

**CONGESTION AS A SOURCE OF VARIATION IN PASSENGER  
AND FREIGHT RAILWAY FUEL EFFICIENCY**

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**ABSTRACT**

Recent railway industry campaigns have highlighted the relative average fuel efficiency of freight and passenger trains as a key benefit of the railway transportation mode. These efficiencies are anticipated to increase rail market share as rising energy costs make less efficient competing modes less attractive. However, the fuel consumption and energy efficiency of a specific passenger or freight rail system, and even individual trains, depend on many factors. Changes in these factors can have various effects on the overall fuel consumption and efficiency of the system. One of these factors is the amount of congestion and delay due to increased traffic on the line. Thus, it is possible that the additional traffic anticipated to shift to the rail mode due to its energy benefits may increase congestion and actually have a negative impact on overall network energy efficiency. Such a case would tend to dampen the future shift of traffic to the rail mode. While simple train performance calculators can evaluate the energy efficiency of a train for an ideal run, more powerful train dispatching simulation software is required to simulate the performance of trains in realistic operating scenarios on congested single-track lines. Using this software, the relative impact of congestion on efficiency can be analyzed and compared to changes in factors related to fuel consumption. In this study, several factors affecting the efficiency of both passenger and freight rail systems were selected for analysis. Rail Traffic Controller (RTC), a train dispatching software, simulated representative single-track rail subdivisions to determine the performance of specific passenger and freight trains under different combinations of factor level settings. For passenger rail, the effects of traffic volume and station spacing on fuel consumption were analyzed while the effects of traffic

volume and average speed were analyzed for freight rail. Each system was analyzed on level track and on territory with grades. Preliminary results suggest that passenger trains, if given priority, maintain their efficiency until large numbers of passenger trains are present on the network, while freight trains experience degradation in energy efficiency as congestion increases. These results will be used to develop a factorial experiment to evaluate the relative sensitivity of freight and passenger rail efficiency to congestion and other system parameters. The paper concludes with a brief discussion of possible technologies to improve efficiency and offset potential losses due to future congestion.

**INTRODUCTION**

Economic growth and global trade have led to dramatic increases in goods movement over the past few decades. This increase in freight transportation demand in the United States has been paralleled by a continued move by the population away from rural areas and towards urban centers, resulting in the creation of mega-regions with interconnected sprawling suburbs and huge demands for passenger transportation. Political opposition, space practicalities and the sheer cost of further expanding the freeway and roadway network have prevented the highway mode from keeping pace with the demand for passenger and freight mobility. As demand nears capacity, the result is growing congestion on the highway network. Besides inconveniencing drivers, congestion has direct economic consequences ranging from lost hours of productivity to increased freight logistics cost of additional inventory, vehicles and drivers, to the cost of fuel consumed while idling or moving in slow traffic.

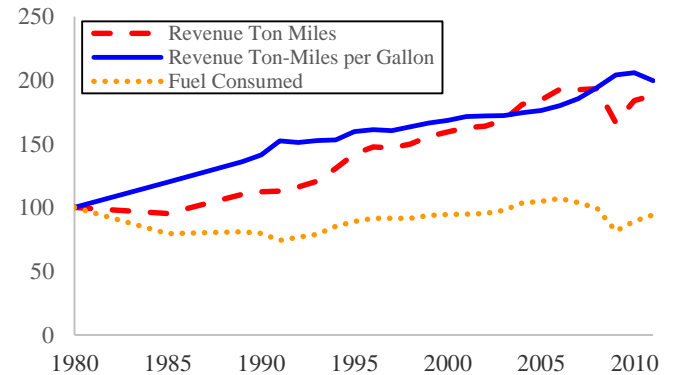
A report commissioned by the National Cooperative Highway Research Program (NCHRP) estimates that across

their sample of 75 cities, the cost of congestion reached 67.5 billion in 2000 [1]. With diesel prices increasing nearly four-fold in the last 15 years and continuing to trend upwards, the share of congestion costs that can be attributed to decreased fuel efficiency will only continue to increase [2]. The NCHRP study also showed that when modelling highway capacity under projected demand, adding truck traffic nearly doubles the amount of highway miles which approach or exceed capacity. This finding, combined with projections of a 61% increase in total tons of freight to be transported by 2040, will create unprecedented levels of congestion on the highway network [1]. Unless political, financial and environmental obstacles can be overcome to facilitate substantial investments in highway capacity, decreasing efficiency and increasing cost of personal transportation by automobile and freight transportation by truck is inevitable. Clearly, to maintain mobility via an efficient and low-cost transportation system, there is a need to shift much of this future traffic growth to alternative modes of passenger and freight transportation.

The deregulation of railroads in 1980 gave Class 1 railroads the flexibility to rationalize routes, focus on the most profitable sectors of their business, invest in infrastructure to support heavier axle loads and renew their fleets with innovative locomotive technology. This has allowed them to greatly improve the efficiency of the railway mode of transportation for both freight and passengers. Comparing an index based on values from 1980 (Figure 1), while revenue ton-miles have practically doubled, diesel fuel usage has remained constant, allowing the revenue ton-miles per gallon of fuel to also double, increasing from 235 ton-miles per gallon in 1980 to 469 ton-miles per gallon in 2011 [3]. Comparatively, the typical highway semi-trailer truck efficiency ranges from 70 ton-miles per gallon to 135; even less when operating in congested urban conditions [4]. This efficiency advantage has been the center of railroad promotional campaigns for many years. While simply portraying rail as an environmentally-friendly “green” mode of transportation may have influenced some shippers, it was not until diesel fuel costs first spiked in the mid-2000s that the improved efficiency of rail created additional financial incentive to shift goods from trucks to the rail mode to reduce fuel costs. It is estimated that the external cost of hauling freight are at least three times higher for trucking than those of freight trains [5].

