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IEEE Guide for the Calculation of Braking Distances for Rail Transit Vehicles

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IEEE Vehicular Technology Society (VTS)

Sponsored by the
Rail Transit Vehicular Interface Committee

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Abstract: The design of automatic train protection and signal systems for fixed guideway (e.g., rail) transit systems requires knowledge of the braking distance of the vehicles utilized on the systems. Methods and assumptions used in calculating the braking distances of rail transit vehicles are provided in this guide. The methods encompass automatic train protection and signal system operation, propulsion and brake system operation, environmental conditions, operator interfaces, tolerances, and failure modes.

Keywords: automatic train control (ATC), automatic train operation (ATO), automatic train protection (ATP), braking, braking distance, fixed-guideway transit, rail transit, signal systems

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IEEE Guide for the Calculation of Braking Distances for Rail Transit Vehicles

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1. Overview

1.1 Scope

This guide provides methods and assumptions used in calculating the braking distances of rail transit vehicles. The methods encompass automatic train protection and signal system operation, propulsion and brake system operation, environmental conditions, operator interfaces, tolerances, and failure modes.

1.2 Purpose

The design of automatic train protection and signal systems for rail transit vehicles requires knowledge of braking distance. This guide provides methods of performing braking distance calculations.

2. Definitions, acronyms, and abbreviations

2.1 Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.[1]

brake assurance: A function in the automatic train protection (ATP) system that monitors the actual achieved braking rate, and, if less than a predetermined value, applies emergency brake.

brake build-up: The time to achieve full commanded braking rate, beginning from the point at which a typical value of 10% of the commanded rate has been achieved.

braking rate: The deceleration of the train, resulting from the retarding effort of the braking apparatus, but excluding train resistance and grade or curvature effects.

curvature: The measure of the amount by which the track does not run in a straight line (i.e., is not tangent).

dead time: The time from a point at which the instantaneous accelerating tractive effort is zero until braking rate has reached a typical value of 10% of the commanded value.

entry point: The civil position of a train at which it enters territory wherein a more restrictive speed limit applies (i.e., a signal boundary or transponder location).

entry speed: The speed of the train at the entry point that is allowed by the signal system or by governing rules and procedures. This speed may include allowable speed and wayside/vehicle equipment tolerances.

equipment reaction time: The time from passage of an entry point until the carborne equipment has detected, processed, and indicated the existence of a more restrictive speed.

full service application: A service brake application of sufficient amount to obtain the maximum service brake rate obtainable.

grades: Civil changes in track elevation; the tangent of the angle formed by the algebraic value of the rise divided by the horizontal component of the run, typically expressed as a percent.

gradient: The horizontal run over which one unit of rise occurs.

jerk rate limit: The limit to the rate of change of acceleration designed into the propulsion, automatic train operation (ATO), and/or braking apparatus.

maximum attainable speed: An entry speed, commonly used with trip-stops with wayside signals, which is the highest speed that a train can achieve at the entry point of the braking model while operating in accordance with the rules of the authority having jurisdiction.

maximum authorized speed: The highest speed at which a train is allowed to operate in the absence of any condition requiring a lesser speed.

operator reaction time: The time from passage of an entry point until an operator has performed a definitive action in recognition of the existence of a more restrictive speed limit.

[1] *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at http://shop.ieee.org/.

rail transit vehicle: For the purposes of this guideline, rail transit vehicles include multiple unit (MU) cars, heavy-rail vehicles, light-rail vehicles, automated people-mover and similar rubber-tired guided vehicles, and locomotive-hauled passenger trains.

reaction time: The time from passage of a point (in time or in civil location) where a new condition exists until the existence of the new condition is recognized by definitive action.

runaway acceleration: Is the maximum possible acceleration of the train, as a result of equipment failure.

safety factor: A percentage increase applied to the calculated braking distance to accommodate such factors as available adhesion, percentage failed brakes, equipment tolerances, efficiency of spin/slide apparatus, other equipment failures (e.g., load weigh system), the dictates of Operating Rules and procedures, and similar factors.

vehicle overhang: The distance between the foremost structure or front coupler face of a train and the location of the front of the train as established by the train control system.

2.2 Acronyms and abbreviations

AREMA	American Railway Engineering and Maintenance-of-Way Association
ATC	automatic train control
ATP	automatic train protection
ATO	automatic train operation
km/h	kilometers per hour
mph	miles per hour
mphps	miles per hour per second
m/s	meters per second
m/s^2	meters per second squared
SI	Système International d'unités (French) International System of Units (English)
TE	tractive effort
TPC	train performance calculator

3. Braking model components

3.1 General

Braking distance is an important consideration in designing rail transit vehicles and train control systems. The braking model is used to determine the distance required for stopping (Clause 5) and for speed reducing (Clause 6) under normal and abnormal conditions. Braking distance is also important for the interaction of trains with civil restrictions.

The braking model is an analytical approximation of the braking distance of the train. The model is intended to be comprehensive and include all commonly-used considerations; specific transit applications may not require use of all model components. The “worst-case” combination of parameters applicable to the vehicles (or combination(s) of vehicles) and physical location(s) being analyzed, as used in calculations, is defined by the authority having jurisdiction. Where a component is not to be included, the development of a comprehensive failure analysis supporting this decision is strongly recommended. Similarly, failure modes or other specific conditions considered and all components values used should be validated by supporting analysis and test results wherever possible.

A simplified illustration of the braking model is shown in Figure 1.

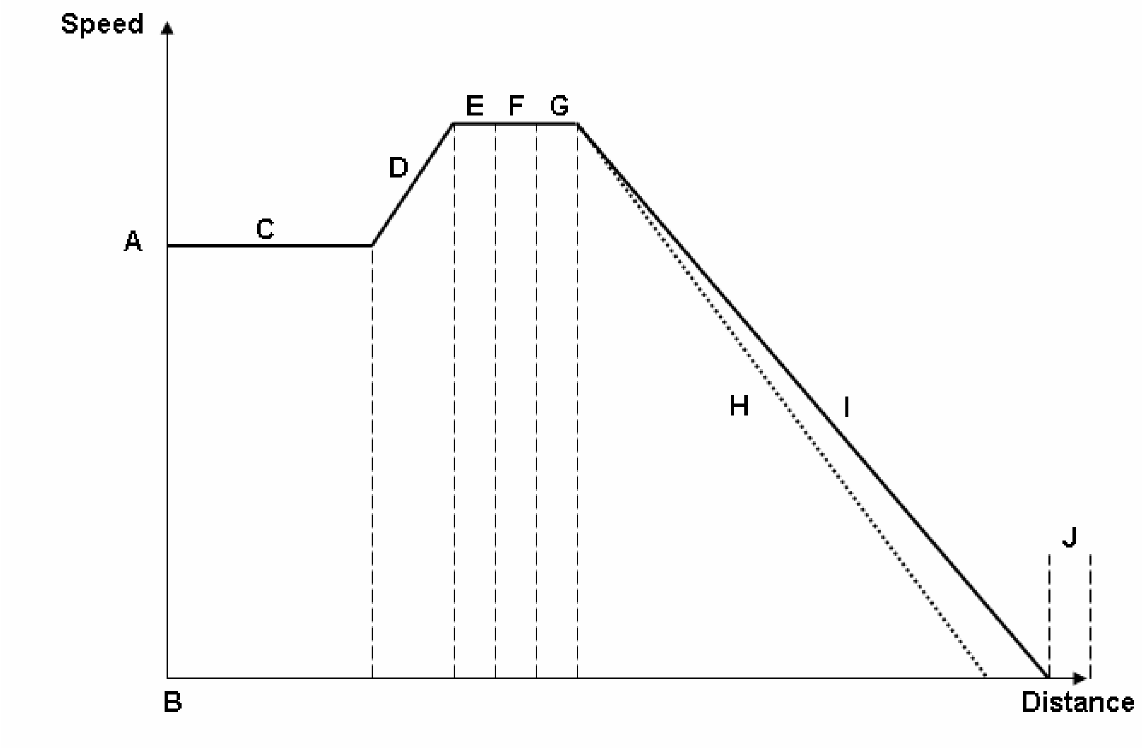

Figure 1—Braking model

3.2 Maximum entry speed (A)

The maximum entry speed (A) is the highest speed at which the train can enter the model.

3.3 Entry point (B)

The entry point (B) is the point where the braking model is initiated.

3.4 Distance traveled during reaction time (C)

Depending on the design and application of the signal equipment, this component may consist of two parts that are concurrent or consecutive events, distance traveled during equipment reaction times and distance traveled during operator reaction time.

3.4.1 Equipment reaction times

The maximum reaction time of the carborne signal equipment to detect and indicate a more restrictive condition, and, in some cases, request braking.

3.4.2 Operator reaction time

Time provided for action by the operator to suppress the overspeed condition, usually by either acknowledgement of the overspeed condition and/or through a manual application of brakes.

