Train Braking Distance Ratio: A Parameter for Railway Signal System Design

Yung-Cheng (Rex) Lai
Graduate Research Assistant
Railroad Engineering
University of Illinois at Urbana-Champaign
B-118 Newmark Civil Engineering Laboratory
205 N. Mathews Ave., Urbana IL, USA 61801
Tel: (217) 244-6063 Fax: (217) 244-0815
lai3@uiuc.edu

Christopher P.L. Barkan
Associate Professor
Director – Railroad Engineering Program
University of Illinois at Urbana-Champaign
1201 Newmark Civil Engineering Laboratory
205 N. Mathews Ave., Urbana IL, USA 61801
Tel: (217) 244-6338 Fax: (217) 333-1924
cbarkan@uiuc.edu

ABSTRACT

The conflict between freight trains and passenger trains is a challenging problem for railroad signal systems. Trains are often spaced at greater distances than required resulting in unused capacity, especially for passenger trains, which are much shorter than freight trains and at a given speed tend to need less stopping distance. Therefore, consideration of railway signal system design that accounts for the different stopping characteristics of freight and passenger trains is potentially useful.

In this paper we examine the variations in theoretical rail line capacity under a variety of operating scenarios. Capacity is expressed as the maximum throughput in trains per day. Six different operating scenarios are considered with various combinations of signal systems, operating practices and train types. It was found that the ratio of freight train stopping distance to passenger train stopping distance is an important variable in signal system design. When considering a new signal system, we differentiate this ratio into five categories followed by the recommended systems. We identified operational patterns in which both passenger and freight trains operate on a system using an “Advance Approach” 4-aspect signal system with block length based on either passenger train stopping distance or one half freight train stopping distance. In this system, both types of trains can operate at or above the capacity possible for either type train operating on a 3-aspect system designed only for freight or passenger train operation.

INTRODUCTION

Fixed block systems are the principal railroad signal system in North America. Block length and the number and type of signal aspects affect rail line capacity, and so do the length, weight, and speed of trains operating on the line. The design of the signal system is critically important to the capacity of the line, but is also dependent on the operating characteristics of the trains that operate on it.

The railway is divided up into a series of blocks with a minimum length determined by the longest stopping distance of trains normally operated on the line (which we refer to as the "design train"), with a margin of safety added to account for variations in train-braking characteristics, poor rail condition, and other circumstances that may affect stopping distance etc. (*1*). The greater the homogeneity in speed and stopping distance of trains operating on a line, the less difference between actual operating characteristics of the trains on the line and the characteristics the line is designed for. An example is rapid transit systems in which all of the trains may be nearly identical (*2*). Under these circumstances, block length and signal aspects can be precisely matched to the train operating characteristics and capacity maximized.

Conversely, the greater the heterogeneity in trains operating on a line, the more difficult it is to maximize capacity. For example, most heavy rail passenger lines in North America share trackage with a variety of other types of trains, both freight and passenger. The consequent variability in stopping distance, particularly of freight trains that may vary considerably in both length and speed, poses a significant challenge to designing a signal system that maximizes capacity.

It is ironic that at a time when freight railroads are increasingly experiencing capacity limitations, particularly in urban areas, that the substantial growth in commuter rail operations in many of these same areas is occurring. The result is potentially serious conflict between freight railroads that must maintain present and future ability to provide service to freight customers, and municipal regions faced with growing need for higher capacity passenger transportation. Therefore, it is important to explore and understand the technological options available in railway traffic control systems that may ease some of this conflict.

Because of the difference in stopping characteristics of freight and passenger trains, designing a signal system that maximizes capacity for one type of train, will generally not result in a system that maximizes capacity of the other. It should be noted that these differences in stopping distances need not be specific to freight or passenger trains, what is important are the trains' characteristics irrespective of type. The results we describe here can be applied to any type of trains with heterogeneous stopping characteristics. However, it is convenient and heuristically useful to refer to short, light trains with shorter stopping distance as "passenger" trains, and long, heavy trains with longer stopping distances as "freight" trains.

This paper examines the variations in theoretical rail line capacity under a variety of operating scenarios. Capacity (expressed in terms of trains per day) is calculated by developing a general equation for the time required for particular trains spaced by the minimum headway. The actual capacity of a line will be less than theoretical (*3,4*) and is subject to a variety of factors. The analysis presented here is intended to provide insight into the relative effects of different signal system designs and operating practices on capacity.

The principle objectives of this paper are to:

- Briefly review the effect of different stopping distances for freight and passenger trains on signal system design and capacity
- Consider the effect of several alternative signal system designs on harmonizing the differing requirements for freight and passenger systems
- Present a new parameter for evaluating signal system design

SIGNAL SYSTEMS

Once the performance characteristics of a particular train have been determined, it is possible to ascertain the required block length and train separation distance for different control systems. Block length and train separation are two of the parameters required to compute rail line capacity. As stated above, block length is determined on the basis of the safe stopping distance of the design train for a rail line, and the number of aspects in the signal system (*1,4*).

A drawback of fixed-block signal systems is that when a train is in any portion of a block, the system considers the entire block to be occupied and causes restricting aspects to be displayed by signals in following blocks, irrespective of the actual stopping distance of the particular following train. Trains are often spaced at larger distances than required which results in unused capacity (*4,5,6*). This is especially a problem for passenger trains. Because of their shorter stopping distance they can safely follow other trains more closely than freight trains, but because of the long blocks needed to accommodate the safe-stopping distance of freight trains they are separated by a greater distance than necessary.

Related to this is that despite their short length and stopping distances, passenger trains functionally occupy nearly as much trackage in fixed block systems as freight trains. As passenger train traffic increases, it has a substantial impact on capacity. Although it has been suggested that adding signal aspects increases capacity (*5,8*), this is not necessarily correct. Changes in block length must also be made and the correct type of aspects must be added to enable closer spacing of trains (*1,6*), and the improvement in capacity is still limited (*4*). Due to different stopping distances, different train lengths, and the operation of freight and passenger trains, it may be inefficient to design a signal system based only on freight train characteristics (*7*). A solution to the fixed block dilemma is moving or flexible blocks such as is possible with Positive Train Control systems (*4,7*); however, it remains to be seen how widely PTC will be adopted. Due to the widespread capital investment in existing track-circuit-based, fixed block systems, there is inertia to continue using these indefinitely in many areas.

