Impact of Operating Heterogeneity on Railway Capacity
09-2652

Mark Dingler
Graduate Research Assistant
Railroad Engineering Program
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
B-118 Newmark Civil Engineering Laboratory
205 N. Mathews Ave., Urbana IL, 61801 USA
Tel: (217) 244-6063
Email: dingler2@uiuc.edu

Yung-Cheng (Rex) Lai
Assistant Professor
Department of Civil Engineering
National Taiwan University
Room 313, Civil Engineering Building
No 1, Roosevelt Road, Sec 4
Taipei, Taiwan, 10617
Tel: +886-2-3366-4243 Fax: +886-2-2363-9990
Email: yclai@ntu.edu.tw

Christopher P.L. Barkan
Associate Professor
Director – Railroad Engineering Program
Department of Civil and Environmental Engineering
University of Illinois at Urbana-Champaign
1203 Newmark Civil Engineering Laboratory
205 N. Mathews Ave., Urbana IL, 61801 USA
Tel: (217) 244-6338 Fax: (217) 333-1924
Email: cbarkan@uiuc.edu

Word Count: 7,640 (5,140 words, 3 Tables, 7 Figures)

ABSTRACT

North American railroads are experiencing rapid growth in traffic demand and increasingly need to expand capacity to accommodate it. Efficient planning of new capacity requires understanding how the mixture of traffic interacts to affect capacity. Different freight and passenger trains have substantially different operating characteristics including speed, acceleration, braking and dispatching priorities. Heterogeneity in the mix of train types using a line reduces its capacity. Train dispatching simulation software was used to analyze the effect of various combinations of intermodal, unit, manifest and passenger trains on a hypothetical signalized single-track railroad subdivision with characteristics typical of a North American rail line. Analyses included the effect of traffic volume, varying percentages and combinations of different train types as well as the effect of priority and speed ratio of the different trains sharing a line. The effect of adding passenger trains to freight-only lines was also evaluated. As has been shown by previous investigators, heterogeneity did reduce capacity but different types of heterogeneity had differing effects, which has implications for capacity planning. This paper attempts to provide a better understanding of the factors of heterogeneity allowing for more effective planning and a more complete understanding of one factor of capacity. Furthermore, the results suggest certain operating strategies that can mitigate the reduction in capacity, although they may increase operating costs. Further research should address under what conditions it would be cost-effective to change operating practices to offset the need to expand infrastructure to accommodate heterogeneous traffic.

KEYWORDS: simulation modeling, rail traffic controller, infrastructure investment, operations, freight train, passenger train

1. INTRODUCTION

North American freight railroads are experiencing rapid growth in demand for their services and are increasingly experiencing capacity constraints. Between 2000 and 2005 the US railroads revenue ton miles increased by over 13% *(1)*. This demand is not expected to abate as the American Association of State Highway and Transportation Officials (AASHTO) predicts the demand for freight rail services will increase 69% based on tons originated, and 84% based on ton-miles by 2035 *(2)*, creating the necessity to add more trains. Meanwhile, Amtrak, VIA Rail, and various commuter operators are also users of capacity on many parts of the rail network, and their traffic and operations are also expanding. In 2007 Amtrak's ridership had its fifth straight year of growth with an increase of 6.3% *(3)*. This growth in demand, coupled with increased profitability since deregulation in 1980, has led to considerable investment in renewal and expansion of railroad infrastructure *(4, 5)*; however, these investments are capital intensive. Efficient planning and financing of new capacity to meet demand requires understanding how expanded operations affect capacity.

A critical aspect of capacity management is understanding how different operational characteristics of train types interact to affect capacity. In North America, intermodal, unit, manifest and local switchers may all share trackage. Some lines also have intercity passenger trains, and in metropolitan regions, commuter trains. Each of these train types has different maximum speeds, accelerations, and braking distances. This type of heterogeneity has a substantial effect on rail line capacity *(6,7)*.

Previous work has considered the impacts of heterogeneous train speeds on capacity and reliability. Vromans et al *(8)* studied the Dutch rail network and its various passenger services in order to homogenize the timetable to increase reliability. For this work they developed several quantitative measures of heterogeneity. Landex et al *(9)* also used the Dutch rail system, but focused on the importance of line segment length regarding overtakes and capacity. Abril et al *(10)* conducted a comprehensive capacity study on Spanish rail lines. They developed a mathematical model and used it to investigate capacity lost due to heterogeneity. The study considered two train speeds, one 50% the speed of the other, on single- and double-track lines.

Others have looked at the impact of heterogeneity on the North American network. Krueger *(11)* developed the CN Parametric Model in an attempt to quantify capacity with heterogeneous traffic using a simulation model. Bronzini & Clarke *(12)* used a single-track simulation model and did some initial work to compare the delay due to mixtures of intermodal and unit trains. More recently, Herrod *(13)* modeled the United States network using mathematical integer programming. He considered the differing impact of faster and slower non-conforming trains and found that the slower the non-conforming train, the greater the impact on the network. These studies considered certain aspects of the impact of heterogeneity on capacity, but no comprehensive study has been performed.

For this study a simulation model was used to conduct a quantitative analysis on the impact of heterogeneity among the principal train types operated in North America. We evaluated the effects of various combinations and scenarios of three different types of freight trains and one type of passenger train with differing levels of heterogeneity on a signalized single-track route. Increase in delay was used as the principal metric to assess capacity impacts under different conditions. The objective of this work is to provide insight into the factors of different train mixtures that increase delay and to assess the economic impact of heterogeneity.

2. METHODOLOGY

2.1 Capacity Attributes

There are a number of different factors that influence rail capacity and metrics to measure it. Among the influences are operating and infrastructure factors including: average and variability in speed, volume, stability, terminal efficiency and heterogeneity. These are interrelated with, and further influenced by, operating infrastructure characteristics such as: siding length and spacing, crossover spacing, number of tracks, signal and traffic control system, grade, and curvature. Consequently it can be difficult to precisely determine the available capacity of a particular route. To complicate matter more, there are also a number of measures to determine the usage of a line. Each of these is useful for looking at a different aspect of railroad operations but are not easily convertible between each other. These measures include average velocity, trains per day, gross tonnage, delay and on-time performance.

In this analysis we used delay as the metric of comparison because it is more objectively measured than some others. We define delay as the difference between the minimum run time, or unopposed running time, for a route and the actual time to traverse the route. This includes the time spent stopped for meets and passes, along with the time to brake and accelerate for the stops. Consequently, as a single-track route becomes more congested more trains are required to make more stops and consequently the delay will increase.