On the passenger side, the efficiency and green perception of passenger rail did not offer a strong financial incentive for drivers to switch modes until fuel prices began to trend upwards and the cost of operating a private vehicle increased. Under these conditions, Amtrak boasts a 44% ridership increase over the last decade and has broken ridership records eight of the last ten years, all the while decreasing diesel fuel use by 13% [6]. Similarly, commuter rail systems have experienced a rapid growth not only in ridership but also in the number of systems in operation over the past decade. Commuter rail ridership increased 28% between 1997 and 2007 and 13% from 2008 to 2011 in spite

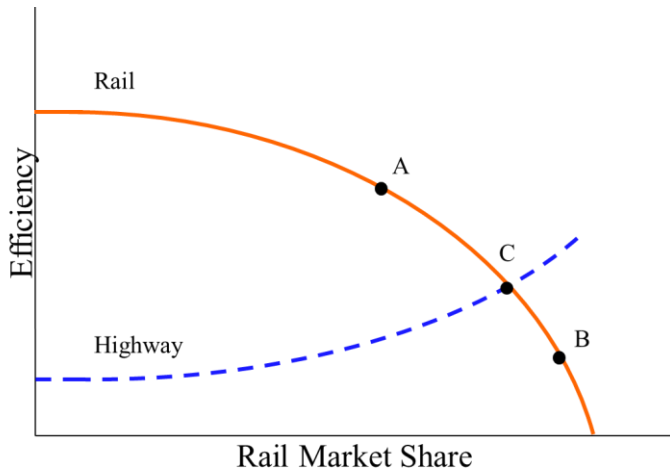
of the recession [7]. Much of this increased ridership and public support of system expansion arose after fuel prices increased and, for many urban commuters, the cost of gas and parking exceeded the cost of regional rail fares. Statistical analyses reveal that increases in commuter rail ridership can be correlated to fuel price increases, with as much as a 0.1% increase in ridership for every \$0.01 increase in fuel price [8].



**FIGURE 1. FREIGHT RAIL PERFORMANCE METRICS INDEXED FROM 1980 VALUES [3]**

It is clear that many shippers and passengers alike are electing to utilize rail transportation due to its efficiency in the face of rising fuel prices. Point A in Figure 2 represents this current status with rail being more efficient than the competing highway mode. However, as traffic demand continues to increase for the rail mode, what are the effects of the additional traffic shifting from the highway mode to the rail system on efficiency? Initially, increases in volume will increase overall efficiency by distributing fixed costs and energy consumption over more units of freight. However, *Railroad Engineering* by Hay shows that as volume on a particular line or network increases further to the point where capacity for additional traffic becomes constrained, the unit cost of transportation on that network starts to increase and economies of scale are lost. Added congestion creates delay for trains and complicates maintenance operations, leading to a shortage of railcars, motive power and crews at terminals and faster degradation of the track infrastructure [9]. Rail traffic delay introduces additional operational costs into the transportation system in the form of opportunity costs from underutilized rolling stock, railcar-hire costs, additional labor costs, and fuel costs from the extra acceleration/deceleration of trains for additional train meets as well as fuel consumed during locomotive idling at meets or in congested terminals and other rail network bottlenecks [10].

Previous study has concluded that portions of the rail network are approaching congested conditions as traffic rebounds to pre-recession levels and that without significant investment in capacity, growth in current rail traffic sources, without including modal shift, will create severe network congestion [11]. Additional traffic resulting from modal shift to take advantage of railway fuel efficiency will compound this congestion and create additional network delay.



**FIGURE 2. RELATIVE EFFICIENCY OF RAIL AND HIGHWAY TRANSPORTATION AND MODAL EQUILIBRIUM**

As delay time begins to hinder the movement of rail traffic due to more frequent train meets with correspondingly more fuel consumed while accelerating from meets and idling on sidings or in congested terminals, increased traffic may decrease rail fuel efficiency. At a certain future traffic level, the combination of decreased fuel efficiency, prolonged transit times and poor service reliability associated with congested rail lines and terminals may degrade the efficiency of the rail mode to the point where there is no longer any incentive for highly competitive shipments to move by rail and they may return to truck, as seen by point B in Figure 2. The loss of traffic will ease some rail network congestion and drive traffic back to the rail mode until equilibrium is reached, point C. This equilibrium has been studied by several researchers via mode choice models that include current truck and rail fuel efficiency metrics as input parameters [12–14]. In order for these models to adequately describe future scenarios and congested rail traffic levels, proper assumptions must be made to capture potential variation in passenger and freight rail fuel efficiency under these conditions. Future efforts to cap or tax carbon emissions may change the delay cost structure and place an even higher premium on rail fuel efficiency. Thus, it is necessary to study the relationship between rail traffic levels, congestion and fuel efficiency in order to better understand how specific changes in traffic levels and operating parameters can affect the attractiveness of rail compared to competing modes.

## METHODOLOGY

Previous research has confirmed the fundamental relationship between traffic volume and delay that describes railway congestion and level of service [15]. The delay-volume relationship takes the form of a curve with relatively little delay at low traffic volumes that gradually builds to an exponential increase in delay at higher traffic volumes. This

research seeks to understand how this relationship translates into a similar curve describing fuel efficiency as a function of traffic volume. Given that fuel efficiency is also influenced by many other factors such as vertical gradient and alignment, axle loads, train length, load factor, operating speed and the inherent efficiency of the locomotives assigned to the train, this research also seeks to understand the relative sensitivity of fuel efficiency to traffic volume compared to these other factors.