Review of Signal System Options

3-Aspect System

In the 3-aspect system (FIGURE 1a), the three aspects are “Clear”, “Approach” and “Stop”. The only restricting aspect, other than “Stop” is “Approach”. Under Northeast Operating Rules Advisory Council (NORAC) rules, the indication for “Approach” is “Proceed prepared to stop at the next signal” (*9*). Since this is the only restricting aspect seen prior to encountering a “Stop” signal the distance between signals must be greater than or equal to the safe stopping distance. Therefore in a 3-aspect system, the block length is equal to, or greater than the safe stopping distance.

Trains must follow at least two block lengths behind another train to be sure of not encountering a restricting speed ("Approach") signal (*1*), consequently twice as much space as is necessary to maintain safety. Trains with stopping distances less than block length will be separated by more than twice the distance they actually need. The consequent long spacing between trains results in a considerable under-utilization of the line's potential capacity. This is not of much concern when a line is operating well below capacity, but if it is near capacity, even at some times in the day, it can have a significant impact on the frequency of service and/or the flexibility in scheduling needed to serve customer needs.

4-Aspect System with "Advance Approach" Signal

Adding another signal aspect allows block length to be reduced and trains to be more closely spaced and thus increase capacity. The other three aspects and indications are the same as in the three-aspect system, and a fourth aspect is added called "Advance Approach" (FIGURE 1b). In this system there are two restricting aspects besides "Stop", "Advance Approach" and "Approach". The indication for "Advance Approach" under NORAC rules is, "Proceed prepared to stop at the second signal" (*9*). Thus, when a train passes an "Advance Approach" signal, it has two blocks to come to a complete stop so their combined length must be greater than or equal to the safe stopping distance of the design train. Put another way, block length must be at least one half the safe stopping distance of the design train.

4-Aspect System with "Approach Limited" or "Approach Medium" Signals

Two other kinds of 4-aspect systems use "Approach Limited" or "Approach Medium" as the fourth aspect. As with the "Advance Approach" 4-aspect system, the other three aspects are the same as a 3-aspect system. The indication of an "Approach Limited" signal is "Proceed approaching the next signal at limited speed" (under NORAC rules, this is 45 mph for passenger trains and 40 mph for freight trains) (*9*). To ensure that a train can comply with the operating rules, block length must be greater than or equal to either, the distance required for the design train to decelerate from Normal speed to Limited speed, or the distance required from Limited speed to Stop, whichever is greater.

The 4-aspect system with "Approach Medium", is similar except the relevant speed is "medium" instead of "limited". The indication for "Approach Medium" is "Proceed approaching the next signal at medium speed" (30 mph under NORAC rules) (*9*). In a manner analogous to the case for "Approach Limited" described above, block length is equal to either, the distance required for the design train to decelerate from Normal to Medium speed, or the distance required from Medium speed to Stop, whichever is greater.

The sum of the required distance from Normal speed to Limited or Medium speed and the required distance from Limited or Medium speed to complete stop is typically greater than the safe stopping distance from Normal speed to Stop. Using an example based on work by Carlson (*10*), the distance required for a train to decelerate from 50 mph to medium speed (30 mph) is 3,333 feet, and the distance from 30 mph to 0 mph is 1,614 feet, whereas the safe stopping distance from 50 mph to 0 mph for the same train is 4,099 feet. The latter figure is 848 feet less than 3,333 + 1,614. Block length would be set at a minimum of 3,333 feet and twice block length is considerably longer than safe stopping distance of the design train.

It should be noted that replacing a 3-aspect system with a 4-aspect system with "Approach Limited" or "Approach Medium" signals does not necessarily improve capacity. In order not to observe a restricting signal, the gap between the leading and following trains should be at least 2 blocks in 3-aspect systems, and 3 blocks in 4-aspect systems (FIGURE 1a, 1b, 1c) (*5*). Therefore, if the block length in a 4-aspect system is more than 2/3 of block length in the 3-aspect, the capacity would actually decrease because the spacing between two trains is increased relative to the 3-aspect system (FIGURE 2).

For example, if the safe stopping distance is 3 miles, train length is 1.5 miles, and Normal speed is 50 mph, the maximum throughput (the maximum traffic flow that a rail line can theoretically accommodate under ideal conditions) is 160 trains per day. Replacing this system with a 4-aspect system with "Advance Approach", the maximum throughput would be 200 trains per day. However, replacing the 3-aspect system with 4-aspect system with "Approach Limited" or "Approach Medium" and a new block length that is 3/4 of the block length of the 3-aspect system, the maximum throughput would be 146 trains per day. Under these conditions, only the 4-aspect system with an "Advance Approach" signal would increase capacity relative to the 3-aspect system. . This difference in capacity of 4-aspect systems using "Advance Approach" versus "Approach Limited" or "Approach Medium" is characteristic, consequently the remainder of this paper only considers multiple aspect systems that use "Advance Approach" under NORAC rules as the fourth aspect.

MAXIMUM THROUGHPUT

There are a number of different ways to represent rail line capacity, such as "Operation Capacity" from the Air Brake Association (*4,11*), or parametric models such as were used by Prokopy et al (*12,13,14*). Different methods use different measures of capacity. In this research, we focused on both freight and passenger trains and use trains per day as the metric for line capacity.

The maximum throughput was used to represent rail line capacity because the relative capacity of different systems can be calculated mathematically and the effect of different signal and operating scenarios compared. Maximum throughput is the maximum traffic flow that a rail line can accommodate under ideal conditions. For purposes of our analysis, we made the following assumptions:

- All trains operate at the same "Normal" speed
- Train movement is directional
- No meets or passes
- Level terrain and consistent rail condition

To calculate the maximum throughput, it is necessary to compute the minimum headway which we define as the minimum interval between trains that trains can be dispatched without restricting their speed. For example, in a 3-aspect system, the minimum train spacing is two blocks (FIGURE 1a) (*5*) and in a 4-aspect system, the minimum spacing is three blocks (FIGURE 1b). Therefore, the minimum spacing is the number of aspects minus one, multiplied by block length. The units for block length are the same as safe stopping distance, miles . Similarly, train length is the length of the design train in miles. The minimum headway is hours per train. The minimum headway is calculated as follows:

$$H_{\min} = \frac{L_B(N-1) + L_T}{V}$$

Where: H_{min} = Minimum headway (hours)

L_B = Block length (stopping distance of the design train in miles)

L_T = Train length (miles)

N = Number of aspects

V = Track speed (mph)

The maximum throughput represents how much traffic a rail line can handle in one day under ideal conditions. It is computed by taking 24 hours divided by the minimum headway. Combined with the minimum headway formula, the maximum throughput is calculated as:

$$T_{\max} = \frac{24V}{L_B(N-1) + L_T}$$

Where: T_{max} = Maximum throughput (trains per day)

T_{max} represents the maximum traffic flow of freight and passenger trains, measured in trains per hour for each type.