2.2 Simulation Model- Rail Traffic Controller

For this study Rail Traffic Controller (RTC) from Berkeley Simulation Software® was selected as the model to be used. RTC is sophisticated software program designed to realistically simulation both freight and passenger operations over a railroad network *(14, 15)*. It is currently being used by all the North American Class 1 railroads for evaluation and planning of their operations. The program allows for the input of track layouts, train consists and schedules and operating rules and constraints. The software then resolves the multi-train conflicts in the same manner as an actual railroad dispatcher. The simulation dispatch logic in the model is cost based; therefore the goal is to generally minimize the total cost of delay to all the trains involved. We used RTC because of its widespread acceptance in the North American railroad industry and because it provides flexibility for rapid evaluation of different scenarios. This enabled us to efficiently consider a variety of scenarios and interactions among different train types.

2.3 Representative Network

Actual route specific characteristics of North American rail lines vary; each has its own siding lengths and spacing, grades and curvatures. Studying the impact of infrastructure configurations is outside the scope of this paper, therefore we created a representative network based on typical characteristics in order to conduct the simulations. The generic line we used is the length of a typical subdivision and has the following attributes:

- single track
- 124 miles long
- 10 miles between sidings
- 2.5-mile signal spacing
- 3-aspect signals
- 0% grade and curvature
- 8,000 ft signaled sidings with #24 powered turnouts

3. IMPACT OF OPERATING HETEROGENEITY

Four train types: intermodal, unit coal, manifest and passenger, were used to quantify the impact of heterogeneity. These train types are reasonably representative of several other trains operating on the North American network. For example auto trains will often have similar type characteristics to intermodal trains and unit grain trains are similar to unit coal trains. Local switchers and commuter trains, that have completely different characteristics due to their frequent stops, were not included in this analysis.

The TRB Workshop on Railroad Capacity and Corridor Planning *(16)* provided typical weights, lengths and horsepower to trailing ton ratios (HPTs) for various train types. We used this information to create the characteristics for the four train types used in this analysis (Table 1). The most important attributes that affect capacity are maximum speed and HPT. Higher speeds allow a train to traverse the network faster but will also increase the braking distance, an important factor in meets, additionally the difference in speed among trains will lead to conflicts with slower trains. The horsepower to trailing ton ratio directly affects how fast a train is able to accelerate after a stop and its ability to reach its maximum allowable speed.

TABLE 1 Trains Used in Simulations

Intermodal	Unit Coal	Manifest	Passenger
90 cars	115 cars	70 cars	20 coaches
6,300 ft	6,325 feet	4,550 feet	1,500 feet
8,100 tons	16,445 tons	7,700 tons	835 tons
2.12 HP/Trailing Ton	0.78 HP/Trailing Ton	1.12 HP/Trailing Ton	5.09 HP/Trailing Ton
4 SD70 4,300 HP Locomotives	3 SD70 4,300 HP Locomotives	2 SD70 4,300 HP Locomotives	1 P42-DC 4,250 HP Locomotive
Maximum Speed: 70 mph	Maximum Speed: 50 mph	Maximum Speed: 60 mph	Maximum Speed: 79 mph

Another important characteristic for each train type is the priority assigned to it. By law, Amtrak passenger trains are given priority, therefore were given the highest priority in the simulations. Of the freight trains considered in this study, intermodal trains were assigned the highest priority, followed by manifests, and unit trains the lowest. When two trains meet, priority is just one factor the dispatcher will take under consideration when determining how to resolve the conflict. Generally dispatchers will try to minimize the total cost of delay *(14)*, this means that the lower value, lower priority trains will enter the siding. One challenge of priority based dispatching is that often the trains with the lowest horsepower to trailing ton ratios (HPT) are the trains with the lowest priority, impeding their ability to accelerate and reach top speed from a stop.

3.1 Delay-Volume Relationship

To better understand the representative route being used, simulations were run to provide base line delay-volume graphs for homogenous traffic of the freight trains used in the study.
Train departures were evenly spaced to depart the terminal at each end of the line over a 24-hour period. Trains were systematically added in pairs, one in each direction, until train starts were being delayed. The resulting delays were recorded, graphed and the data used to create delay-volume curves for the route (Figure 1).

The trend between each of the three train types is rapidly evident. For each volume of traffic unit coal has the highest delay followed by manifest and intermodal. The higher allowable speeds and ability to accelerate more rapidly allows intermodal to have the highest volumes with the lowest delay. For instance at 60 trains per day unit coal experiences a delay of 119 minutes per 100 train miles, while manifest experiences 79 minutes and intermodal 43 minutes.

No specific capacity for each train type can be taken from each graph, as capacity for a line is based on when the delay reaches unacceptable levels. This unacceptable level is variable, as one railroad's customers or commodity groups all may have different acceptable levels of service and corresponding tolerance of delay. Up to this level, greater tolerance of delay will permit more traffic to traverse the same infrastructure.

