

Impact of Passenger Train Capacity and Level of Service on Shared Rail Corridors with Multiple Types of Freight Trains

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The North American rail network is experiencing capacity constraints because of traffic growth and increases in traffic heterogeneity. Further increases in speed and frequency of passenger service will combine with record levels of crude oil carload and intermodal traffic to demand even more network capacity. Understanding the interaction between passenger trains and this mix of freight traffic can help railroads develop effective strategies to improve network capacity and mitigate delay. Although previous research has focused on heterogeneity between two train types, actual rail lines are subject to multiple classes of trains such as passenger, priority intermodal, manifest, and bulk freight trains. To understand this environment better, this study presents a capacity evaluation process to analyze the performance of lines serving three train types. Although any combination of three train types can be considered, this study focuses on the interaction of passenger, intermodal, and bulk freight trains. The presented process can estimate the maximum train throughput for a particular corridor based on the unique characteristics and required level of service for each train type. A case study demonstrates three potential uses of the capacity evaluation process: the impact of additional passenger trains on lines with multiple types of freight trains, the sensitivity of capacity to the required level of service of each train type, and the effect of train speed heterogeneity between three types of trains. The results of this study provide better insight into the interaction of multiple train types and will aid railroads in maximizing the utility of their network.

Congestion on the rail network has increased in recent years because of changes in both freight traffic patterns and passenger rail transportation demand. In 2013, railroads in the United States set records for both intermodal and crude oil carloads. The growing freight demand in both of these sectors is handled by two different train types, priority intermodal and bulk unit trains, introducing more traffic heterogeneity to the current network. Previous research showed that heterogeneity between intermodal and bulk freight trains is a source of network congestion and delay (1, 2). A similar mechanism governs the expansion of state-supported passenger service on regional short-haul intercity corridors. On the basis of state and local government interest, planning studies, recent equipment purchases, and infrastructure investment, it is expected that the frequency and speed of passenger service on freight corridors will continue to increase. Just as in the

case of two freight trains, speed heterogeneity between passenger and freight trains disrupts the operation of existing freight traffic when passenger trains are added to a line (3, 4).

Previous research was limited to describing the heterogeneity effects of two train types: passenger trains and freight operations, or intermodal and bulk trains. Actual rail lines are subject to multiple classes of trains with passenger trains operating alongside both priority intermodal and bulk unit trains on the same infrastructure. To better capture this scenario, this research expands on past efforts to develop a framework to evaluate the effect of heterogeneity between three train types on delay, level of service (LOS), and line capacity. Although any combination of three train types can be considered, this study focuses on the interaction of passenger, intermodal, and bulk freight trains to answer several key research questions. Case studies demonstrate how the impact of adding passenger trains varies depending on the mixture of freight trains currently operating on the line, how the two classes of freight trains are affected differently by the addition of a passenger train, how the LOS of particular train types can govern line capacity under different combinations of train types, and how the benefits of eliminating speed heterogeneity vary with the mixture of freight trains on the line.

BACKGROUND

Quantifying the impact of heterogeneity on railway capacity has been a focus of railway operations researchers. In Europe, Carey proposed several headway-related indexes to measure traffic heterogeneity at a single location on a network (5). Vromans et al. developed two representative indexes that take the headway interval of two consecutive nodes in a network (stations, yards, or junctions) into account (6). Landex and Nielsen combined the two indexes developed by Vromans and created a single compact index (7). However, even though it is an appropriate index for the analysis of passenger corridors with directional traffic, the computational process relies on a predetermined train schedule. Thus it is not applicable for freight-dominant corridors in North America, where the planned train schedules are continually adjusted in real time to set meets and passes on a single track according to the current status of the network.

With the lack of a true train timetable, use of train delay to assess the capacity impact of train heterogeneity is more appropriate for the North American rail system. Krueger suggested that the impact of speed and priority variation between trains can be captured by the average speed and the expected number of meets and passes (8). Harrod used a train-dispatching optimization model to capture the effect of passenger operation on a freight corridor and prove the

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Transportation Research Record: Journal of the Transportation Research Board, No. 2475, Transportation Research Board, Washington, D.C., 2015, pp. 63–71.
DOI: 10.3141/2475-08

negative impact of frequency and speed of passenger trains on freight traffic delay (9). To evaluate the impact of passenger trains on freight traffic, Sogin et al. analyzed the incremental impact of additional passenger trains by simulation and discovered that the average delay increases with the number of added passenger trains (3, 10, 11). Lai et al. proposed a base train equivalent unit to quantify the relative effect of traffic heterogeneity on line capacity (12). Dingler et al. used simulation to investigate the relationship between delay and traffic mixture under different traffic volumes (1). Shih et al. examined several infrastructure strategies that can be used to improve the line capacity of shared corridors (13). Also, Shih et al. developed an optimization model to maximize the line capacity of shared corridors by determining the optimal location of sidings (14).

These studies have several shortcomings and limitations. The factors derived by Krueger can be applied to a complex traffic mixture, but the specific interactions between multiple train types cannot be directly observed. Sogin et al. (3, 10, 11) investigated a single type each of passenger and freight trains, whereas Dingler et al. (1) and Lai et al. (12) only focused on two types of freight trains. Since only two train types are involved, these studies could not investigate the relative impact of traffic heterogeneity between multiple train types. Moreover, the aforementioned studies do not consider the effect of establishing a specific LOS for each individual train type. For a variety of railway business reasons, certain train types may be more sensitive to delay and demand a higher LOS than others. Krueger did establish the overall LOS of the corridor, but it does not represent the desired performance of specific types of traffic (8).