Daily operation of passenger trains in commuter operation, typically involves two directional traffic peaks per day (morning & afternoon). If the line has freight service there will generally also be one or more peaks for freight trains. To the extent that these peaks do or do not conflict and allow speed and directional fleeting operation, they may reduce or enhance line capacity (*4*). T_{max} for freight trains is their theoretical maximum capacity during their peak traffic period, and T_{max} for passenger trains is their capacity during their peak period.

LINE CAPACITY ANALYSIS

We consider six different operation patterns to evaluate which is best for lines with both type of train (TABLE 1). The first and the second scenarios are the basic systems optimized for freight trains or passenger trains, respectively. These represent the base case conditions to which the others are compared. The third and the fourth scenarios consider operation of freight trains on the base passenger train system, and operation of passenger trains on the base freight train system, respectively. These illustrate the conflict between the different types of trains. The fifth scenario considers operation of both types of train on a modified 4-aspect base passenger train system. The sixth scenario considers operation of both types of train on 4-aspect freight train system.

The profiles of the freight trains and passenger trains used in analyses are as follows (*15*):

- 150-car Freight Train:

  Train Length: 1.5 miles

  Stopping Distance with 50 mph Track Speed: 8,000 feet

- 8-car Passenger Train:

  Train Length: 650 feet

  Stopping Distance with 79 mph Track Speed: 6,000 feet

These train characteristics are representative examples presented here for illustrative purposes. The principal results are general to any combinations of trains with the key parameter of interest being the different trains' safe braking distance.

Scenario One: Base Freight Train System

The base freight train system (BFTS) is a 3-aspect system where the block length is equal to the safe stopping distance for freight trains (FSD) (FIGURE 3a). The theoretical maximum throughput of this system is 265 freight trains per day (TABLE 2) which is the basis for comparison of the maximum throughput for freight trains operating on other systems considered below.

Scenario Two: Base Passenger Train System

As in scenario one, the base passenger train system (BPTS) is a 3-aspect system; however, the block length is equal to the safe stopping distance for passenger trains (PSD) instead of freight (FIGURE 3b). The maximum throughput for this system is 791 passenger trains per day (TABLE 2). This value is the basis for comparison of the maximum throughput for passenger trains operating on other systems.

Scenario Three: Operating Passenger Trains on Base Freight Train Systems

This scenario considers the impact of passenger trains on the BFTS. This system is the same as scenario one but the train types are different (FIGURE 4a). The maximum throughput for freight trains in this system is unchanged; however, the maximum throughput for passenger trains is 24.02% less (TABLE 3a) than passenger trains in BPTS (scenario two). Operating passenger trains on BFTS results in a substantial loss of rail line capacity.

Scenario Four: Operating Freight Trains on Base Passenger Train Systems

This scenario shows the effect of operating freight trains in a system in which block length is based on passenger train stopping distance (FIGURE 4b). The first rail line depicts freight train stopping distance longer than block length. Therefore, we have to either let the block length equal freight train stopping distance (which is the equivalent of scenario 3) or replace the signal system with a 4-aspect system with "Advance Approach" signal as depicted in the second and third rail lines in FIGURE 4b.

From TABLE 3b, the maximum throughput of this 4-aspect system for freight trains is 7.72% less than freight trains in BFTS (scenario one). Also, the maximum throughput of this 4-aspect system for passenger trains is 32.17% less than passenger trains in BPTS (scenario two). The impact of this scenario on line capacity is more severe than the impact of scenario three on line capacity.

Scenario Five: Operate Both Kinds of Trains on Base Passenger Train System With a 4-Aspect with "Advance Approach" Signal

This scenario reduces the conflict between freight and passenger trains operating on the same line. A 4-aspect system with "Advance Approach" is used with block length equal to PSD. By adhering to operating patterns permissible under NORAC rules, a passenger train need not begin braking immediately after passing a signal displaying an "Advance Approach" aspect. Since block length in this system equals PSD, the passenger train only needs to begin braking after passing a signal displaying "Approach". Consequently, the maximum throughput for passenger trains in this system is the same as in scenario two.

A 4-aspect system is used as long as freight train stopping distance is less than 2 times block length (FIGURE 5a). The maximum throughput of this system for freight trains is 7.72% less than scenario one (TABLE 4a). Although there is an impact on capacity, it is much less than scenario three or four. In fact if a current line has a 3-aspect system with block length equal to PSD, freight trains would almost certainly have to be operating at lower speeds or with constrained train weight in order to have sufficient stopping distance. Implementation of scenario five in this case might even increase freight train capacity on lines with these conditions because speed or length might be able to be increased.

To implement this system, the 3-aspect signal in the BPTS (scenario two) would be replaced with a 4-aspect system with block length unchanged (= PSD). Successful execution of scenario five would require passenger train operating crews to understand the stopping characteristics of their trains and respond differently to the "Advance Approach" indication than a freight train crew. Operators of freight trains would need to immediately begin braking when they pass an "Advance Approach" signal whereas passenger crews would not. It should be emphasized that although this use of the "Advance Approach" aspect is consistent with the current NORAC operating rules; it is different than the operating rules used by many railroads outside the eastern US.

Scenario Six: Operate Freight and Passenger Trains on 4-Aspect "Advance Approach" System Based on Freight Train Stopping Distance

Another alternative is to operate both kinds of trains on a 4-aspect freight train system with an "Advance Approach" aspect (FIGURE 5b). This system increases capacity for freight trains, but not necessarily for passenger trains. Block length is one half FSD due to the addition of the "Advance Approach" signal. The maximum throughput of this system for freight trains increases 20.08% and would remain the same for passenger (TABLE 4b).

This alternative can improve rail line capacity; however, it is generally more costly relative to BFTS because the number of signals is doubled. Under certain conditions discussed below the maximum throughput for passenger trains would be less than in scenario two. Rail lines with block length based on PSD are probably fairly rare. Scenario six is likely to be more common than scenario five because most freight railroads will already have 3-aspect systems with block length equal FSD in place.

Sensitivity Analysis of Different Maximum Stopping Distance

To further understand the relationship between train stopping distances and the effect on capacity of scenarios five and six, we conducted sensitivity analyses on the effect of different stopping distances (*10*) while other parameters were held constant (TABLE 5). The analysis showed that maximum throughput variations for freight and passenger trains varied with freight train stopping distance (FIGURE 6). Although only freight train stopping distances were changed, the variable of interest is actually the FSD:PSD ratio.