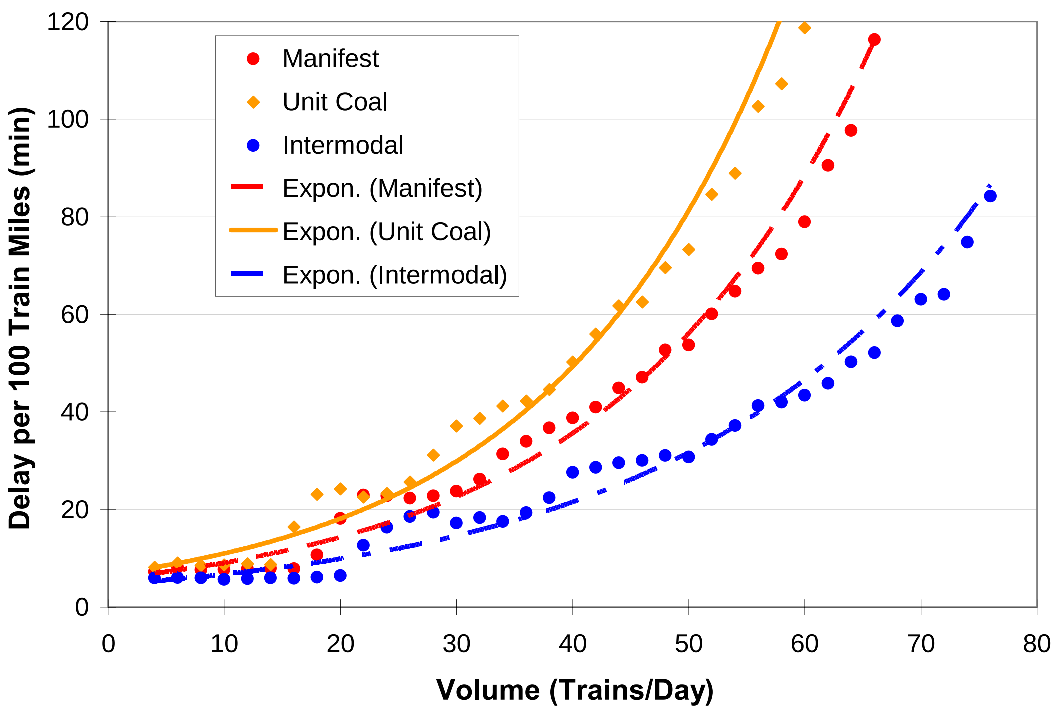


FIGURE 1 Delay-Volume Graph with Trend Lines.

3.2 Freight Heterogeneity Assessment

When multiple train types are operated on a rail line, there is a complex interaction of a number of variables that affect delay. These variables include, speed ratio, physical characteristics, priority, volume, traffic mix (i.e. percentage of different train types) and speed difference. An extensive series of simulations were run to understand the impacts of heterogeneity using pairwise combinations of the three freight train types.

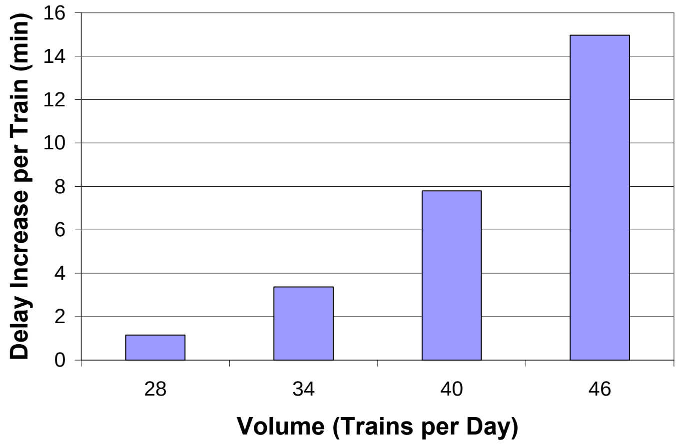
The percentage of each type was systematically increased and the effect on delay recorded. Each pairwise scenario was run at four traffic volumes: 28, 34, 40 and 46 trains per day. These are theoretical volumes and are not practical for sustained operation on a daily basis because they do not allow time for maintenance or other activities that require track time. Therefore, the impacts are more characteristic of the spacing between the trains than the actual volume. The CN parametric model suggests that practical capacity is about two thirds of theoretical capacity *(11)*; therefore volumes of 19, 23, 27 and 31 trains per day are a truer estimate of the actual train volumes possible in the scenarios tested. However for the purposes of the comparisons being made in this paper, theoretical volume is satisfactory and is used throughout this paper.

At each volume the train mix was altered incrementally by varying the percentage of trains from 100% of train type A and 0% of train type B, to 0% type A and 100% type B. The order that trains were dispatched was also controlled, for example, with unit coal and intermodal, 10% heterogeneity corresponded to one coal train, followed by nine intermodal trains. In all scenarios, the ratios and traffic pattern were the same in both directions.

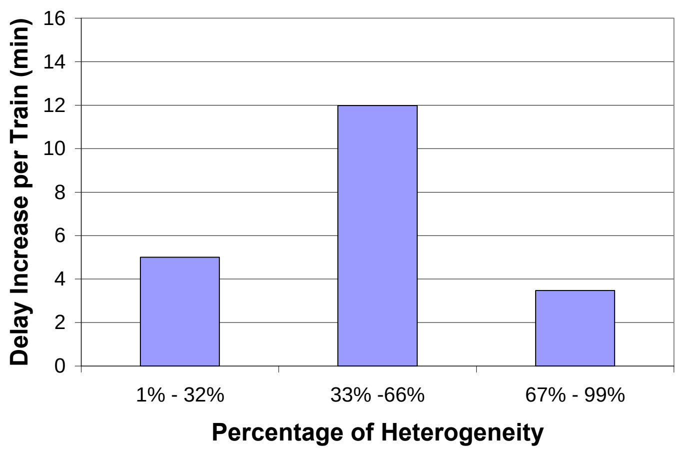
The results reveal several trends with respect to volume, percent heterogeneity and train types (Figure 2). The delay increase per train due to heterogeneity is defined here as the difference between the delay of the particular mixed traffic scenario and the weighted average of the delays for homogeneous traffic of the two train types. This was used to isolate the additional delay due to heterogeneity. Not surprisingly there is a strong relationship between traffic volume and delay (Figure 2a).

The percentage of heterogeneity also affects delay, with the greatest delay occurring when heterogeneity is the highest (33 to 66 percent) (Figure 2b). The two groups of low heterogeneity (the first and last thirds) might at first be expected to be similar to one another; however they are comprised of greater or lesser percentages of trains with differing characteristics, which in turn affect delay differently.

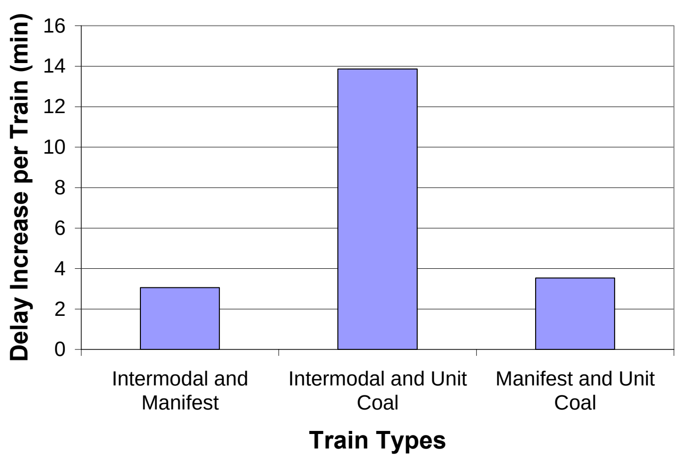
Related to the effect of differing percentages of two train types on delay is the interaction of the particular pairwise combination of train types. This effect is greatest when intermodal, with maximum speeds up to 70 mph, and unit coal trains, with the lowest maximum speed of 50 mph operate together (Figure 2c). This combination results in over three times the delay seen with intermodal operating with manifests, or manifest with unit coal trains.