3.5 Runaway acceleration (D)

The runaway acceleration component of the model is the distance traveled during the worst-case time beginning with the indication for braking and ending with the initiation of propulsion removal. During runaway acceleration, the maximum available positive tractive effort is applied.

3.6 Propulsion removal (E)

This is the distance traveled during the worst-case time beginning with the point at which positive tractive effort begins to be reduced and ending with the achievement of nominally zero tractive effort.

3.7 Dead time (coast) (F)

This is the distance traveled during the worst-case time beginning with nominally zero tractive effort and ending with the achievement of a typical value of 10% of the guaranteed braking rate.

3.8 Brake build-up (G)

This is the distance traveled during the worst-case time beginning with the achievement of a typical value of 10% of the guaranteed braking rate and ending with the achievement of the guaranteed braking rate.

3.9 Guaranteed braking rate (H, I)

The guaranteed braking rate is a de-rated deceleration rate defined by an authority having jurisdiction as further described below.

3.9.1 Minimum braking rate (H)

The minimum performance braking rate characteristics (typically friction braking only) are those of the worst-case train on dry, level tangent track. This rate can be specified and verified through test.

3.9.2 Braking rate with safety factors (I)

Safety factors modify the minimum braking rate by increasing the braking distance to compensate for identified worst-case conditions. The safety factor is typically used to capture a range of issues that may not be addressed in other components of the braking model. The application and use of these safety factors is described in detail in 4.6.3.

3.10 Vehicle overhang (J)

This is the distance between the foremost structure or front coupler face of a train and the effective location at which the train control system locates the front of the train, such as an antenna on the lead truck, a magnetic transponder, etc.

4. Application of the braking model

4.1 General

The following subclauses provide considerations and guidelines for determining the brake model components described in Clause 3 for applications on level tangent track. Compensation of the brake model, to include the effects of track grades, track curvature, and train resistance, is described in Clause 5.

4.2 Maximum entry speed

Entry speed (A) is generally calculated using some or all of the following components:

a) The actual speed of the train, calculated either by the vehicle or the carborne ATC/ATP equipment. This speed is usually the speed allowed in the territory prior to the entry point;

b) The maximum measured overspeed permitted, which typically is 3-5 km/h (2-3 mph) greater than the speed allowed in territory prior to the entry point;

c) A speed error component, which is a sum of different sources of speed measurement error. These speed measurement errors can be a result of spin/slide, wheel diameter discrepancies, speed measurement errors, etc.

NOTE—Although the SI unit for speed is m/s, it is more common in the international railway community to express speed in km/h. Accordingly, this standard may use either, as deemed appropriate. [2]

4.3 Entry point

The entry point (B) is the point where a train enters a more restrictive territory or must initiate braking because of a forthcoming restrictive condition. An entry point can be defined as a fixed location, such as signal boundary, impedance bond, insulated joint, or transponder, or can be defined as the point at which braking must be initiated because of the restrictive condition.

4.4 Distance traveled during reaction time

The distance traveled during reaction time (C) is dependent upon the type of signal system:

a) For trip-stop (tripper) type signal systems, there is essentially no distance traveled during reaction time due to the activation of braking upon passing the entry point. The only distance to be considered is the location of the entry point relative to the location of the actual trip device (if not covered by component J, vehicle overhang).

b) For signal systems that continuously or intermittently govern train speed, this is the distance traveled by a train from the entry point to the point at which the carborne ATC/ATP equipment recognizes and responds to a more restrictive speed condition. The speed of the train used during this reaction time is generally the maximum entry speed as determined in 4.2.

c) For signal systems without either continuous or intermittent enforcement (i.e., aspects only), this is the distance (typically, but not necessarily, zero) traveled by a train from the entry point to the point at which the operator recognizes and responds to a more restrictive speed condition. The speed of the train used during this reaction time is generally the maximum entry speed as determined in 4.2.

[2] NOTES in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

Depending on the design and application of the signal system, this component may consist of two parts that are either independent and concurrent or consecutive events.

4.4.1 Equipment reaction time

The distance traveled in this reaction time includes worst-case time for the wayside and/or carborne ATC/ATP equipment to detect, process, and indicate a need for braking. This can also include the time for the carborne ATC/ATP equipment to annunciate the more restrictive speed aspect to the train operator.

4.4.2 Operator reaction time

The time provided for the operator to recognize the need for braking (i.e., based upon visual and/or audible annunciation). Operator reaction time should also include any additional time for the operator to suppress the overspeed condition, either by acknowledgement of the overspeed condition and/or through a manual application of the brakes.

4.5 Runaway acceleration

The runaway acceleration component D begins at the end of the reaction-time distance and continues until removal of positive tractive effort has been initiated via the action of a high-integrity backup control path, such as a penalty brake application.

This component of the model assumes the maximum acceleration rate for the speed at the end of reaction time, based upon the vehicle performance characteristics. This may include the assumption of a load weigh system failure in conjunction with the weight of an empty vehicle such that the tractive effort available for a fully loaded vehicle is used.

If the train accelerates at any time during component C the ATP system will detect an overspeed condition and initiate the start of component D (See NOTE). This will always result in a shorter stopping distance than assuming the overspeed condition (from acceleration or the recognition of a lower speed requirement) occurs precisely at the end of component C. The component D should include the time for the ATP to detect and indicate the overspeed condition to other carborne equipment. This time is typically the time required to recognize overspeed and de-energize the overspeed brake relay or other output, which initiates the high integrity backup control path.

NOTE— For systems without overspeed enforcement, operators are prohibited from exceeding the commanded speed limit by rule.

Random failures of individual pieces of propulsion apparatus are, in general, less severe in their consequences than are train-wide or systemic failures, and are therefore not separately considered.

Runaway acceleration is typically included in braking models that feature automatic train operation (ATO) and/or microprocessor based propulsion control logic. The presence of propulsion controls utilizing non-vital microprocessor technology does not in itself require that a runaway acceleration component of greater than zero time duration be included in a braking model. However, where such a component is not to be included, the development of a comprehensive failure analysis supporting this decision is strongly recommended.

4.6 Power to brake transition

Components E, F, and G represent events that, by their nature, take place as functions of time. The total change in speed during components E, F, and G is very small, because the duration of these events is short compared to the time required for a complete stop. Annex C describes and illustrates several practical examples of propulsion removal, coast, and brake application. For the reason given above, the horizontal axes of Figure C.1 through Figure C.4 can be interpreted with equal utility as time or as distance. In practice, the more rigorous curves of Figure C.1 through Figure C.4 are often approximated by constant values, as discussed in more detail below for each transition. This results in the speed versus distance curves of components E, F and G as shown in Figure 1 being straight lines. In most cases, the effect of the varying transitions shown in Figure C.1 through Figure C.4 will not have a major impact on the ultimate stopping distance. Annex C gives insight should it be determined that the variation could be significant.

4.6.1 Propulsion removal

The propulsion removal component corresponds to the distance traveled during the period of time in which tractive effort transitions from a net positive value to a zero (coast) value, usually on a jerk rate-limited basis. The resulting acceleration is typically assumed to be the average of the acceleration rate of the vehicle at the train speeds over the acceleration period.

Propulsion removal may consist solely of the transition of propulsion tractive effort from a positive value to zero. When emergency braking has been applied, simultaneous or overlapping transitions of decreasing propulsion tractive effort and of increasing braking effort result in a net zero value at the defined end of the propulsion removal component. The time duration of this component depends in part on whether propulsion is removed gradually via an intentionally jerk rate-limited control path, or removed, usually more abruptly, via a high-integrity backup control path.

Annex C describes and illustrates several practical examples of propulsion removal.

4.6.2 Dead time (coast)

The coast component corresponds to the distance traveled during the period of time during which tractive effort remains steady at a zero or near-zero value, beginning at the end of propulsion removal and ending when the braking rate has achieved a typical value of 10% of the value it will have during the braking component. The coast component may have negligible or zero time duration under certain conditions of relative timing of propulsion system power removal and brake system brake application, as illustrated in Annex C.

4.6.3 Brake build-up

The brake build-up component corresponds to the distance traveled during the period of time during which the braking rate transitions from a typical value of 10% to the full value it will have during the braking component. Brake build-up may consist solely of the transition of braking rate from a typical value of 10% to the full value, or it may, where emergency braking has been applied, include simultaneous or overlapping transitions from propulsion to brake. The braking rate developed during brake build-up is typically assumed to be half the full braking rate of the braking component. The time duration of this component also depends on whether braking effort is applied gradually via a jerk rate-limited control path, or applied via a high-integrity backup control path such as a penalty brake application.

Annex C describes and illustrates several practical examples of brake buildup.

4.7 Guaranteed braking rate

4.7.1 Use and Nomenclature

As defined, the guaranteed braking rate component begins when the full deceleration rate is achieved, and ends with zero speed. Braking rates are commonly stated in units of meters per second squared (m/s^2) or miles per hour per second (mphps). In computer calculations using industry standard train resistance formulas, units in Newtons or pounds of force are used to describe the impact of braking on vehicle motion. All of these parameters are related through Newton's Second Law as shown in Equation (1):

$$\text{Force} = (\text{Mass}) \times (\text{Acceleration}) \tag{1}$$

However, there are several specific issues associated with the braking rate that will be discussed here in terms of applying a deceleration rate to the braking distance model.

