Original Article

Institution of MECHANICAL ENGINEERS
Journal of RAIL AND RAPID TRANSIT

Proc IMechE Part F:
J Rail and Rapid Transit
2014, Vol. 228(8) 845–856
© IMechE 2013
Reprints and permissions:
sagepub.co.uk/journalsPermissions.nav
DOI: 10.1177/0954409713496762
pif.sagepub.com
SAGE

Effect of train-type heterogeneity on single-track heavy haul railway line capacity

Mark H Dingler[3], Yung-Cheng (Rex) Lai[2] and Christopher PL Barkan[1]

Abstract

North American heavy haul railroads are experiencing growth in traffic demand and increasingly facing capacity constraints. A key factor influencing railroad operations is heterogeneity in train characteristics. Different train types can have substantially different operating characteristics including maximum speed, power-to-ton ratio and dispatching priority. This heterogeneity causes conflicts between trains that increase delays and reduce capacity. Dispatching simulation software was used to analyze the effect of various combinations of intermodal and bulk trains on a hypothetical, signalized, single-track line with characteristics typical of a North American freight railroad subdivision. This assessment studied the relationship between volume, heterogeneity and delay. Further work identified the key factors that contribute to the increased delays due to heterogeneity. The train characteristics of speed, acceleration, braking and priority were considered for their effect on the increased delays due to heterogeneity. Understanding these factors that affect delay allows for more effective network capacity planning and efficient rail operations. The results also suggest certain railway operating strategies that may reduce the delays caused by train-type heterogeneity thereby improving service reliability.

Keywords

Rail transportation, capacity, heterogeneity, single track, freight traffic

Date received: 24 April 2013; accepted: 3 June 2013

Introduction

Efficient use of existing railroad infrastructure and effective planning for new infrastructure or other capacity-enhancing systems requires an understanding of how operations affect capacity.[1–4] Railroad operations are a complex interaction of many factors, one key factor being the interaction of trains with different operating characteristics.[5–10] In North America, intermodal, manifest, unit and local trains may all share trackage. Some lines also have intercity passenger trains and in metropolitan regions, commuter trains. Each of these train types can have considerably different characteristics and this heterogeneity can have a substantial effect on rail line capacity.[4,11,12]

With homogenous traffic, delays on a single-track line are almost solely due to meets.[13,14] With heterogeneous traffic, delay is also caused by conflicts that occur as a result of differences in train characteristics, some of which increase frequency and duration of meets and passes.[6,15] These additional delay-causing situations with heterogeneous traffic include:

- train delayed by a slower preceding train;
- train delayed by a preceding train with slower acceleration;
- trains experiencing longer meets waiting for higher-priority trains;
- train delayed waiting for another train to pass;
- Trains experiencing more conflicts due to lower average speed resulting from other delays due to heterogeneous traffic.

The magnitude of these delays is dependent on the specific train mix, volume and amount of heterogeneity.

Bronzini and Clarke[16] used simulation to develop delay/volume curves for traffic with varying amounts

[1]Rail Transportation and Engineering Center, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, USA
[2]Department of Civil Engineering, National Taiwan University, Taiwan
[3]CSX Transportation, Jacksonville FL, USA

Corresponding author:
Yung-Cheng (Rex) Lai, Department of Civil Engineering, National Taiwan University, Room 313, Civil Engineering Building, No 1, Roosevelt Road, Sec 4, Taipei, 10617 Taiwan.
Email: yclai@ntu.edu.tw

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

of intermodal and unit trains on a theoretical single-track line. Dingler et al.[6] performed preliminary simulation analyses to determine the impacts of heterogeneity with freight and passenger traffic. Dinger et al.[10] conducted another study to determine the benefits of various operational and infrastructure changes at reducing train delay. However, none of the previous research work comprehensively looked into the relationship among delay, volume and heterogeneity on single-track heavy haul railway line capacity. Consequently, in this paper, simulation software is used to conduct a quantitative analysis of the impact of heterogeneity among intermodal and bulk trains, which are among the most frequently operated trains on the North American railroad network. The effects of different volumes and percentages of each train type on a signalized, single-track route are evaluated. Delay is used as the principal metric to assess capacity impacts under different scenarios. The objective of this research is to provide insight into the impact of train type heterogeneity and understand the key characteristics of traffic heterogeneity that have the greatest impact on delay.

Table 1. Route used in analysis.

Single track with 10 mile siding spacing 262 miles long
10 miles between siding centers
8700 ft signaled sidings with 24 powered turnouts
2.75 mile signal spacing
two-block, three-aspect signaling
0% grade and curvature

Table 2. Train composition characteristics used in simulations.

Intermodal	Bulk
16 three-pack spine cars	115 loaded hopper cars
Nine five-pack well cars	
5659 ft (1725 m)	6325 ft (1928 m)
5900 tons	16,445 tons
3.64 HPTT	0.78 HPTT
Five 4300 HP Locomotives	Three 4300 HP Locomotives
Maximum speed: 70 miles/h	Maximum speed: 50 miles/h

Methodology

Capacity metric

Delay is used as the principal metric for capacity comparisons in this study. We define delay as the difference between the minimum, or unopposed, run time and the actual run time required to traverse the route. This includes the time spent stopped for meets and passes, along with the time for braking and accelerating. The total delay is divided by train miles to obtain a normalized value of delay per 100 train miles. Multiple operational and infrastructure scenarios are considered in order to calculate the effectiveness of various methods of reducing delay. The dispatch simulation software, Rail Traffic Controller (RTC) from Berkeley Simulation Software, is used to simulate multiple traffic scenarios, with train delay being the primary metric to measure capacity and the cost of train operations. RTC is a sophisticated software program designed to realistically simulate both freight and passenger operations over a railroad network.[12,17] The software uses infrastructure and traffic inputs specified by the user to resolve multi-train conflicts in a manner intended to mimic the decisions made by a railroad dispatcher. RTC permits rapid evaluation of different operating scenarios and is considered as the standard by the North American railroad industry.

Representative rail line

Specific characteristics of individual rail lines are unique and route characteristics influence railroad operations. For the research reported in this paper a hypothetical rail line was created so as to have the characteristics of a typical midwestern North America, single-track mainline subdivision (Table 1). Although the attributes are somewhat idealized, the purpose is to provide a consistent basis for relative comparison of different scenarios of interest in this research under a reasonably realistic set of operating conditions. However, there is no intent to imply that the results presented here represent absolute predictive measurements for a particular set of conditions.