(a)



(b)



(c)

FIGURE 2 Additional Delay Minutes per Day due to Heterogeneity sorted by (a) Percent Heterogeneity (b) Volume and (c) Train Type

3.2.1 Factors of Heterogeneity

Although the effect of volume, percent heterogeneity and train type is evident from these results, the specific factors that cause delay due to the interaction of the particular train types is unclear. Additional scenarios were analyzed to clarify these factors. In the following series of experiments the volume and physical characteristics of the trains were held constant, but the speeds and priorities were adjusted (Figure 3).

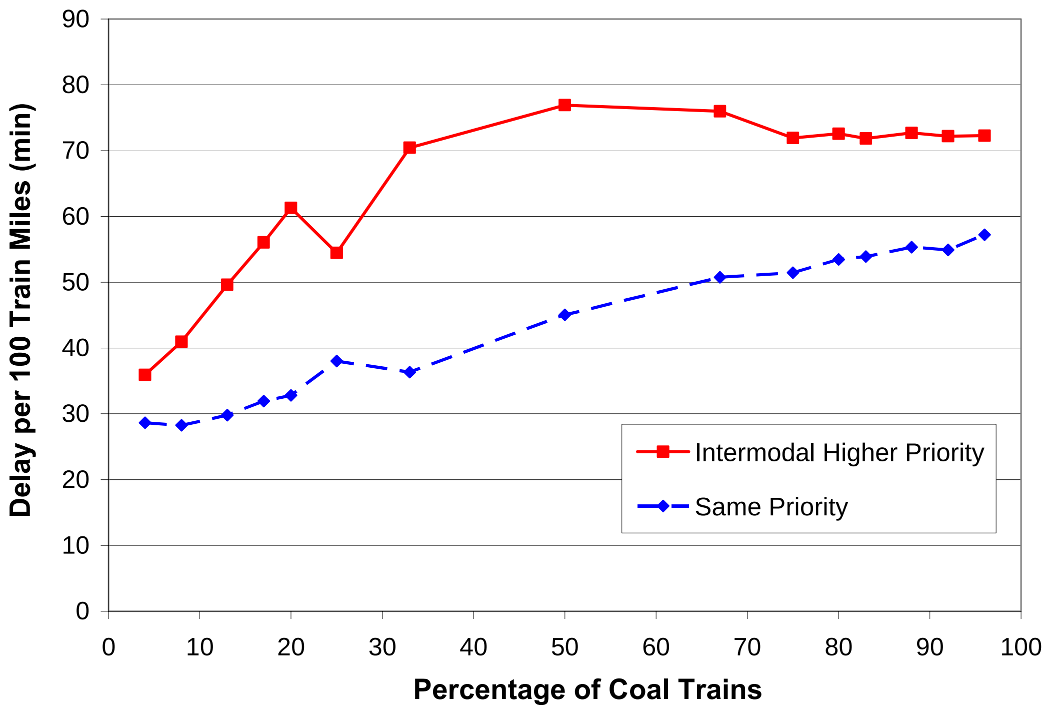
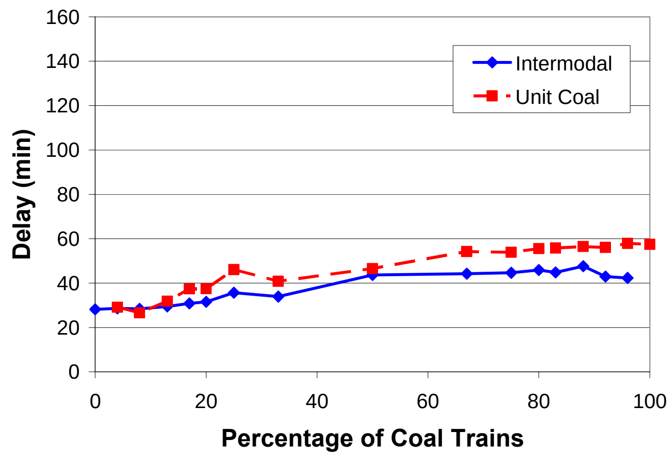


FIGURE 3 Intermodal and Unit Coal at 60 MPH

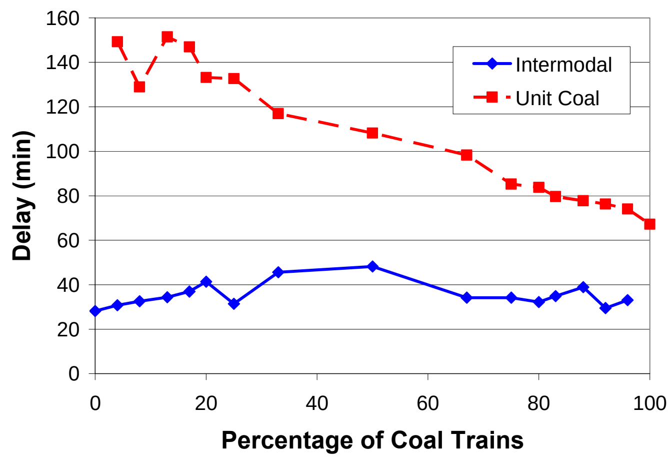
To gain a better understanding of the impact of a train's priority and physical characteristics, several tests were done. First, maximum speed was held constant between intermodal and unit coal trains. Next, in addition to the same maximum speed, the priorities for both train types were set equal, leaving the physical and consequent operating characteristics (i.e. HPT, length and tonnage), as the only difference.

When the trains are the same except for their physical characteristics the delay shows no increase due to heterogeneity. The delay follows the weighted average of the delays for homogeneous traffic of the two train types. As the number of trains with greater delay, in this case unit coal, increases, so does delay. When the priorities were not the same, there was a large increase in delay as heterogeneity increased. These results indicate that difference in priority, rather than speed and acceleration characteristics is the principle factor affecting delay. While train characteristics alone have no impact due to heterogeneity, they become a factor when priorities are introduced. It is generally the slower trains with lower HPT that have lower priority. These trains therefore take longer to accelerate from the stops, decreasing capacity.