The braking rate is assumed to be a constant deceleration for the entire braking component of the model. The actual deceleration experienced by a train may in fact be non linear in nature. For the purposes of this guide and for simplification, a constant rate is used to define the braking rate from the beginning of full brake effect to the end point.

Although there are several terms used within the industry to describe braking rate, a common usage is "guaranteed brake rate," which includes minimum braking rate (H) and braking rate factors (I).

4.7.2 Minimum braking rate (H)

This represents the effect of a brake application derived from the worst-case train (in number of cars, type of cars, net train weight because of passenger loading, etc.) at the brake controller position specified in the train handling rules, or the action taken by the ATP system.

The braking rate used in the braking distance model can be determined empirically by actual stopping tests conducted on the train or vehicle. Annex D describes typical test procedures and data to be recorded.

4.7.3 Braking rate with safety factors (I)

The deceleration that is described in this component of the braking distance model may include an allowance for other factors. These safety factors are described below. A typical safety factor is 35% and is based upon the application of friction brakes only, applied through fail-safe or safety-critical circuits.

There is varying practice with this component of the braking model. Some authorities having jurisdiction include the safety factor in component H, the minimum braking rate, where some others separate the functions of braking and safety factor to recognize where different considerations are made. For the purpose of this guide, the individual "safety factors" are presented here so that they are not confused with actual train braking.

It should be noted that the safety factor can be applied as an additive to one or any combination of parts from the braking model. Industry practice varies, however with the advent of modern computer based calculation methods, it is becoming more common to apply the safety factor to just components H (the minimum braking rate) than to apply it to the entire braking distance (components A through H).

The safety factor is typically used to capture a range of issues that may not be addressed in other components of the braking model. When determining an appropriate safety factor to use for the net effect of these issues in combination, a probabilistic approach can be used to avoid creating an unrealistically-restrictive safety factor. The range of issues to be considered are dependant upon the specific rail transit vehicle characteristics and include, but are not necessarily limited to, the following:

a) Adhesion levels (e.g., available adhesion on wet rail or in the presence of fallen leaves or other contaminants). Adjustment for poor rail adhesion conditions is the most common issue in safety factor selection. These conditions include, among others, wet rail, leaves, and other contaminants found between the wheel and rail. Most braking distance field tests are performed under ideal (or nearly ideal) rail adhesion conditions. The safety factor must consider a level of adhesion that can occur in actual service conditions.

b) The percentage of failed brakes on a train, both the percentage of brakes on a train in which the train can continue service and the additional brakes that may fail upon brake application. Consideration should be given for brakes cut-out or otherwise inoperative within the train or vehicle. Typical wording in operator instructions are given below:

— "Trains may not be dispatched from any terminal with less than 100% of the brakes operative."

— "A car or locomotive is considered to have inoperative brakes if either one truck or both trucks are cut out."

— "A train that encounters a failure of the brakes en route that results in 85% or more of the brakes remaining operative may proceed at Normal Speed to the next repair facility or terminal location, whichever is closest, where the defective equipment must be repaired or set out. If moved to a terminal location, the defective equipment may be dispatched as a shop train to return to a repair facility."

This adjustment must compensate for operating rules and instructions on the amount of inoperable brakes. There are strict limits for railroad applications imposed by the applicable regulatory agency. For transit application, state and local authorities may have their own requirements that must be reviewed.

c) Operating rules and train handling procedures. The authority having jurisdiction provides important information for the development of braking distance criteria. This information prescribes the procedures for operating trains and vehicles in both normal and emergency conditions. As such, they must be reviewed for any instructions or procedures that would impact the stopping, and starting of trains or vehicles, and any actions required by operators that would prevent or modify strict adherence to the signal rules.

d) Equipment tolerances (vehicle braking systems, etc.).

e) Spin/slide systems. Vehicle types that are equipped with spin/slide protection must be reviewed to ensure that the spin/slide protection does not adversely affect the overall safety factor.

Typical train handling instructions may include wording similar to the following:

"When operating train consists that are equipped with wheel slide detector feature, the action of the wheel slide feature should be taken into account during periods of poor rail adhesion. If the wheel slide system malfunctions causing the wheels to "lock up" resulting in the train wheels sliding along the rail, the brakes must be released enough to allow the wheels to resume rolling, after which brakes can be reapplied."

In this case, the release and reapplication of the brakes would need further review to determine the extent of increased braking distance requirements.

f) Load weigh system failures.

g) Magnitude of the braking rate used in component H.

If the authority having jurisdiction chooses to apply the braking model using a non safety-critical braking system, a "brake assurance" function may be provided. If a brake assurance function is used, the model should be adjusted to accommodate the presence or absence of model components and their respective response times according to the design of the particular brake assurance function.

4.7.4 Other/additional brake systems

Most modern trains and vehicles are equipped with other/additional braking systems such as dynamic or track brakes that work in conjunction with the normal "fail safe" brake. While these systems have become more reliable, they might not be considered to be "safety-critical" brakes for use in braking distance calculations for several reasons including:

— A failure of the control power to the other brake system(s) may not prevent unrestricted operation. If the braking effort is artificially too high from the additional brake, and it becomes inoperative at any time, hazardous conditions may prevail,

— Some of these types of brake become ineffective at low speeds, and

— These types of brake are not dependent on closed loop principles that prevent brake operation without previous knowledge.

For these and other reasons, other additional braking may not be applied to braking distances unless these other additional braking mode(s) can be shown to be implemented in a "fail safe" manner.

4.8 Vehicle overhang

The braking distance model component accounts for the fact that the trailing train may encroach into the braking distance (such as by the ATC receiver offset [in track circuit-based signal systems] or on-board trip device offset) before braking is initiated. Additionally, position error introduced by the device(s) used to detect the more-restrictive condition can be accounted for in vehicle overhang (or alternatively in the entry point).

5. Stopping distance compensation

5.1 General

Some elements of the model involve changes of speed within the time duration of the model element. The mathematical equation of the motion of an object under constant acceleration/deceleration is well-known to be given by Equation (2):

$$D_f = D_i + v_i t + \tfrac{1}{2}(at^2) \qquad (2)$$

Where:

D_f Distance final
D_i Distance initial
v_i Initial velocity
t Elapsed time
a Acceleration/deceleration

Using equations of motion, and setting the initial distance $D_i = 0$, we can mathematically compute distance in terms of acceleration and initial velocity as shown in Equation (3):

$$D_f = K_1 \times \frac{v_i^2}{2a} \qquad (3)$$

In SI units, the factor K_1 can be seen to equal 0.07716 when used to arrive at a braking distance in meters where initial velocity is provided in kilometers per hour and deceleration in meters per second per second.

In Imperial units, the factor K_1 can be seen to equal 1.4667 when used to arrive at a braking distance in feet where initial velocity is provided in mph and deceleration in mphps.

However, the application of the model considered in these formulas and in Clause 6 only considers level, tangent track. In a more general case, the model elements may vary depending on such factors as the prevailing track grades, track curvature, and train resistance while the train traverses the component and should be calculated accordingly. Application of various compensations to the components of the model is shown in Table 1 at the end of this clause.

5.2 Compensation for grade

The stopping distances calculated on level, tangent track must be compensated for grades when modeling the stopping distances. A descending grade reduces the effective braking rate and therefore lengthens the stopping distance. An ascending grade increases the effective braking rate and therefore shortens the stopping distance.

Grade designates the rise and fall of track per unit of horizontal distance, and is typically identified as a percentage. For example, a 4% grade signifies that a particular section of track rises four (4) units vertically over 100 horizontal units.

Determining grade-compensated distance in terms of acceleration and initial velocity is performed by using the following equations of motion:

For SI units, using the SI form of Equation (3) and adding the effect of gravity on a grade yields the following in Equation (4):

$$D_f = 0.0386 \times \frac{v_i^2}{0.0894G + a} \tag{4}$$

Where:

- D_f Distance final (m)
- v_i Initial velocity (km/h)
- G Grade (percent)
- a Acceleration/deceleration (m/s^2)

For this equation, G is positive for ascending grades and negative for descending grades.

For Imperial units (again with the effect of gravity on grades) Equation (3) becomes the following in Equation (5):

$$D_f = 0.7333 \times \frac{v_i^2}{0.2G + a} \tag{5}$$

Where:

- D_f Distance final (ft)
- v_i Initial velocity (mph)
- G Grade (percent)
- a Acceleration/deceleration (mphps)

Again, G is positive for ascending grades and negative for descending grades.

A simplified stopping distance grade correction factor that has been used in point mass calculations is $4/(4+G)$, with G = grade expressed as a percentage. The factor of 4 is based upon use of historic braking rates. However, this approximation of the effect of gravity becomes inaccurate as a downgrade (G) exceeds –3%. For these reasons, this simplified correction factor should be used with care. The use of a train performance calculator (TPC, see Annex B) has superseded most use of such simplified factors.