The change in maximum throughput for passenger trains relative to the baseline case is 0% (FIGURE 6a). For freight trains, change in maximum throughput increases up to FSD:PSD = 2. This is because as 2 x PSD approaches FSD the system converges on a 4-aspect freight train system.

When the ratio is higher than 2, it means 2 x PSD is less than FSD and capacity is reduced unless other changes are made. Under these conditions the 4-aspect system with block length equal to PSD will no longer provide adequate stopping distance for freight trains, and a new type of 5-aspect system is needed. It would employ a new, fifth aspect with the indication "Proceed prepared to stop at the third signal." Freight trains would thus have three blocks to come to a complete stop when passing this signal. This causes the change in maximum throughput to drop from 23.12% to nearly 0% greater than baseline because 3 x PSD is much longer than FSD if the ratio is only a small amount greater than 2. After this change, the change in maximum throughput for freight trains continues to increase with the FSD:PSD ratio, until 3 x PSD approaches FSD. However, it is expected that such high FSD:PSD ratios will be rare.

In FIGURE 6b, the change in maximum throughput for freight trains increases slightly with the FSD:PSD ratio. By contrast, the maximum throughput for passenger trains decreases rapidly. When FSD:PSD > 1.3, the change in maximum throughput for passenger trains is negative, that is, passenger train capacity is less than it would be for a system designed exclusively for passenger trains (scenario two).

If FSD:PSD is greater than or equal to 2, passenger trains are able to stop within one block. Therefore, the operating strategy would be the same as scenario five which means operators of freight trains would need to immediately begin braking when they pass an "Advance Approach" signal whereas passenger crews would not. The results from scenarios five and six would be the same when FSD:PSD = 2 because both operation patterns are functionally the same. For example, the change in maximum throughput for freight trains is 22% and for passenger trains are 0% for both scenarios. However, when FSD:PSD > 2, the change in maximum throughput for passenger trains is always 0% in scenario five, but it is negative in scenario six. This is because block length is longer than PSD when FSD:PSD >2 in scenario six and results in reduced capacity.

In the case of a modification to an existing line scenario six may be more costly to implement than scenario five, depending on the current block spacing. If block spacing approximates PSD then less modification will be required than in scenario five. Few if any additional signals would need to be installed although some additional signal heads might be required for the fourth aspect. Conversely, scenario six would require a doubling in the number of signals and modification in the track circuits to accommodate the shorter blocks needed.

DISCUSSION

New System Design

Procedures for railway signal system design should consider the characteristics of the different types of trains operating on a given rail line (*7*). We found that the FSD:PSD ratio is an important variable affecting signal system design.

The FSD:PSD ratio represents the difference between freight train stopping distance and passenger train stopping distance. When considering a new signal system, we differentiate this ratio into five categories:

a. FSD:PSD ≈ 1.0

b. 1 < FSD:PSD < 1.3

c. 1.3 < FSD:PSD < 2

d. 2 < FSD:PSD < 2.4

e. FSD:PSD > 2.4

In the first case, the ratio is close to 1 and both types of trains have similar stopping distances, hence, there is little difference and thus minimal conflict between freight and passenger trains due to this factor. A 3-aspect system with block length equal to FSD or PSD, whichever is greater, would be appropriate.

If the ratio is less than 1.3 but somewhat greater than 1, the systems in scenarios five and six are both acceptable. The length of the existing blocks would determine which was more economical. The optimal system depends on both capacity and cost. The value of the increased capacity would have to be compared to the additional cost to install and maintain the modified signal system to determine if the enhancement is cost effective.

In general the FSD:PSD ratio will be less than 2 and greater than 1.3. In this most common case, operating a system like scenario five is less costly than a system like scenario six. Also, the change in maximum throughput for passenger trains in scenario six is negative when the FSD:PSD ratio is greater than 1.3 (FIGURE 6b).

If the ratio is between 2 and 2.4, scenario six becomes less costly and the change in maximum throughput for freight trains is greater than that in scenario five. On the other hand, the change in maximum throughput for passenger trains is unacceptable in scenario six when the ratio is greater than 2.4. Therefore, scenario five becomes the better choice.

Add Commuter Trains on Freight Rail Line

Adding commuter trains on freight rail line may reduce freight train capacity on a line. However, the impact can be reduced if the commuter operator is willing to upgrade the signal system appropriately. From TABLE 3a, the maximum throughput for freight train is 265 trains per day and for passenger trains is 601 trains per day on the base freight train system. If the commuter operator is willing to upgrade the signal system to a 4-Aspect "Advance Approach" System (Scenario Six), the maximum throughput for freight trains will become 318 trains per day and for passenger trains become 791 trains per day (TABLE 4b). These results demonstrate that the capacity can be improved by 20.1 % and 31.6% respectively if both types of trains can be fleeted by type or speed.

CONCLUSION

We found that the ratio of FSD to PSD distance is an important variable for signal system design. If this ratio is close to 1, a 3-aspect system with the block length equal to the higher value of FSD and PSD would be appropriate. If the ratio is less than 1.3 and greater than 1, then scenarios five and six are both acceptable. If the ratio is greater than 1.3 and less than 2 , scenario five is likely to be the more feasible and cost-effective choice. If the ratio is less than 2.4 and greater than 2, scenario six becomes a better choice. Scenario five is recommended when the ratio is greater than 2.4.

The potential operating conflict between freight trains and passenger trains is an important issue in North America. This problem will become more severe as interest in operating passenger trains on freight railroads increases. It will often be sub-optimal for both freight and passenger operators to design railway signal systems that don't consider the characteristics of both kinds of trains. Both freight and passenger rail operators will benefit if the characteristics of both train types are considered in the railway signal system design.

