; did not achieve objectives for higher-speed; a dead end.

DESIGN STANDARD	PROGRAM SCHEDULE	OTHER FEATURES	COMMENTS
UIC	Announced 1989; Prototype December 1991	Improved brakes, doors, windows, pressure sealing	Originally targetted 250 km/h (156 mph), but success of trial on DB high-speed line has upped objective; as of July 1990 working with Siemens *and Krauss-Maffei (power cars) to* produce complete train
UIC	Truck design 1986; "Neiko" tilt mechanism 1990	Truck can also be equipped with "Navigator" forced radial steering	Tilt mechanism depends on inclined links between bolster and truck frame to create virtual tilt center above C_g, augmented by central airspring to reduce tilt inertia; most of effective tilt angle comes from elimination of differential suspension compression.

PREVIOUS U.S. EXPERIENCE WITH TILT-BODY TECHNOLOGIES

Foreign-designed-and-built tilt trains have been considered for possible application in the United States. Two such technologies, the Canadian *LRC* and the Spanish Talgo *Pendular*, have been tested in the U.S. with equipment provided by the developers, although they have not subsequently been used in revenue service. Tests have also been carried out on a *modified Amcoach*, retrofitted for tilting.

Early Experience with LRC

The original LRC technology, developed between 1967 and 1970, led to the first prototype train, which consisted of a 12-cylinder diesel-electric locomotive and one banking coach, in July 1971. This train was built to verify the feasibility of providing a safe high cant deficiency operation over existing infrastructure in North America with passenger comfort. Extensive testing was performed on the prototype train between 1971 and 1976 in Canada, at the U.S. Department of Transportation, Transportation Test Center near Pueblo, Colorado and in the Northeast Corridor. These series of high-speed tests, which were performed at speeds up to 210 km/h (130 mph), verified many aspects of the train such as ride quality, the effectiveness of the tilting mechanism, vehicle stability and curving, and track loading. The tests demonstrated that a low center of gravity, low profile train such as the LRC, could safely negotiate curves at much higher speeds than were presently permitted in the U.S. and provide reasonable ride comfort.

Two LRC trainsets were leased by Amtrak in 1980. This equipment consisted of two 16-cylinder diesel-electric locomotives and 10 banking coaches. In a joint FRA/Amtrak project, high-speed curving tests were carried out in the summer and fall of 1980 on the LRC locomotive, the LRC banking coach, a standard Amcoach, and the AEM-7 locomotive.[9] The vehicles were equipped with instrumented wheels, car-body accelerometers and displacement transducers. In repetitive runs in the Northeast Corridor, the Amcoach was tested up to 229 mm (9 in) of cant deficiency, and the LRC train was tested at up to 381 mm (15 in) of cant deficiency. Similar runs, up to a cant deficiency of 279 mm (11 in), were also performed on the AEM-7 locomotive at a test site on the Philadelphia-Harrisburg line equipped with the required electrification. In addition, the vehicles were run on a large sample of curves at high cant deficiency to investigate the transient performance of the vehicles over a wide range of typical perturbations.

Safety considerations which were examined relating to operation at higher cant deficiencies included vehicle overturning, wheel climb, rail rollover and track panel shift (discussed later). It was found that the maximum safe cant deficiency limit of each train tested was set by the **vehicle overturning safety criteria** for the **coach**, and in particular by the steady state side-to-side weight transfer. The safety limit was set by the coaches rather than the locomotives after making allowance for 90 km/h (56mph) crosswind loading which is more restrictive for coaches.

Results showed that, except for a few unusually harsh curves, the LRC train could run safely up to 229 mm (9 in) of cant deficiency, while maintaining less than the recommended AAR comfort limit of 0.1g steady-state lateral acceleration **by tilting the coaches**. A conventional train consisting of the AEM-7 locomotive and Amcoaches would run safely at 203 mm (8 in) of cant deficiency at the expense of "strongly noticeable" (about 0.15g) steady-state lateral acceleration.

Banking Amcoach

In a second joint FRA/Amtrak project in 1982, tests were performed on the F40PH diesel-electric locomotive and an *Amcoach modified for banking*, with and without the banking system in operation.[10] The modified coach used a truck frame with softer primary suspension and an air actuated torsion bar device, supported by bearings secured to the carbody, to tilt the body by overcoming the secondary airsprings. An electronic controller initiated the full four-degree available tilt when the damped lateral acceleration of the truck frame reached a threshold level of 0.04g. Safety at high cant deficiency was evaluated by comparing direct wheel/rail force measurements to safety criteria. Again, a general cant deficiency limit, imposed by the steady state overturning criterion, was found to be 203 mm (8 in) for both the *banking Amcoach* and the *standard Amcoach.* The general cant deficiency limit of the F40PH locomotive was found to be 229 mm (9 in), although several exceptions were identified by the transient overturning criteria. The banking system of the modified Amcoach was successful in maintaining a low level of steady state carbody lateral acceleration at high cant deficiency, although a recommendation was noted that fail-safe devices should be required to prevent one truck of a banking coach from operating while the other is disabled.

CONEG Tests

During the spring and fall of 1988, Amtrak/FRA, working closely with the Coalition of Northeastern Governors (CONEG), conducted high-speed tests of tilt and turbo equipment in the Northeast Corridor between Boston and New York City.[11] These tests were performed to evaluate the feasibility of utilizing existing and proven technologies to achieve the CONEG objectives of reduced trip time and enhanced passenger comfort. These tests were also required to validate the train performance models used to predict running times for various equipment options and configurations, as well as to assess the benefits of proposed fixed plant improvements. The route, particularly suited to a tilt technology assessment, was 367 km (228 miles) long, in which there were 238 curves; typically, the percentage of track which had more than one degree of curvature was about 40%. The total length of these curves was more than 121 km (75 miles).

The equipment technologies tested were the Amfleet cars (currently in Northeast Corridor operation), the RTL and RTG turboliner trainsets (currently in operation, New York - Albany), the Spanish Talgo *Pendular* passive tilting coaches and an *LRC* active tilt trainset. The Amfleet cars were tested to provide a baseline for comparison of the candidate equipment. All equipment types were instrumented to measure speed and carbody lateral acceleration, and were operated at higher-speeds around curves than were commonly permitted.

The FRA required that sufficient instrumentation be installed on each trainset in order to relate test behavior to previously tested equipment known to be safe. The cant deficiency was limited by sensible considerations of passenger comfort and safe passenger mobility. Because of the frequent proximity of many curves, high cant deficiency speeds could not always be achieved due to the low acceleration capabilities of the locomotives. The performance of all tests was verified in accordance with Congressional intent by the FRA and by consultants to the CONEG Policy Research Center Inc.[12]

Measurements were analyzed into steady-state lateral acceleration, peak lateral acceleration, jolt (the maximum difference in trainset lateral acceleration within any one second interval) and absolute peak-to-peak lateral accelerations. Tests were conducted incrementally to attain maximum curve speed, permitting analysis of applied forces and dynamic responses during and at the conclusion of each test run, before proceeding to the next incremental level of cant deficiency.