This study addresses these limitations by proposing a method to depict the interaction of multiple types of trains and account for the LOS of individual train types. In the following section, the

methodology of the capacity evaluation process is described. Then the developed process is applied to a case study with three types of trains to model the relationship between rail line capacity, traffic mixture heterogeneity, and the required LOS for each train type.

METHODOLOGY

The capacity evaluation process presented in this study requires train delay data as an input. For this study, the delay data were obtained from the rail traffic controller (RTC) simulation of a hypothetical rail line. However, actual train delay data from lines with different traffic mixtures or outputs of other simulation platforms could also be used in the process.

To develop the required train delay data, an experimental design was created to select traffic scenarios for RTC simulation analysis. The scenarios were then simulated with given train characteristics to obtain corresponding train delay information. A polynomial regression model was constructed based on the delay output. The delay model was later transformed into a model for line capacity according to the desired LOS for each train type. Each step in this process is described in the following sections (see Figure 1).

Experimental Design

The general capacity evaluation process can be applied to lines with any number of train types. This study examines three train types because the interactions between train types are easier to visualize and there are fewer combinations to consider.

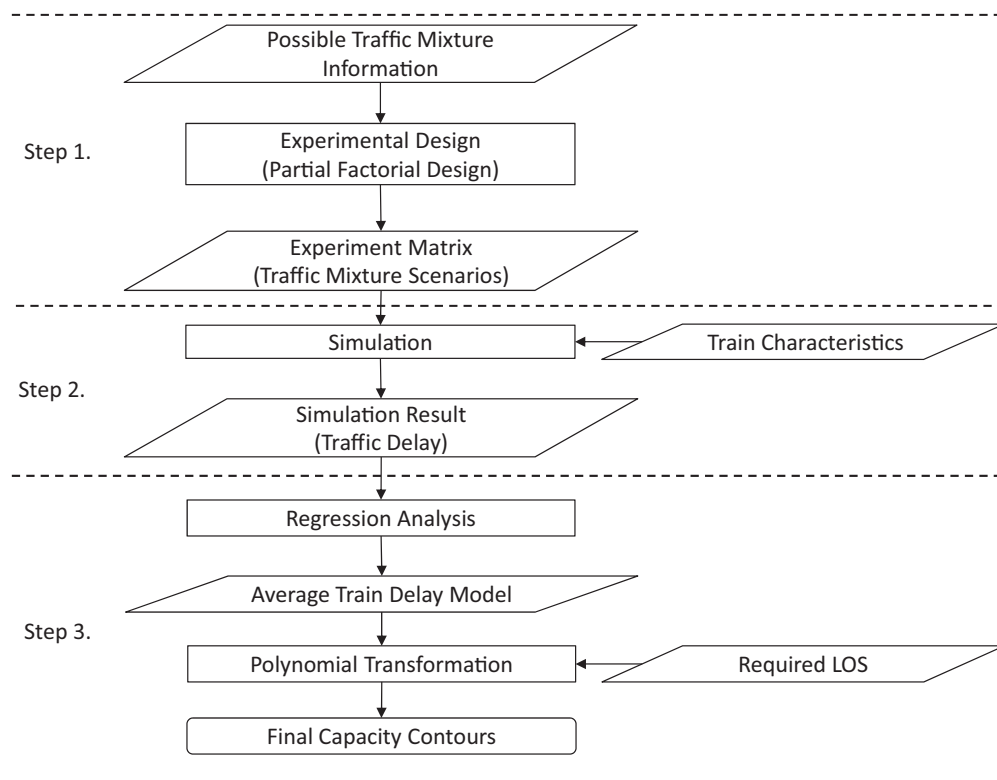


FIGURE 1 Flowchart of simulation-based capacity evaluation process.

TABLE 1 Simulation Parameters: Train Characteristics

Parameter	Passenger Trains	Intermodals	Units
Locomotives	2 GE P42	3 EMD SD 70	3 EMD SD 70
Number of cars	7 articulated Talco cars	93 platforms	115 loaded hopper cars
Length (ft)	500	5,659	6,325
Weight (tons)	800	5,900	16,445
Horsepower/ton	15.4	3.64	0.78
Maximum speed (mph)	75	50	35
Scheduled stops	30-mi station spacing	None	None

Although any combination of three train types can be used, traffic composed of two types of freight trains and one type of passenger train was selected to represent the general traffic mixture on shared corridors for this study. To provide the greatest contrast between train types, the freight traffic is composed of intermodal and bulk unit trains. The intermodal train type is used to represent freight trains with higher speed, priority, and LOS. The unit train type represents freight trains with lower speed, priority, and LOS. The attributes of each type of freight train (Table 1) were set according to the characteristics of train types in the Association of American Railroads *National Rail Freight Infrastructure Capacity and Investment Study* (15).

Passenger trains are modeled after those used in short-haul regional intercity service subject to most efforts to increase passenger service speed and frequency. The particular passenger train consist matches those used for the Amtrak Cascades service in the Pacific Northwest. For the purposes of this study, the trains are scheduled to make station stops for 3 min every 30 mi.

The route infrastructure is a 242-mi single-track line with sidings spaced at a uniform 10 mi, detailed as follows:

- Total length = 242 mi;
- Siding spacing = 10 mi;
- Average signal spacing = 2 mi;
- Turnout speed = 45 mph;
- Traffic control system = 2-block, 3-aspect centralized traffic control; and
- Grade and curvature = both 0%.