REFERENCES

1. Phillips, E. J. *Railroad Operation and Railway Signaling*. Simmons-Boardman Publishing Corporation, Chicago, 1942.
2. Vuchic, V. *Urban Public Transportation.* Prentice-Hall, Inc., 1981
3. Chang, W. *A Study of the Traffic Capacity of Railways by the Application of the Relation between Delays to Train Operation and Number of Trains Operated.* University of Illinois at Urbana-Champaign, Illinois, 1941.
4. Pachl, J. *Railway Operation and Control*. VTD Rail Publishing, Mountlake Terrace, Washington, 2002.
5. Armstrong, J. *The Railroad: What It Is, What It Does.* Simmons-Boardman Books, Inc., 1998.
6. Dick, M.H. (ed.), Railway Track and Structures Cyclopedia, 8th Edition. Simmons-Boardman Publishing, New York, NY. 1955.
7. Dick, C. T. Impact of Positive Train Control on Railway Capacity. University of Illinois at Urbana-Champaign, Illinois, March 2000.
8. Armstrong, J. All About Signals. Trains., June & July 1957.
9. Lang, J. A. and K. Burkholder. NORAC Signal Rules. Northeast Operating Rules Advisory Council, April 1998. http://www.eastrailnews.com/ref/norac/index.html Accessed July. 20, 2003.
10. Carlson, F. Brakes – who needs 'em? Proceeding of the Air Brake Association, 2003.
11. The Air Brake Association. *Management of Train Operation and Train Handling*. The Air Brake Association, Chicago, 1972.
12. Prokopy, J. C. and R. B. Rubin. *Parametric Analysis of Railway Line Capacity*. Report DOT-FR-5014-2. FRA, U.S. Department of Transpiration, 1975.
13. Krueger, H. Parametric modeling in mail capacity planning. In: Proceedings of Winter Simulation Conference, Phoenix, Arizona, 1999.
14. Leilich, R.H. Application of simulation models in capacity constrained rail corridors. In: Proceedings of Winter Simulation Conference, 1998.
15. Walters, W. and K. Davis. Train Crossing Safety. 2001. http://esf.uvm.edu/sirippt/posters/train/train.html Accessed July. 20, 2003.

FIGURES

TABLES

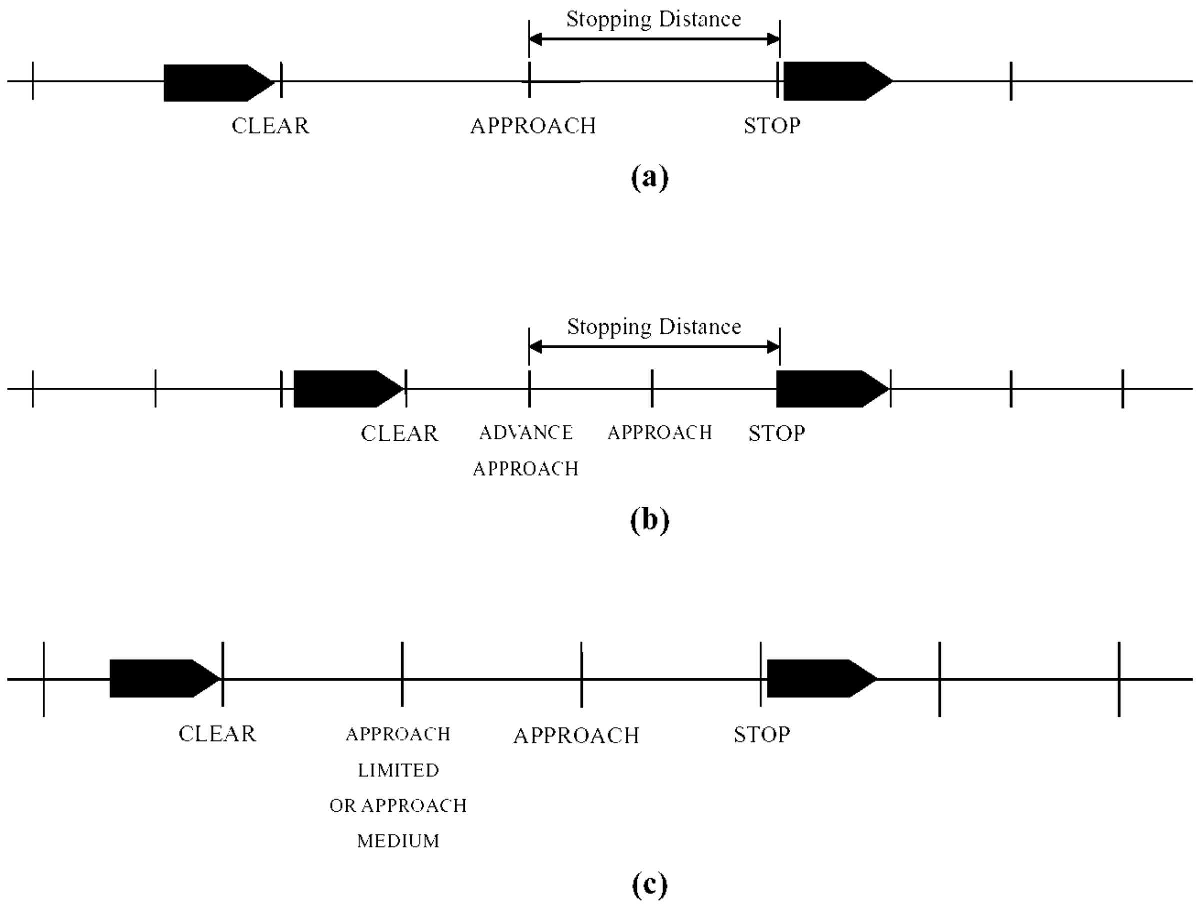


FIGURE 1 (a) 3-Aspect Signal System; (b) 4-Aspect System with “Advance Approach”; (c) 4-Aspect System with “Approach Limited” or “Approach Medium.”

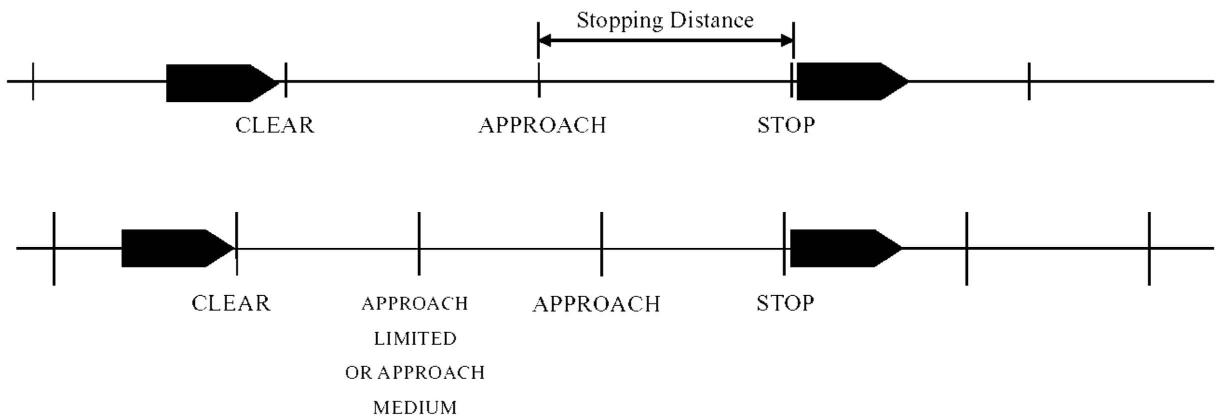


FIGURE 2 3-Aspect System vs. 4-Aspect System with “Approach Medium” or “Approach Limited”