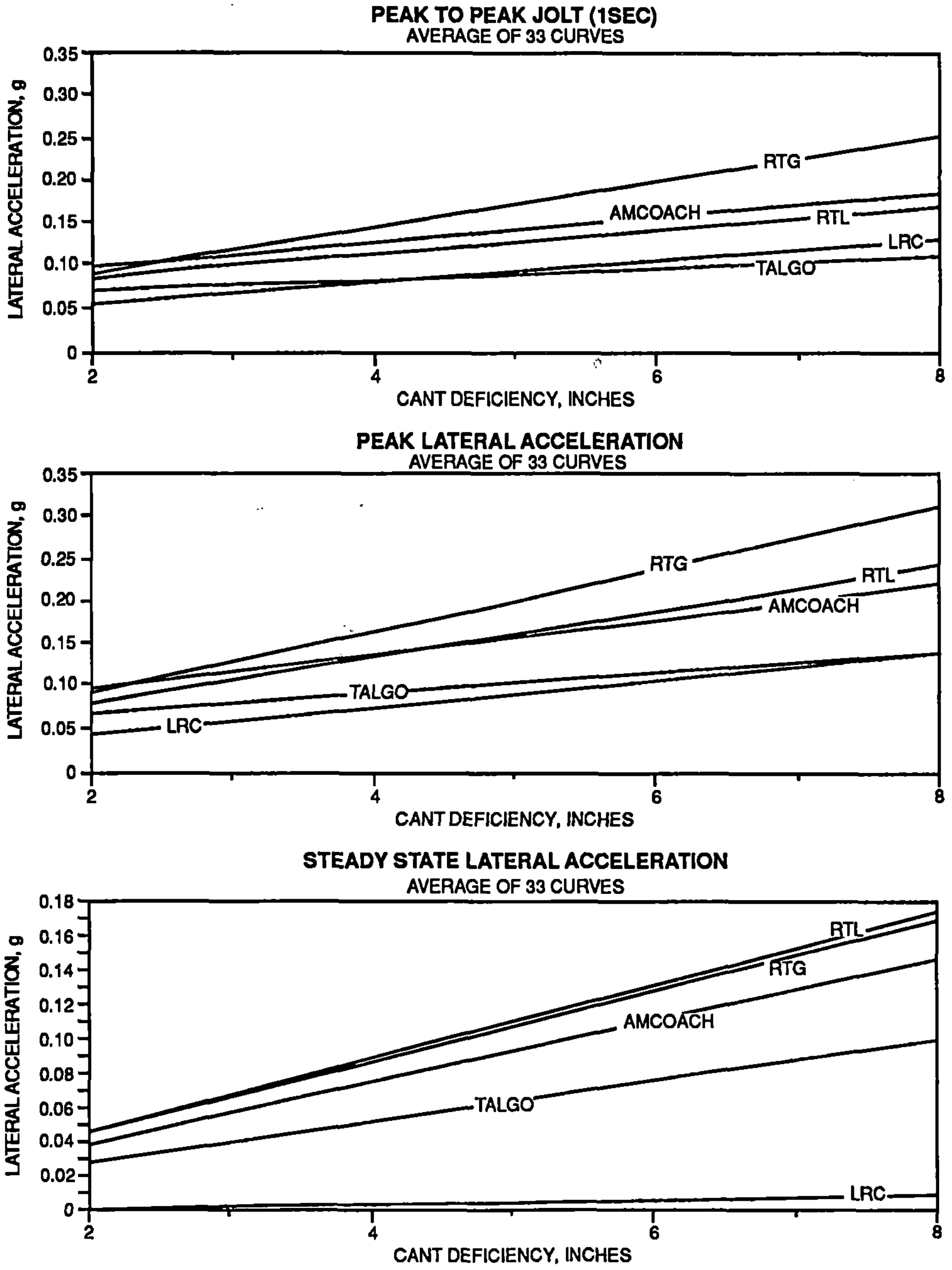
Review of all test data disclosed that passenger trains could operate at higher cant deficiency speeds "without compromising passenger comfort and derailment safety limits." The running time from Boston to New Haven could be reduced to 1 hour and 56 minutes, 24 minutes faster than trains operating at conventional 76 mm (3 in) cant deficiency speeds.

The trends of steady-state and peak lateral accelerations and jolt, averaged from 33 curves, provided an overall comparison of the test vehicles; a comparison of the trend lines with increasing cant deficiency up to eight inches is shown in **Figure 12.**[12] The steady-state lateral acceleration of the LRC was sustained near zero "g" by its active-tilt system. The Talgo showed a large reduction in steady-state acceleration but its passive-tilt system did not completely cancel these accelerations. Both the LRC and Talgo offered significant improvements over the baseline vehicle in dynamic performance and lower steady-state accelerations.

The LRC exhibited a somewhat smaller peak lateral acceleration at low cant deficiencies, but very little difference as cant deficiency increased. The peak-to-peak jolt of the Talgo was less sensitive to cant deficiency than the LRC. Both the LRC and Talgo handled jolts extremely well, although the LRC was superior only on long smooth curves. The LRC coach, with an active suspension tilting mechanism, exhibited a lateral acceleration, increasing in the entry spiral of a curve until the control system tilted the body to cancel the steady-state lateral acceleration. However, as the car left the curve, the body remained tilted until the control system responded to remove it. This system lag produced a significant negative lateral acceleration at curve exit. During curve entry transition, the LRC was vulnerable to track perturbations which cause jolts. The Talgo kept the steady-state lateral accelerations below 0.1g and its negative lateral acceleration at curve exits was usually insignificant. It was superior on short curves and rough-entry curves.

The steady-state and peak lateral acceleration measurements were also used to monitor derailment safety during the test runs. The most restrictive of the derailment safety criteria is the vehicle overturning criterion which is formulated to prevent excessive side-to-side weight transfer in curving. The steady-state and peak lateral accelerations were used to estimate the respective wheel load transfer, using calculations based on known vehicle suspension characteristics and previous measurements of some vehicles with force sensing wheels. Truck, rather than body accelerations, were used to estimate wheel load transfer of the active suspension LRC coach because the tilt action eliminated the means of estimating steady-state load transfer. All test vehicles were deemed to be within the safety limits up to a cant deficiency of 203 mm (8 in).

In parallel with the measurements, passenger evaluations of ride quality were obtained from a survey of volunteers recruited by CONEG to ride each of five train trips made to simulate revenue service.[13] The passengers riding at these higher curve speeds reported the occurrence and severity of each instance of discomfort, and provided subjective ratings of the entire trip. Generally, the results indicated passengers' acceptance of higher than normal curve speeds. Over 84% of the passengers in the test rated the ride quality of their runs at these higher curve speeds as either good or excellent. The average number of reports of curve-related discomfort per passenger over the course of the 251 km (156 mi) distance from Boston to New Haven was only 8.2.



(Source: Amtrak Evaluation of Tilt and Turbo Train Technologies, 1989)

Figure 12: Comparison of Carbody Lateral Acceleration Trend Lines

From an analysis of the discomfort reports, the increase in discomfort was attributed to the increase in lateral acceleration forces (steady-state and jolt) felt by passengers as curve speeds increased. The reports also showed that steady-state and jolt acted together to exacerbate passenger discomfort. The reports on individual curves and ratings of overall ride quality indicated that tilt trains can make a difference. The tilt trains provided the most comfortable ride of the demonstration trains and produced quite acceptable levels of comfort even at the highest curve speeds tested (only about 7% of passengers expressed discomfort).