These infrastructure characteristics emulate the properties of a busy, single-track line. Using a general route can help avoid extra variation from specific curvature and grade profiles in order to isolate the more fundamental relationships between delay and traffic mixture.

An experiment matrix of simulation scenarios is needed to obtain a delay response surface for the line under study across a range of traffic volumes and mixtures. Partial factorial design is used to select a subset of simulations from a full factorial design to eliminate redundant trials (16). This partial factorial subset has a similar delay response to that of the original experiment but is more efficient to run since it uses fewer simulation scenarios. The factors and corresponding levels used in the partial factorial design are given in Table 2. Three parameters are used to characterize the traffic conditions: total train volume, number of passenger trains, and unit trains as a percentage of total freight traffic (percentage of unit trains). The last value provides a measure of the level of freight train heterogeneity on the

TABLE 2 Factors Involved in Experiment

Factor	Value		
	Low	Medium	High
Total volume (trains per day)	6	22	38
Number of passenger trains per day	0	6	12
Percentage of unit trains	0	50	100

route and, given values for the other two factors (total volume and number of passenger trains), allows for quick calculation of the number of intermodal and unit freight trains. The number of passenger trains and percentage of unit trains also facilitate the analysis of the incremental impact of additional passenger trains on different freight traffic mixtures. Two constraints are applied when the experiment matrix is created: the number of passenger trains cannot exceed the total traffic and for each train type the number of trains in each direction must be balanced. The partial factorial design contains 24 traffic scenarios (compared with 243 in the full factorial design).

Rail Traffic Controller

RTC software enables detailed simulation of rail traffic performance in a stochastic train operating environment. RTC considers factors related to both infrastructure and traffic properties, including maximum allowable track speed, signal system, train schedule, locomotive type, and railcar characteristics. The fundamental dispatching logic used by RTC to resolve movement conflicts is to delay or reroute one or more trains based on accumulated train delay and priority. Consideration of train priority reflects railway business objectives and generates more realistic results. This dispatching logic makes RTC the most commonly used line capacity simulation tool for Class 1 railroads in North America.

In the conduct of the RTC simulations for the experimental design, the departure pattern of trains is randomized to represent possible variation in train schedules. A 30-day simulation for each scenario is repeated six times in RTC with different randomization values to generate enough traffic data to support statistical analysis. The randomized simulation process and repetition ensure the existence of data points for each simulation scenario.

Regression Analysis and Transformation Process

The results of the simulations were used to construct a multivariate regression model for train delay of each individual train type. The model contains 24 scenarios (720 days of simulation) and, with an *R*-squared value of .93, is precise enough to capture the delay response of the traffic.

To provide a measure of capacity, the regression model with volume as an input and delay as an output must be transformed into a model for volume based on allowable delay (LOS) for each train type. Figure 2 uses an example to graphically illustrate the basic transformation process. The upper diagram in Figure 2 shows the relationship between the average delay of intermodal trains from the regression model, freight traffic mixture (percentage of unit trains), and total traffic volume under scenarios with eight passenger trains per day. By setting the maximum allowable average delay for intermodal

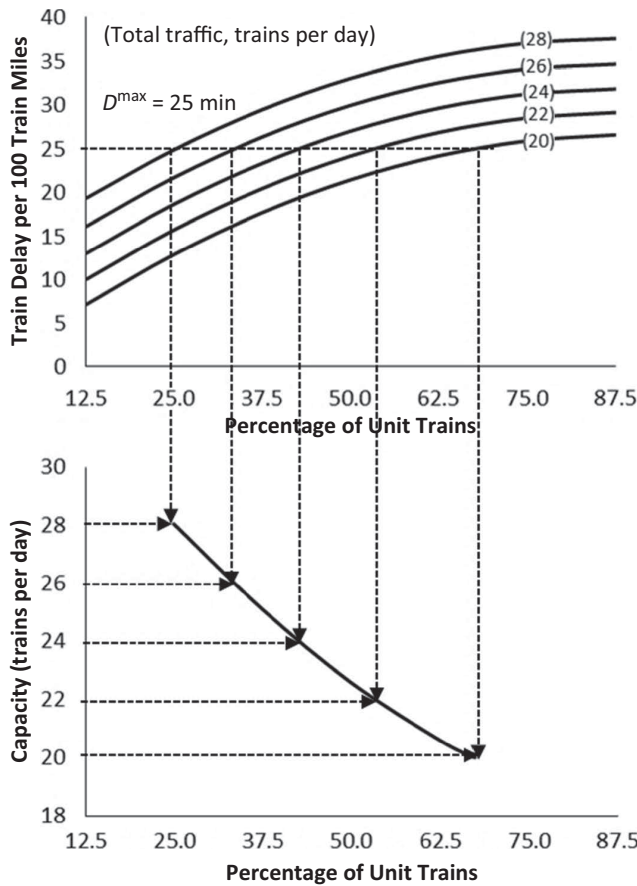


FIGURE 2 Example of capacity evaluation process (eight passenger-train scenario).

trains (D^{\max} , 25 min in Figure 2) as the required LOS, the maximum traffic volumes that can be operated on the corridor without violating the LOS standard can be obtained. These points can be transferred to the lower set of axes and used to construct a line indicating the maximum allowable traffic volumes for different traffic mixtures. This line is regarded as the capacity curve of the intermodal trains under different freight traffic mixtures when eight passenger trains are operating per day.