Train types

Combinations of intermodal and bulk trains were used to investigate the impact of heterogeneity. Bulk goods transported by rail include coal, ore, grain and stone typically in long, heavy, unit trains with low horsepower-to-trailing ton (HPTT) ratios (e.g. <1.0). Intermodal trains transport trailers and containers carrying consumer goods and other high-priority shipments to and from domestic and international markets. Since these shipments require fast, reliable service, intermodal trains travel at higher speeds and have higher HPTT ratios (e.g. >3.0). Using commodity-based railroad transportation statistics it can be estimated that bulk and intermodal traffic account for roughly 60% of the US Class 1 railroad's revenue, 75% of the tonnage and 80% of the carloads.[18]

While each individual train is different, the attributes for each train type were selected to match their average characteristics (Table 2). The number of cars and units were obtained from the Cambridge Systematics National Rail Freight Infrastructure Capacity and Investment Study[11] conducted for the

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

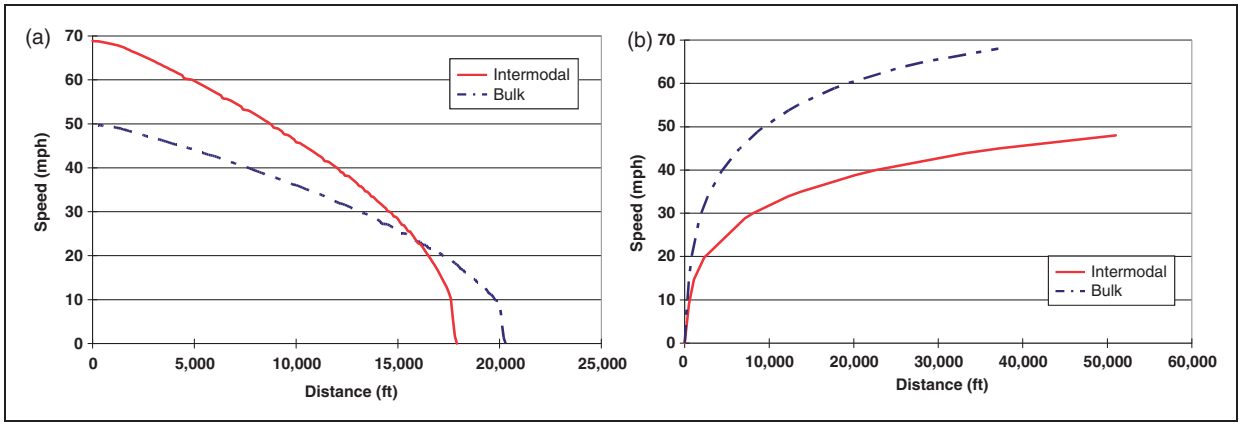

Figure 1. (a) Braking curve and (b) acceleration curve of bulk and intermodal trains.

Association of American Railroads.[18] Typically well cars with five articulated units are used to transport international containers and spine cars with three articulated units are used to transport domestic trailers. The number of cars was determined based on the relative amounts of domestic and international intermodal traffic. Tonnages and lengths were based on averages for each car type. The power-to-ton ratios were based on experience and information from the Transportation Research Board's Workshop on Railroad Capacity and Corridor Planning.[19]

Train priority is a non-physical characteristic assigned to it by the dispatcher. When two trains meet, priority is one factor the dispatcher will take into consideration when determining how to resolve the conflict. Dispatchers will generally try to minimize the total cost of delay.[12] This means that the trains carrying lower value or less time-sensitive freight, will have lower priority and enter the siding, while the higher-priority train holds the mainline and proceeds with little or no delay. In this study, intermodal trains were assigned the higher priority, as is typical in most railroad operations.

While the chosen attributes approximate actual characteristics, at the most basic level the "intermodal" trains represent freight trains with the highest maximum speeds, power-to-ton ratios and dispatching priorities, while the "bulk" trains represent those with the lowest speeds, power-to-ton ratios and dispatching priorities. Although referred to as "intermodal" and "bulk" for convenience, what is actually of significance in the analyses are their specific operating characteristics, not the particular type of consist.

When considering the impact of heterogeneity it is important to consider how the operating characteristics of the train affect its operation. Tonnage, power and length of a train have a direct impact on its ability to accelerate and brake, and consequently its effect on capacity. In typical operation a train will slow to a stop gradually using a mixture of air and dynamic brakes. The braking distances in RTC were calibrated with the assistance from a Class 1 railroad to approximately match the braking distances of each type of train making a typical brake application.

To better understand the differences in operating characteristics of the two trains in the analysis their braking and acceleration distances were compared (Figure 1). Intermodal trains brake at a faster rate, but due to their higher initial speeds, their braking distance is only about 2,000 feet less than the bulk train. On the other hand, there are large differences in the acceleration distances for the two train types. Intermodal trains have a much higher HPTT ratio and therefore are able to accelerate to maximum speed more quickly.

Experimental design

A series of simulations were developed with different traffic volumes and levels of train heterogeneity. Eleven different volumes were tested from eight to 48 trains per day simulated in increments of four. Each volume was based on an equal temporal distribution of trains in each direction over a 24-h period. This was not intended to represent practical, sustained operation, which includes windows for inspection and maintenance, but rather to provide a basis for relative comparison of the effect of various factors of interest. The results are therefore more characteristic of the spacing or headway between trains than the actual volume. Seven different levels of heterogeneity were tested based on the percentage of the different train types. The tests were done with 12.5, 25, 50 and 100% of each train type. The traffic was composed of a single train of the lower percentage type, followed by the corresponding number of trains for the other train type. For example, 12.5% bulk trains means that every bulk train was followed by seven intermodal trains. The ratios and traffic pattern were the same for trains traveling in both directions. For each configuration a series of 25 simulations were performed with the departure time of each train randomized with a uniform distribution over a 30-min interval, up to 15 min before or after the scheduled departure time for that train.

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

Delay/volume/heterogeneity relationship

To better understand the relationship between delay, volume and heterogeneity, simulation results were combined to create a surface over the three axes (Figure 2). The delay/volume/heterogeneity surface reveals two trends: delay increases with increasing volumes and it is dependent on the traffic mix. To further investigate these trends, each axis was analyzed individually (Figure 3). This permits the investigation of the delay/volume relationship, delay/heterogeneity relationship and volume/heterogeneity relationship.