To begin this line of research, a single-variable study was performed in order to isolate the fuel efficiency effects of certain factors of interest specifically related to measures of railway congestion. Table 1 displays the main factors under investigation for the freight and passenger efficiency analysis. For freight operation, traffic volume is the main factor of interest as it captures the impact of a shift in highway freight transportation demand to rail. However, train speed was also investigated since slowing trains down is one tactic employed by the railroads to reduce fuel consumption and increase efficiency during periods of particularly high fuel costs. For passenger operation, traffic volume and stop spacing were analyzed because they represent factors that will change as highway traffic demand is transferred to regional passenger and commuter rail transportation, increasing the number of train runs and the required density of stations.

**TABLE 1. ANALYSIS FACTORS**

Train Type	Factor
Freight	Traffic Volume
	Train Speed
Passenger	Traffic Volume
	Station Spacing

The fuel efficiency response from changes to the above factors was determined via simulation of train operations over a hypothetical single-track railway subdivision that is 242 miles in length. Single-track operation is representative of the North American railway network of which only 11 percent of the entire rail network and 30 percent of higher-density mainlines are double track [16].

The total traffic volume values were varied from eight to 40 trains per day in increments of eight trains, allowing for an even directional split of 75 percent freight trains and 25 percent passenger trains for the traffic mixture. The freight speed was varied from 20 mph to 70 mph in increments of 10 mph and the station spacing was simulated at intervals of 5, 30, 80, 120, and 240 miles with the latter representing an express run over the subdivision under study. These station spacing increments were chosen to represent various levels of passenger rail services. The 5-mile spacing represents typical commuter rail operations, 30 represents a regional intercity service, 80 and 120-mile spacing represents varying levels of long-distance intercity service, and the 240-mile run represents an express intercity service such as the Amtrak “Auto Train”.

Since North American freight trains vary greatly in terms of lading, length, and tonnage, their base fuel efficiency can also vary greatly. To capture any difference in response between trains of varying base efficiency, two different types of freight train types were considered. The first train type is a mixed-freight or “manifest” train based on the “average” freight train derived from AAR annual statistics [3]. Based on the statistical averages, this train includes both loaded and empty cars, and the loaded cars do not carry the full payload that might be expected under a 286,000-pound gross rail load. For comparison, the second train type is a fully-loaded bulk commodity unit train. The exact specifications for each freight train are shown in Table 2 along with the passenger train consist. The nine-car passenger train is assumed to include one coach configured for business class and one café car that does not include any revenue seats.

The metrics used to analyze freight fuel efficiency and passenger fuel efficiency are ton-miles per gallon and seat-miles per gallon respectively. Each of the factors were calculated by summing the total ton-miles or seat-miles accumulated by all trains for a particular factor level simulation and then dividing by the total fuel consumed by all trains in the same simulation. Thus, these values are the gross average for all trains; they are not simply the arithmetic average of the efficiency metrics for individual trains.

The seat-miles per gallon metric was chosen to normalize the effect of ridership on fuel efficiency, as opposed to the passenger-miles per gallon metric, which is influenced

by the ridership and the percentage of seats occupied by passengers (i.e load factor). Seat-miles per gallon gives the efficiency of a passenger train as if all the seats were occupied by passengers, illustrating the potential per-trip efficiency of a system. However, this metric is heavily influenced by the number of seats per railcar, so changes in seating configuration can overshadow the base efficiency of a system.

### Rail Traffic Controller

For an ideal non-stop run, or for a set schedule with all stops and dwell known, a simple train performance calculator (TPC) can be used to calculate the efficiency metrics for a freight or passenger train over a known route. On single-track railways in North America, such conditions will rarely be encountered as even priority trains are likely to make multiple stops at passing sidings to meet other trains and differences in train speeds can necessitate running below maximum speed and overtake maneuvers. The acceleration, deceleration and time spent idling while waiting for the opposing train all decrease fuel efficiency and the frequency of these events will increase as traffic increases. Given that North American mainlines do not adhere to a strict schedule of operations and meeting points between trains are not predetermined but are set by train dispatchers during the course of operations, the amount and number of delay incidents encountered by a particular train can vary greatly between runs. This variation and uncertainty in train operating patterns grows in complexity as traffic increases, particularly when both passenger and freight trains are operating on the same rail corridor, decreasing the utility of simple TPC runs. To capture the variation in operations experienced as traffic increases to congested conditions, more sophisticated simulation software that emulates train dispatching decisions must be used to generate the time and distance inputs for the train performance calculation. For this study, Rail Traffic Controller (RTC) software developed by Berkeley Simulation Software was employed.

RTC is widely accepted by the railroads in North America as a standard simulation model for rail traffic analysis and is particularly attuned to simulation of single-track operation. Based on detailed information including maximum allowable track speed, curvature, grades, signal system, train departure time, and locomotive and railcar characteristics, the train dispatching logic in RTC can generate a dispatching result by detecting conflicts between trains and modifying the train paths to avoid infeasible train movements. In addition, RTC may delay or reroute one or more trains according to their given priority to reflect the business objective of the railroad. The emulation of dispatching decisions under given train priority makes RTC more realistic than other analytical and simulation models.