The graphical transformation process can also be performed algebraically by a polynomial transformation. The original polynomial model for delay of each train type can be represented as a quadratic function of total traffic volume (Equation 1). The quadratic equation can be used to solve for traffic volume and transform the original function into Equation 2. The capacity contour of each train type can be obtained from Equation 2 by substituting the delay of train type t (D_t) with maximum allowable delay (D_t^{\max}) according to the desired LOS. This transformation process is applied to each train type. Thus each combination of passenger train volume and freight traffic mixture will have three different allowable total traffic volumes based on the specific LOS for each train type. The final capacity contour is constructed from the lowest of the individual train-type traffic volume values to create a minimum contour that governs the capacity of the line (Figure 3).

$$D_t = f_t(P, U)Q^2 + g_t(P, U)Q + h_t(P, U) \quad (1)$$

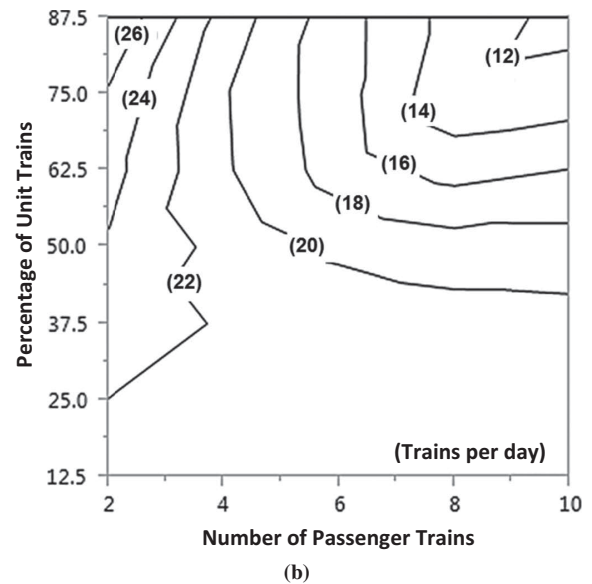
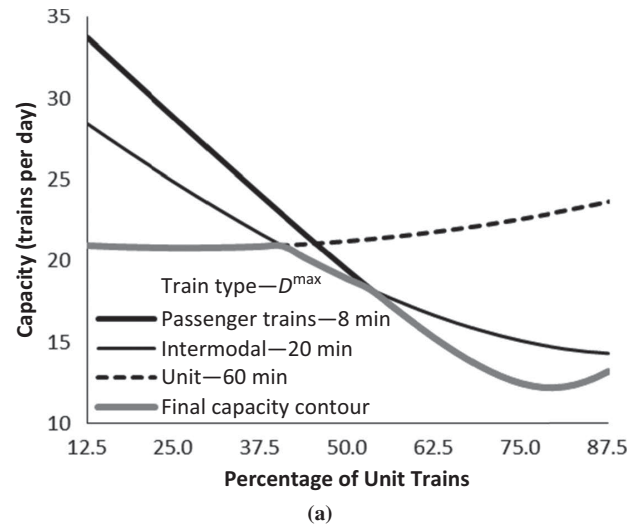


FIGURE 3 Relative relationship of capacity profiles for specific volume of passenger trains: (a) final capacity contour (eight passenger-train scenario) and (b) capacity surfaces.

$$Q = \frac{-g_t(P, U) + \sqrt{g_t^2(P, U) - 4f_t(P, U)[h_t(P, U) - D_t]}}{2f_t(P, U)} \quad (2)$$

where

D_t = average delay per 100 mi of train type t ,

P = number of passenger trains in traffic,

U = percentage of unit trains in total traffic,

Q = total traffic volume,

f_t, g_t = functions representing second- and first-order parameter of delay-volume function of train type t , and

h_t = function representing intercept of delay-volume function of train type t .

The final capacity contour illustrated in Figure 3a shows the relative relationship of capacity profiles for a specific volume of

passenger trains. To show the whole three-dimensional capacity surface over a range of passenger train volumes, a contour plot is generated (Figure 3*b*). The plot shown in Figure 3*a* would represent a slice through the capacity surface in Figure 3*b* at eight passenger trains per day.

CASE STUDY AND ANALYSIS

This section begins with a study of the incremental impact of passenger trains on the capacity of lines with different mixtures of existing freight train types. The analysis determines the relative impact of passenger trains on each freight train type. Since the required LOS is somewhat subjective and may vary between railways and other practitioners, a sensitivity analysis was conducted on the maximum allowable delay of each train type to better understand its effect on capacity. The final part of the case study aims to capture the impact of traffic heterogeneity on line capacity by comparing scenarios with different speed heterogeneity between the three train types.

Incremental Impact of Passenger Trains on Line Capacity

The simulation results demonstrate that when passenger trains are added to lines with different existing freight traffic mixtures, the impact of the passenger trains is distributed disproportionately between the train types. Intermodal trains experience little additional delay when passenger trains are added to a line in which the intermodal trains compose the majority of the freight traffic (Figure 4). However, for lines in which bulk trains are dominant, the passenger trains have a more substantial impact on intermodal train delay.