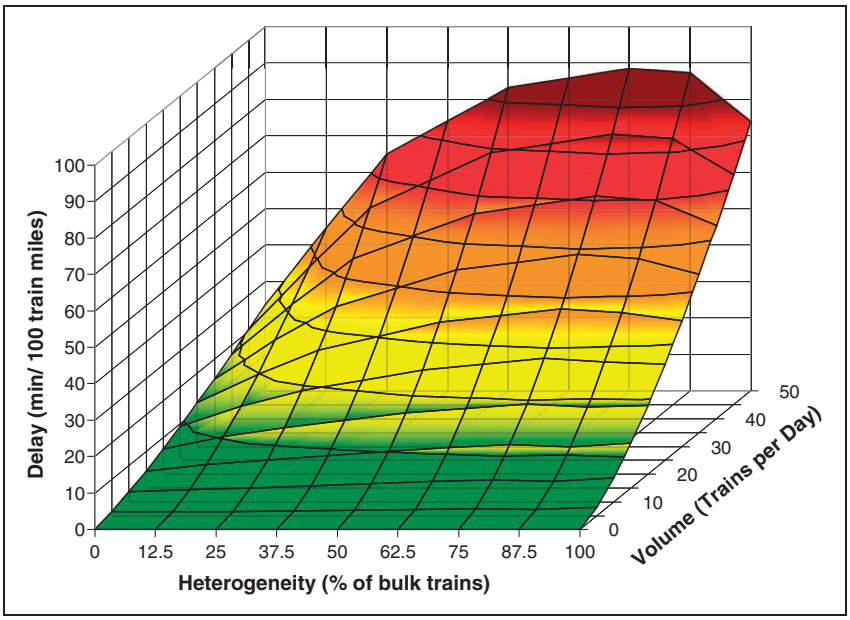

Figure 2. Delay/volume/heterogeneity relationship for intermodal and bulk trains.

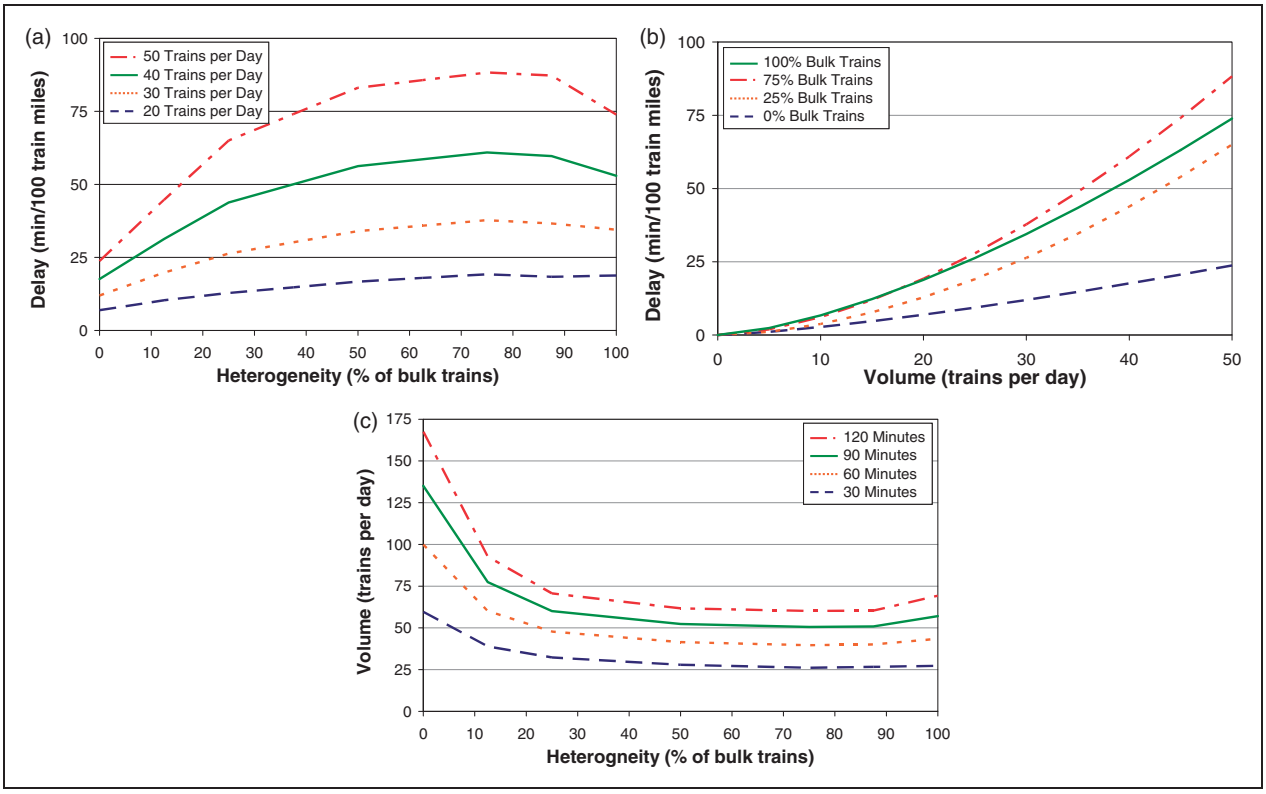

Figure 3. The (a) delay/heterogeneity, (b) delay/volume and (c) volume/heterogeneity relationships for intermodal and bulk trains.

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

Delay/heterogeneity relationship

The delay/heterogeneity graph shows the effect of heterogeneity on delay at various volumes (Figure 3(a)). Delay is greatest when the traffic is heterogeneous. However, the maximum average delay is not when heterogeneity is largest (50%) but when the traffic is 75% bulk trains and 25% intermodal. The traffic composition resulting in the greatest delay depends on the trains' characteristics. In this example bulk trains experience greater delay due to their slower maximum operating speed. The combined effect of the larger number of these slower-performing trains and heterogeneity is greatest when the traffic is 75% bulk trains.

Delay/volume relationship

The delay/volume graph shows the effect of volume on delay at various levels of heterogeneity (Figure 3(b)). It is evident that the effect of additional trains on delay is nonlinear. Delay increases at an increasing rate with higher volumes. At higher volumes there are additional meets and shorter headways resulting in greater delays. The delay/volume relationship is different for various traffic compositions. Higher levels of heterogeneity cause greater delays and the delays increase more rapidly than with homogenous traffic.

Volume/heterogeneity relationship

Another aspect of the delay/volume/heterogeneity surface that should be considered is the relationship between volume, heterogeneity and various levels of delay (Figure 3(c)). Delay is often used by the railroads to determine capacity. Capacity planners determine the acceptable amount of delay to meet their level-of-service requirements. In this example, if the maximum allowable delay is 60 min per 100 train miles and the traffic consists of only intermodal trains, the maximum capacity is 100 trains per day. If the traffic changes to an even mix of intermodal and bulk trains, capacity drops to 42 trains, 21 intermodal and 21 bulk trains. Therefore, by adding 21 bulk trains the ability to run 79 intermodal trains is lost. This effect is greatest when a few bulk trains are added to a route that is primarily intermodal traffic.