For this study, RTC was used to simulate mixed-use freight and passenger train movements on a 242-mile subdivision of single-track mainline dispatched with centralized traffic control (CTC) signals. The route parameters for RTC are shown in Table 2. This table shows the

**TABLE 2. ROUTE AND TRAIN PARAMETERS**

Route Characteristics	Length (mi)	242
	Type	Single Main Line
	Siding Spacing (mi)	10
	Percent Freight	75
	Max Passgr. Speed (mph)	79
	Max Freight Speed (mph)	50*
	Trains per Day	20*
	Grade (%)	-1, 0, 1
Train Characteristics (Manifest)	Locomotive Type	SD70-4300
	Number of Locomotives	2*
	Loaded Cars	56
	Empty Cars	18
	Tare Weight (tons)	30
	Revenue Tons/Loaded Car	62.9
Train Characteristics (Bulk)	Locomotive Type	SD70-4300
	Number of Locomotives	4*
	Number of Cars	100
	Gross Rail Load (lbs)	286,000
Train Characteristics (Passenger)	Locomotive Type	GE P-42
	Number of Locomotives	2
	Number of Cars	9
	Seats per Train	566
	Gross Rail Load (lbs)	70

\*Factors varied under study

average values for each parameter and the asterisk signifies factors, mentioned previously, that are varied to investigate their relationship to fuel efficiency. Note that given its significant impact on train resistance and required drawbar pull, the influence of gradient is also investigated by creating a route entirely composed of level (0 percent) gradient and a second route that is entirely on a 1 percent grade. For the latter scenario, all “west-bound” traffic travels upgrade for the duration of the trip and east-bound traffic moves downgrade.

To ensure that the results are not dominated by particular train schedule assumptions and to better emulate the unscheduled North American operating environment, each particular scenario is simulated multiple times with trains being randomly dispatched from each end terminal during a 24-hour time period. Each of the replications is simulated for five days of traffic so the final transportation and efficiency metrics for a particular combination of factor levels represent multiple days of randomly scheduled train operations. The replication ensures that any particularly poor schedules are balanced by relatively good schedules to produce a reasonable average result.

The TPC embedded within RTC generates data on the fuel consumption of every train running through the study corridor. RTC does this by calculating the speed profile and throttle/brake settings (Figure 3) of each train based on the assigned locomotive types, train consists, elevation, curvature and track conditions (Table 2). Unlike a stand-alone TPC, service reliability metrics such as train delay are also output from RTC. The RTC algorithm requires that all trains from a given day of traffic be dispatched within a 24-hour period. If this is not possible under severe congestion where there are too many adjacent train conflicts in one area resulting in irreconcilable train paths, RTC may fail to find a reasonable dispatching result. In such cases with extremely high train delays, RTC will not generate any performance or efficiency metrics. This is indicative of breakdown conditions on the railroad where fuel efficiency in ton-miles per gallon essentially drops to zero. Cases such as these limit the range of traffic volumes that can be modeled on the route under study.

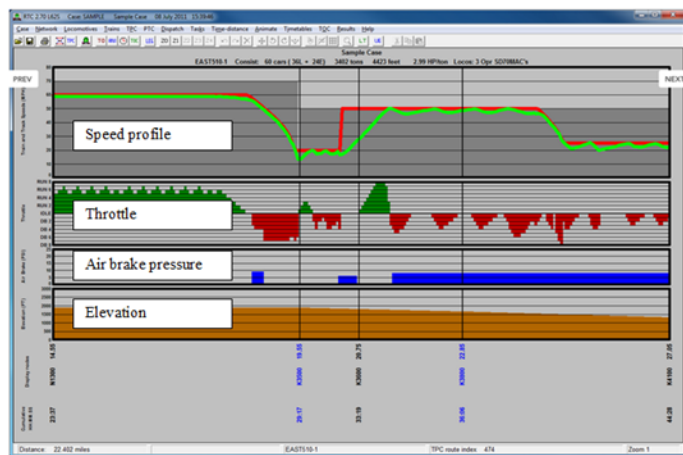


FIGURE 3. RTC TPC SAMPLE OUTPUT

## FREIGHT RESULTS

Figure 4 shows the response of manifest freight train fuel efficiency to varying traffic levels. The graph divides the response by gradient to present averages for all trains on the level (zero-grade) route as well as trains traveling uphill and downhill in the 1 percent grade scenario. It should be noted that while the upgrade trains average approximately 240 ton-miles per gallon, the efficiency values for the trains on the level and downhill grade routes far exceed the values of 400 to 500 ton-miles per gallon typically quoted for average rail fuel efficiency. This is in mostly due to the advantageous grade resistance conditions experienced by these trains. Previous research of actual train fuel consumption data has shown that individual trains may operate at anywhere from 200 to over 1,000 ton-miles per gallon depending on their exact route and configuration [17].

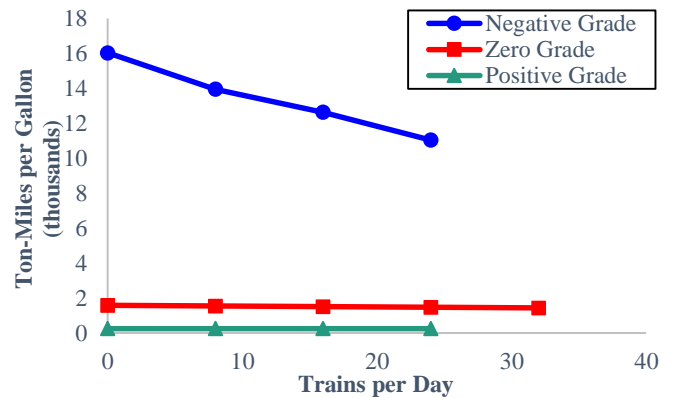
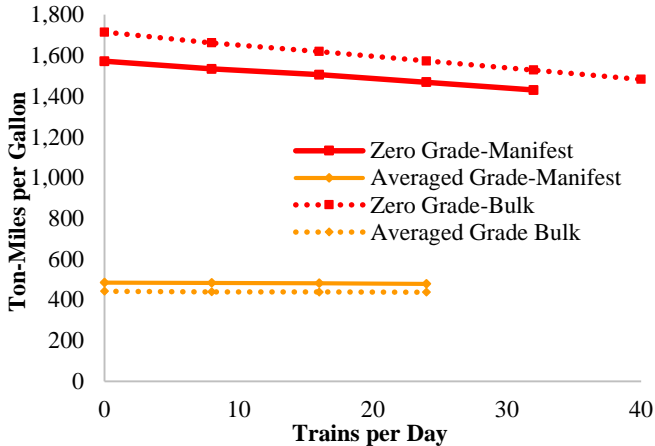