To further illustrate the disproportional impact of additional passenger trains on different types of freight trains, a case was considered in which the maximum allowable delays are fixed at 8, 20, and 60 min for passenger, intermodal, and unit trains, respectively. Figure 5 illustrates how the line capacity as defined by the LOS of

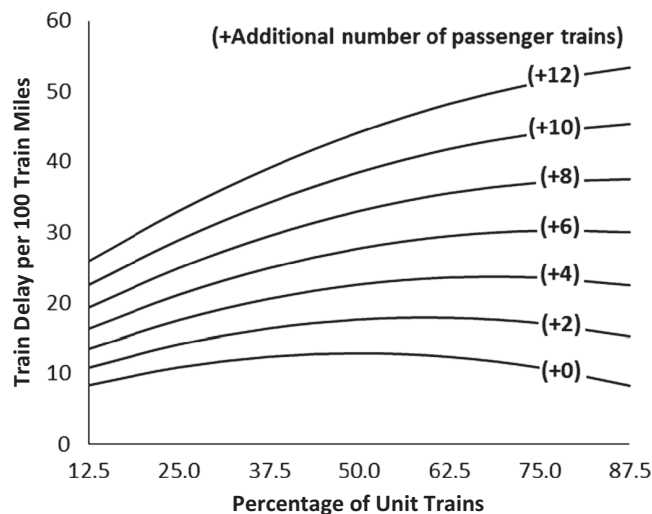


FIGURE 4 Example of disproportional impacts of passenger trains on intermodal under different freight traffic mixtures (20 freight-train scenario).

each train type over a range of freight traffic mixtures changes when there are 0, 2, 6, and 8 passenger trains operating on the line. In a comparison of the graphs, the passenger capacity contour becomes more critical (moves downward) as the number of passenger trains increases followed by the intermodal and unit train contours. This finding implies that added passenger trains affect the performance of other passenger trains the most, followed by intermodal and then bulk trains. Moreover, the graphs also show that the shape of the final capacity contour changes as the number of passenger trains changes. For the scenario with zero passenger trains per day, capacity increases with the percentage of unit trains. When the number of passenger trains increases to more than two per day, the portion of the final capacity contour corresponding to a higher percentage of unit trains starts to decline when the percentage of unit trains increases. This finding implies that the freight traffic mixture (percentage of unit trains) with the lowest capacity changes as the number of passenger trains is increased. Thus, it is not just the volume of existing freight trains that is important when the ability of a line to support additional passenger traffic is assessed but the exact mixture of freight trains operating on the line. Certain freight traffic mixtures exhibiting large heterogeneity are more negatively affected than others. This finding may help planners better predict potential congestion when new passenger service is proposed on different types of freight corridors.

The analysis just described demonstrates how additional passenger trains disproportionately reduce freight train capacity, depending on the initial freight traffic mixture. This incremental impact of passenger trains can be evaluated by an index called the equivalent freight capacity loss (EFCL), which is calculated by dividing the total loss of freight capacity by the number of passenger trains added. Figure 6 shows the EFCL for the combinations of freight and passenger traffic considered in this study.

The region in which a single passenger train has the largest capacity impact is between four and eight passenger trains per day and the initial freight traffic mixture is more than 80% unit trains. This region corresponds to the most extreme heterogeneity conditions on the line. The critical location is not at the point of the highest percentage of unit trains and number of passenger trains because the ratio of passenger trains to total traffic increases when the number of passenger trains increases. For example, the capacity of a scenario with six passenger trains and 87.5% unit trains is approximately 17 trains/day and the capacity of a scenario with 10 passenger trains and the same percentage of unit trains is approximately 12 trains per day. The proportion of passenger trains in the first scenario is around 35% and is 83% in the second scenario. Since most of the trains in the second scenario are passenger trains, the average traffic speed is higher and the interference from train type heterogeneity is lower compared with the first scenario.

LOS Sensitivity Analysis

The required LOS for each train type may change according to shipper demands, individual railway business objectives, and the condition of the rail network. For example, lines connecting through a congested terminal may require a stricter LOS for certain trains to maintain the on-time performance of traffic. Since changing the LOS of a particular type of train alters the position of its capacity surface, a change to one train type may cause changes in the final capacity surface.