Delays due to heterogeneity for each train type

Train-type heterogeneity increases average delay but the delays are different for each train type. At 48 trains per day, the delays to each train type were considered individually (Figure 4). In every traffic mix the bulk trains have higher delays than the intermodal traffic. The intermodal train delay is relatively constant over all traffic mixes with the greatest delays at the highest levels of heterogeneity. Bulk trains have much higher delays but the delays decline as the percentage of bulk trains increases. When the percentage of intermodal trains is lower it becomes less likely for a bulk train to meet a higher-priority intermodal train. When this occurs, it often results in a meet that causes greater delays than would have occurred if a train of equal priority had been encountered. Much of the increased delay due to heterogeneity is the result of additional delays to the bulk trains, not an increase in the delays to both train types. The difference in delay between the intermodal and bulk train traffic decreases at lower volumes and as a result, delays due to heterogeneity are also lower.

Delay/volume/heterogeneity relationship for delays due to heterogeneity

When traffic is homogenous the average delays for intermodal and bulk trains are different.

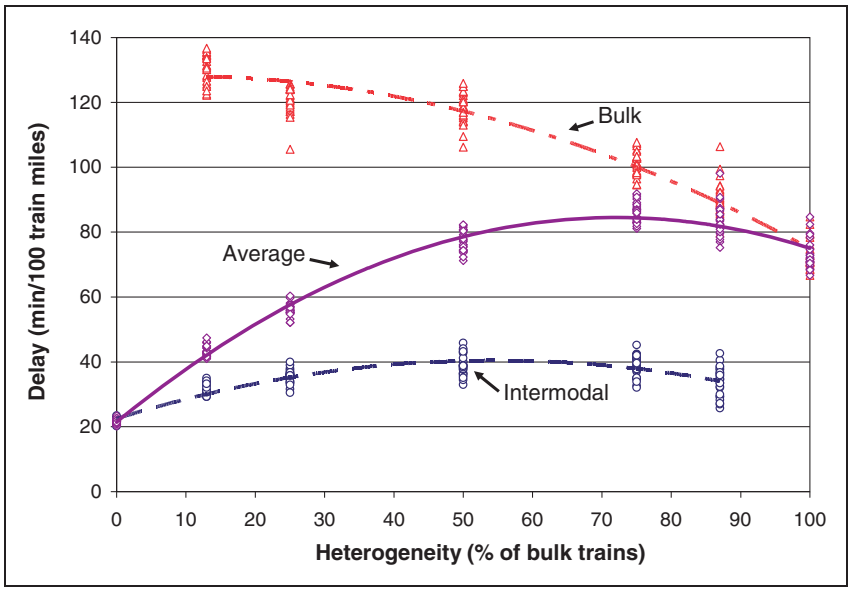

Figure 4. Delay separated by train type at 48 trains per day.

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

Therefore, as the traffic mix changes, some of the delay is due to more trains experiencing a differing delay due to their characteristics, rather than the result of heterogeneity alone. In order to account for this effect the hypothetical delay that would occur for the same traffic mix in the absence of any heterogeneity-caused sources was subtracted from the delay for each particular mixed-traffic scenario (Figure 5).

It is clear that heterogeneity causes only some of the total delay a train experiences. The percentage of the total delay caused by heterogeneity increases with greater traffic volume and levels of heterogeneity. However, even at 48 trains per day, when the traffic is an even mix of intermodal and bulk trains, heterogeneity accounts for only 40% of the total delay. With smaller volumes and less heterogeneity this percentage is even lower.

As with total delay, the delay/heterogeneity, delay/volume and volume/heterogeneity relationships are considered (Figure 6). The trends are different from those for total delay and provide further useful insights into the impact of heterogeneity. Since the delays are only due to heterogeneity the volume/heterogeneity relationship does not offer any additional insight into the effects of heterogeneity.

Delay/heterogeneity relationship

Unlike total delay, the delay due to heterogeneity is when heterogeneity is greatest (Figure 6(a)). While the maximum total delay occurs at 75% bulk (25% intermodal), the maximum delay due to heterogeneity is when there is an even mix of intermodal and bulk trains. When the volumes are low there is almost no

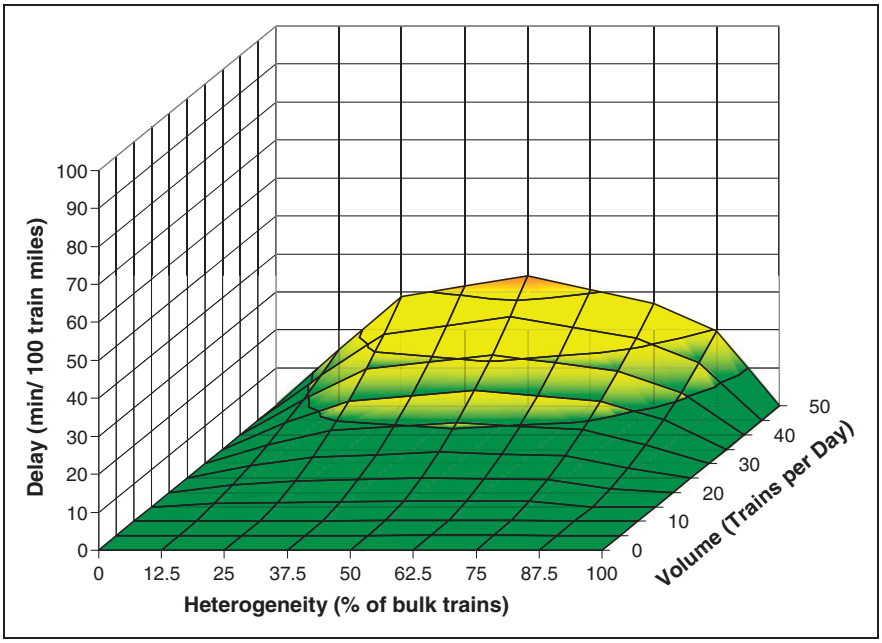

Figure 5. Delay/volume/heterogeneity relationship for intermodal and bulk trains with delay due to heterogeneity isolated.