A larger percentage of passengers on the tilt trains rated the quality of their ride as "excellent" than did those passengers on either the Amfleet baseline or Turbo trains. One significant finding of the survey was that most passengers accepted the practice of higher unbalance levels in train travel.

Conclusions from U.S. Tilt-Body Train Experience

The general conclusions of the U.S. experience can be summarized:

- Speeds of passenger trainsets can be increased through curves to reduce trip time on existing guideways and still operate safely,
- Tilt-body vehicles offer the potential to maintain good passenger ride comfort in curves at the higher cant deficiencies, and still remain safe, and
- The practical limits to speed in curves will be safety-related, not passenger-comfort related, if tilt-body technology is used.

TILT OPERATIONS IN THE U.S. - ISSUES AND OPPORTUNITIES

There are several important issues - and potentially important opportunities - that would arise if U.S. railroads were to make use of vehicles equipped with tilt-body capabilities. These issues encompass a range of safety, technical compatibility, and regulatory compatibility considerations. Some of the issues and most of the opportunities arise from the consequences of body tilting itself, and would pertain even for designed-for-America equipment. An obvious example of an issue in this class is the effect of body tilting on compatibility with the clearance envelope for a given (existing) railroad or route. In terms of opportunities, active body tilting may permit co-location of high-speed rail or maglev in some existing rights-of-way without unacceptable degradation of ride quality.

There are also important issues that exist because all but one (the LRC) of the existing tilting technologies have been designed and built for different sets of technical and safety standards and operating conditions than exist in the U.S. The issues in this class are the same in principle as those that affect non-tilting foreign technologies like the French Train "Grande Vitesse" (TGV) or the German Intercity Express (ICE).

The most obvious example of this category is the difference between FRA structural strength standards and those of UIC Code 566. Treatment of these *generic* issues affecting technologies originating outside the U.S. is beyond the scope of this investigation, and the reader is directed to the recent report, "*An Assessment of High-Speed Rail Safety Issues and Research Needs*,"[7] prepared for the FRA Office of Research and Development, for a comprehensive overview. Buff strength, as an example, is a measure of occupant compartment structural integrity. This measure is adequate for a particular type of car construction (body-on-under-frame) and for low-speeds, when train buckling is not a great concern. Different vehicle structural designs may allow increased occupant compartment structural integrity and decreased vehicle weight. The FRA currently is examining the issue of crashworthiness in a major study on "*Collision Avoidance and Accident Survivability*" scheduled for completion in the summer of 1992. Some of the generic issues - notably the example cited above - do bear directly on the tilt-specific issues, and are discussed below.

Body Tilting Issues

There are five issues that must be addressed prior to the use of tilting rolling stock in the U.S., even if all the generic issues related to use of equipment built to non-U.S. standards are resolved. These issues are:

- Effects of increased curving speed on operating safety, including "worst case" scenarios,
- Compatibility with clearance envelopes for existing tracks and equipment types,
- Maintainability and reliability, including availability of appropriate facilities and skilled labor,
- Effect of U.S. alignment geometry and track maintenance standards on the effectiveness of foreign tilt mechanisms in maintaining passenger comfort, and
- The incremental costs and benefits of tilting.

Increased Curving Speed and Operating Safety[14]

The fundamental basis for safe curving at higher speed is satisfactory control of forces acting at and across the wheel-rail interface. Existing FRA regulations (49 CFR Part 213) specify track geometry deviations for various speed regimes and a maximum allowable cant deficiency of 7.6 cm (3 in). The FRA regulations do not directly address track-train forces, lateral/vertical force ratios, or allowable maximum lateral and vertical static or dynamic loads. Industry standards and practices also do not address these areas.

The criteria applied to determine whether a rail vehicle can safely negotiate a curve at a given speed differ from jurisdiction to jurisdiction internationally. All are concerned with assessing the risk of vehicle derailment through four basic mechanisms: vehicle overturning, wheel climb, gage widening (rail rollover, rail lateral deflection), and lateral track shift.

These criteria are basically reference standards against which experimentally-measured wheel force values are assessed, taking into account the effects of wind loading as well as the forces generated by curve negotiation.

In the context of this assessment, it is important to distinguish between aspects of body tilting, if any, which might impact the potential for derailment, and the more general safety concerns related to traversing curves at higher unbalanced speeds.

Vehicle Overturning

For tilt body operation, the issue in vehicle overturning is the likelihood that the combination of lateral inertial force acting at the center of gravity of the vehicle in higher cant deficiency operation, coupled with the loading due to cross wind acting at its center of pressure (C_p) will be sufficient to remove any vertical load from the inside wheels in the curve. (It is the intended higher cant deficiency operation which is the fundamental issue; vehicle overturning is a design concern for any vehicle in worst case situations, such as travelling at underbalance speed [or stationary] through a superelevated curve with a crosswind inward to the curve).

The lateral inertial force may be considered as comprising the steady-state force as developed in the body of the curve, and transient or dynamic forces resulting from transition spirals and alignment perturbations. Transient phenomena involve time duration which may or may not be sufficiently long for actual overturning to take place. Most overturning criteria deal with the forces acting through the c.g., with the wind loading force used as a modifying factor which can be computed separately and applied additively.

The concept of weight vector intercept (WVI) has been traditionally used to quantify criteria for vehicle overturning. The WVI is the distance from the centerline of the track to the point where the resulting force vector acting on the vehicle (from the lateral centrifugal and wind forces, and vertical gravitational force) intersects the plane of the railheads. A WVI of zero indicates symmetrical loading, while a WVI approaching 760 mm (30 in) for standard gauge track (one-half the track gauge) signals impending overturning.

The most familiar, yet overly conservative criterion, the AAR's so-called "One-third Rule," states that the WVI, neglecting wind loading, must lie within the center third of the track (no more than 254 mm [10 in] each side of the track centerline for standard gauge track).

The criterion applied to the tests in the Northeast corridor was the Vertical Wheel Load Reduction Ratio, used at that time by JNR and later by its successor companies. This criterion measures lateral weight transfer in terms of the percent reduction in the vertical load on the inside (low-rail) wheels, and explicitly deals with both steady-state and transient load transfer effects. A reduction in wheel load by 60% of the nominal value is permitted for steady-state curving, while an 80% reduction is allowed for transient peak wheel unloading (in terms of WVI for standard gauge track, this translates to 457 mm [18 in] steady state and 610 mm [24 in] peak). In establishing these limits, the transient overturning computations included the effects of transition spirals but not of track alignment perturbations causing short duration transients, and comparison of measured data through irregular track to the criteria may be somewhat conservative. The effect of wind loading is quantified by estimating the force generated by a wind velocity acting perpendicular to a surface area of the whole vehicle with a drag coefficient of one.