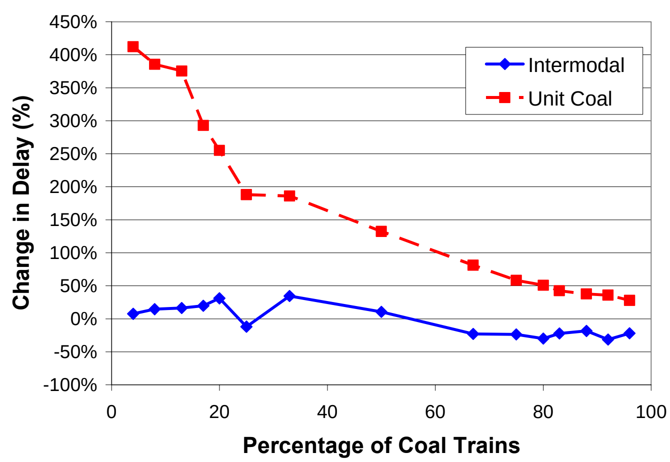
The increase in delay when the trains had different priorities was not caused by an increase in delay of all trains, only the unit trains experienced the extra delay (Figure 4). Between the two scenarios, when the priority of intermodal trains was increased, the delay on the unit coal trains greatly increased and with a minor or no decrease in delay for intermodal. The additional delay due to the different priorities is largest when there are many more intermodal trains than unit coal train. When the traffic was 4% coal trains, the unit coal trains saw a 413% increase in delay due to priority, this was coupled with a minor increase in delay for intermodal. When the number of unit trains outnumbered intermodal trains the increase in delay was less dramatic. At 92% unit coal trains, the coal trains saw a 36% increase in delay with a resulting decrease in delay for intermodal of 30%. The increased priority for intermodal trains, a characteristics given in order to decreased delay, came at the cost of increasing the average delay for all trains, the minor decreases in delay for intermodal resulted in greatly increased delay on unit coal



(a)



(b)



(c)

FIGURE 4 Delay of Intermodal and Unit Coal when their Priorities are the (a) Same and (b) Different and (c) Percent Change in Delay due to Different Priorities

The influence of speed has already been shown but it is unclear if the speed ratio or speed difference is more important when determining delay. To investigate this, two scenarios in which trains with maximum speeds differing by 10 mph were run. Then two more scenarios with the same speed ratio as the original two scenarios were run and the results compared (Table 2).

For all but one case, the correlation between the scenarios with the same speed ratio was higher than that of the scenarios with the same speed difference. This suggests that heterogeneity is influenced more by the speed ratio of the two trains than the absolute difference in speed.

TABLE 2 Correlation Coefficients of the Speed Ratio and Speed Difference

	Speed Ratio		**Δ Speed**
Intermodal and Unit Coal	0.899	0.900	0.814
Manifest and Unit Coal	0.214	0.514	0.289
Intermodal and Manifest	0.878	0.864	0.806
Intermodal and Intermodal	0.378	0.675	-0.200

3.2.2 Cost of Heterogeneity

The cost due to heterogeneity can be quantified in two ways, opportunity cost and delay cost. Opportunity cost is based on the number of train starts that are lost if the traffic is heterogeneous Based on the results of the delay-volume curve for intermodal, at 46 trains per day the delay is 30 minutes. With traffic being a mix of half intermodal and half coal the delay increases by 283%, up to 85 minutes. At that delay level, if the traffic was homogenous with intermodal trains, the theoretical capacity would be 76 intermodal trains per day. The lost capacity is therefore 30 intermodal trains, or using the same method 6 unit coal trains.

Another way to look at the cost of heterogeneity is delay cost. The cost can be calculated by summing four components: unproductive locomotive cost; idling fuel cost; car/equipment cost; and crew cost. A recent estimate by one Class 1 railroad is that train delay costs approximately $261 per train-hour *(17)*. In the scenario mentioned above, operating a total of 46 intermodal and unit coal trains per day in an equal proportion, the cost due to increased delay from heterogeneity would be over $3.14 million per year. Although the cost is based on the particular characteristics and scenarios considered in this paper, it provides some idea of the magnitude of the costs of heterogeneity.

When adding trains to a route there is a trade off between the opportunity and additional delay cost and the marginal benefit of each added train. The cost of each additional train is variable based on the number of that train type already operating. For the specific case analyzed, an even mix of intermodal and unit coal the added delay due to each train type was graphed (Figure 5). The additional delay for each train, as compared to the homogenous condition, decreased as more of each train type was added. When there is only 20% coal trains each unit coal train on average adds a little over 6 minutes of delay to each train operating on the route. This corresponds to a total of 1,679 hours of delay annually added by each additional coal train. It is clear when adding a train to a route the incremental cost is much higher when there are fewer of the corresponding train type operating already. This must be considered by a railroad when considering additional traffic.