FIGURE 4. TRAFFIC VOLUME VS. MANIFEST FREIGHT TRAIN EFFICIENCY

Since a line that is entirely on a 1 percent downgrade or upgrade is not a common condition, and equipment must ultimately cycle back in the opposite direction up or down the grade, the performance of the uphill and downhill trains were combined to estimate performance of trains on a route where the individual 1 percent upgrade and downgrade segments average out to a level grade condition. Figure 5 illustrates this “averaged” grade condition that represents the combined data from the negative and positive grades. This allows for a better, more direct comparison to the zero grade scenario as in both cases the average grade is 0 percent. This figure also shows a comparison of the manifest train versus the bulk train. The bulk train is more efficient on the level grade because it maximizes economies of scale. However, it is more sensitive to increasing traffic because of the increased force necessary to accelerate and decelerate the train.

It is interesting to note that the averaged grade condition for both the bulk and manifest train is still much less efficient than the level grade scenario. Thus it is not the case where the additional fuel consumed in going upgrade is exactly balanced by the fuel saved by the natural acceleration from the negative grade resistance on the downgrade. Even in



**FIGURE 5. TRAFFIC VOLUME VS. FREIGHT EFFICIENCY-FOR BOTH TRAIN TYPES ON DIFFERENT GRADES**

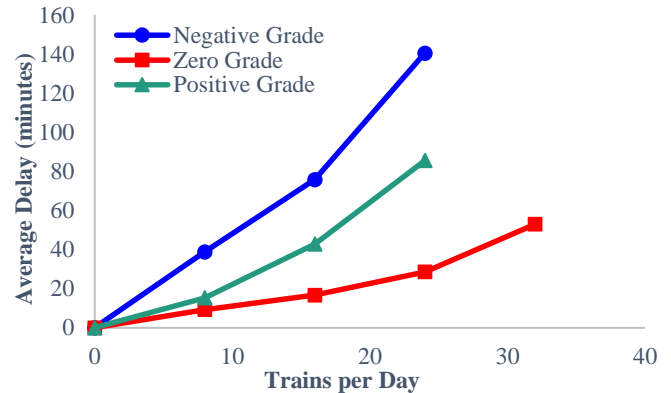
the downgrade case, fuel is being consumed while locomotives are idling and to provide additional cooling for the dynamic brakes. The 480 to 485 ton-miles per gallon exhibited by the manifest train are actually fairly close to the published industry average of 469 ton-miles per gallon.

In both cases, the freight trains exhibit a decrease in fuel efficiency as traffic volume increases. However, the effect is largely linear and for the more realistic conditions of averaged grade, the negative trend is very slight. Only a minimal degradation in fuel efficiency is observed before breakdown conditions are encountered and RTC fails to find an acceptable dispatching result. This result will be discussed further in the analysis section of the paper. Note that this breakdown condition occurs at a lower traffic volume when gradient is present due to the additional delays associated with braking and accelerating trains on grades.

Figure 6 illustrates the delay-volume relationships for the different grade scenarios. The trains in the 1-percent grade scenario exhibit steeper delay-volume curves, indicating that operation on the grade is in a more congested condition even at low traffic volumes. The primary reason for this is the low speed at which the fully loaded trains can travel uphill on the 1-percent grade. The trains are only powered with enough locomotives to achieve the maximum balancing speed on level track. Trains on the uphill grade have a considerably lower maximum speed and take much longer to traverse the single-track bottleneck sections between passing sidings than the trains moving downhill at track speed. The result is that the downhill trains (negative grade) experience the most delay as they must wait longer for the slower uphill trains to move between sidings. The uphill trains experience more delay than the trains on level track as, after being stopped, the uphill train will struggle to accelerate and lose considerable amounts of time compared to the free-running case.

Besides increasing delay, the lower speed of the uphill trains result in reduced fuel consumption and more efficient train operation when the train is moving. Thus, the efficiency of the upgrade and averaged grade cases may be

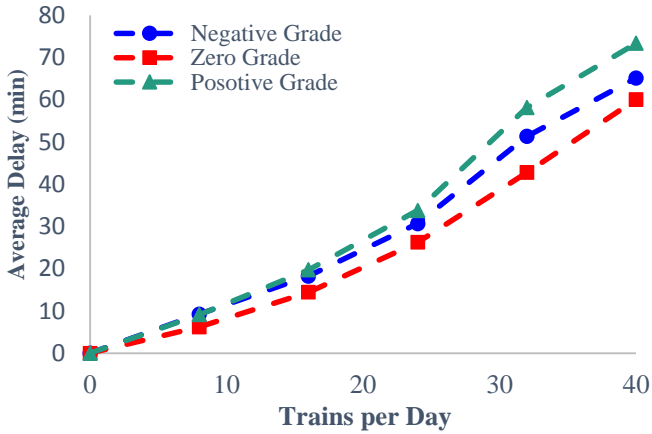
overstated because of the influence of decreased train operating speed. In order to fully isolate the effects of congestion on train efficiency, the negative and positive grade scenario was reanalyzed with four locomotives instead of two. Although this is not common operating practice for all Class 1 railroads, increasing the available locomotive power allows the upgrade trains to maintain the maximum allowable track speed throughout the entire route which decreases the disparity in delay between the zero grade and 1-percent grade scenario.