This criterion was used as a basis for assessment in the 1980-82, 1983, and 1988 cant deficiency tests of, variously, LRC, F40PH, Amfleet, Talgo, RTG Turbo I and RTG Turbo II equipment on the NEC. As discussed, it was the vehicle overturning criteria which was the most restrictive derailment safety limit on the passenger equipment operating at high cant deficiency. A wind speed of 90 km/h (56 mph) was used as the limiting value in the assessment because it is the greatest expected in the NEC within 4.5 meters (15 ft) of the ground for a 10-year mean recurrence interval. In this case, the crosswind allowance by itself could equal a wheel unloading of almost 20%.

A question remains as to which of the two criteria, steady-state or transient, might limit the cant deficiency allowable for safe operation. The maximum cant deficiency satisfying the steady-state overturning criteria for a particular vehicle with a maximum crosswind can be determined analytically from a knowledge of the suspension characteristics, mass distribution and surface area, and correlates well with tests. The estimation of limiting cant deficiency based on transient criteria is more difficult to validate, both analytically and by test. For the JNR criterion, use of a cant deficiency limit based on steady-state weight transfer implicitly assumes that there are no track perturbations capable of causing additional transient wheel unloading greater than 20%[2]. Few exceptions to the limits based on the steady-state criterion were found in the NEC tests, and all exceptions were associated with switches, undergrade bridges, or grade crossings.

The risk of derailment from vehicle overturning is of particular concern with passive-tilting technologies. Since passive-tilting is based on pendular motion, even a relatively modest tilt angle will result in additional outward lateral displacement of the c.g. and the weight vector intercept. The only effective countermeasure is to make the c.g. of the vehicle as low as possible, and to restrict the maximum tilt angle, so that the consequent overturning moment is minimized.

This concern with the risk of overturning, as well as passenger comfort considerations related to tilt rate, have effectively limited the passive-tilt angles to 5° or less, in contrast to the 7° to 10° that are commonly achieved with active-tilt systems. The successful Talgo *Pendular* coaches combine a limited tilt angle with a low center of gravity achieved by supporting the body structure *between* the articulating trucks, rather than on top of the trucks as is the case in most conventional passenger equipment. The UAC *Turbotrain* also adopted this strategy, and this was one of the features of that equipment that performed consistently well.

The inclusion of wind-induced lateral force in assessing the risk of vehicle overturning results in more stringent cant deficiency limits for coaches, which are typically much lighter, and have a larger lateral area (due to their greater length) than for (shorter, heavier) locomotives, since the vertical gravitational force is limited by the vehicle mass. There is a clear incentive to minimize the area of the vehicle side exposed to crosswinds, and to optimize vehicle aerodynamics to address this as well as more conventional concerns. Again, the Talgo coaches do very well in that regard, being about half the length of the LRC coach.

Wheel Climb

Wheel climb refers to a phenomenon in which the forward motion of the axle combines with the wheel and rail profiles, surface conditions, and interactive forces, to permit the wheel flange to roll, with creepage or slip, up onto the head of a rail.[15] This derailment condition may be temporary or it may result in wheel drop. Wheel climb, which has been known to occur in steady-state curving, spiral negotiation, and dynamic curving, is often exacerbated by braking and traction forces in curves, and is almost always accompanied by some wheel unloading.

The maximum ratio of lateral force (L) to vertical force (V), or maximum L/V ratio on any individual wheel, continues to be used in assessing proximity to wheel climb derailment. As the ratio between lateral and vertical forces increases, the risk of derailment due to wheel climb rises.

A comprehensive review of wheel climb derailment and the criteria used to estimate the critical values of L/V is given in the AAR Report No. R-717 cited above. The criterion as applied during the NEC tests was to limit the L/V ratio to 0.90, except for short duration transients[9]. Testing revealed that L/V ratios remained below 0.5 during high cant deficiency curving, except at switches in high speed, low cant deficiency curves.

The L/V ratio is very much a function of the angle of attack of the wheel to the rail. As such, the propensity to derail through wheel climb will be primarily a function of the truck performance and only secondarily by carbody tilting.

Technologies equipped with steerable trucks (the X2000, the SIG truck with *Navigator*) will clearly have an advantage in this regard, as do vehicles such as the LRC, which has suspension elements interlocked with the tilt mechanism to reduce the angle of attack in curves, and the ETR-450 which has an active lateral secondary suspension and a longitudinally-flexible primary suspension. The advanced-concept tilt trains, such as the Fiat "AVRIL" and the RTRI 250X concept with independent-wheel trucks and active suspensions may well offer the best control of wheel climb, albeit at a price in terms of added complexity and sophistication.

With passive-tilting technologies, in which the roll stiffness of the carbody may be softer, an important design criteria is to ensure that no harmonic roll effects lead to dynamic wheel unloading (lower V) which might enhance the potential for wheel climb (and vehicle overturning).

Gage Widening

Under the influence of static wide gage track and large lateral forces between wheel and rail, sufficient lateral rail deflection can occur to allow a wheel to drop between the rails. This *gage widening* derailment process may involve *rail rollover* and/or *lateral translation* of the rail cross-section, and will be influenced by the rail-tie fasteners which restrain the rail from translation, rollover, and longitudinal creep. The restraining force can vary substantially, from about 3.6 tonnes (4 tons) for elastic fasteners such as are used in the NEC and generally on concrete ties, to about 1.6 tonnes (1.8 tons) for new wood ties with cut spikes. Lateral rail deflection without roll occurs when the lateral spreading force reaches the limit of adhesion (between the rail base and tie surface) for the vertical load carried.[16] Lateral rail deflection typically occurs on lower-speed track and is usually a result of the loss of adequate cross-tie and rail fastener strength.

Gage-spreading forces between the wheels and rails arise from an angle of attack of the wheel to the rail, and the resulting forces may be large in curving, dependent on the performance of the truck. Long and rigid trucks which prevent the axle from steering adequately induce large forces. Transmission of loads from heavy bodies, such as locomotives, when excited by track perturbations has also been a concern in gage-widening derailments. Gage widening can be self-sustaining, in that, as the rail-tie fastening becomes degraded, track geometry irregularities become more pronounced which, in turn, lead to higher wheel/rail loads and gage-spreading forces. Accordingly, regular track inspections are required to minimize the risk.

For the NEC high cant deficiency tests, the instantaneous ratio of the sum of lateral forces to the sum of vertical forces of the wheels on the high rail side of a truck (known as the truck L/V ratio) was used to quantify the likelihood of rail rollover, based on AAR studies. Truck L/V ratios measured at the high rail side of the tested vehicles remained low relative to the critical levels, for cant deficiencies up to 11 inches.

Recent contributions made to the prediction of gage widening are presented and theories discussed in the above-cited AAR Report No. R-717. From a vehicle standpoint, improved truck technology will be instrumental in minimizing the risk of gage widening in high cant deficiency operation.

Lateral Track Shift

This final curving safety criterion addresses the likelihood of derailment as a consequence of lateral movement of the entire track superstructure (rails, fasteners, ties) through the ballast. Any shift of noticeable magnitude (of the order of one inch) is regarded as an incipient derailment. Track panel shift has become increasingly important as the speed of vehicles increases and more continuous welded rail (CWR) is used. Vehicle-induced forces which have increased in magnitude with speed are generally large inertial loads arising from high cant deficiency operation and from heavy dynamic response to poorly aligned track.