5.3 Compensation for curvature

Some applications of the braking models also adjust the acceleration rate of the train because of track curvature. Track curvature causes a resistance that slows the train down and thus has the same effect as an ascending grade.

Typically in Imperial units, Hay [B1] recommends a resistance of 0.8 lbs per ton of vehicle weight per degree for horizontal track curvature in railway applications, which equates to 0.008 miles per hour per second per degree of curvature in Imperial units. Hay [B1] recommends the use of a resistance of 1.0 lbs per ton of vehicle weight per degree of horizontal track curvature for transit applications. Assuming the use of a 0.8 factor, this leads to a stopping distance equation, in Imperial units, of Equation (6):

$$D_f = 0.7333 \times \frac{v_i^2}{0.008R + a} \tag{6}$$

Where:

D_f Distance final (ft)
v_i Initial velocity (mph)
R Curvature (degrees)
a Acceleration/deceleration (mphps)

The equation for curvature-compensated stopping distance in SI units may be derived straightforwardly from Equation (6) by using the classic definition of curvature in degrees (the angle subtended by a chord of 100 ft., see Hay [B1]) and applying routine Imperial-SI conversions:

$$D_f = 0.0386 \times \frac{v_i^2}{\left(\frac{6.245}{R}\right) + a} \tag{7}$$

Where:

D_f Distance final (m)
v_i Initial velocity (km/h)
R Curve radius (m)
a Acceleration/deceleration (m/s^2)

For simplicity, it is typical to ignore the spiral transition portion of the curve and either take the curve as beginning and ending at the point where the actual curve radius is achieved (which leads to a very slightly conservative calculation of braking distance) or at the point of tangency (which leads to a very slightly optimistic calculation of braking distance).

5.4 Compensation for train resistance

Some applications of braking models also adjust the acceleration rate based upon train retardation forces using a train resistance formula. The use of commonly accepted formulas for train resistance has been the norm for a number of years, and is well documented in Hay [B1].

In SI units, a train resistance equation may be expressed in a generalized form taking into account fundamental contributors to train resistance as shown in Equation (8):

$$TR = K_{rr}M + F_{coeff}MV + (A_{coeff} + S_{coeff}(n-1))AV^2 + K_cM / C \tag{8}$$

Where:

- TR Train resistance in N
- K_{rr} Rolling resistance in N/kg
- M Total train mass in kg
- F_{coeff} Flange coefficient in N/(kg km/h)
- V Velocity in km/h
- A_{coeff} Frontal air drag coefficient in N/(m^2(km/h)^2)
- S_{coeff} Skin-effect air drag coefficient in N/(m^2(km/h)^2)
- n Number of cars in the train
- A Frontal area in m^2
- K_c Curve coefficient N m/kg
- C Curve radius in m

When working in Imperial units, the most commonly-used formula is the modified Davis train resistance formula. The original Davis equation was modified in 1970 by the then American Railway Engineering Association (AREA, now American Railway Engineering and Maintenance-of-Way Association, AREMA). It was developed in recognition of the changes in resistance factors (particularly car configuration, higher speeds, and improved track structure) compared with the 1920's era of the original Davis Equation. Hay [B1] gives an extended discussion of the evolution of the modified Davis Equation. The modified Davis Equation, in Imperial units, takes the form in Equation (9):

$$R_{\mathrm{u}} = 0.6 + (20/w) + 0.01V + (KV^2/wn) \tag{9}$$

Where:

- R_u Resistance in pounds per ton
- w Weight per axle = W/n,
- n Number of axles,
- W Total car weight on rails in tons,
- V Speed in miles per hour,
- K Air resistance (drag) coefficient with a value of approximately 0.07.

Once the train resistance is determined, Newton's second law can be used to modify the value of "*a*" in Equation (2) and Equation (3).

5.5 Miscellaneous

Traditionally, it was assumed that the mass of a train was at a point, either the front or the center of the train. This point mass was used in determining the effect of grades. With the use of more sophisticated computer models it is possible to model the effect of each car in the train and its location relative to the grade changes.

Most transit systems use the weighted average grade ahead of the train. Some authorities having jurisdiction simplify this by use of the largest magnitude grade ahead of the train, but this can adversely affect the calculated braking distance if there is even a small portion with a large magnitude of grade.

Table 1—Typical compensation effects on model components

Model Component	Component Name	Compensation Factors to Apply[a, b]		
		Grade	Curvature	Train Resistance
A	Maximum Entry Speed	N/A	N/A	N/A
B	Entry Point	N/A	N/A	N/A
C	Distance Traveled during Reaction Time	1	1	1
D	Runaway Acceleration	2	2	2
E	Propulsion Removal	2	2	2
F	Dead Time (Coast)	2	2	2
G	Brake Build Up	2	2	2
H	Minimum Brake Rate	2	2	2
I	Brake Rate Factors	1	1	1
J	Vehicle Overhang	N/A	N/A	N/A

[a]This component is characterized by "maintain speed" where the operator is in control and external forces do not influence the train performance.
[b]This component is characterized by coasting where external forces influence train performance.

6. Speed reducing

The same principles associated with the calculation of stopping distance are applicable to braking for civil restrictions or operating rules requirements, such as for curves, diverging routes, or passing through station platforms without stopping.

Posted speed limits for civil restrictions or operating rules requirements are typically based on comfort speeds rather than speeds that cannot be exceeded safely. When calculating the braking distance required for speed reducing, the worst-case factors in the braking distance model are only needed to ensure that the train does not exceed the overturning or derailing speed. Normal braking factors, as opposed to worst-case factors, could be used for reducing to the comfort or posted speed as long as worst-case factors remain in effect for checking overturning or derailing speeds. This would allow for a higher average speed from the beginning of the speed reduction through the restriction than if worst-case factors were used throughout.

Annex A

(informative)

Bibliography

[B1] Hay, William W., *Railroad Engineering,* 2nd ed, New York: John Wiley & Sons, 1982.

[B2] IEEE Std 1474.1™-2004, IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional Requirements.

Annex B

(informative)

Use of train performance caluculator (TPC)

A train performance calculator (TPC) provides simulated time, distance, speed, and acceleration data for a single train operating on a particular rail alignment. For braking distance analysis, a TPC can support the analysis of single train operations, such as point-to-point running times, time and distance to stop and time and distance to accelerate.

A typical TPC supports both text and graphical output. Text output options include tables of data indicating results of the simulation run. Graphical output includes user-defined combinations of time, distance, speed, acceleration, maximum speed limit, grade, and curvature in appropriate increments.

One important point to remember in using TPC's for distance calculations is that the vehicle parameters need to be picked carefully. For instance, the maximum acceleration rate of a vehicle will normally decrease past the cut-off speed of the propulsion system. In this case, should the entry speed be greater that the cut-off speed, the TPC calculations will reflect the lower acceleration. When the acceleration factor is used as part of the braking distance model, calculations to check the TPC need to be adjusted accordingly. Should the TPC acceleration curves not reflect the effect of the cut-off speed; the braking distance calculation will be overstated with a possible loss in system capacity.

The TPC's train movement equations are typically based on train resistance formulas such as the modified Davis equation. However, there exist other standardized and widely used formulas for use in different technology transit vehicles that exhibit unique characteristics.

When applying TPC to grade compensation, the calculated train performance based on either point mass or distributed mass methodologies is an important factor. Point mass calculations involve the assumption that the entire train weight is concentrated at a single point. Prior to the advent of modern TPC's, this was a popular method for calculating train performance as it simplifies the math involved. Distributed mass calculations, now routinely available from state-of-the-art TPC's, include the distribution of the vehicles' weight throughout the length of the train as it would be in a test as described in Annex D. The results are the same when an entire train is on the same grade, as is the case for the normalized braking distances discussed here. However, they can differ substantially when the train is straddling one or more grade intercepts, as would be the case when evaluating real world conditions. Distributed mass provides more accurate results and should be used in the evaluation of braking distances.

Since the parameters in the resistance equation vary from vehicle to vehicle and train to train, TPC calculations require calibration against observable tests. This calibration can be run to match the TPC results over grades and curves of the actual field test, then the TPC alignment data can be modified and run again taking out the effect of the grades and curves to normalize the field test for use as component H of the braking distance guidelines.

Annex C

(informative)

Practical examples of power removal, dead time (coast), and brake applications

Figure C.1 through Figure C.4 illustrate several practical examples of propulsion removal (component E), dead time (coast) (component F), and brake build-up (component G), as illustrated conceptually in Figure 1. Components E, F, and G represent events that, by their nature, take place as functions of time. Because the duration of these events is short compared to the time required for a complete stop, however, the total change in speed during components E, F, and G is very small. As a result, the horizontal axes of Figure C.1 through Figure C.4 can be interpreted with equal utility as time or as distance.