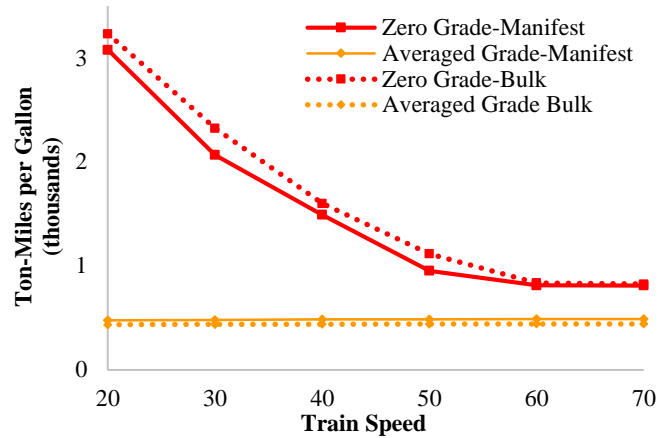
**FIGURE 6. TRAFFIC VOLUME VS. MANIFEST FREIGHT DELAY**

Figure 7 illustrates how the strategy of additional locomotive power effectively eliminated the difference in delay between the different grade scenarios. With the extra locomotive power on the 1-percent grade case, the delay-volume curves for both the upgrade and downgrade scenario are shifted downwards to nearly match the original delay-volume relationship for the level-grade scenario. Adding extra locomotives and increasing train speed upgrade eliminated the extra delay experienced by the downhill trains waiting for the slow upgrade trains. It also allowed the upgrade trains to more quickly accelerate and experience less delay when recovering from a stop for a meet.

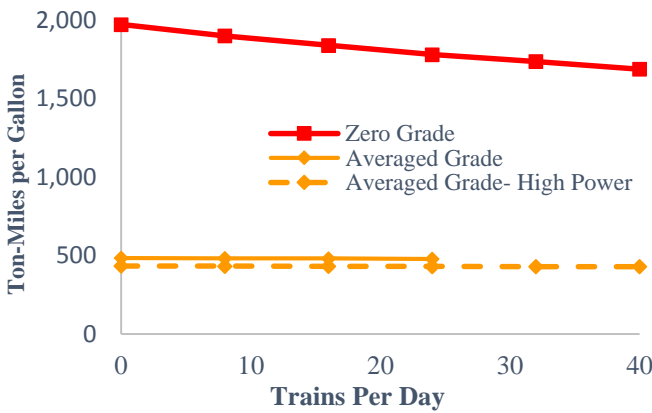
Figure 8 compares the efficiency of the four-locomotive consist (dashed line) to the two-locomotive consist for the level and averaged grade cases. Despite matching the delay of the level-grade scenario, the extra fuel consumed in moving upgrade at higher speed prevents the four-locomotive scenario from matching its efficiency. However, even though the number of locomotives is doubled, the averaged grade case with four locomotives is only 10 percent less efficient than the averaged grade case with two locomotives. An added benefit is that the extra locomotive power and elimination of delay reduces congestion on the grade, allowing RTC to find feasible dispatching results for higher traffic volumes. Thus it appears that adding motive power can be an effective way to reduce delay and increase capacity with a minimal sacrifice in efficiency. However, additional locomotive acquisition or lease costs would be incurred.



**FIGURE 7. TRAFFIC VOLUME VS. HIGH POWER MANIFEST FREIGHT TRAIN DELAY**



**FIGURE 9. TRAIN SPEED VS. FREIGHT EFFICIENCY FOR BOTH TRAIN TYPES ON DIFFERENT GRADES**



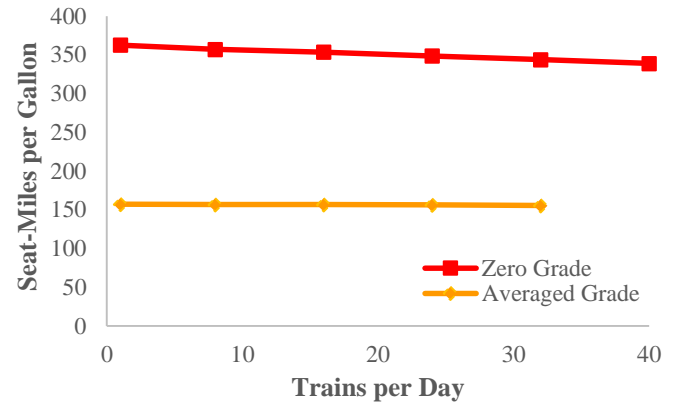
**FIGURE 8. TRAFFIC VOLUME VS. MANIFEST FREIGHT TRAIN EFFICIENCY FOR VARYING GRADE AND POWER**

Although the previous trends relating efficiency, delay and motive power are only illustrated in detail for the manifest freight train, similar relationships were also observed for the bulk commodity unit train.

As was alluded to earlier during the discussion of the slow speed of uphill trains, the case study examining the relationship between operating speed and fuel efficiency for freight trains demonstrates that slowing trains down improves their operating efficiency. As shown in Figure 9, unlike highways where peak fuel efficiency is reached at 50 to 55 mph, diesel-electric freight rail is operating almost entirely on the downward slope of the speed-efficiency curve. This is consistent with previous research showing that peak efficiency is obtained at speeds just above the adhesion limit in the range of 15 to 20 mph [18]. However, for the averaged grade case, there is virtually no improvement in fuel efficiency as train speed decreases. This may be due to the large amounts of fuel required to overcome the grade resistance on the 1-percent grade and the comparatively smaller amounts required to overcome resistances that vary with speed.