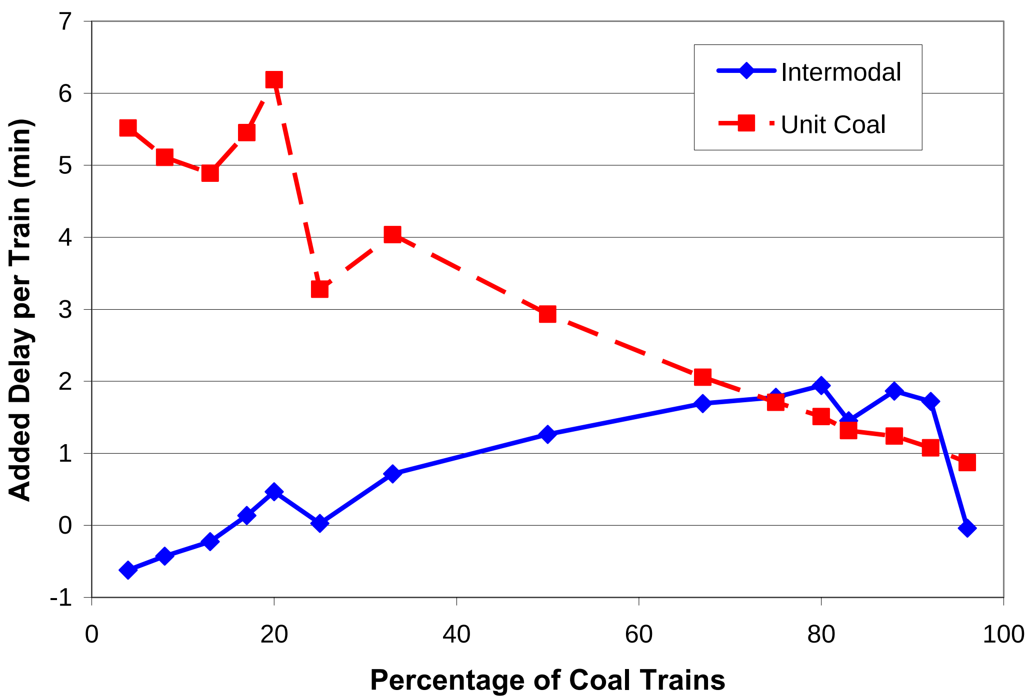


FIGURE 5 Additional delay due to each additional intermodal and unit coal train

3.2.3 Comparison of RTC heterogeneity results to the CN Parametric Model

Some previous work has been done to quantify the effects of heterogeneity using the CN Parametric Model *(11)*. In order to evaluate the effectiveness of the CN model as a tool to study heterogeneity effects, simulations from RTC and the CN model were analyzed and compared. The CN model enables estimation of the capacity of a route based on certain key operating characteristics: average speed, speed ratio, priority and peaking. From these operating characteristics the model calculates the delay-volume curve. The same scenarios run in RTC were performed using the parametric model.

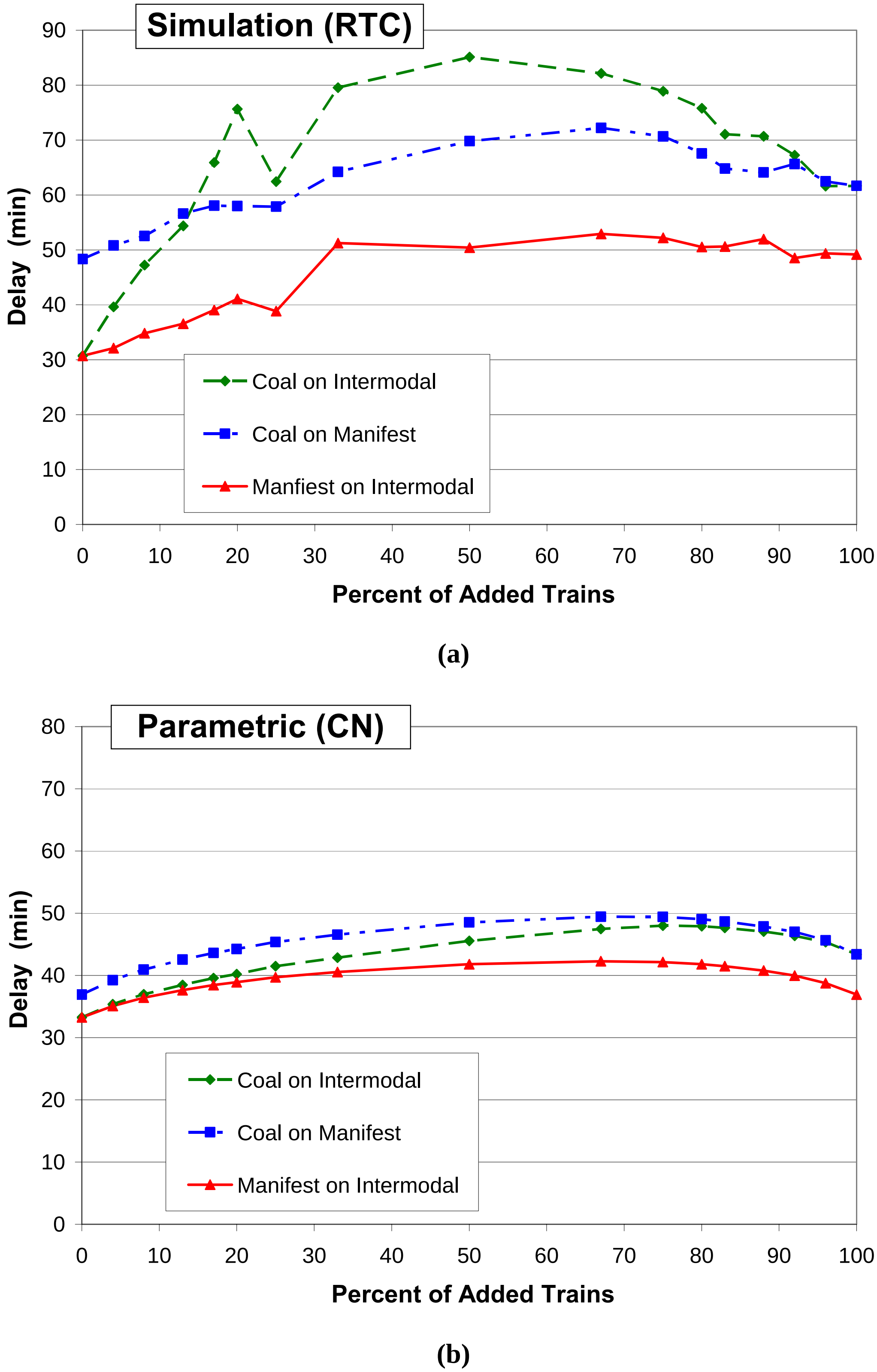


FIGURE 6 Train Delay at 46 Trains per Day based on (a) RTC and (b) CN Parametric Model

The results from the parametric model show an increase in delay as the slower train type is added, with a peak in delay at about 75% slower trains. The train mix with the highest delay in the parametric model is coal and manifest, with the least delay seen with manifest and intermodal. The shapes of the heterogeneity-delay curves are constant for all volumes, the difference being the magnitude of delay.

When compared to RTC the results are similar at low levels of heterogeneity. The differences are seen in the train mix, and the amount of heterogeneity, with the largest delay. RTC has the lowest delay with coal and manifest, while the opposite is seen using the parametric model. Using RTC there is a distinct increase in delay between 33% and 66% heterogeneity, while in the parametric model the greatest delay was found at 75% heterogeneity.

These results suggest that the CN parametric model is a less robust does tool for understanding the effects of heterogeneity. Emphasis is placed on average speed in its calculation of delay, the train mix with the lowest average speed, manifest and coal, is given the highest delay. This is contrary to the RTC model results, which has the trains with the greatest difference in speed experiencing the greatest delay. For the parametric model the average speed is calculated using the average minimum run times of the different train types. This is limiting as it only takes into account the minimum time to traverse the route, with no meets or passes. In more heavily congested lines, the trains may never be able to reach maximum speed due to frequent stops for meets or passes.