Figure C.1 illustrates a typical power-to-service-brake transition in the absence of any penalty brake application. Power is removed in a jerk rate-limited manner (component E), the train coasts briefly (component F), then service brake builds up in a jerk rate-limited manner (component G). In this case the three components are distinct and well defined.

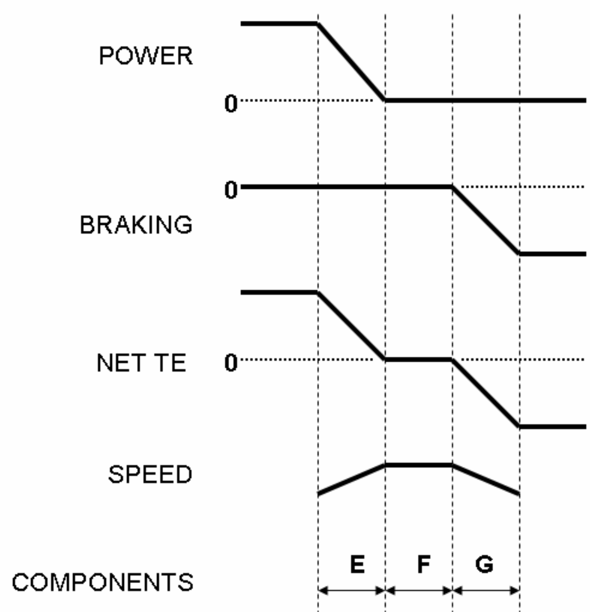

Figure C.1—Normal power-to-service brake transition

Figure C.2 illustrates a special case of power-to-service-brake transition, again in the absence of any penalty brake application. The relative timing of jerk rate-limited power removal (component E) and jerk rate-limited brake build-up (component G) is so arranged that a seamless transition directly from power to braking is achieved. In this case, as well, the components are distinct and well defined, but the dead time (coast) (component F) has a duration of zero.

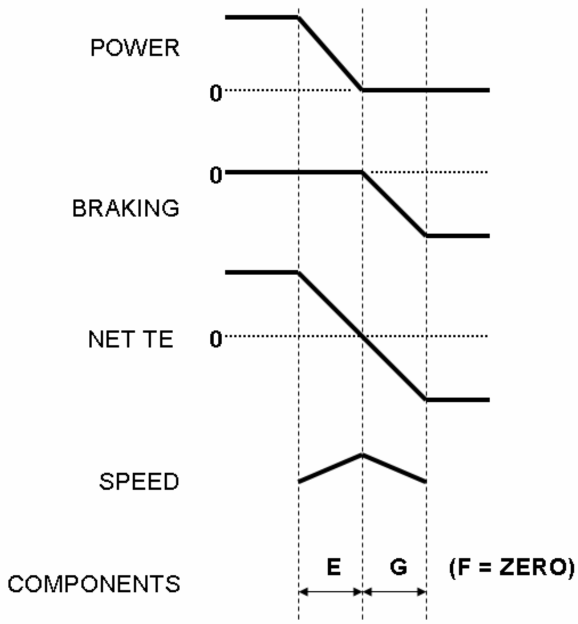

Figure C.2—Power-to-penalty brake transition, zero dead time (coast)

Figure C.3 illustrates an ideal penalty brake application. Power removal and brake build-up begin at the same instant and, in this ideal case, have the same (very short) time duration; thus, both power removal and brake build-up proceed simultaneously. In this case, power removal (component E) and brake build-up (component G) are arbitrarily assigned to the intervals of time before and after the zero crossing of the net tractive effort curve. Again, the dead time (coast) (component F) has a duration of zero.

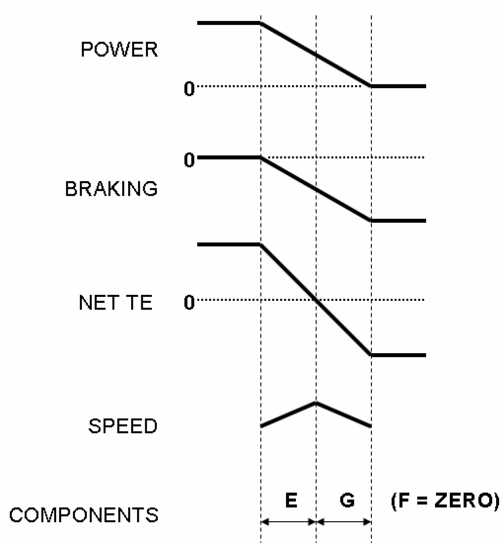

Figure C.3—Transition with ideal penalty brake application

Figure C.4 illustrates a more typical penalty brake application. Power removal begins at once, but there is a small delay before penalty brake begins to build up. The result is that the two transitions overlap to produce a multi-segment transition in the net tractive effort curve. Normally no attempt is made to handle such a multi-segment transition in detail; rather, an appropriate straight-line approximation, such as the one shown at the bottom of the figure, is used. Again, power removal (component E) and brake build-up (component G) are arbitrarily assigned to the intervals of time before and after the zero crossing of the (approximated) net tractive effort curve, and the dead time (coast) (component F) has a duration of zero. The figure represents only one of many possible combinations of time delay and time duration.

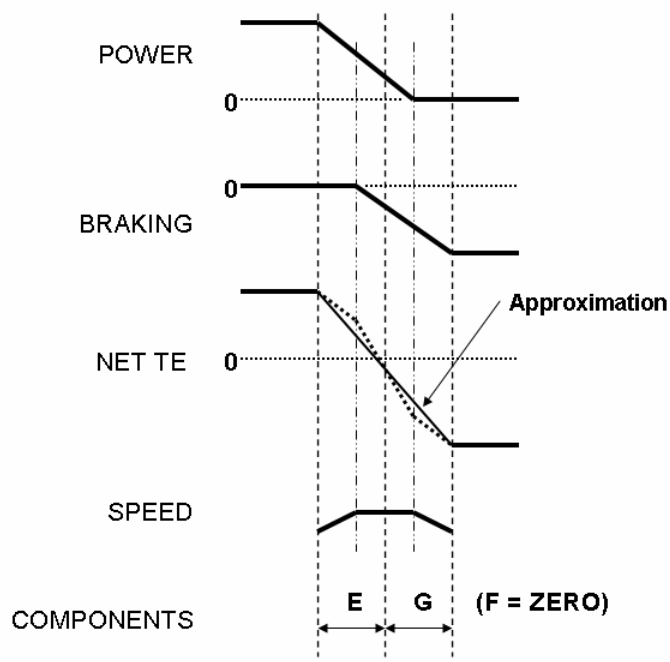

Figure C.4—Transition with typical penalty brake application

In practical calculations, it is common with any short, transitional component simply to use a constant tractive effort equal to an appropriate average value for the component concerned. This simplifies the calculations with negligible loss of accuracy.

Similarly, where the overall time duration of a series of transitional components (such as components E, F, and G) is short compared to the overall braking event, as with an penalty brake application, it is common to combine the components into a single component, which in turn, is approximated for computational purposes as described above.

Annex D

(informative)

Empirical determination of minimum brake rate (H)

It is possible to determine the minimum brake rate (H) applicable to the braking distance model through empirical means. The actual vehicles under consideration (in the case of a fleet composed of different types of vehicles, the worst case is used) are instrumented or measured under known conditions in controlled tests. These tests are typically conducted on dry, level, tangent track that has well known and accurate geometry. In addition, the weight of passengers is simulated with appropriate weights on board the vehicles.

Tests are performed that bring the vehicle up to a range of speeds as it passes a fixed location. A defined brake application to stop the train is performed for appropriate operational conditions. The data collected from the vehicle instrumentation, as well as field measurements, are used to determine the stopping distance used for component H of the model. Portions of component I can also be determined during these empirical tests, such as operation with a defined percentage of inoperative brakes, etc. This distance is evaluated in a number of ways. Initially, the distance is compared to several runs with the same initial velocity to determine the appropriate braking distance. Note that this is the performance characteristic of the vehicle, and the related brake factors (component I) are then added to the distance as described in 4.7.2.

In cases where level, tangent track is not available, the alignment that is used must have a precise and known geometry. Utilizing a TPC program that compensates for grades and curves, a non ideal alignment can be calibrated by comparing and adjusting the TPC parameters to closely match the empirical test. Once calibrated, the grades and curves may be removed from the TPC alignment data to run the train on the ideal alignment for minimum brake rate determination. The overall distance traveled may be interpreted as a constant deceleration to stop over the same alignment.

Data is collected as the vehicle is stopped using an appropriate brake application, manipulated per the operating and train handling rules of the authority having jurisdiction. In many cases, the vehicle's on-board event recorder system can be used to collect the necessary data. For example, the event recorder data based on each train's black box recorder, if available, logs key events in train operator performance and train dynamics that are useful in the analysis as listed above. Typical data recorded in these tests include:

a) Vehicle speed,
b) Acceleration/deceleration,
c) Brake pipe pressure, and if so equipped, the signal level on the control network or proportional control trainline (e.g., P-wire),
d) Control network latency, if applicable,
e) Brake cylinder pressure,
f) Service handle movement indication as an on/off signal,
g) Data record number,
h) Date and time (HH:MM:SS format),
i) Braking distance traveled,
j) Cab signal aspect, and
k) Explanation of event that triggered generation of the record (for speed or time changes).