Track lateral stability is dependent on the characteristics and condition of the ballast, the width of the ballast section outside the end of the ties, the degree of compaction due to traffic, the shape, weight, material and spacing of the ties, the stiffness of the rail and fasteners as well as changes in ambient temperature. Results from tests on one type of track construction and condition may not be applicable to another when establishing safety limits for allowable forces. As an example, compaction due to traffic appears to have a large effect: the lateral resistance of loaded ties is reported to double after 100,000 gross tonnes (110,000 G Tons) of traffic, and to stabilize at around three times the value for uncompacted ballast after 1.5 MGT (1.65 MG Tons). The tie-related factors, including material (concrete) add up to 60% to lateral resistance. On the other hand, repeated passes over irregular track may reduce buckling strength, and ground-borne vibrations may cause loss of lateral ballast resistance. The situation is further complicated by thermally-induced forces in CWR.

The criterion used in the NEC tests was based on measurements on French track using the *Wagon Derailleur* car[17], modified to account for internal forces in CWR due to temperature changes and lateral carbody forces due to unfavorable crosswinds, for wood-tie track on compacted ballast. It was assumed that a single axle bears half the lateral wind load. Criterion was established both for maximum axle lateral force and maximum truck force. Measurements, little more than half the critical levels, indicated that safety against lateral track shift did not limit the cant deficiency for the trains under test.

As well as the curving criteria discussed above, U.S. standards and practices do not consider vertical impact loads, beyond definition of the maximum axle load acceptable under AAR interchange rules - 30 tonnes (33 tons). These dynamic forces adversely affect rail life and pose a risk of derailment through fracturing of the rail. Railways in Europe and Japan have developed a number of criteria for vertical impact load.[18] The consequence of these criteria is to limit the static axle load to 20 tonnes (22 tons) or less and the unsprung mass to about 2 tonnes (2.2 tons). It would be informative to explore how the equipment tested in the NEC would fare in terms of this criterion.

Compatibility With Clearance Envelopes for Existing Lines and Equipment

Tilt-body operation could very well require greater right-of-way clearances than rolling stock in current operation. Compatibility with clearance envelopes for existing tracks and equipment types must be carefully examined on routes over which the tilting equipment may be employed. If tilt capability is procured to increase speed in curves and reduce travel time *on existing tracks*, the purpose is somewhat defeated should new or extensively rebuilt tracks be required to accommodate tilt.

Particular clearance considerations include:

- Interference between tilted vehicles and wayside obstacles in curves, both side-to-side and overhead,
- Interference between tilted vehicles and all equipment-type vehicles (tilted or stationary) on adjacent track in curves, and
- Interference between tilted vehicles in a failed condition anywhere in the system and either wayside obstacles or other failed tilt vehicles on adjacent track, including, in the worst case, vehicles tilted at the opposite extremes.

For the tilt-body vehicle, this requires calculations or measurements of the maximum tilt and the lateral offset of the center of gravity that would be expected in normal operation at the maximum cant deficiency for a safe comfortable ride. In fact, a more conservative "worst case" approach would be to consider the vehicle's maximum tilt throughout the system as an indication of potential trouble should a tilt system fail in its maximum tilt position. However, a "fail-safe" tilt system design should obviate this requirement to some degree.

Track centerline spacing is a major clearance factor. The Amtrak Specification for Construction and Maintenance of Track (MW-1000) give standards for new construction as: tangent track, 4.27 m (14 ft, 0 in) track centers; curved track, increase track center spacing 25 mm (1 in) for each 0.5 degree of curvature and add 89 mm (3.5 in) for every 25 mm (1 in) difference in superelevation between the two tracks. This standard for new construction provides a 152 mm (6 in) minimum clearance for various curvatures and superelevations for conventional domestic equipment. Amtrak's Standard Minimum Roadway Clearances (Drawing No. 70050-A) describe wayside clearances which must be observed as new construction standards. However, caution must be exercised since much of existing track is not new construction, and existing track centers are frequently 3.66 m (12 ft) and sometimes less in the Northeast Corridor.

A clearance evaluation for tilt-body vehicles in Northeast Corridor operation was included as part of the IPEEP in 1978.[19] The existing dimensions of the Northeast Corridor were accommodated by ensuring that procured equipment would stay within the clearance envelope described by Amtrak Drawing No. 70050-G titled "*Maximum Dimensions for Passenger Equipment Moved in Penn Central Electrified Territory In-between New Haven and New York; New York and Washington; New York and Harrisburg; and Washington and Harrisburg*". These dimensions provided sufficient clearance at the mid-point and ends of cars with 18.14 m (59 ft, 6 in) truck centers and conventional (inactive) suspension systems for curves up to 13 degrees.

An example from the clearance evaluation for the prototype active-tilt LRC passenger coach in the Northeast Corridor is shown in **Figure 13,** in which a comparison of the LRC car is made against the Northeast Corridor Construction Limit Outline, both "at rest" and at the "full-tilt" condition. The Construction Limit Outline allowed for a body roll and lateral offset of 3° and 51 mm (2 in) respectively for conventional equipment as well as limits for normal service conditions such as wheel wear, maximum spring travel and faulty springs, without fouling wayside obstacles. It can be seen that the LRC car was a borderline case, slightly exceeding the limit outline and requiring a more comprehensive examination. The most restrictive conditions were determined to be a moving train passing a stopped train on a 152 mm (6 in) superelevated curve, and a moving train passing a stopped train in a particular tunnel in Baltimore, MD.

Maintainability and Reliability

The keystones of conventional North American railroad equipment design have been historically, and to a considerable extent remain, the rugged simplicity and interchange compatibility. Perhaps the most outstanding example of this emphasis is the three-piece truck (wheelset, sideframe, bolster), which literally supports rail freight movements and is the basis for most trucks on existing Amtrak passenger vehicles, albeit with a more sophisticated secondary suspension. With AAR interchange compatibility, a freight car can be operated anywhere from southern Mexico to northern Canada, and may spend much of its service life off the tracks of the owning railroad. Passenger equipment has traditionally remained on its owning railroad, but the vehicles were built to meet AAR interchange requirements, and so reflected a similar simplicity. Robust mechanical, electrical and/or pneumatic designs were and are standard, with more sophisticated electronics just starting to have a real impact on the national locomotive fleet. Complex subsystems, especially those with hydraulic components such as dampers, have been regarded with distrust by the North American railroad industry, and with some reason, given the way this equipment was operated and maintained.

One of the consequences of these factors was the necessity to be able to maintain vehicles virtually anywhere, with limited facilities and often under very primitive conditions (e.g., outside, in winter). Another consequence was that such maintenance as was done was virtually always reactive; that is, performed because something had failed and the car could not be used until repairs were made. This approach to maintenance was largely dictated by an inability to monitor either utilization or elapsed time at the level of the individual car - a situation that is rapidly changing for the better on the freight side and has largely been abandoned by Amtrak. However, the common "wait 'til it breaks then fix it" philosophy, would certainly affect attitudes toward complex vehicles and programmed preventative maintenance.