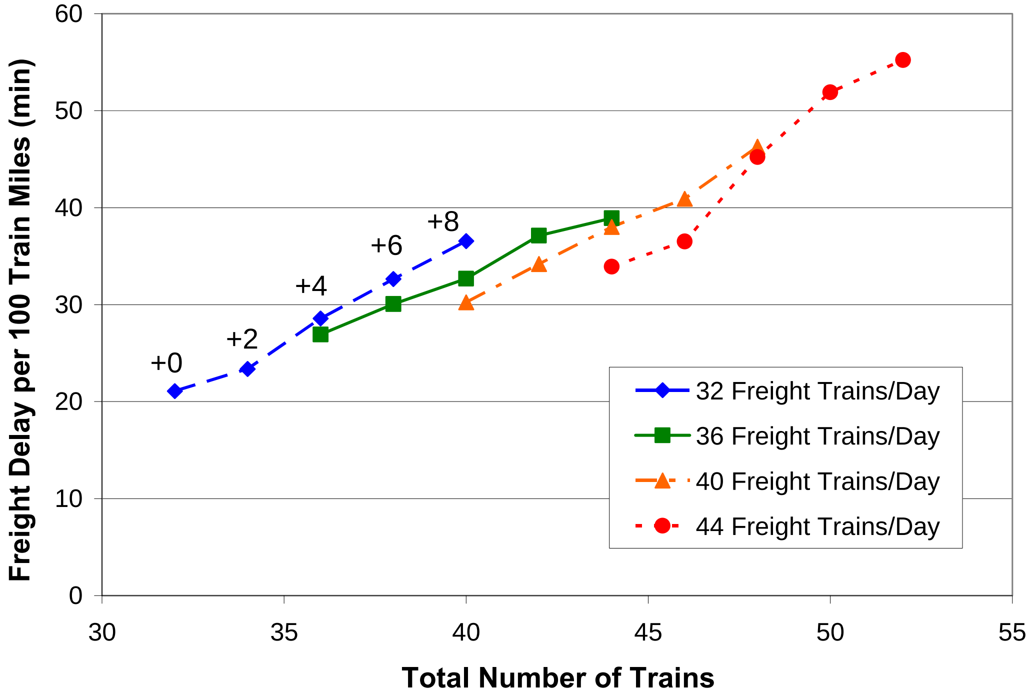
The CN parametric model excels at providing a fast way to estimate the delay and the resulting capacity on a line with limited heterogeneity, but at higher levels of heterogeneity it appears less effective. The CN parametric model is good for network level analysis, but is not sufficient for considering the questions addressed in this study.

3.3 Passenger with Freight Heterogeneity Assessment

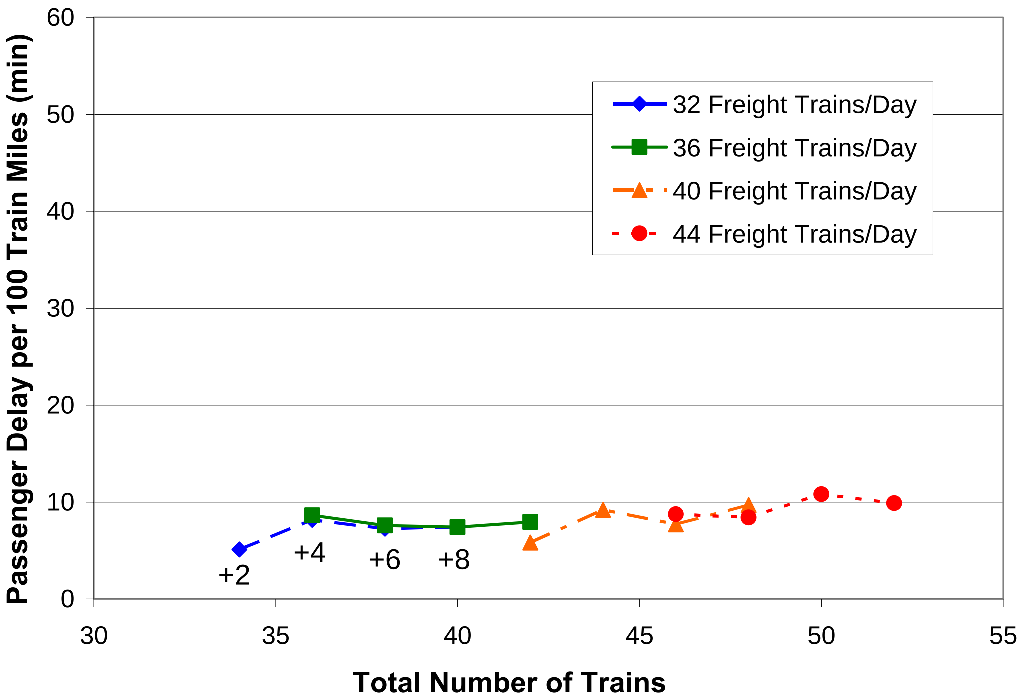
So far we have only considered different types of freight trains. Adding passenger trains to a freight-only line (or vise versa) adds considerable new heterogeneity because the pertinent characteristics of these trains tend to be even more different than the variances amount freight trains. We added various numbers of passenger trains to freight traffic to determine their effect. The increased volume decreased the headway between trains; therefore, the impact was two fold, increased heterogeneity and increased volume.

We used a mix of 80% manifest and 20% intermodal trains spaced evenly through the day for the base freight train volumes. To the baseline freight traffic of 32, 36, 40 and 44 trains per day, pairs of passenger trains, up to four in each direction, for a total of eight, were added. The schedule was adjusted to keep even spacing between freight trains and added passenger trains. If an intermodal and passenger train were scheduled adjacent to one another in the schedule, the passenger train would be dispatched first to eliminate overtakes. The presence of stops was ignored; therefore the impacts due to passenger trains will be much greater if the stops occupy the mainline.

The qualitative effect on heterogeneity introduced by passenger trains is the same as for freight trains, only greater. A passenger train has faster acceleration, higher maximum speed (79 mph) and higher priority than any freight train. Each pair of passenger trains added, increases the delay of the freight trains (Figure 7a). When multiple scenarios with the same volume are compared, in every case the scenario with the greater number of passenger trains has more delay. Consequently additional passenger trains cause greater delays than the same number of freight trains would. The delay on the passenger trains was independent of the number of freight trains as the delay stayed roughly constant over the different simulations (Figure 7b). This result is to be expected since passenger trains will be given priority at meets and passes.