Acceleration and deceleration can be read directly from the output of an accelerometer. The accelerometer range should be at least +/– 1G (9.8 meters per second squared [m/s^2] or 32.2 feet per second per second).

All field braking distance tests can be recorded for post processing. Time-dependent data (e.g., vehicle speed, etc.) should be referenced to a common time base to allow comparison among various data channels.

Annex E

(informative)

Samples of the application of the Guide for the Calculation of Braking Distances

This annex provides samples of the application of the Guide for the Calculation of Braking Distances. It is not representative of any actual property, but can be used as a reference of how each parameter in the braking model could be applied. For ease of understanding, a separate sample of the guide is shown or referenced for the following scenarios:

a) Passenger railroad (E.1)
b) Rail transit with acceleration runaway (E.2)
c) Rail transit without runaway acceleration (E.3)
d) Rail transit with profile to stopping target location (E.4)
e) Rail transit profile application (trip-stop based signaling) (E.5)
f) Communications-based train control (CBTC) (E.6)

Each sample will describe the type of signal system considered, the model parameters, and how their value affects the calculation of braking distance. Parameter listings A through J refer to the model components as illustrated in Figure 1 and explained in 4.1 through 4.8. In addition to the parameter listing, a graph of the resultant braking distance curve is shown to illustrate the differences in the applications. For simplicity, the effects of grades and curves are neglected in these samples.

NOTE— These graphs are for illustrative purposes only and are not drawn to scale.

E.1 Sample passenger railroad application

This sample is used to show how the braking distance model can be used to represent a generalized passenger railroad application that may fall under the jurisdiction of regulatory agencies. These would include properties that are part of the general system of railroads in North America.

For this sample, the train control system consists of continuous cab signals with enforcement of designated speeds at each code rate. No special train handling rules are considered such as split or multiple reduction of the train brake for stopping. Sample values for the braking model components are described below:

A. Maximum entry speed: Variations in this value can come from instrumentation error or speed sensors being out of calibration. Wheel inspections and speed calibrations are typically performed at prescribed intervals, and in some applications system errors are ignored. For the sample case, no increase in the measured speed was used.

B. Entry point: The entry point is simply the beginning of the measured braking distance, and is fixed by definition to the beginning of braking distance.

C. Distance traveled during reaction time: Although there are a wide variety of interpretations, this time is taken as eight (8) s for this sample. It is typically applied as a maintained-speed condition without considering the effect of grades and curves.

D. Runaway acceleration: Since this is generally reserved for applications that include automatic train operation or cases where propulsion system failures can cause similar effect, this parameter is “zeroed out” for this application.

E. Propulsion removal: This is a detailed braking distance parameter that is not always applied to this sample type. Therefore, it is assumed to be zero.

F. Dead time (coast): This is a detailed braking distance parameter that is not always applied to this sample type. Therefore, it is assumed to be zero.

G. Brake build up: Brake build up is a representation of the time it takes to build up braking effort. In simple models it can be combined into the minimum brake rate or braking rate factors. In this sample, the brake build up is assumed to be zero.

H. Minimum brake rate: For this sample, an overall brake rate is used. That implies that the minimum brake rate, the braking rate factors and the vehicle overhang are all included in one combined braking rate. The rate used in this sample is 0.393 m/s^2 (0.88 mphps).

I. Braking rate factors: See H, above.

J. Vehicle overhang: See H, above.

Figure E.1 illustrates the overall braking model for this sample.

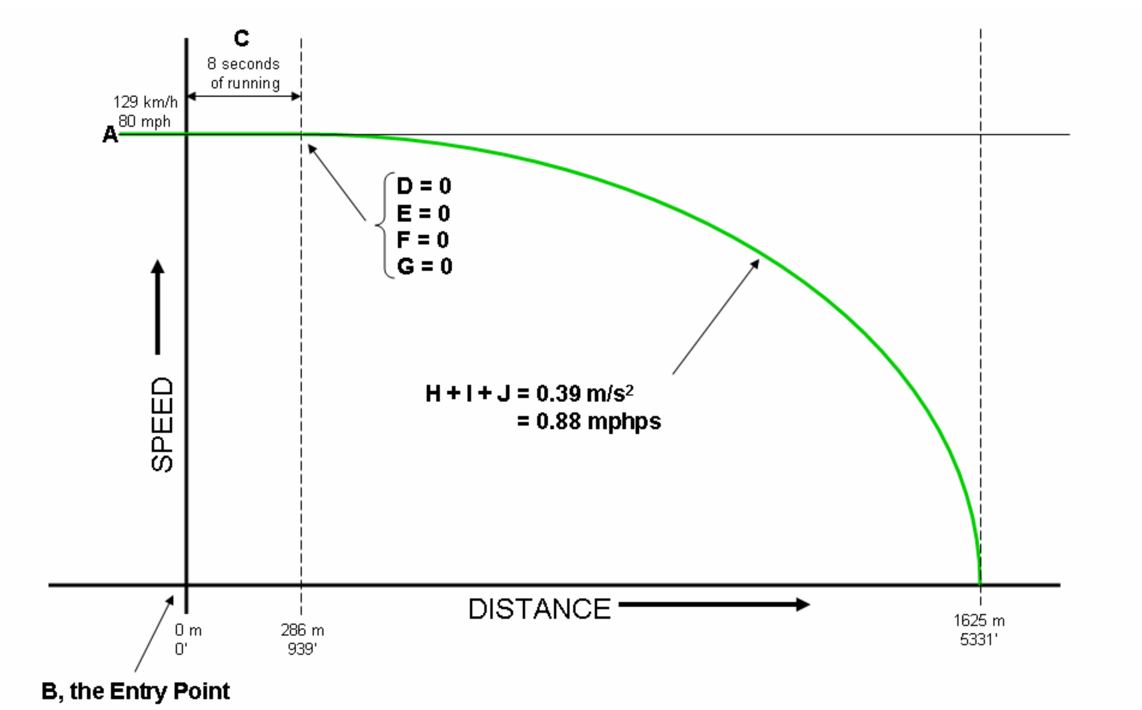

Figure E.1—Sample passenger with runaway acceleration

E.2 Sample rail transit application with runaway acceleration

For this sample, the train control system is assumed to consist of continuous cab signals with enforced speed commands at each code rate, and full ATO. Sample values for the braking model parts are described below:

A. Maximum entry speed: Variations in this value can come from instrumentation error or speed sensors being out of calibration. For the sample case, the increase in the measured speed was set to 5 km/h (3 mph). For example, the maximum entry speed for 80 km/h (50 mph) territory is 85 km/h (53 mph) in this sample.

B. Entry point: The entry point is simply the beginning of the measured braking distance, and is fixed by definition to the beginning of braking distance.

C. Distance traveled during reaction time: Just as in the passenger railroad sample there are a wide variety of interpretations of this factor. For this sample, the reaction time is set to six (6) s. The distance traveled is calculated as this maximum entry speed multiplied by the reaction time, a distance. It is also typically applied without respect for the effect of grades and curves.

D. Runaway acceleration: Since this sample includes automatic train operation, this parameter is included and is set, for this sample, to 0.29 m/s^2 (0.66 mphps) for two (2) s.

E. Propulsion removal: This detailed braking distance parameter can be applied to this sample. It is a way of smoothing the braking distance model as would be determined through actual field testing. For this sample, this parameter is set to one (1) s. This provides for a distance at the velocity achieved after runaway acceleration.

F. Dead time (coast): This detailed braking distance parameter can be applied to this sample. It is a way of modeling a part of equipment reaction to a speed enforcement condition. For this sample, this parameter is set to one (1) s. This provides for a distance at the velocity achieved after propulsion removal.

G. Brake build up: Brake build up is a representation of the time it takes to build up braking effort to the full minimum brake rate. It is a way of modeling a part of equipment reaction to a speed enforcement condition. For this sample, this parameter is set to two (2) s. This provides for a distance at the velocity achieved after dead time (coast).

H. Minimum brake rate: For this sample, an overall brake rate is used. That implies that the minimum brake rate and the braking rate factors are both included in one combined braking rate. The rate used in this sample is 0.626 m/s^2 (1.4 mphps).

I. Braking rate factors: See H, above.

J. Vehicle overhang: For this sample, this is the distance from the front of the vehicle to the first axle. The first axle is used to sense cab signal and is where the vehicle electrically enters a block. For this sample, the vehicle overhang is set to 3 m (10 ft).

Figure E.2 illustrates the overall braking model for this sample.