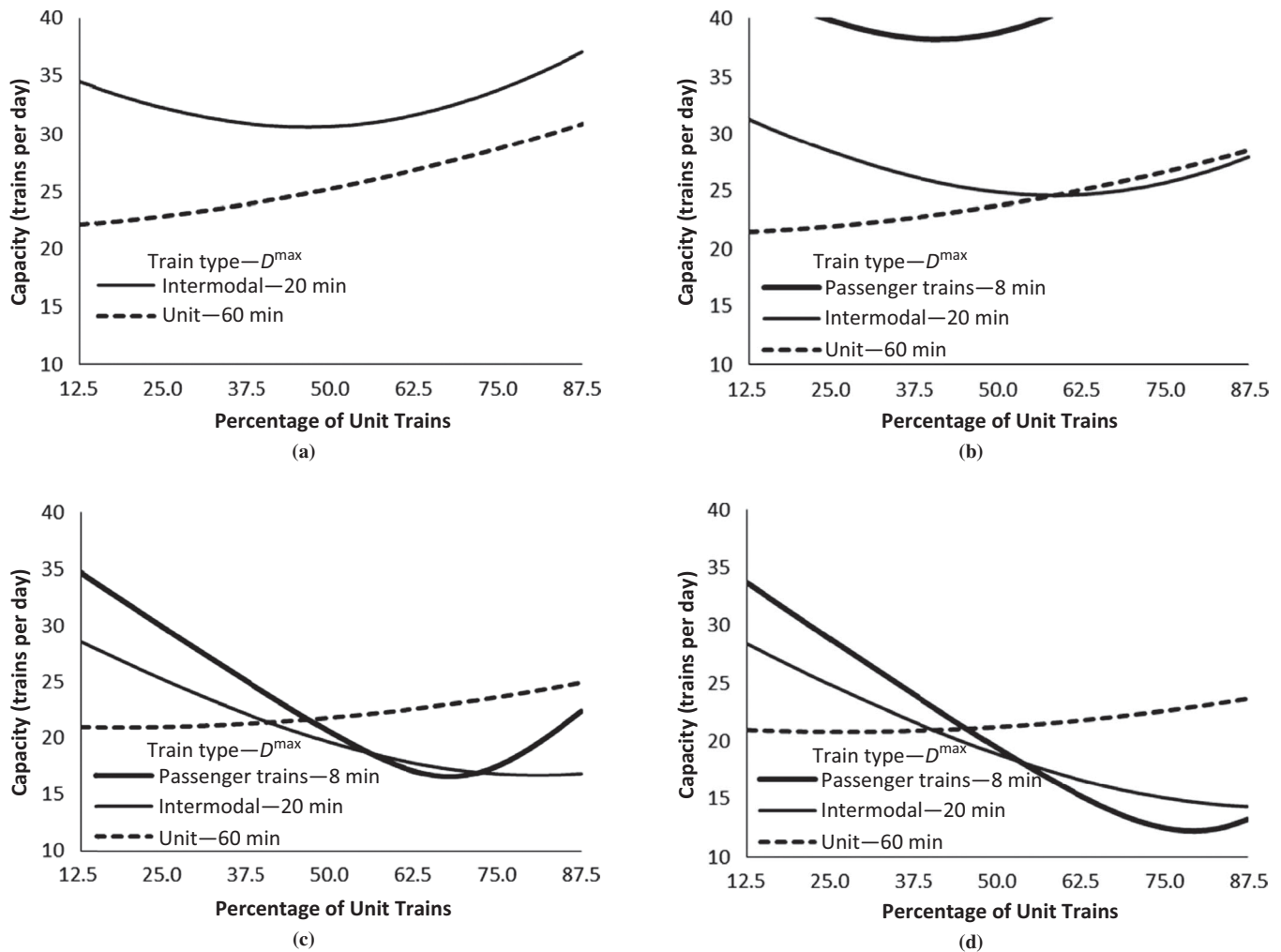


FIGURE 5 Incremental impact of passenger trains on capacity contours and final capacity contour for scenarios with (a) no passenger train traffic, (b) two passenger trains per day, (c) six passenger trains per day, and (d) eight passenger trains per day.

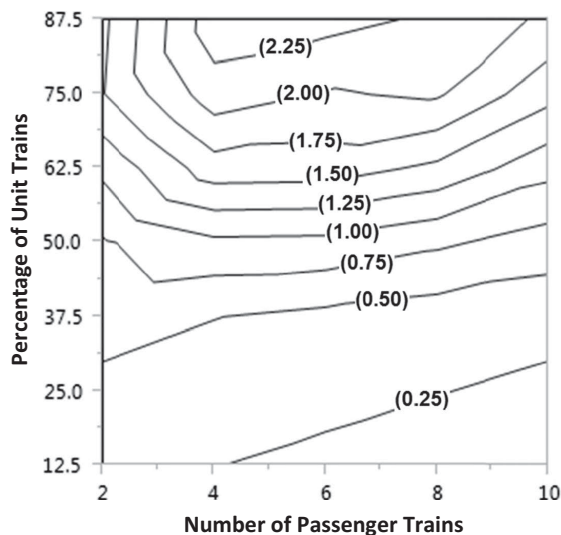


FIGURE 6 EFCL per passenger train.

Figure 7 illustrates the fluctuation of capacity caused by 10% increases and decreases in the maximum allowable delay of each train type. For example, in a corridor where the traffic mixture includes four passenger trains per day and 50% of the freight trains are unit trains, if the intermodal LOS must be reduced by 10% because of the network congestion, achieving this LOS improvement requires a capacity reduction of approximately two trains per day.

An interesting pattern develops in Figure 7. Increases in allowable delay of a particular type of freight train only increase capacity when there are few passenger trains and that particular type of freight train represents a minority of freight traffic.

Speed Homogeneity

Dingler et al. found that reducing the heterogeneity of train speed or priority increased line capacity (2). However, homogenizing train priority is not always appropriate because it can reduce the service reliability of time-sensitive trains. In contrast, changing train speed has a relatively low impact on service reliability of these time-sensitive trains as long as the minimum run time is satisfied. This subsection