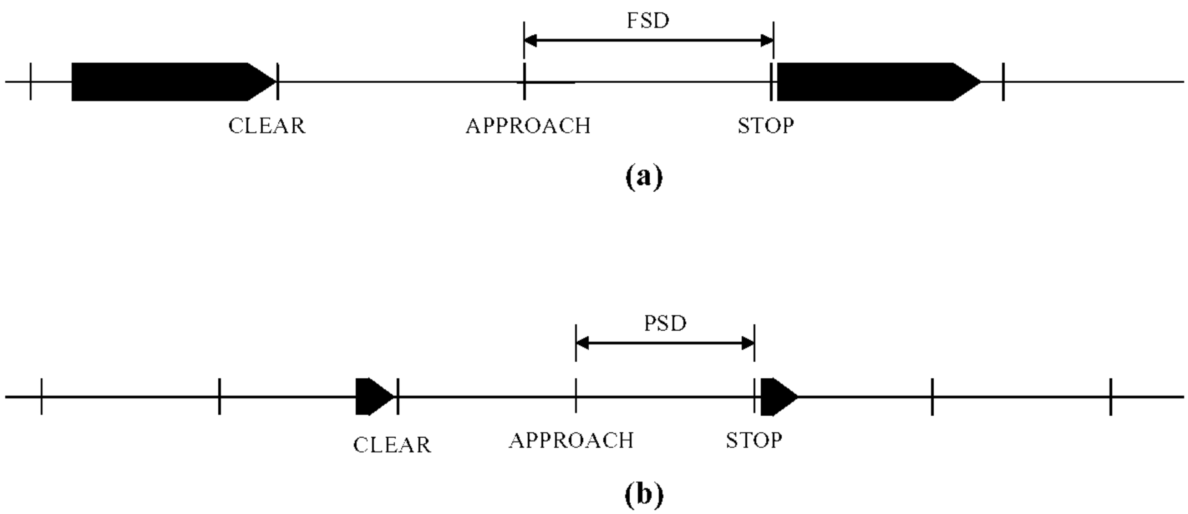


FIGURE 3 Operational Patterns of (a) Base Freight Train System (Scenario One); (b) Base Passenger Train System (Scenario Two).

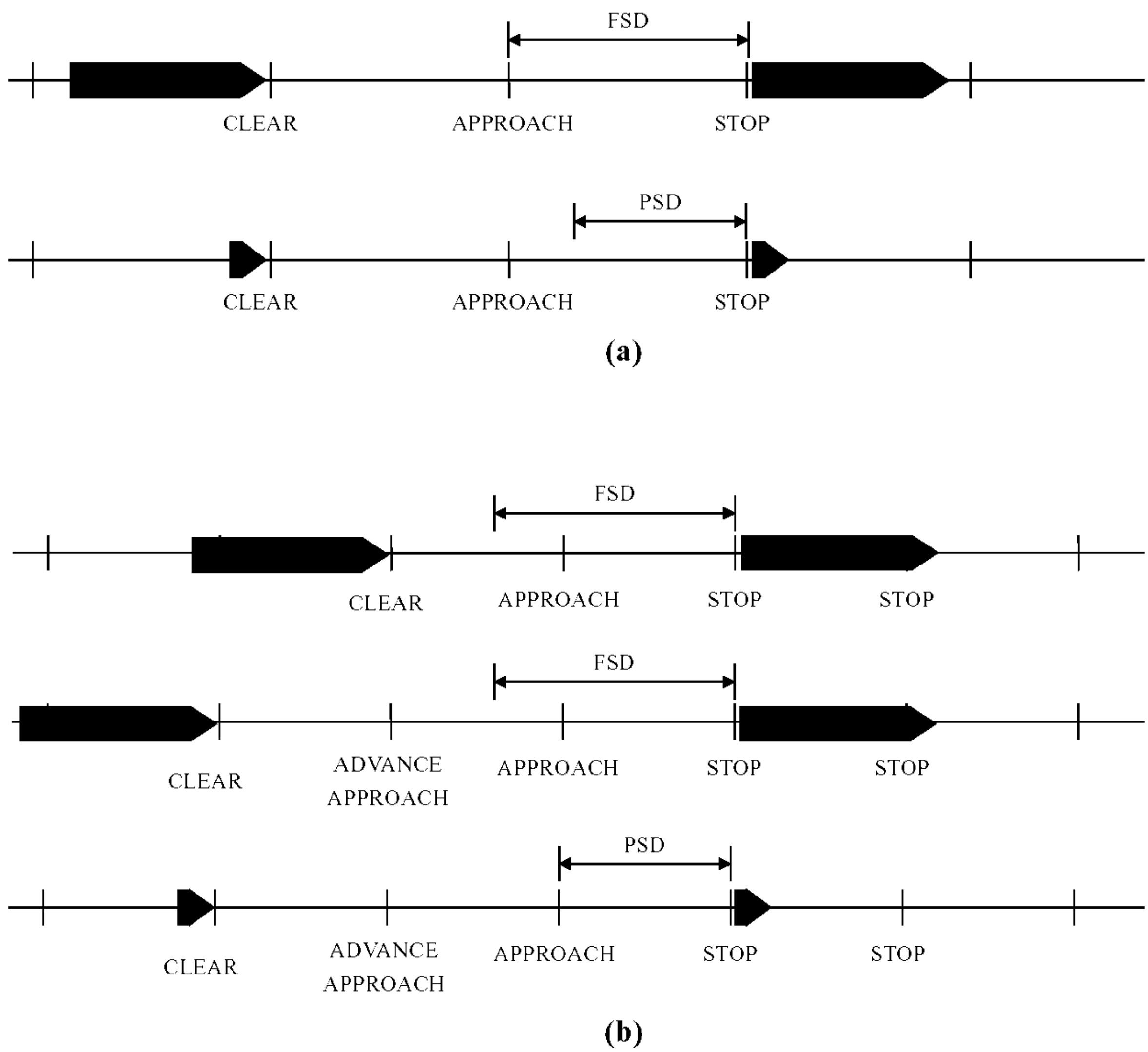


FIGURE 4 Operational Patterns of (a) Passenger Trains Operating on Base Freight Train System (Scenario Three); (b) Freight Trains Operating on Base Passenger Train System (Scenario Four).