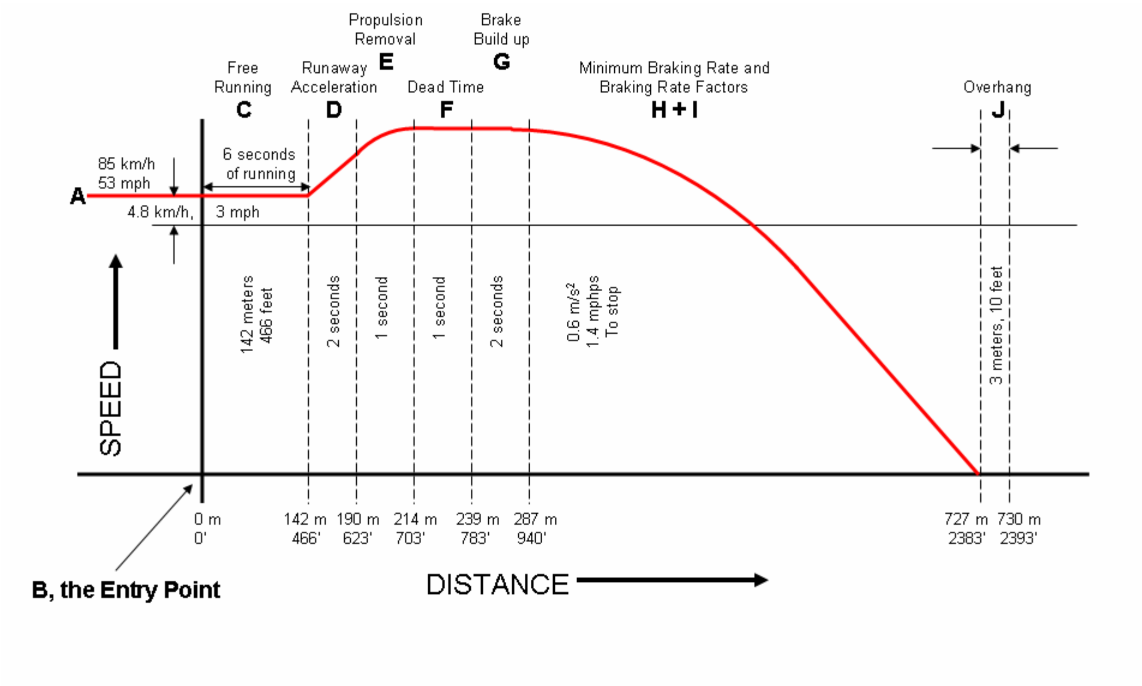

Figure E.2—Sample rail transit (with runaway) braking model

E.3 Sample rail transit application without runaway acceleration

For this sample, the train control system consists of cab signals with enforced speed commands at each code rate. No ATO is included, and for the purpose of this sample application it is assumed that there is no other facility that would require runaway acceleration. Sample values for the braking model parts are described below:

A. Maximum entry speed: Variations in this value can come from instrumentation error or speed sensors being out of calibration. For the sample case, the increase in the measured speed was set to 5 km/h (3 mph). For example, the maximum entry speed for 80 km/h (50 mph) territory is 85 km/h (53 mph) in this sample.

B. Entry point: The entry point is simply the beginning of the measured braking distance, and is fixed by definition to the beginning of braking distance.

C. Distance traveled during reaction time: Just as in the passenger railroad sample there are a wide variety of interpretations of this factor. For this sample, the reaction time is set to six (6) s. The distance traveled is calculated as this maximum entry speed multiplied by the reaction time in seconds providing a distance. It is also typically applied without respect for the affect of grades and curves.

D. Runaway acceleration: Since this sample does not include ATO or any other facility requiring it, this parameter is set to zero (0).

E. Propulsion removal: This detailed braking distance parameter can be applied to this sample. It is a way of smoothing the braking distance model as would be determined through actual field testing. For this sample, this parameter is set to one (1) s.

F. Dead time (coast): This detailed braking distance parameter can be applied to this sample. It is a way of modeling a part of equipment reaction to a speed enforcement condition. For this sample, this parameter is set to one (1) s. This provides for a distance at the velocity achieved after propulsion removal.

G. Brake build up: Brake build up is a representation of the time it takes to build up braking effort. It is a way of modeling a part of equipment reaction to a speed enforcement condition. For this sample, this parameter is set to two (2) s. This provides for a distance at the velocity achieved after dead time (coast).

H. Minimum brake rate: For this sample, an overall brake rate is used. That implies that the Minimum Brake Rate and the braking Rate Factors are both included in one combined braking rate. The rate used in this sample is 0.626 m/s^2 (1.4 mphps).

I. Braking rate factors: See H, above.

J. Vehicle overhang: For this sample, this is the distance from the front of the vehicle to the first axle. The first axle is used to sense cab signal and is where the vehicle electrically enters a block. For this sample, the vehicle overhang is set to 3 m (10 ft).

Figure E.3 illustrates the overall braking model for this sample.

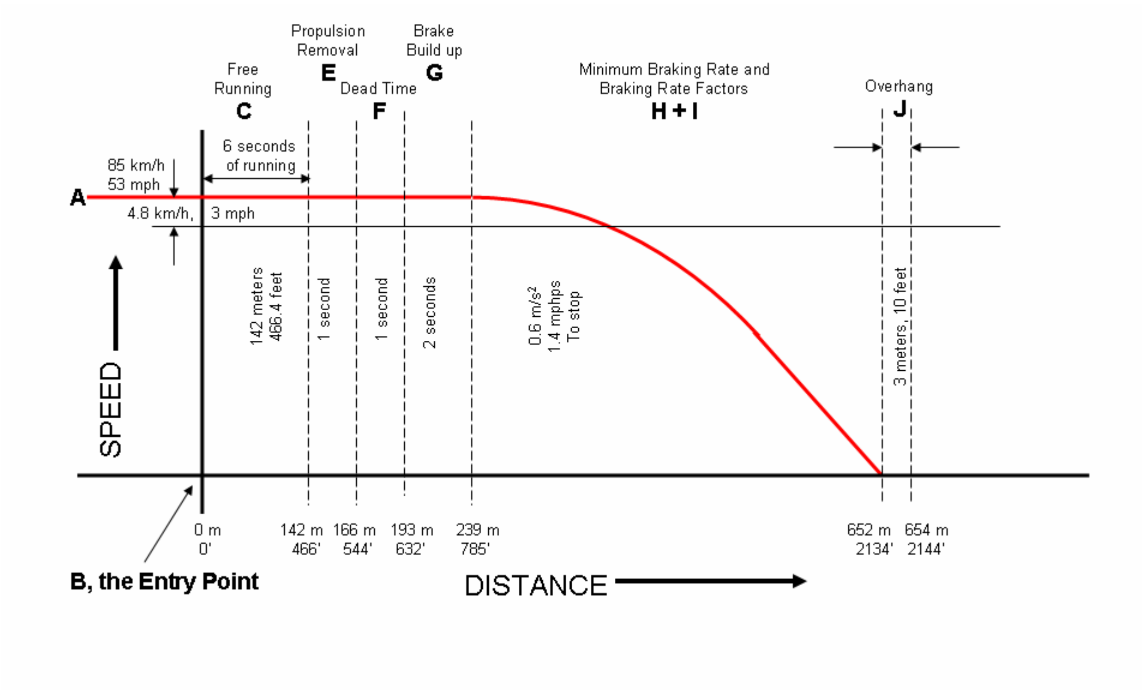

Figure E.3—Sample rail transit (with no runaway acceleration) braking model

E.4 Sample rail transit profile application

This sample is used to show how the braking distance model can be used in profile type train control. Profiling is the ability to enter sections of track where the train control system knows the location of the final target. With this knowledge, the train is allowed to motor into the section at the entering speed until reaches a point where braking is required to stop short of the target. In practice, the braking distance is computed in the reverse order of the other examples where the target location is “zero distance to go,” and the brake initiation point (or where, in this case, the operator is alarmed to the need to brake) is the calculated distance to stop with respect to the current speed.

For this sample, the train control system consists of wayside communications devices describing the operating requirements to the vehicle. In addition, full ATO is included. Sample values for the braking model parts are described below:

A. Maximum entry speed: Variations in this value can come from instrumentation error or speed sensors being out of calibration. For the sample case, the increase in the measured speed was set to 5 km/h (3 mph). For example, the maximum entry speed for 80 km/h (50 mph) territory is 85 km/h (53 mph) in this sample.

B. Entry point: The entry point is simply the beginning of the measured braking distance, and is fixed by definition to the beginning of braking distance.

C. Distance traveled during reaction time: Just as in the passenger railroad sample there are a wide variety of interpretations of this factor. For this sample, the reaction time is set to six (6) s. The distance traveled is calculated as this maximum entry speed multiplied by the reaction time, a distance. It is also typically applied without respect for the effect of grades and curves.

D. Runaway acceleration: Since this sample includes ATO, this parameter is included and is set to 0.29 m/s^2 (0.66 mphps) for two (2) s.

E. Propulsion removal: This detailed braking distance parameter can be applied to this sample. It is a way of smoothing the braking distance model as would be determined through actual field testing. For this sample, this parameter is set to one (1) s. This provides for a distance at the velocity achieved after runaway acceleration.