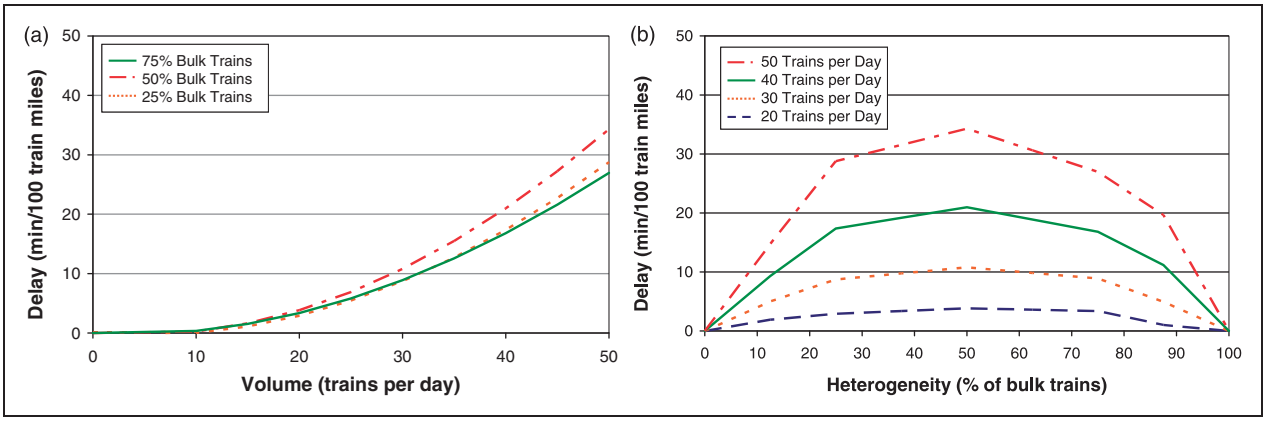

Figure 6. The (a) delay/heterogeneity and (b) delay/volume relationships for intermodal and bulk trains with delays due to heterogeneity isolated.

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

impact of heterogeneity on delay, with the delays due to heterogeneity increasing with greater volumes.

Delay/volume relationship

The delays due to heterogeneity have a nonlinear relationship (Figure 6(b)). There is little effect of heterogeneity until about 15 trains per day. At low traffic levels the headways between trains are great enough that passes are limited and excess siding capacity allows for efficient meets and passes. However, as traffic volume increases beyond this, meets become more frequent and headways shorter, thereby magnifying the differing characteristics and creating additional conflicts.

Analysis of factors that cause delays due to heterogeneity

Although the effect of volume and heterogeneity on delay is clear, the specific factors causing the increased delays due to heterogeneity are not. Additional simulations were conducted to investigate the sensitivity of delay to speed, braking performance, acceleration performance and dispatching priority. While not possible in actual operations, the use of simulation enables each factor to be isolated to determine its effect on delay and capacity. Two scenarios were studied for each factor: in the first scenario the selected factor was the only source of heterogeneity and the delays due to this factor were considered. The second scenario is the opposite condition: the factor was eliminated from the base scenario and the reduction in delay due to this action was evaluated.

Impact of heterogeneity in speed

Trains travel at different speeds depending on their service requirements. Higher-valued commodities typically travel in higher speed trains than less time-sensitive commodities. The resultant heterogeneity in train speed can create additional conflicts and delays. With heterogeneous train speeds, a faster train may overtake a slower one. Before there is an opportunity to pass, the faster train may have to slow to the speed of the preceding train. Once a siding is reached the train being overtaken will have to reduce speed to enter the siding and stop thereby allowing the faster train to pass. In this manner heterogeneous train speeds can cause extra delay for both the faster and slower trains.

In the first investigated scenario considered intermodal trains traveling at 50 and 70 miles/h at four different traffic levels: 12, 24, 36 and 48 trains per day (Figure 7). At the two lower volumes the delay due to the heterogeneity in speed is negligible. However, at 36 and 48 trains per day the speed difference causes delays. In general, delay due to speed heterogeneity is greatest at the highest volumes and levels of heterogeneity. In typical operations the higher-speed trains receive a higher dispatching authority, otherwise when a higher-speed train reaches the point where it needs to overtake a slower train it will not be able to pass the slower train, thus increasing delays. However, in this scenario the priorities of the two trains train types were equal and therefore some additional delays are the result of faster trains being slowed down.

In the second investigated scenario the only change from the base scenario was a reduction in speed of the intermodal trains to 50 miles/h in order to eliminate the speed difference between trains (Figure 7(b)). The impact of this change varies depending on the volume of traffic. At 12 trains per day the change in delay is minimal. When the volume increases to 24 trains per day delays are reduced at all levels of heterogeneity. At 36 trains per day the delays are reduced when the majority of the traffic is bulk, and increases when the traffic is mostly intermodal. At the highest volume,

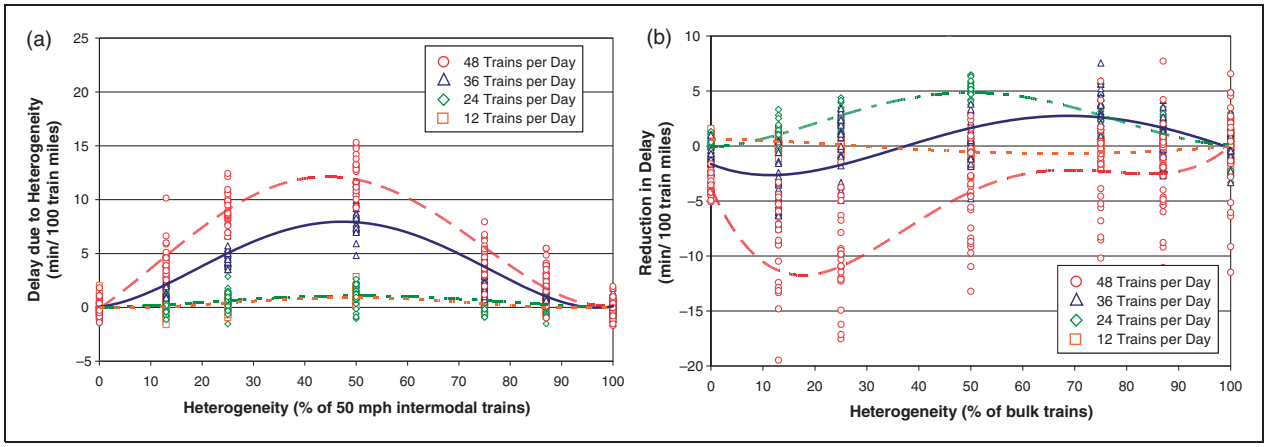

Figure 7. Delays due to (a) train speed heterogeneity and (b) reduction in delay from base scenario when speeds of intermodal trains are reduced to 50 miles/h.