Put simply, active-tilt passenger vehicles are all sophisticated and complex, and incorporate unfamiliar and often quite precise components in critical subsystems. They must be maintained in a purpose-built, or at least purpose-renovated facility, in accordance with an aviation-style maintenance schedule linked to utilization and/or elapsed time, by skilled workers familar with the full range of advanced components in the equipment. Suppliers and railroads in Europe and Japan have decades of experience designing, managing, and executing these types of programmed maintenance activities, both for vehicles and track. For these railroads, the advent of tilt-body trains represented an increase in complexity, but a rather modest one, a change of degree rather than of nature in the skills, facilities, and procedures required.

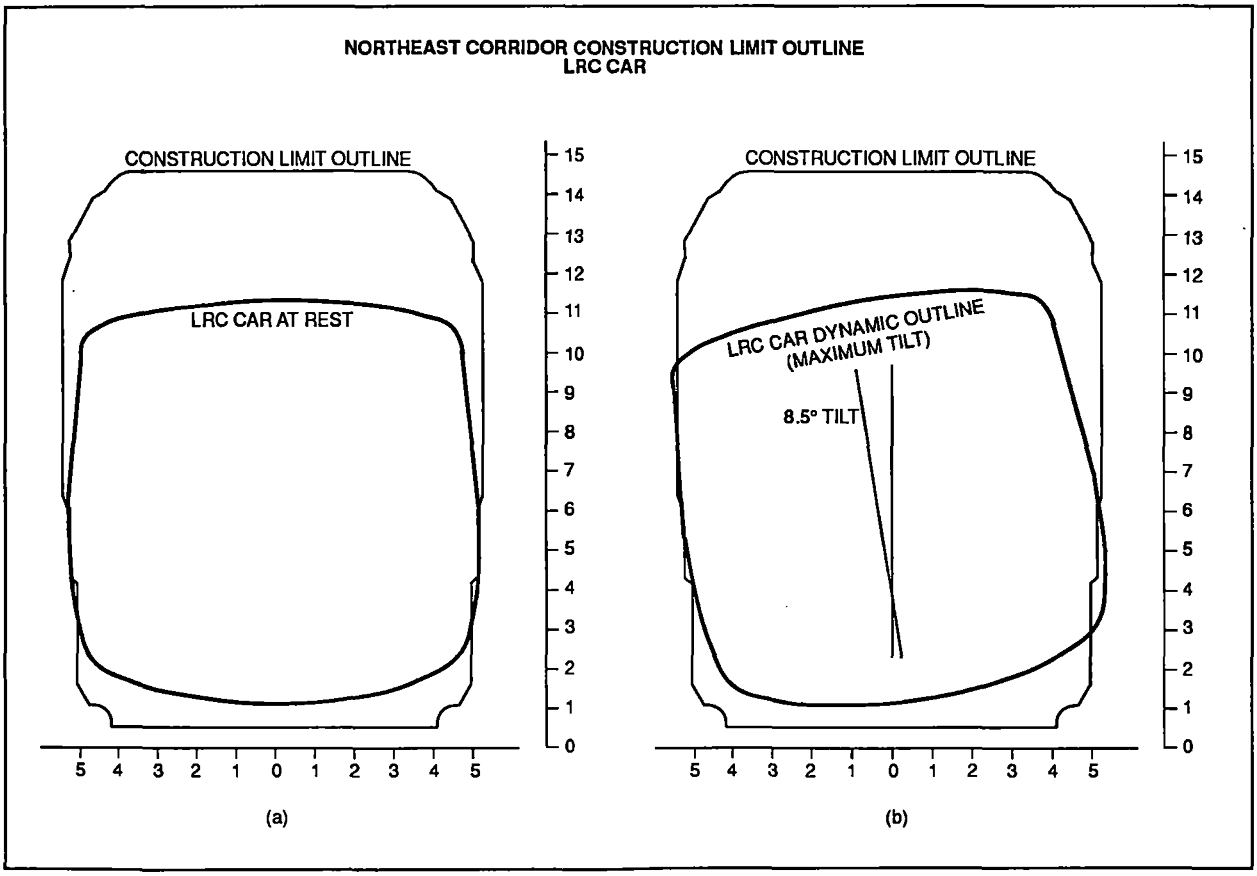


Figure 13: Northeast Corridor Construction Limit Outline, LRC Prototype Car, Maximum Tilt

Take for example, as part of the implementation and commissioning process for the X2000, SJ, in concert with ABB Traction, have developed a comprehensive program of scheduled maintenance. It is based on a detailed analysis of possible failure modes and a comprehensive component database with MTBF and MTTR data for each component, and detailed information on labor qualifications and standard unit inputs for labor and materials.

Table 5 summarizes the programmed maintenance procedures developed by ABB and SJ for the X2000 equipment, including the nature and interval for each class of scheduled maintenance planned for the X2000. Note that this table does not include an estimate of the level of effort involved in refurbishment of components that are changed out during any of these scheduled activities.

From the joint experience of ABB and SJ with the experimental trainset and with similar components in revenue service with SJ and elsewhere, SJ anticipates that the ratio of scheduled maintenance to corrective or emergency maintenance will be between 4:1 and 5:1 (i.e., about 16% to 20% of maintenance effort will be corrective; the rest will be scheduled). This is typical for European passenger equipment, and for some types of (non-tilting) technology, such as the TGV, the ratio is even higher, approaching 9:1.

Table 6 summarizes the scheduled maintenance activities for Amfleet cars. No level-of-effort estimates were available for these activities.[20] Although the level of detail in the respective source materials varies, it is clear that the X2000 tilt-train program is more comprehensive in scope and deals with more critical subsystems and components in an aggressive fashion (i.e., replacing all truck dampers after nine months of operations, and changing out all vital components after three years, rather than depending on inspections and judgement to determine the timing of component changeouts).

This difference has a direct bearing on the operational reliability of the equipment and cost of operations. Even though it is complex, the maintenance program will largely ensure that faults capable of disrupting service or posing a risk to passengers and crew will be detected before a failure occurs. It should be noted that a significant number of the reliability problems that plagued the VIA Rail Canada LRC fleet were eliminated or much reduced after VIA Canada opened its purpose-built maintenance facilities in Montreal and Toronto and took over the contracts of its maintenance employees from Canadian National and Canadian Pacific. The latter change allowed VIA to institute effective training and trouble-shooting programs. The more complex tilt-body equipment has been designed to facilitate inspection and maintenance activities, typically in conjunction with the design of the facilities and tools required to best do those activities. Coupled with skilled and well-educated labor and effective training programs, the results at FS (Italian State Railway) for the ETR 450, for example, have been very good.