## PASSENGER RESULTS

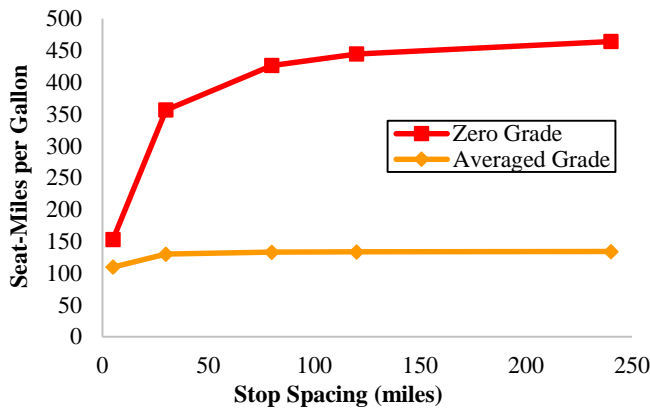
Figure 10 shows the effect of congestion on passenger efficiency. Note that the metric is seat-miles per gallon as opposed to ton-miles per gallon. Due to the speed and priority of the passenger trains, they appear to be largely insensitive to increases in traffic volume on this freight-dominated corridor. If this were a line with a greater proportion of passenger trains, such as a commuter line where the majority of the trains are passenger trains, the passenger trains may start to become more sensitive to traffic volume as even the priority trains will eventually start to interfere with each other on single track.



**FIGURE 10. TRAFFIC VOLUME VS. PASSENGER EFFICIENCY**

The final factor study shown in Figure 11 examines the influence of stop spacing on passenger train fuel efficiency. Operating passenger trains with less frequent stops can greatly improve efficiency in terms of seat-miles per gallon. Under these conditions, since the short passenger train consists typically have more power available than that required to overcome train resistance at maximum track speed, the train spends more time in cruise mode as opposed to

constantly consuming fuel at the maximum rate to accelerate from station stops. For the averaged grade condition, much more fuel is simply consumed overcoming train resistance so the impact of additional acceleration is lessened and there is little variation once stop spacing exceeds 30 miles. While this is intuitive for conventional diesel-electric trains, a hybrid locomotive or a system using electric propulsion with regeneration or wayside storage may actually benefit from the frequent stops and starts and become more efficient.



**FIGURE 11. STOP SPACING VS PASSENGER EFFICIENCY**

**ANALYSIS**

The results of this research show the expected trends: decreasing efficiency for a congested system and higher speeds, and increased efficiency at less frequent stop spacing. However, there are still several interesting findings from the results.

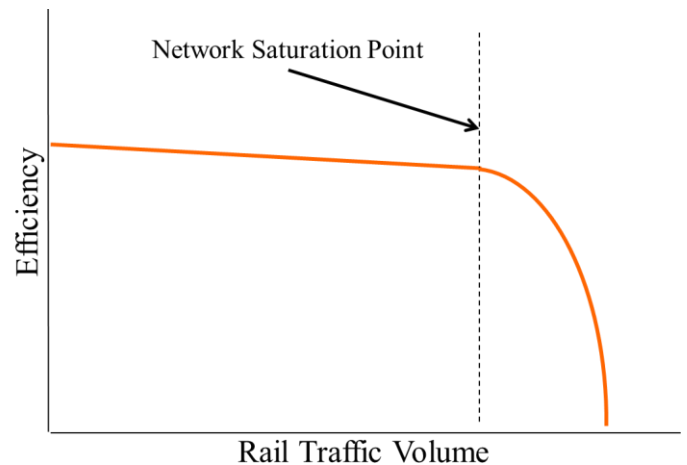
First is the relative sensitivity of the factors on the negative grade scenario as compared to the positive and zero grade scenarios. This is likely due to train dispatching logic that gives preference to uphill trains because it is more difficult and time consuming for them to stop and start again. Thus, the trains on the negative grade tend to be held for meets more frequently and experience more delay, as shown in Figure 6, negatively affecting their efficiency.

The next observation is the minimal drop in manifest freight train efficiency when comparing the scenarios with two and four locomotives on the averaged grade. The high-powered cases were run in order to isolate the negative effects of congestion and delay from the positive effects of a lower balancing speed for uphill trains. Ultimately delay has such a detrimental effect on fuel efficiency that the extra fuel required to use four locomotives to power the faster trains is nearly offset by fuel saved through reduction in delay. The result is a scenario that is only slightly less efficient than the case of slower underpowered trains that use less fuel while in motion but spend more time idling and waiting under congested conditions. The case with added power has the

additional benefit of increased capacity and better service reliability

The last observation is the seemingly incomplete nature of the data, specifically for the negative/positive grade case. As mentioned previously, for a given traffic volume, RTC requires that all of the trains be dispatched within 24 hours. If there are too many conflicts on the network or the trains are simply going too slow to complete the route in the allotted time, the simulation will “break” and RTC will not produce results. For the freight trains, congestion levels of more than 24 trains per day on the 1-percent grade do not produce results. The high-power and zero grade cases also reach breaking points albeit at higher traffic levels.