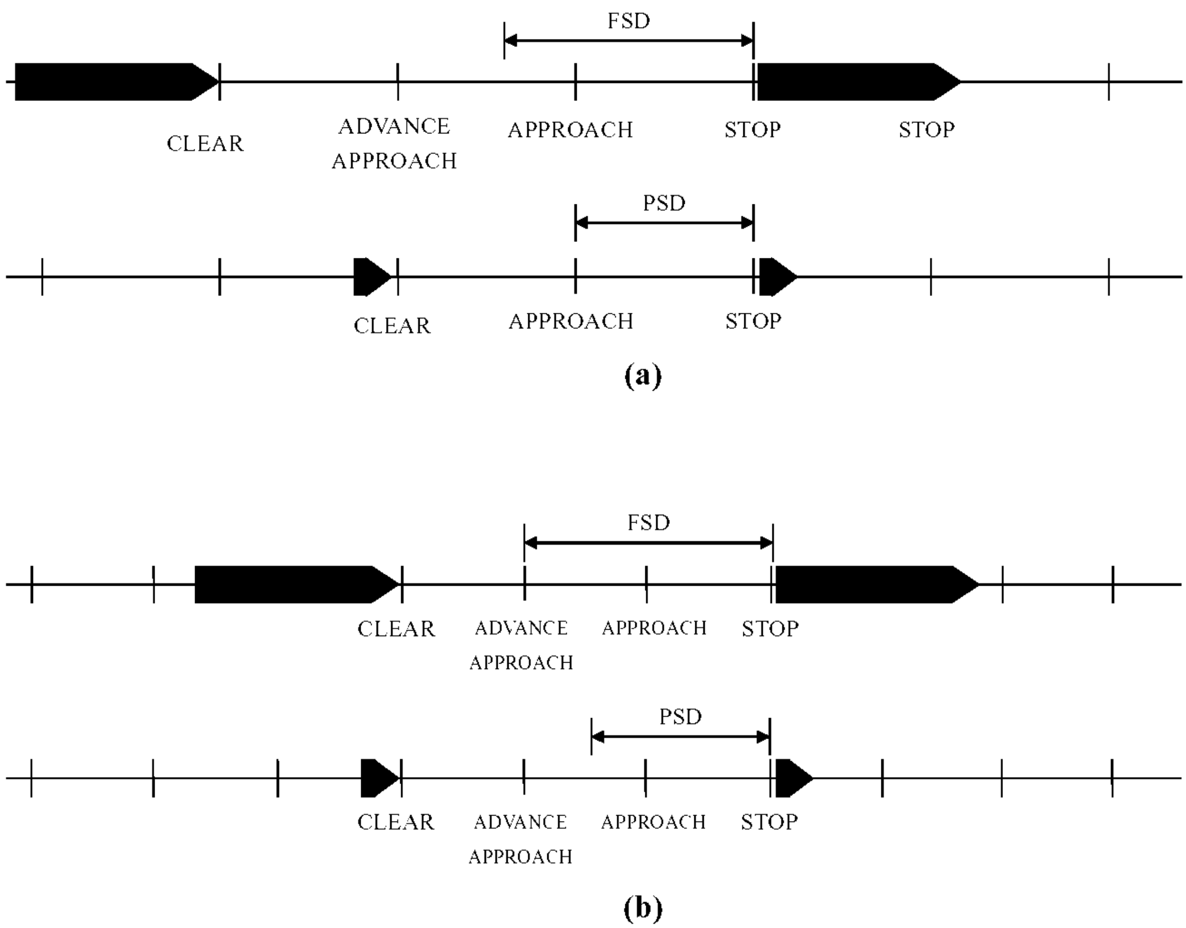
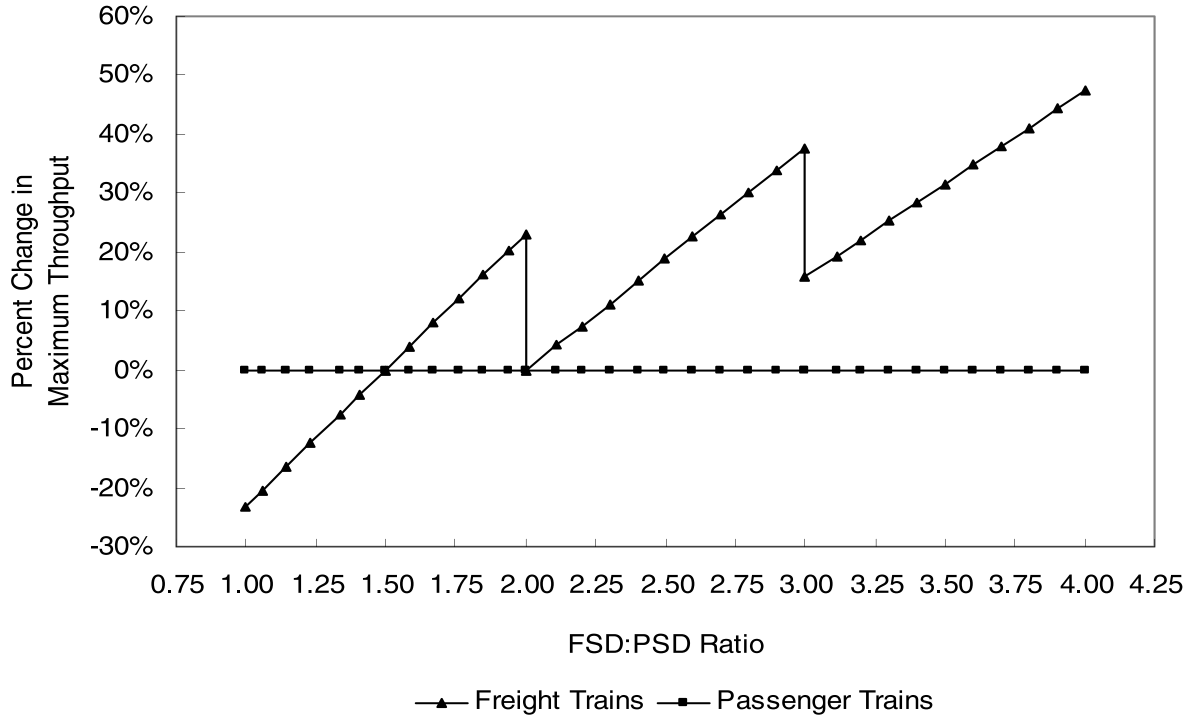
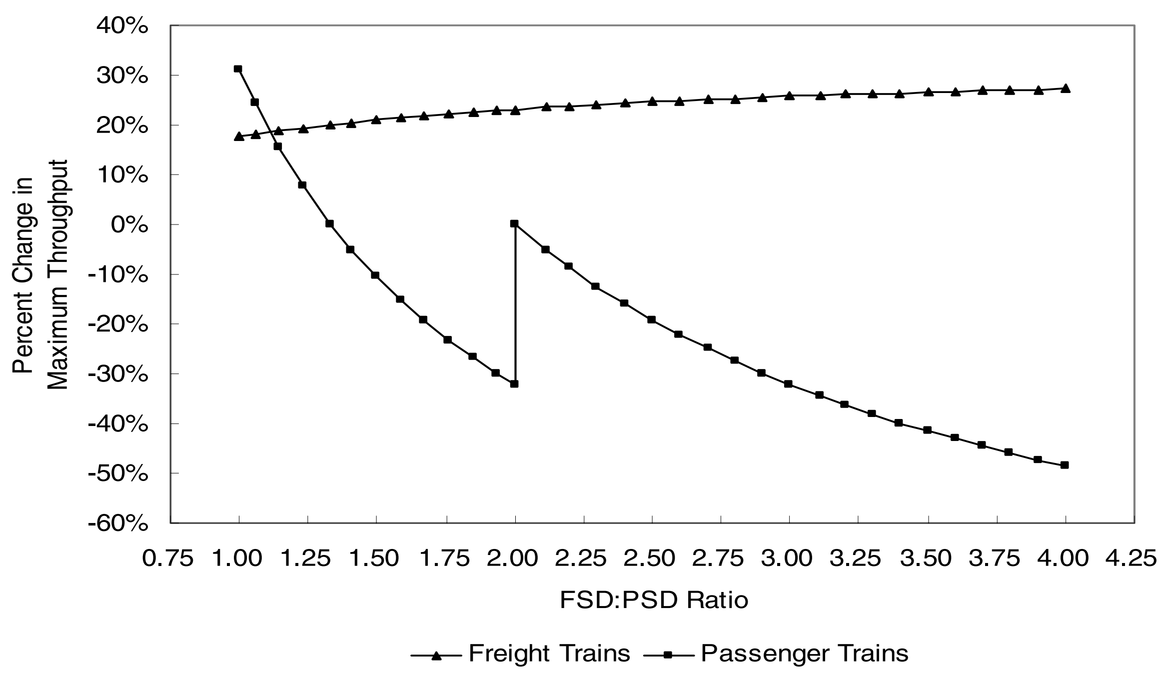