The bottom line with respect to maintainability and reliability is that there will have to be a major shift in the philosophy of vehicle maintenance towards aviation practices, together with an expansion of labor and management skills to deal with complex hydraulics, sensors, and microelectronics. U.S. operators will also have to deal with the skills and knowledge base needed to cope with ac traction motors, steerable trucks and other elements of tilt-train design that are not directly linked to the tilt mechanism, but form an essential part of the equipment. If this is done, and the specified maintenance activities

TABLE 5
X2000 PREVENTATIVE MAINTENANCE SCHEDULE AND REQUIREMENTS

FREQUENCY	TYPE OF ACTIVITY	LEVEL OF EFFORT
Each Trip	General Visual Check	0.9 hours, 0.9 person-hours
6300 km (3900 miles) or Weekly	Safety Check: general inspection of bogies and brakes, check of brake function, external check of hydraulics for leaks, inspection of pantograph	1.0 hours, 3.0 person-hours
25150 km (15,625 miles) or Monthly	First-Stage Preventative Maintenance: brake and brake control tests, internal check of hydraulic system for leaks, door function and controls, pantograph contacts, other general inspections	3 hours, 13 person-hours
100,600 km (62,500 miles) or Quarterly	Second-Stage Preventative Maintenance: All work specified above, plus test of magnetic rail brakes, pressurized air system, dampers and tie-rods, wires and cables, measurement/correction of wheel profiles, inspection of cooling system and filter change, inspection of fire and other safety equipment and batteries	8 hours, 36 person-hours
301,750 km (187,500 miles) or once every 9 months	Third-Stage Preventative Maintenance: All work specified above, plus total brake function and control validation, HVAC inspection, test/validation of on-board computer system, inspection of electrical joints and cooling pipes, check of solid-state electronics, and high-voltage equipment, oil change on compressors, change of brake shoes/pads, change of primary dampers and yaw dampers, oil change in gear box and transmissions	24 hours, 115 person-hours
603,500 km (375,000 miles) or 18 months	Fourth-Stage Preventative Maintenance: All work specified above, plus check of set limit values in control system, change of hydraulic oil, air spring inspection, coupling lubrication	24 hours, 170 person-hours
1,207,000 km (750,000 miles) or 36 months	First Major Overhaul: Exchange of vital components (motors, fans, compressors, gear boxes, trucks, hydraulic cylinders, valves and compressor units, active components in brakes and pressurized air system, vacuum pumps), cleaning of all electrical cabinets, oil exchange in converter system, selective renewal of interior components	21 days, 1400 person-hours
3,621,000 km (2,250,000 miles) or 9 years	Second Major Overhaul: All of above work, plus additional component exchange on brakes, electrical contacts and compressed-air system; complete renewal of train interior and exterior	42 days, 5000 person-hours

TABLE 6
SCHEDULED MAINTENANCE ACTIVITIES - AMFLEET CARS

FREQUENCY	TYPE OF ACTIVITY
DAILY	General Inspection; check brake linings, drain toilet holding tanks
MONTHLY	Check battery system; check A/C system; check/clean food service car condensors
QUARTERLY	Inspect/clean HVAC; Inspect journals; check trucks, brakes and electrical system
SEMI-ANNUALLY	Lubricate journals; inspect/clean water coolers and toilets; inspect/service shock absorbers and bolster center pivot.
YEARLY	Clean/check couplers; check/service HVAC; inspect/service door system and handbrakes.
2-YEAR	Check/test/service brakes
3-YEAR	Service brakes in accordance with AAR PC Rule 2
4-YEAR	Remove, clean, test door mechanism;overhaul brake cylinder, tie rod, bearing; replace air hose
5-YEAR	Overhaul airbrakes; overhaul truck; Remove, inspect and repair journal bearings

performed as programmed, there is no reason why these technologies should not perform as well in the U.S. as anywhere else in the world.

Effects of U.S. Alignment Geometry and Track Maintenance Standards

The principal issue here stems from the fact that, to date, essentially all tests on tilt-body equipment in the U.S. have been conducted in the NEC. While there were very good and practical reasons for using the NEC, one must be cautious in extrapolating these results to other rail lines. There are several reasons why this caution is justified, and why additional investigations are needed to establish the general applicability of tilt-body equipment.

First, the track quality in the NEC is arguably some of the best in the country. While the alignment geometry of the line north of New York is certainly not exceptional, the track geometry is very good and the track structure is excellent. While categorized as FRA Class 6 track - the best track classification available under current U.S. regulations - there is no question that the quality is much closer to that of the "conventional" (160-200 km/h; 100-125 mph) tracks of Europe and Japan, certainly well above the Class 5/Class 6 boundary.

At present, there are no data to demonstrate how tilt-body equipment will respond to the alignment and track geometry conditions on routes which are still Class 6, but marginally so. The implications of operation on rougher track must be assessed not only in terms of the ability of the tilt and suspension systems to deliver acceptable ride quality at higher curving speeds but also in terms of the effects on component life, required maintenance cycles and the life-cycle costs of alternative technologies.

The Incremental Costs and Benefits of Tilting

While assessment of technology-specific costs and benefits is beyond the scope of this report, there are several underlying principles that need to be borne in mind when considering supplier claims with respect to cost, or examining the cost experience of a foreign operator.

First among these is that, with the possible exception of the LRC, any other tilt technology imported to the U.S. will be operating on a technological "island," with little or no opportunity to benefit from economies of scope or scale, and with the prospect of being at the end of a rather long supply line in terms of parts and expertise. This in itself will raise the level of effort required for many activities, at least in the early stages of deployment. For a foreign operator whose work force and facilities are already attuned to the technological complexities and maintenance requirements of equipment of this class, whether tilting or non-tilting, the addition of tilting trainsets to its fleet will represent an increment to an already established national network. The first U.S. operator could be faced with what amounts to a *state change* in process as well as skills and facilities. The nature of the cost base for a cost assessment in the U.S. will be fundamentally different than would be the case in Europe or Japan. Estimated cost increments should not be extrapolated to U.S. situations.

Second, there should be a clear understanding of cost causality and of the input factors (materials, labor by skill class, tools and equipment, facilities, etc.) required for all aspects of the life cycle of the tilt equipment, including all associated processes and procedures. These data will allow development of a realistic model of activities reflecting differences in utilization, procedures and factor quantities, and ultimately of the life-cycle costs.

With respect to assessing the benefits of tilting, at the level of an operator, the key issue is to make sure that the trip time gains from body tilting are based only on speed improvements on curves which are constrained by passenger comfort considerations. There may be other features of a given technology that will improve the curving characteristics of the vehicles. Specificity and attention to the details of a given route are essential for credibility.

Overview of Safety Issues, for Equipment Not Designed to U.S. Standards

Equipment and technology developed outside the U.S. may be built to a variety of technical standards which may differ from those applicable to conventional railroad equipment and infrastructure in the U.S. The issues arising from the potential application of foreign tilt technology are the same in principle as those affecting non-tilting technologies like the TGV or the ICE.

As noted previously, a comprehensive and thorough assessment of the safety issues and concerns associated with the types of high-speed rail systems like the tilt body has been recently prepared for the FRA.[7] That report lists individual safety issues and sub-issues which are typically the subject of a set of regulations, standards and practices, and the types of accidents affected by the issue.