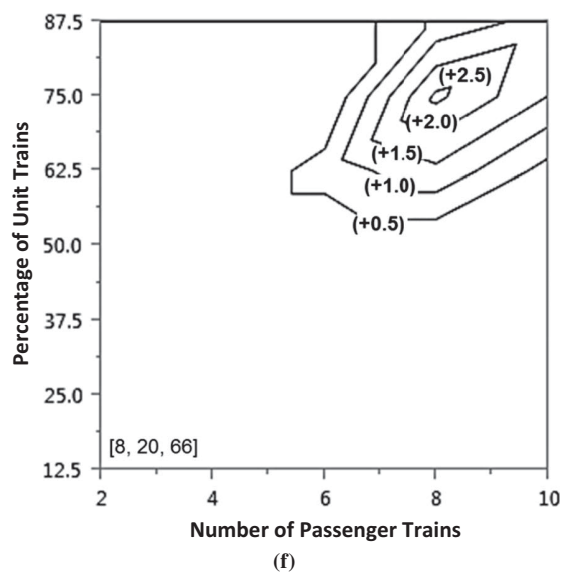
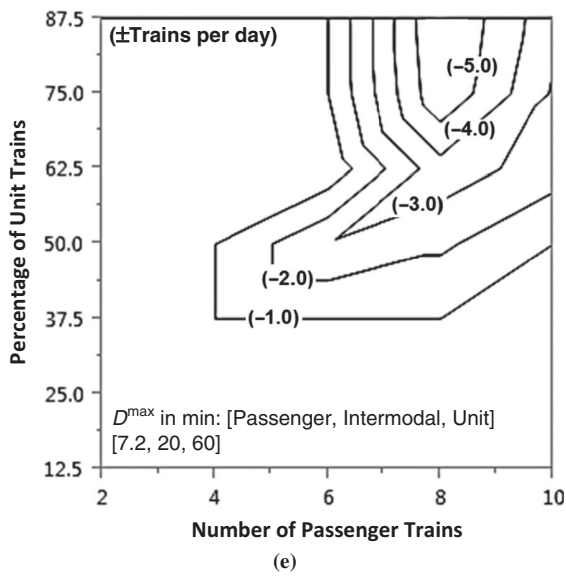
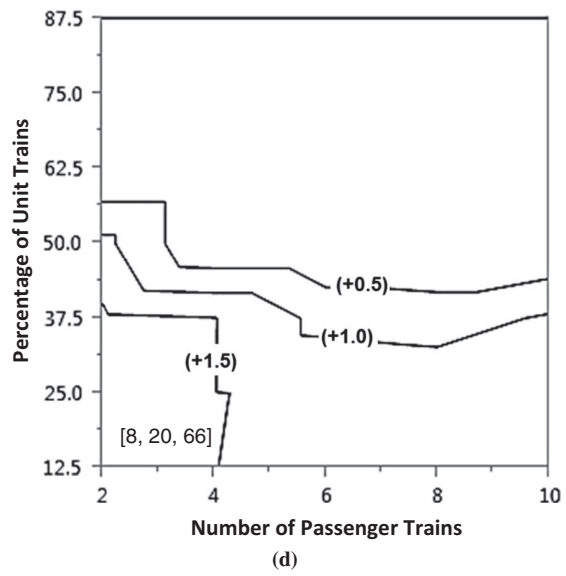
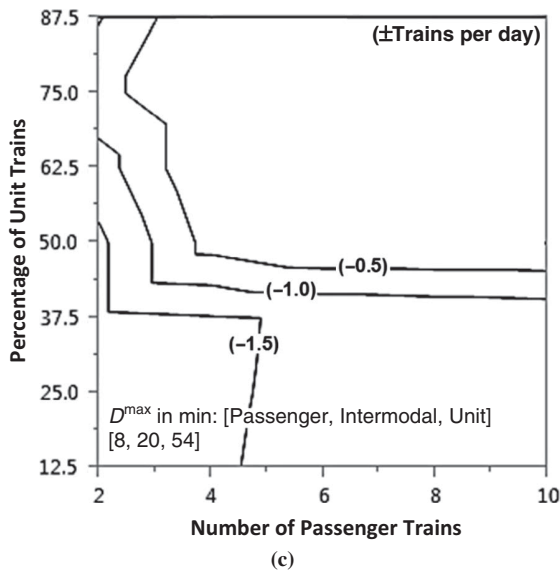
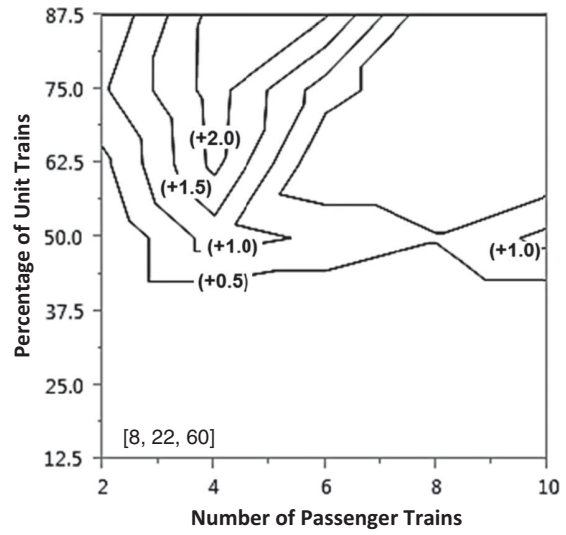
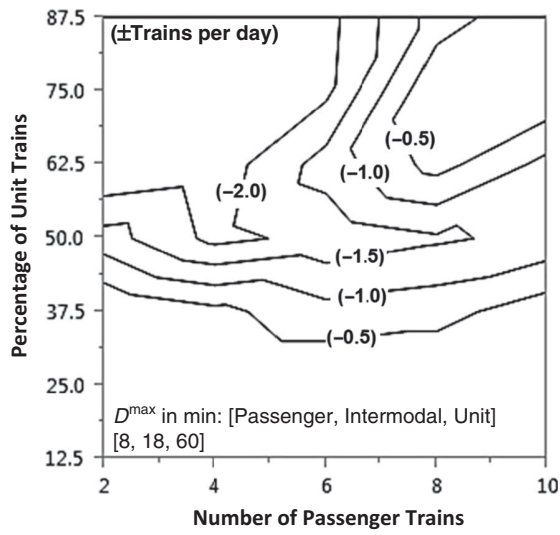


FIGURE 7 Sensitivity of line capacity to changes in maximum allowable delay for (a) 10% decrease and (b) 10% increase in required LOS of intermodal; (c) 10% decrease and (d) 10% increase in required LOS of unit; and (e) 10% decrease and (f) 10% increase in LOS of passenger trains.

analyzes a scenario in which train speeds are made more homogeneous to evaluate the effect on capacity.