FIGURE 5 Operational Patterns of (a) Both Kinds of Trains on Base Passenger Train 4-Aspect System (Scenario Five); (b) Both Kinds of Trains on Base Freight Train 4-Aspect System (Scenario Six).



(a)



(b)

FIGURE 6 Sensitivity Analysis of Operation of (a) Both Kinds of Trains on 4-Aspect Passenger Train System (Scenario Five); (b) Both Kinds of Trains on 4-Aspect Freight Train System (Scenario Six).

TABLE 1 Signal and Operation Patterns

Scenario	Train Type	Block Length	Number of Aspects
1	Freight	FSD	3
2	Passenger	PSD	3
3	Passenger	FSD	3
4	Freight	PSD	3
5	Freight & Passenger	PSD	4*
6	Freight & Passenger	0.5 x FSD	4*

FSD = Freight Train Stopping Distance
PSD = Passenger Train Stopping Distance
* Passenger trains operate on 4-aspect system with “Advance Approach” but functions much like a 3 aspect system because of their ability to stop safely in one block length

TABLE 2 Signal System and Operational Parameters for Base Freight Train System (Scenario One) and Base Passenger Train System (Scenario Two).

Type of Train	Block Length (miles)	Number of Aspects	Track Speed (mph)	Minimum Headway (hours)	Maximum Throughput (trains/day)	Change in Maximum Throughput
Freight	1.52	3	50	0.091	265	0.0%
Passenger	1.14	3	79	0.030	791	0.0%

TABLE 3 Signal System and Operational Parameters for (a) Passenger Trains on Base Freight Train System (Scenario Three); (b) Freight Trains on Base Passenger Train System (Scenario Four).

(a)

Type of Train	Block Length (miles)	Number of Aspects	Track Speed (mph)	Minimum Headway (hours)	Maximum Throughput (trains/day)	Change in Maximum Throughput
Freight	1.52	3	50	0.091	265	0.0%
Passenger	1.52	3	79	0.040	601	-24.0%

(b)

Type of Train	Block Length (miles)	Number of Aspects	Track Speed (mph)	Minimum Headway (hours)	Maximum Throughput (trains/day)	Change in Maximum Throughput
Freight	1.14	3	50	0.075	318	20.0%
Freight	1.14	4	50	0.098	244	-7.7%
Passenger	1.14	4	79	0.045	537	-32.2%

TABLE 4 Signal System and Operational Parameters for (a) Both Kinds of Trains on Base Passenger Train 4-Aspect System (Scenario Five); (b) Both Kinds of Trains on Base Freight Train 4-Aspect System (Scenario Six).

(a)

Type of Train	Block Length (miles)	Number of Aspects	Track Speed (mph)	Minimum Headway (hours)	Maximum Throughput (trains/day)	Change in Maximum Throughput
Freight	1.14	4	50	0.098	244	-7.7%
Passenger	1.14	4*	79	0.030	791	0.0%

(b)

Type of Train	Block Length (miles)	Number of Aspects	Track Speed (mph)	Minimum Headway (hours)	Maximum Throughput (trains/day)	Change in Maximum Throughput
Freight	0.76	4	50	0.075	318	20.1%
Passenger	0.76	4*	79	0.030	791	0.0%

* Passenger trains operate on 4-aspect system with "Advance Approach" but functions much like a 3 aspect system because of their ability to stop safely in one block length

TABLE 5 Values for FSD, PSD and FSD:PSD Ratio Used in Sensitivity Analysis

FSD (miles)	PSD (miles)	FSD:PSD Ratio
1.136	1.136	1.000
1.200	1.136	1.056
1.300	1.136	1.144
1.400	1.136	1.232
1.515	1.136	1.334
1.599	1.136	1.408
1.699	1.136	1.496
1.801	1.136	1.585
1.901	1.136	1.673
2.000	1.136	1.761
2.100	1.136	1.849
2.200	1.136	1.937
2.272	1.136	2.000
2.400	1.136	2.113
2.500	1.136	2.201