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

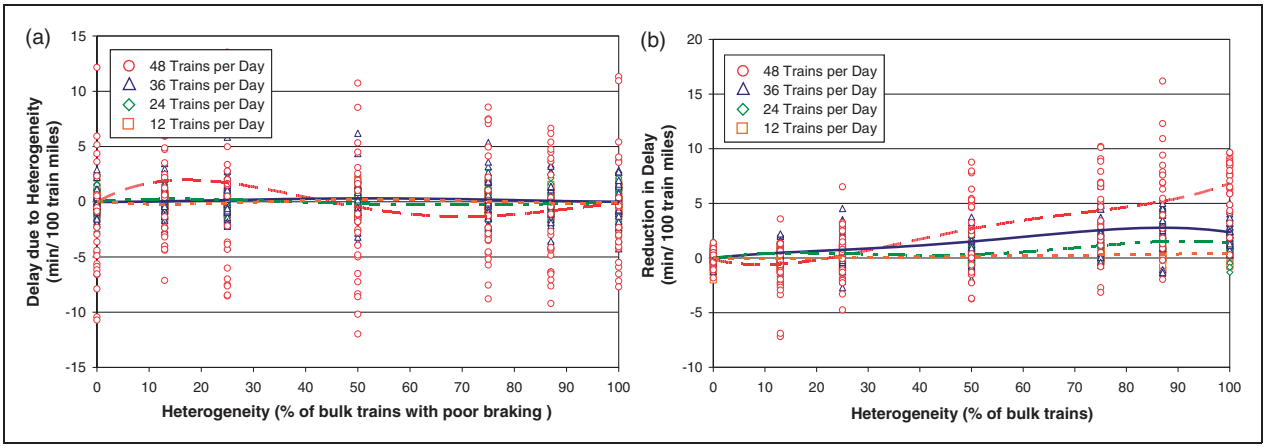

Figure 8. Delays due to (a) braking performance heterogeneity and (b) reduction in delay from base scenario when braking performance of bulk trains is improved to match that of intermodal trains.

48 trains per day, delays increase with all levels of heterogeneity.

At the lowest volumes there may not be any passes due to the large headways between trains; consequently, reducing speed to eliminate meets has no effect. When volumes increase delay is reduced due to the elimination of speed difference conflicts. However, slower train speeds increase the time a train occupies the track, resulting in more meets and the associated delay. At the highest volumes the delay from the increased number of meets outweighs the savings from the elimination of passes. Additionally, the reduction in speed from 70 to 50 miles/h for the intermodal trains increases run times by 35.34 min per 100 train miles. Therefore, while delay is reduced at 24 trains per day, the run time actually increases due to the slower speed.

Impact of heterogeneity in braking performance

Trains with different lengths and tonnages require different distances to stop. Braking distance affects both signal spacing and delay during a meet. A train with a poor braking performance will take longer to reduce speed and thus require more time to resolve a conflict. Longer meet delay will increase run times and can result in additional conflicts due to longer track occupancies.

The first investigated scenario considered bulk trains with normal braking performance, and with the braking performance of intermodal trains (Figure 8). Braking performance affects the delays experienced by a train, however, conflicts between trains with different braking performances does not result in additional delays. The delay that occurs while a train is braking is relatively minor compared with the time lost while a train waits in a siding or the time it takes the train to accelerate back to top speed. Since trains were not delayed by preceding trains with poorer braking performance; heterogeneity in braking performance has little impact.

In the second investigated scenario heterogeneity in braking performance was eliminated by improving the braking performance of the bulk trains to match that of the intermodal train (Figure 8(b)). The changes result in a reduction in delay corresponding to the percentage of bulk trains. As the percentage of bulk trains increases, so does the reduction in delay. The reduction also increases with higher volumes since there are a greater number of stops for meets and passes. However, the changes do little to reduce heterogeneity-caused delays.

In this research, only the impact of braking performance on delay with fixed signal blocks is considered. In actuality, braking performance affects signal spacing and allowable train speeds. Another implication of heterogeneity in train braking is the inability to optimize the signal system for a specific train type. Signal spacing is typically set based on the longest, full-service stopping distance of any train that regularly operates on a line. If traffic is homogeneous signal spacing can be designed for that specific train type thereby enabling shorter headways. Alternatively, without a change in signal spacing improved braking performance can allow for faster train speeds since it is possible for a faster train to stop in the same distance as an unimproved train at a slower speed.

Impact of heterogeneity in acceleration performance

Another type of train heterogeneity is acceleration performance. Acceleration is directly related to the power-to-ton ratio of a train. A higher power-to-ton ratio allows a train to accelerate faster and reach higher top speeds. There are two ways acceleration performance can influence capacity. First, heterogeneity in train acceleration performance can potentially impact capacity if a following train is delayed while a train ahead of it accelerates to maximum track speed. As traffic volume increases, the number of meets and

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

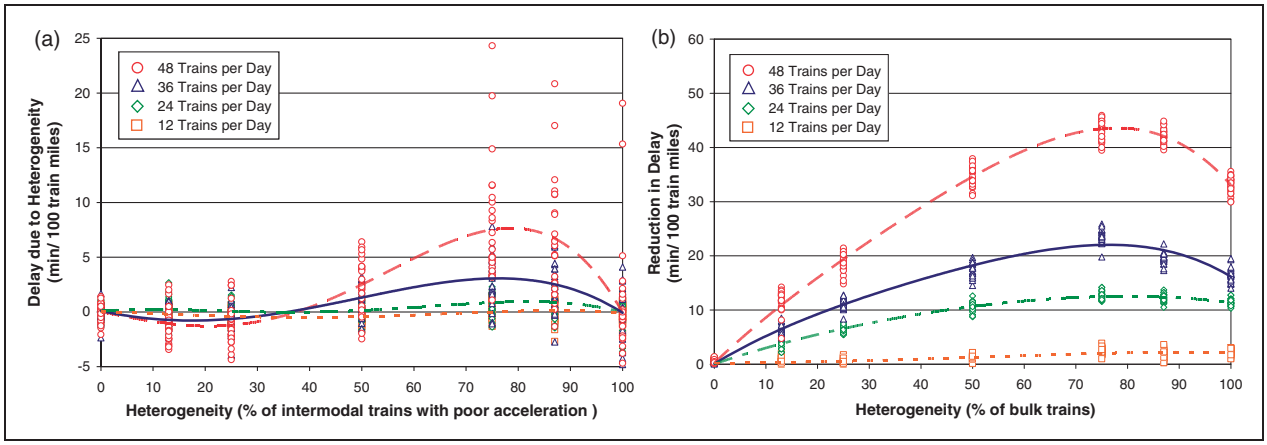

Figure 9. Delays due to (a) acceleration performance heterogeneity and (b) reduction in delay from base scenario when acceleration performance of bulk trains is improved to match that of an intermodal train.

passes increases while headways are reduced, increasing the potential for this type of conflict. Second, the acceleration performance of a train affects its delay because it increases the time it takes for a train to reach maximum track speed after a conflict.

The first investigated scenario considered traffic composed of bulk trains with normal acceleration performance and the acceleration performance matching intermodal trains (Figure 9). The delays due to heterogeneity in acceleration performance depend on traffic mix. Delays are minimal when most trains have a superior acceleration performance, but increases with the percentage of trains with an inferior acceleration performance. When the majority of trains have a poor acceleration performance, it is more likely for a trailing train to be slowed by a train accelerating from a meet, thereby causing additional delay.