(a)



(b)

FIGURE 7 Delay vs. Number of Trains for (a) Freight Trains and (b) Passenger Trains (Figures Indicate the Number of Additional Passenger Trains in Each Scenario)

Freight train delays were further analyzed to provide insight into the incremental behavior of each added passenger train (Table 3). For the lower densities the effect of each additional pair of passenger trains varied. However, in general the effect of each pair of trains was linear, with the eighth passenger train causing as much additional delay as adding the first passenger train to a route. This is because the passenger trains are spread out over the day and therefore do not interact with each other. Each passenger train meets the same number of freight trains as the other passenger trains through the day. The exception to this may be at 44 trains per day. In this case there seemed to be a greater effect with higher number of passenger trains. This suggests that if traffic reached high enough levels the incremental nature of delay might change.

TABLE 3 Incremental Delay Minutes for each Added Passenger Train

Freight Trains per Day	**Number of Added Passenger Trains**			
	2	**4**	**6**	**8**
32	45	74	76	77
36	70	64	76	67
40	98	96	88	99
44	71	154	164	145

4. DISCUSSION

This assessment provides insight into the impacts of heterogeneity on freight and passenger train traffic. A mixture of train types increases delay more than a comparable increase in trains with the same operating characteristics. Consequently, disproportionally more time is required for trains to traverse the route, reducing its capacity. Several trends regarding heterogeneity were found with respect to volume, the amount of heterogeneity, and the train types being operated. Impact due to the specific train types is influenced by the priorities of the trains, the physical train characteristics and the speed ratio.

To reduce the impact of heterogeneity one must mitigate the factors contributing to the increased delay. These were found to be priority, train characteristics and speed ratio. Priorities often cannot be easily changed. However, changing the speed ratio by increasing the speed limit of the slower trains or decreasing the speed of the faster trains might be feasibly under some circumstances. Increasing the horsepower to trailing ton ratio of the slower trains will also help mitigate some of the impacts of the physical train characteristics on delay.

Passenger trains are another source of heterogeneity on some freight lines in the North

American network. When passenger trains, with their high priorities and speeds, are added to baseline of freight trains, the impact is greater than if the same number of additional freight trains were added. For all but the highest volumes, each additional passenger train led to a roughly constant increase in delay. This facilitates estimating the cost of adding additional passenger trains to a route.

5. CONCLUSION AND FUTURE WORK

There is increasing demand for the rail in the North American network and considerable capital is being invested in new infrastructure. For this capital to be invested efficiently requires understanding the different operational characteristics of the traffic. We performed analyses using dispatch simulation software to determine the impacts and causes of heterogeneity with freight and passenger traffic. The scenarios involved varying combinations of three freight train and one passenger train types. Several trends were found and investigated as the causes of the impacts due to heterogeneity.

Understanding the impact of heterogeneity on capacity is just the first step. Additional work will be done looking at mitigation techniques to reduce the impact and restore capacity. One hypothesis to be tested is how cost effective it would be to increase power on trains with lower HPTs. This would allow them to exit sidings and accelerate to full speed more rapidly. The extra costs of locomotives and fuel must be compared to the benefit of the extra capacity to determine the cost-effectiveness of this approach compared to expanded infrastructure. Future work will also include development of a double track model for additional heterogeneity tests, and evaluation of commuter train characteristics on single- and double-track lines.

ACKNOWLEDGEMENTS

The authors are grateful to Eric Wilson for his assistance in this research. Support for the first author's graduate study has been from a CN Railroad Engineering Research Fellowship at the University of Illinois at Urbana-Champaign.

REFERENCES

1. Association of American Railroads *Railroad Facts*, Washington D.C., 2006
2. American Association of State Highway and Transportation Officials (AASHTO) (2007) *Transportation - Invest in Our Future: America's Freight Challenge*, AASHTO, Washington, DC.
3. Amtrak, Annual Amtrak Ridership Sets All-Time Record; Fifth Straight Year of Increases, *News Release*, October 23, 2007
4. Gallamore, R. Regulation and Innovation: Lessons from the American Railroad Industry. In *Essays in Transportation Policy and Economics* (J. A. Gomez-Ibanez, W. B. Tye, and C. Winston, eds.), Brookings Institution Press, Washington, D.C., 1999.
5. Grimes, G.A. and C.P.L. Barkan. Cost-effectiveness of railway infrastructure renewal maintenance. *ASCE Journal of Transportation Engineering* 132: 601-608.
6. Pachl, J. R*ailroad Operating and Control.* VTD Rail Publishing, Mountlake Terrace, 2002
7. International Union of Railways (UIC), 2004, *UIC leaflet 406*, UIC International Union of Railways, France
8. Vromans M. J.C.M., Dekker R., Kroon L.G., (2004) Reliability and Heterogeneity of Railway Services, *European Journal of Operational Research*, 172 (2006) 647–665
9. Landex A., Kass A. H., Schittenhelm B., Schneider-Tilli J., (2006) Evaluation of Railway Capacity, *Proceedings of Trafficdays*, Aalborg, Denmark
10. Abril M., Barber F., Ingolotti L., Salido M.A., Tormos P., and Lova A. (2007), An Assessment of Railway Capacity, *Transportation Research Part E*, doi:10.1016/j.tre.2007.04.001
11. Krueger, H. (1999) Parametric Modeling in Rail Capacity Planning, *Proceedings of Winter Simulation Conference*, Phoenix, AZ.
12. Bronzini M.S., Clarke D.B., (1984), Estimating Rail Line Capacity and Delay by Computer Simulation, *Tribune des Transports*, Vol. 2-1, Pages 5-11

13. Herrod, S., (2006), Optimal Scheduling of Mixed Speed Trains on a Single Track Line, Presented at INFORMS 2006

14. Washington Group International, Inc. (2007), RTC Simulations: LOSSAN North Railroad Capacity and Performance Analysis, Draft Final Report

15. Parsons Brinckerhoff Quade & Douglas, Inc. (2002), The Long Term Financial Feasibility of the Northwestern Pacific Railroad, Draft Final

16. Transportation Research Board (TRB) (2002) TRB Workshop on Railroad Capacity and Corridor Planning, *Proceedings*, January 13, 2002

17. Lai, Y.C. *Increasing Railway Efficiency and Capacity through Improved Operations, Control and Planning*, Ph.D. Dissertation, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, 2008.