F. Dead time (coast): This detailed braking distance parameter can be applied to this sample. It is a way of modeling a part of equipment reaction to a speed enforcement condition. For this sample, this parameter is set to one (1) s. This provides for a distance at the velocity achieved after propulsion removal.

G. Brake build up: Brake build up is a representation of the time it takes to build up braking effort to the full minimum brake rate. It is a way of modeling a part of equipment reaction to a speed enforcement condition. For this sample, this parameter is set to two (2) s. This provides for a distance at the velocity achieved after coast dead time.

H. Minimum brake rate: For this sample, an overall brake rate is used. That implies that the minimum brake rate and the braking rate factors are both included in one combined braking rate. The rate used in this sample is 0.626 m/s^2 (1.4 mphps).

I. Braking rate factors: See H, above.

J. Vehicle overhang: For this sample, this is the distance from the front of the vehicle to the first axle. The first axle is used to sense cab signal and is where the vehicle electrically enters a block.For this sample, the vehicle overhang is set to 3 m (10 ft).

Figure E.4 illustrates the overall braking model for this sample.

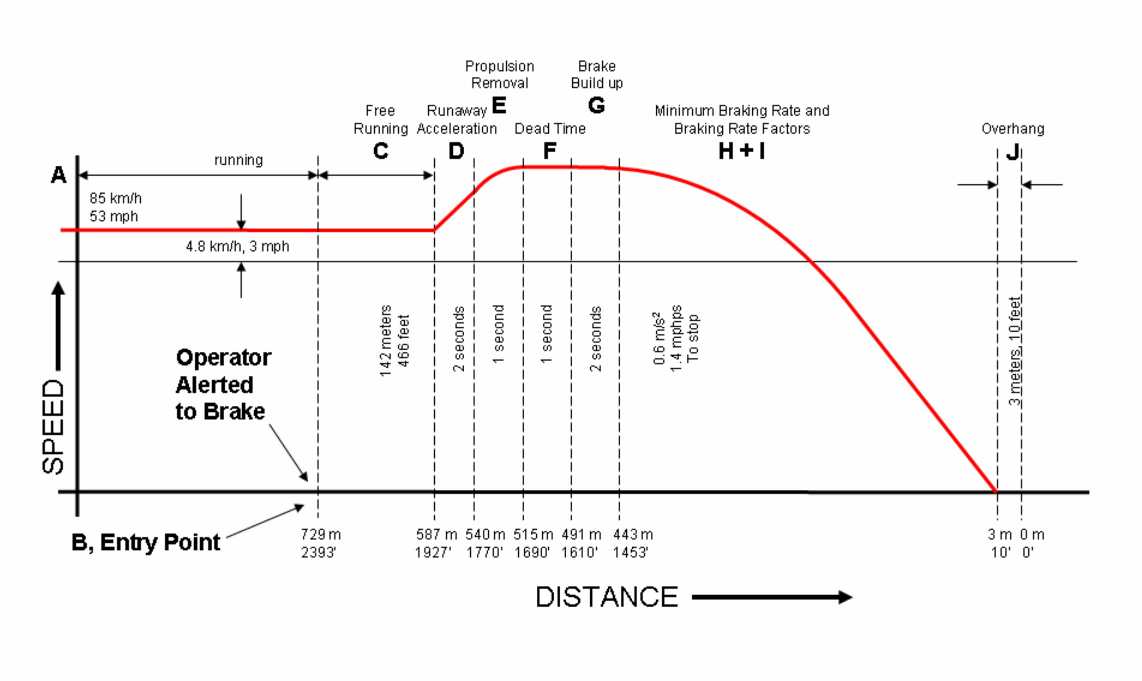

Figure E.4—Rail transit profile braking model

E.5 Sample rail transit trip-stop based signaling application

This sample is used to show how the braking distance model can be used in trip stop (tripper) type train control. In trip stop signaling, enforcement is achieved through the use of wayside trip arms that physically break the braking system continuity. Therefore, should a train pass an erect trip stop; an emergency brake application is initiated.

For this sample, the train control system consists of wayside trip stops interfaced with a signal system controlled from the field. There is generally no interaction from the train to the wayside devices other than train detection (through track circuits) and the trip arms of the trip stops. For the purpose of calculating stopping distance, this braking model is fairly simple. The application of this information is much more complex, and is not the purpose of this guideline. Sample values for the braking model components are described below:

A. Maximum entry speed: In these systems, it is not unusual to calculate the entry speed based on train acceleration from an adjacent station stop or previous constraint at its fastest rate until the train reaches the entry point. Thus, the maximum attainable speed subject to the capability of the train is used to determine the maximum entry speed. This speed could be greater than the actual track speed or normal operating speed.

B. Entry point: The entry point is simply the beginning of the measured braking distance (location of the trip stop mechanism), and is fixed by definition to the beginning of braking distance.

C. Distance traveled during reaction time: Although all systems require time to respond to changes in the environment, trip stop signaling typically uses little to no reaction time to simplify the model. Only the time needed to create braking effort after a trip would be included. For this example the distance traveled during reaction time is set to zero (0).

D. Runaway acceleration: For this example the distance traveled during runaway acceleration is set to zero (0).

E. Propulsion removal: Similar to reaction time, this parameter is typically not used in trip stop signaling and is set to zero (0) for this example. When used, it includes only the effect on the distance immediately after a trip.

F. Dead time (Coast): For this example the distance traveled during dead time (coast) is set to zero (0).

G. Brake build up: Similar to reaction time, this parameter is typically not used in trip stop signaling and is set to zero (0) for this example. When used, it includes only the effect on the distance immediately after a trip.

H. Minimum brake rate: For this sample, an overall brake rate is used. That implies that the minimum brake rate and the braking rate factors are both included in one combined braking rate. The rate used in this sample is 0.98 m/s^2 (2.0 mphps).

I. Braking rate factors: See H, above.

J. Vehicle overhang: For this sample, this is the distance from the front of the vehicle to the trip device mounted on the vehicle. For this sample, the vehicle overhang is set to 3 m (10 feet).

Figure E.5 illustrates the overall braking model for this sample.

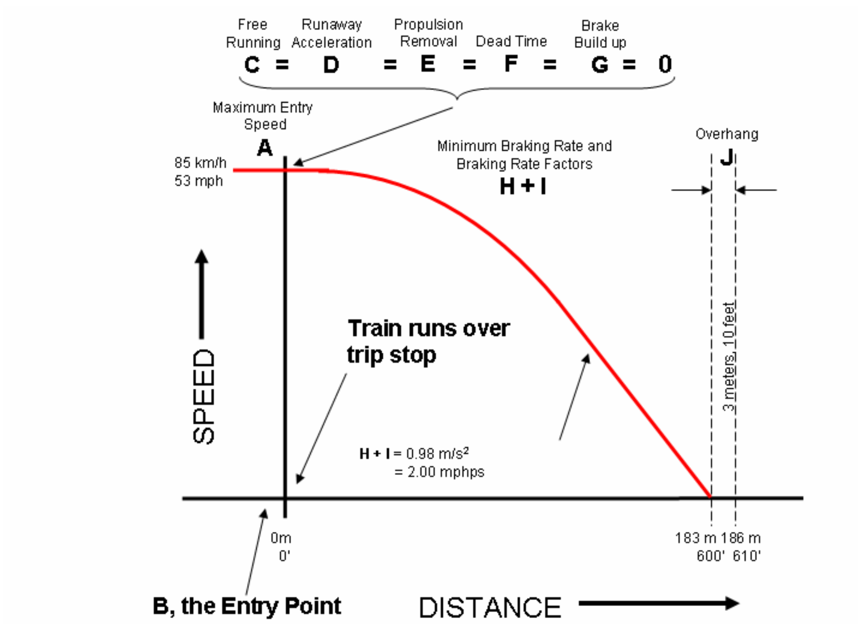

Figure E.5—Rail transit trip-stop based signaling braking model

E.6 Sample communications-based train control (CBTC) profile

Annex D of IEEE Std 1474.1-2004, IEEE Standard for Communications-Based Train Control (CBTC) Performance and Functional Requirements [B2], contains a figure (Figure D.1) depicting a “Typical Safe Braking Model.” This model is identical in concept to the model herein; however, slightly different terminology and designations of model components are used. For the convenience of those who may wish to merge the model of IEEE Std 1474.1-2004 with that herein, the following Table E.1 may prove useful.

Table E.1—Speed and position nomenclature comparisons, IEEE Std 1474.1-2004 and IEEE Std 1698-2009

Speed/position item	IEEE Std 1698-2009	IEEE Std 1474.1-2004
Maximum entry speed	A	Point X
Entry point	B	Point Y
Distance traveled during reaction time	C	A
Runaway acceleration	D	B
Propulsion removal	E	B
Dead time (coast)	F	Included in B and C
Brake build-up	G	C and D
Minimum guaranteed braking rate	H	E
Braking rate factors	I	Included in E
Vehicle overhang	J	Position uncertainty