The second investigated scenario removed heterogeneity in acceleration performance from the base scenario by improving the acceleration performance of bulk trains to match that of intermodal trains (Figure 9(b)). This change leads to the revelation that acceleration performance is a significant factor causing delays to bulk trains and increased delays due to heterogeneity. The reduction in delay increases with greater traffic volumes and with an increasing percentage of bulk trains, however, the greatest reduction is not with homogenous bulk train traffic but when 75% of the trains are bulk. Since the reduction in delay occurs when the traffic is heterogeneous, improved acceleration performance not only reduces delay to each bulk train but also reduces train conflicts that result in delay.

In typical operations lower-priority trains often have poorer operating characteristics. This can increase congestion on a route because these trains will make more frequent stops to resolve conflicts, increasing the possibility of following trains being delayed. Without priorities, the trains with poorer operating characteristics would make less frequent stops reducing the possibility of these types of conflicts. Therefore, acceleration performance alone does not significantly influence delays but in combination with priorities it can cause the additional delays that result from heterogeneous train traffic.

Impact of heterogeneity in priority

The last characteristic considered is the dispatching priority assigned to trains. Intermodal trains with their higher-value merchandise and greater customer demand for fast, reliable service are typically given the highest priority by railroad dispatchers. Bulk trains are typically less time-dependent and therefore given lower priority on the network.[20] Without differential priorities during a conflict, the first train to arrive at a siding will enter it and wait for the other train. With priorities, the lower-priority train will often have to stop at an earlier siding and wait so as to prevent delays to the higher-priority train. Consequently, priority can increase both the number and duration of meets.

The first investigated scenario considered traffic composed of intermodal trains with high and low priorities (Figure 10). When priority is considered alone the increased delays are due to more frequent and longer delays of lower-priority trains during meets. As would be expected, these delays are greatest at the highest volumes and levels of heterogeneity. The second investigated scenario considered the base scenario with all the traffic having the same priority (Figure 10(b)). With homogenous traffic all the trains are the same and have equal priority; consequently, removing heterogeneity in priority does not change the delays in these scenarios. However, with heterogeneous traffic, removing priorities reduces delay with the greatest reduction at the highest levels of heterogeneity and traffic volumes.

The magnitude of the delay caused by heterogeneity in train priorities depends on the characteristics of the trains. In typical operations the trains with the lowest priority often have the poorest operating

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

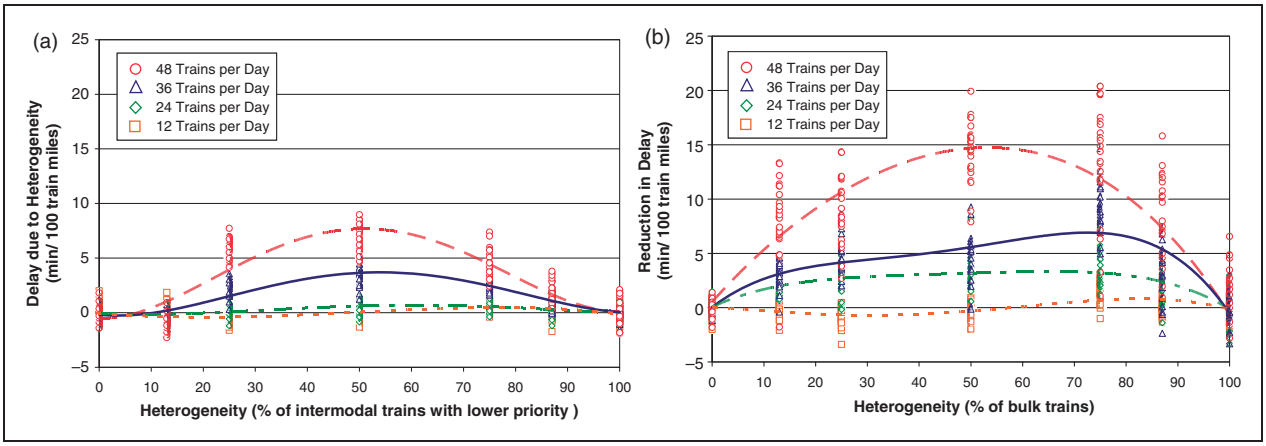

Figure 10. (a) Delays due to heterogeneity in priority and (b) reduction in delay from base scenario when priorities are equalized.

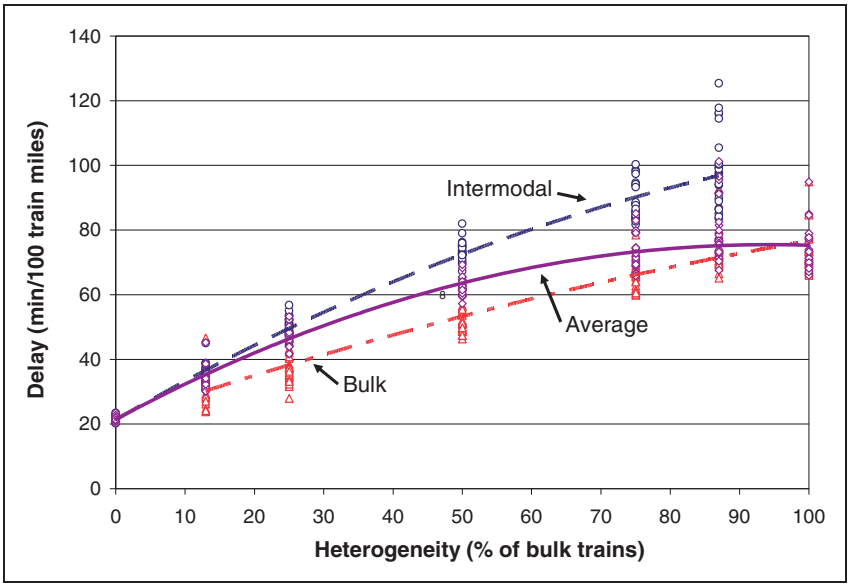

Figure 11. Delay by train type when priorities are equal at 48 trains per day.

characteristics. Ironically this means that these trains with the slowest acceleration experience the most additional stops due to meets and passes. While the other factors considered contribute to delays with and without heterogeneous traffic, priority only reduces delays due to heterogeneity.

To further investigate the effect of priority on train-type heterogeneity, the delay to each type of train was individually studied (Figure 11). When the priorities are equal the delays to each train type are similar and the delays increase with a greater percentage of bulk trains. Unlike when intermodal trains are given a higher priority (Figure 4), in this case the intermodal trains have a greater delay than bulk trains. Since it is less likely that a faster train will pass a slower train when there are no priorities, there may not be enough time for the train to reach its top speed before slowing for another meet. With equal priorities, the average delays are less than when the traffic has differential priorities but the reduction comes as a result of increased delays for the higher-priority intermodal traffic.