To reduce heterogeneity, the maximum speed of passenger, intermodal, and unit trains is adjusted to 60, 55, and 50 mph, respectively, from the original 75, 55, and 35 mph. The benefit of reducing speed heterogeneity varies based on the initial freight traffic mixture (Figure 8). When the percentage of bulk trains increases, the benefit from adjusting speeds becomes much more pronounced. This variation in capacity improvement under different freight mixtures suggests that the relative impact of passenger trains on intermodal and unit trains changes with speed. The impacts of passenger trains on intermodal and unit trains both decrease, but the decrease for intermodal trains is less than that for unit trains.

The implication of this finding is that altering train speed may increase the minimum running time of some trains but can help

accommodate more passenger and freight traffic while maintaining the required LOS. For this reason, altering train speed may be an option to temporarily increase capacity in order to recover from disruptions when the minimum running time of each train has already been exceeded.

CONCLUSION

A capacity evaluation process is proposed in this study to evaluate line capacity under different traffic mixtures involving three types of trains. Using the values of number of passenger trains per day, percentage of unit trains, and required LOS of each train type as input, the process develops a capacity surface for each individual train type. The final capacity contour is defined by the minimum value of all surfaces. This process can be extended to lines with any combination of three or more train types.

The case study demonstrates the incremental impact of adding passenger trains to lines with mixtures of different types of freight trains. The capacity evaluation process can depict the incremental impact of one train type on the other train types and the overall capacity of the line. In general, the addition of a priority passenger train has a disproportionate impact on train types. For example, on a freight rail line dominated by unit trains, intermodal trains are the most negatively affected by the addition of passenger trains since the intermodal trains must relinquish a preferred schedule spot for use by a priority passenger train. Despite being in the majority, bulk trains sustain relatively little impact, even though they exhibit a greater speed differential compared with the passenger trains. Instead of only looking at average delay across all train types, practitioners can use this process to identify the impact on other types of trains as a result of adding trains. This procedure will allow infrastructure owners to better assess the delay costs of congestion created by added trains.

The sensitivity analysis of capacity to LOS illustrates how the capacity benefit of relaxing the allowable delay for certain train types varies according to the freight traffic mixture on the line. Increases in allowable delay for a particular type of freight train only increase capacity when there are few passenger trains and that particular type of freight train represents a minority of freight traffic. In contrast, increasing the allowable delay of priority passenger trains only increases the capacity when the speed and priority heterogeneity of all traffic are reached to a certain degree.

Together, these two findings suggest that the LOS of the minority freight train type plays a key role in establishing the capacity of a line with three or more types of trains. The final case study result demonstrated that reducing speed heterogeneity can enhance capacity and reduce the incremental impact of additional passenger trains on the slowest-speed freight train types. Since minimum running times must still be met, harmonizing operating speeds could be a method to add "temporary capacity" to recover from disruptions.

ACKNOWLEDGMENTS

This research was supported by the NURail Center (Tier 1 University Transportation Center under the Office of the Assistant Secretary for Research and Technology, U.S. Department of Transportation) and the Association of American Railroads. The authors thank Eric Wilson of Berkeley Simulation Software for the use of RTC.

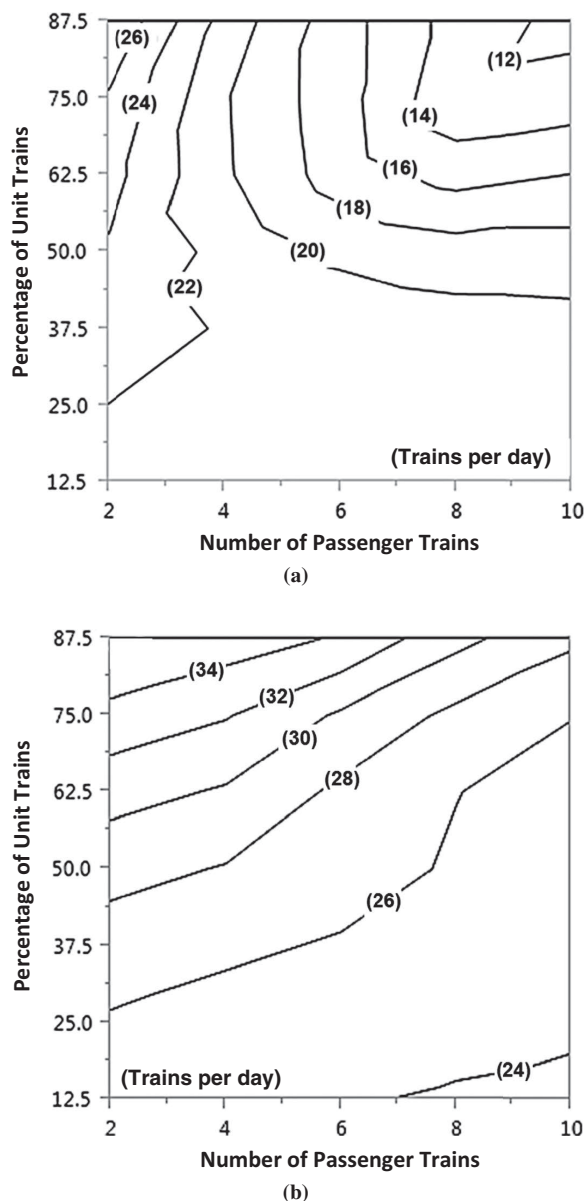


FIGURE 8 Capacity of (a) original scenario and (b) homogeneous scenario.

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The Standing Committee on Freight Rail Transportation peer-reviewed this paper.