The existing FRA regulations, developed over decades in response to safety problems not solved by industry standards and practices, do not consider railroad operations in excess of 176 km/h (110 mph) or at more than 76 mm (3 in) of cant deficiency. Accordingly, they address specific issues discretely and do not treat whole railroads as integrated systems. That approach, which has proven satisfactory thus far for conventional railroads, as evidenced by the remarkable safety record of the railroad industry in the last decade, appears to be in need of some modification for application to new tilt-body technologies such as the ETR-450. These new technologies are designed and operated as part of an integrated system having a significantly higher order of interdependent subsystems than conventional railroads.

Integrated, highly interactive, fault-tolerant systems invite regulatory treatment as a system. For example, the curve sensors, the on-board microprocessor network, the speed control system, and the braking systems for tilt-body technologies are so interdependent and interactive that the safety of any component of those subsystems can be fully understood only in the context of the whole system. This may be difficult to achieve in a set of rules of general applicability, each of which governs one of those subsystems.

There is now no standard for fault-tolerant systems. How many components of such systems and what kinds of them may fail before a train is prohibited from leaving the terminal? How many components of such a system and what kinds of them may fail en route before a train is required to stop or proceed only at restricted speed to the nearest repair point?

Similarly, there is now no standard for the reliability of the computer hardware and software on which these systems rely. Moreover, many safety issues pertaining solely to passenger service have not been addressed by regulation. Instead, because Amtrak is the sole provider of intercity rail passenger service, those issues have been dealt with separately in the context of the special relationship between Amtrak and the FRA. (The Secretary of Transportation is a member of Amtrak's Board of Directors, appoints two of them, recommends candidates for the other positions to the President, holds all of Amtrak's preferred stock, and holds security interests in virtually all of Amtrak's equipment and real property). With new providers of intercity rail passenger service entering the market, it is highly desirable that passenger safety issues now be handled through rules of particular applicability. It is clear that some additions to and modifications of some of the existing rules are also needed.

Although the FRA and Amtrak have worked out practical solutions pertaining to seat securement, luggage securement, equipment securement in dining cars, fire detection and suppression, and emergency training for passenger crews, no regulations currently exist. The FRA should not rely on attaining and maintaining the same sort of relationship with the management of each technology operator as FRA has with Amtrak.

The FRA track safety standards offer a somewhat different case in point. They do not permit rail passenger operations at speeds above 176 km/h (110 mph) or at cant deficiencies in excess of 76 mm (3 in). Amtrak operates at speeds up to 200 km/h (125 mph) on the Northeast Corridor under a waiver and will have to seek a similar waiver to operate tilt-body equipment at more cant deficiency than 76 mm (3 in). It seems undesirable to entertain a waiver petition every time a new high-speed or high cant deficiency service is contemplated. Amendments to the regulations setting standards for high-speed, high cant deficiency passenger service seems to be in order, and a review of the power brake rule also seems appropriate. There is now no standard for the types of vital braking systems on which high-speed tilt-body technology systems typically rely.

The issue of crashworthiness and adherence to U.S. standards is of direct relevance to foreign tilt-technology vehicles which are typically light-weight in design. Should light-weight tilt-body trainsets such as the ETR-450, Talgo, or X2000 be required to meet the buff strength standards of conventional American railroading? Should there instead be some standard requiring controlled crushing to protect occupants of these trainsets? Should collision posts be required? Should there be an applicable anti-climb standard?

Buff strength is a measure of occupant compartment structural integrity. This measure is adequate for a particular type of car construction (body-on-underframe) and for low-speeds, when train buckling is not a great concern. Different vehicle structural designs may allow increased occupant compartment structural integrity and decreased vehicle weight. The FRA currently is examining the issue of crashworthiness in a major study on "*Collision Avoidance and Accident Survivability*" scheduled for completion in the summer of 1992.

This subject and the potential regulatory issues (in areas such as emergency preparedness, fire safety and equipment, and track inspection standards), many of which are quite complex, are underway and will take considerable time to address.

In addition, items not addressed in this technology-oriented report, such as environmental issues and personnel qualifications and training, will be the subject of other potential regulatory reviews to be conducted in the future.

SUMMARY

Prospective deployment of tilt-train technology in the U.S. presents a number of challenges that must be met as a condition of success. Perhaps the most important will be alteration of the attitudes toward complex vehicles and programmed preventative maintenance that have traditionally prevailed in the U.S. "railroad culture."

Active-tilt passenger vehicles are sophisticated and complex, and incorporate unfamiliar and often delicate components in critical subsystems. If these vehicles are to perform safely and reliably in commercial operation, there will have to be a major shift in the philosophy of vehicle and infrastructure maintenance, away from the traditional reactive practices of railroads and towards the aggressive programmed preventative maintenance followed by commercial aviation.

A significant expansion of management and labor skills willbe required by operators and by regulators to deal with the complex hydraulic components, sensors, and microelectronics essential to effective and reliable active body tilting. U.S. operators and regulators will also have to acquire the knowledge base required to deal effectively with ac traction motors, steer-able trucks, active lateral suspensions and other elements of tilt-train design that are not part of the tilt mechanism, but that are essential components of the equipment.

Deployment of tilt-body equipment originally designed for conditions outside the U.S. may also require alteration of infrastructure maintenance practices. While alterations to alignment geometry may not be required, it is not clear whether changes to the measurement and maintenance of track geometry parameters will be needed. There are significant differences in the geometric standards adhered to by U.S. and foreign railroads, and indeed to the nature of the measurements upon which assessments of geometric conditions are based. Investigation of the behavior of key subsystems on U.S. track will be required to determine the extent to which either equipment design and/or track maintenance practices may need to be altered to replicate foreign performance, especially outside the Northeast Corridor.

U.S. application of tilt-body technologies will also pose a challenge to recognize the limits of what tilting can accomplish and to carefully avoid overstatement of the benefits to be gained, both within the management structure of operators and regulators, and among the travelling public-at-large. Body tilting is not a universal solution to the constraints on higher-speed operation on existing track. Its effectiveness will vary significantly from route to route.

The challenges noted above should not prevent selective application of tilt-body technologies. On some routes, active body tilting will offer a cost-effective mechanism to exploit market opportunities contingent on reduced trip time and improved ride quality. The other features incorporated in tilt technologies may also contribute significantly to overall improvement in the commercial performance of passenger rail. Even greater potential may be found beyond the scope of existing tilt-body technologies. Incorporation of active tilt mechanisms in very high-speed (200 - 320 km/h) wheel-on-rail or maglev systems could allow co-location of these technologies in some existing highway, rail and/or utility rights-of-way without unacceptable degradation of ride quality.

ENDNOTES

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11. CONEG (Coalition of Northeastern Governors), Tilt and Turbo Train Test and Evaluation, January 1989.

12. Amtrak Evaluation of Tilt and Turbo Train Technologies, Amtrak Report, 1989.

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14. Much of the material in this section is drawn from Chapter 5 and Appendix B of the reference in endnote 10 above. Appendix B of this reference is based on the work of Battelle Columbus Laboratory carried out as part of the IPEEP Program, and reported by Dean and Ahlbeck, "Criteria for the Qualification of Rail Vehicles for High-Speed Curving," IPEEP Working Paper, Oct. 1977; and "Criteria for High-Speed Curving of Rail Vehicles," ASME Paper No. 79-WA/RT-12, December 1979.

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