Discussion

Traffic volume, heterogeneity and delay are all closely related. Routes that have the highest volumes and are facing the greatest capacity constraints, experience the largest delays due to heterogeneity. The two principal train characteristics that reduce capacity are heterogeneity in train priority and acceleration performance. Neither causes substantial delays due to heterogeneity alone, but in combination they result in additional stops for the lower-priority trains, which are least able to accelerate back to top speed. Other sources of heterogeneity, braking and speed difference have little effect on delay. On a single track route, reducing train speed to homogenize traffic increases the occupancy time of the track between sidings thereby increasing delays and reducing capacity.

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

Although not considered in this study, passenger trains can introduce substantial heterogeneity on a line. They create additional delays because their pertinent characteristics are substantially different than the variation among freight trains. Passenger trains have higher maximum speeds, power-to-ton ratios and dispatching priorities, than all other freight trains. When passenger trains are added to baseline freight schedules, their impact is greater than if the same number of freight trains is added. This additional effect needs to be considered when additional passenger trains are proposed for a route. These trains not only take up train slots that could otherwise be used by freight, but they can also create additional delays for existing freight traffic.[21]

Understanding the trends and causes of capacity lost due to heterogeneity among trains is important when planning for new traffic. Train type can be as important as the number of trains when considering the impact on capacity and thus volume should not be the sole measure of line capacity. This research has shown that even at a constant volume, traffic can experience widely varying delays, depending on the mix of trains. A route may be operating at capacity at a variety of different volumes depending on the traffic mix. Additionally, depending on the current traffic mix, additional traffic will have a different impact on capacity. For example, when the majority of traffic is intermodal the addition of a few bulk trains will have a much greater effect than adding a few intermodal trains to a network operating mostly bulk trains

Conclusions

There is increasing demand for freight rail transport in North America and considerable capital is being invested in new infrastructure. Investing this capital efficiently requires understanding the different operational characteristics of the intended traffic. Analyses have been performed using dispatch simulation software to determine the impacts of heterogeneity in freight traffic. This assessment reveals the relationship between volume, heterogeneity and delay. Further work identified the key factors that contribute to the increased delays due to heterogeneity. The train characteristics of speed, acceleration, braking and priority were considered and the combination of priority and acceleration performance were found to have the greatest effect. Understanding these factors that affect delay allows for more effective network capacity planning and efficient rail operations. The results also suggest certain railway operating strategies that may reduce the delays caused by train-type heterogeneity thereby improving service reliability.

Funding

This research was supported by the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign, but received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

1. Krueger H. Parametric modeling in rail capacity planning. In: Farrington PA (ed.) *The 1999 Winter simulation conference*, Phoenix, AZ, 5–8 December 1999, pp. 1194–1200. The University of Michigan: IEEE.
2. Kraft ER. Jam capacity of single track rail lines. *Proc Transport Res Forum* 1982; 23(1): 461–471.
3. Harrod S. Capacity factors of a mixed speed railway network. *Transport Res Part E* 2009; 45(5): 830–841.
4. Lai YC and Barkan CPL. An enhanced parametric railway capacity evaluation tool (RCET). *Transport Res Record: J Transport Res Board* 2009; 2117: 33–40.
5. Abril M, Barber F, Ingolotti L, et al. An assessment of railway capacity. *Transportation Res Part E* 2008; 44(5): 774–806.
6. Dingler MH, Lai Y-C and Barkan CPL. Impact of train type heterogeneity on single-track railway capacity. *Transport Res Record: J Transport Res Board* 2009; 2117: 41–49.
7. Dingler MH. *The impact of operational strategies and new technologies on railroad capacity*. Master's Thesis, University of Illinois, USA, 2010.
8. Lai YC, Dingler MH, Hsu CE and Chiang PC. Optimizing train network routing with heterogeneous traffic. *Transport Res Record: J Transport Res Board* 2010; 2159: 69–76.
9. Lai YC, Dingler MH, Lin SY and Liu KC. Optimal track class assignment for a railroad network. *J Oper Res Soc* 2013; Epub ahead of print. DOI: http://www.palgrave-journals.com/jors/journal/vaop/ncurrent/full/jors2012159a.html.
10. Dingler MH, Lai YC and Barkan CPL. Mitigating train type heterogeneity on a single track line. *Proc IMechE, Part F: J Rail Rapid Transit* 2013; 227(2): 140–147.
11. Cambridge Systematics. *National rail freight infrastructure capacity and investment study*. Report, 2007. Cambridge, MA: Cambridge Systematics. Available at: http://www.camsys.com/pubs/AAR_Nat_%20Rail_Cap_Study.pdf.
12. American Association of State Highway and Transportation Officials. *Transportation – invest in our future: America's freight challenge*. Report, 2007. Washington, DC: American Association of State Highway and Transportation Officials. Available at: ftp://ftp.mdt.mt.gov/research/LIBRARY/TIF3-1-FREIGHT_CHALLENGE-AASHTO.PDF.
13. Pachl J. *Railroad operating and control*. Mountlake Terrace, WA: VTD Rail Publishing, 2002.
14. UIC 406: 2004. Capacity.
15. Dingler MH, Koenig A, Sogin S and Barkan CPL. Determining the causes of train delay. In: *The 2010 AREMA annual conference*, Orlando, FL, 29 August–1 September 2010.
16. Bronzini MS and Clarke DB. Estimating rail line capacity and delay by computer simulation. *Trib Transp* 1985; 2(1): 5–11.
17. Parsons Brinckerhoff Inc. *The long term financial and economic feasibility of the Northwestern Pacific Railroad*. Report, 2003. Eureka, CA: Parsons Brinckerhoff Inc. Available at: http://humboldtbay.org/sites/humboldtbay.org/files/documents/rev_plan_2003/NWP_Final_1_03.pdf.

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015

18. Association of American Railroads. *Analysis of class I railroads*. Report, 2008. Washington, DC: Association of American Railroads.
19. Transportation Research Board. *Proceedings from transportation research board workshop on railroad capacity and corridor planning*. Washington DC: Transportation Research Board, 2002.
20. Congressional Research Service. *Rail transportation of coal to power plants: reliability issues*. Report no. RL34186, 2007. Washington DC: Congressional Research Service. Available at: http://cnie.org/NLE/CRSreports/07Oct/RL34186.pdf.
21. Sogin S, Lai YC, Dick CT and Barkan CPL. Comparison of capacity of single- and double-track rail lines using simulation analyses, Transportation Research Record. *Journal of the Transportation Research Board* 2013.

Downloaded from pif.sagepub.com at UNIV OF ILLINOIS URBANA on January 7, 2015