Finally, trains on the negative grade were noticeably more sensitive to the increasing traffic level. However, the trains on level grade and the “averaged” grade were not (Figure 5, 10). Rather than decreasing drastically as the traffic level increases, the trend is only slightly negative. However, once the rail line reaches its capacity limit, efficiency drops quite suddenly to zero as no trains can navigate the line without experiencing excessive delay or being involved in irreconcilable routing conflicts. Although this study is examining a specific and basic network, the idea of a breaking point at a given traffic level is something which can be potentially extrapolated to any network. Figure 12 shows this basic relationship between efficiency and traffic volume with the dotted line signifying the theoretical “network-saturation” point.



**FIGURE 12. FUNDAMENTAL RELATIONSHIP BETWEEN RAIL TRAFFIC VOLUME AND EFFICIENCY**

**CONCLUSION**

Returning to the questions posed in the introduction, a rail line that experiences traffic growth due to modal shift driven by efficiency will tend to maintain its relative efficiency as long as it has the capacity to absorb more traffic. There is only a very slight gradual decline or erosion in rail fuel efficiency as delay increases but not enough to cause the



modal traffic shift to reach equilibrium before the capacity of the rail line is reached. At a certain point, the rail line will reach capacity and become saturated with the new traffic. At this point, efficiency drops dramatically. However, in this situation the relative efficiency of the rail line becomes moot as, even if it could maintain its fuel efficiency, the line simply cannot handle any more traffic. Thus, when examining the potential for modal shift driven by efficiency, the ultimate capacity of the rail line will govern how much traffic can change modes, not a volume corresponding to a point where the fuel efficiency of rail gradually declines to a level where there is no longer an economic incentive to shift additional traffic to the rail mode.

Identifying the saturation point for a network could be valuable for freight and passenger rail operators as their networks become more crowded under increased demand. As Figure 8 suggests, increasing the number of locomotives for a train can provide some capacity relief but it will still reach a saturation point and major investments will be needed to accommodate new traffic. To just maintain current GDP share, the Class 1 railroads would require a 65% increase in capacity by 2040 using a modest estimate for GDP growth of 2.5% [19].

## STRATEGIES TO PRESERVE EFFICIENCY

Given that modal shift for fuel efficiency will be limited by network capacity and not by a gradual decline in railway efficiency under increasing traffic and congestion, future efforts to improve fuel efficiency should also seek to increase capacity of the rail mode on both freight and passenger operations. Stodolsky 2002 identifies “emerging technologies” which can lead to energy savings for both passenger and freight rail [20]. Of these technologies, operations optimization, consist management, and train fleet management have the unique benefit of increasing energy savings as well as network efficiency and thus capacity.

Operations optimization is the scientific process of identifying the most fuel efficient operation of a locomotive in terms of speed and braking profiles. The “Locomotive Engineer Assist Display & Event Recorder” (LEADER) produced by New York Air Brake is an example of this approach. LEADER gives the engineer a visual representation of track and train features such as track curvature, signaling, brake pipe pressure, speed limit and fuel consumption that allow the engineer to operate the train in the most efficient manner possible [21]. There are many factors which can affect this efficiency by as much as 12-20%, including crew changes, mixing weather conditions, deterioration of track and locomotive maintenance condition. With the efficiency varying to such an extreme degree, it is difficult for operators to plan for fuel stops, resulting in more stops than necessary and decreasing efficiency. Operations optimization is especially important for Amtrak and Class 1 operators in North America because of shared trackage rights and frequent run through trains. Crews operating with unfamiliar or

uncommon equipment and train configurations increase the need for operations optimization.

Consist management is manipulation of train length, car placement, and locomotive placement based on operating speed, tonnage, and terrain. Positioning railcars correctly in a train consist can have major impacts on not only the individual efficiency of a train but also on yard efficiency and capacity. The metric used for passenger train efficiency, seat-miles per gallon, implies an inherent improvement in efficiency for a longer train consist as the resistance of the locomotive is distributed over more seats. Freight trains operate on this principal, capitalizing on new locomotive technologies and distributed power in order to have longer, heavier trains that are also more efficient. For these trains, particularly intermodal trains, car placement is crucial for fuel efficiency. Lai 2008 and Kumar 2011 show how severely gaps in intermodal trains degrade aerodynamic performance and thus efficiency [22] [23]. Car placement can also improve performance in classification yards by limiting the amount a consist has to be reconfigured based on the final destinations of different cars. New developments in rail yard modeling are allowing railroads to capitalize on consist management to increase their yard performance with a direct improvement in network performance and fuel consumption in terminals.

Train fleet management focuses on technologies that function to improve train scheduling using information based technologies. Positive train control (PTC) can provide in-cab status information and “command-and-control” instructions for the engineer. This up-to-the-minute information allows for dispatchers to more easily manage networks and guide trains through them in the most efficient manner. It also greatly reduces the risk of an accident due to human error, improving safety as well as reducing train delay due to these incidents.

All of these technologies can help increase the network saturation traffic level for a railroad while providing more efficient operations. Combined with infrastructure improvements such as double-tracking lines and yard capacity increases, these approaches should help the railroads meet the increasing demand on their systems in the future while maintaining the efficiency of rail transport.

## FUTURE WORK

The primary limitation to conducting a single-variable study is that interactions and the relative effect of the individual variable studied in comparison to other influencing factors is not determined. In this study, the effects of congestion, speed, and stop spacing on fuel efficiency are examined, but it is still to be determined if these effects are significant when compared to other parameters such as train length, cargo type, gross rail load, etc. In order to fully understand the relative impact of specific factors on fuel consumption, a factorial experiment and sensitivity analysis will be performed. Instead of testing one variable at multiple levels, all variables that impact fuel consumption (Table 2) will be varied utilizing design of experiments techniques to

gain comprehensive results and develop an efficiency response surface. This will provide a more complete understanding of all factors affecting the efficiency of freight and passenger trains.

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