Energy and Emissions Impacts of Operating Higher Productivity Vehicles Update: 2008

March 2008

Prepared by the American Transportation Research Institute
and its Western Highway Institute

In cooperation with
Cummins Inc.

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OF OPERATING HIGHER PRODUCTIVITY VEHICLES

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ABSTRACT

With the introduction of new on-road heavy-duty diesel engines meeting more stringent emission standards beginning in 2007, ATRI and Cummins Inc. teamed to update their previous investigation of the energy and emissions impacts which can result from operating commercial vehicles at various weights and configurations.

Using Cummins' sophisticated Vehicle Mission Simulation (VMS) modeling tool, six different vehicle configurations were modeled over a typical route to estimate and analyze fuel consumption. Additionally, estimates of the greenhouse gas emission, CO_2, as well as emissions of PM and NO_x were also developed.

Percentage increases in fuel efficiency, measured in ton-miles per gallon, were observed for nearly every higher productivity vehicle configuration at various weight increases under a weight-limited scenario. Increases in fuel efficiency were also observed for longer combination vehicle configurations under a cube-limited scenario. The observed improvements in fuel efficiency translate directly to improvements in environmental efficiency for emissions of CO_2, PM and NO_x over the modeled route.

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INTRODUCTION

According to a recent estimate, the total tonnage of primary freight shipments in the United States will increase from 15.55 billion tons in 2006 to 19.85 billion tons in 2018, an increase of nearly 28 percent over the 12-year period.[1] Trucks' share of this tonnage is projected to rise from 69 percent in 2006 to 70 percent in 2018.[2] With trucks continuing to dominate the overall freight transportation landscape, growth in both the number of trucks and miles driven on our nation's roadways is expected to increase over the next decade.

The challenge facing the U.S. transportation system is how to accommodate this growth while at the same time improving energy and environmental efficiency. Among the options for addressing this challenge include increasing the maximum operating weight and/or length of over-the-road trucks.

The American Transportation Research Institute (ATRI) and Cummins Inc. teamed to update their previous investigation of the energy and emissions impacts which can result from operating commercial vehicles at various weights and configurations.[3] As was previously done, six common vehicle configurations were modeled over a typical route to estimate fuel consumption and corresponding emissions. Additional analyses conducted as part of this study include:

- A fifth gross vehicle weight (GVW) was modeled to allow impacts associated with "cubed-out" vehicles to be investigated;[4]
- Impacts to the greenhouse gas emission, carbon dioxide (CO2), were investigated;
- Refinements to Cummins' Vehicle Simulation Model were incorporated into the analysis; and
- Data are reported based on the operation of engines meeting the U.S. Environmental Protection Agency (EPA) 2007 engine emission standards which are 90 percent lower in particulate matter (PM) and average 50 percent less oxides of nitrogen (NOx) emissions than pre-2007 engines.

The results of this analysis provide a comparative estimate of the potential energy and emissions impacts of operating different vehicle configurations at various weights.

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[1] American Trucking Associations, *U.S. Freight Transportation Forecast…2018*, p. 2 (2007).

[2] Ibid.

[3] American Transportation Research Institute, *Energy and Emissions Impact of Operating Higher Productivity Vehicles* (September 2004).

[4] Gross vehicle weight refers to the total weight of a vehicle. For over-the-road trucks, this includes the combined weight of the tractor, semitrailer and/or trailer and any cargo. "Cubed-out" vehicles are those which are constrained by available space rather than by weight.

BACKGROUND

Prior to 1956, states primarily regulated the weights of vehicles operating on state highways. With the advent of the Interstate Highway System, Congress believed the federal investment required more direct federal controls on the weights of vehicles using Interstate Highways.[5] On July 1, 1956, a maximum GVW of 73,280 pounds was established along with maximum weights of 18,000 pounds on a single axle and 32,000 pounds on tandem axles. States having greater weight limits in place when the federal limits went into effect were allowed to retain those limits under a grandfather clause.

Congress increased maximum allowable GVW and axle weights in 1975, in part to provide additional cargo-carrying capacity for motor carriers faced with large fuel cost increases at the time.[6] The maximum GVW limit on Interstate Highways was increased to 80,000 pounds and single and tandem axle maximum load limits were increased to 20,000 pounds and 34,000 pounds, respectively.

Not all states immediately adopted the 80,000 pound weight limit. Motor carriers traveling through a state that retained the 73,280 pound limit had to restrict loads to that weight even though most states had adopted the 80,000 pound weight limit. A small group of “barrier states” along the Mississippi River had retained the 73,280 pound limit and effectively limited much of the East-West traffic crossing the Mississippi River to the lower weights in those states.[7] In response, Congress, in the Surface Transportation Assistance Act of 1982, required states to adopt the federal weight limits on Interstate Highways.

The most significant legislative action related to federal weight limits since 1982 was the freeze on longer combination vehicle (LCV) operations imposed in the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) and extended in the Transportation Equity Act for the 21st Century (TEA-21).[8] LCVs have operated in many western states and on some eastern turnpikes for a number of years. The “LCV freeze” enacted in ISTEA prohibited states from allowing any expansion of LCV operations either in terms of routes upon which LCVs may operate or the vehicle weights or dimensions that may be allowed.

Over the years special exemptions to federal weight limits have been enacted for individual states, sometimes applying only to the transportation of specific commodities that are important to a state’s economy. These special exemptions, along with the grandfather rights, allow states to operate vehicles exceeding

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[5] U.S. Department of Transportation, *Comprehensive Truck Size and Weight Study*, Vol. 1, p. 2 (2000).
[6] Ibid.
[7] Ibid.
[8] Longer combination vehicles are tractor-trailer combinations with two or more trailers that may exceed 80,000 pounds gross vehicle weight (GVW).

federal weight limits. Table 1 shows the 22 states that allow vehicles to operate in excess of the federal weight limits.

Table 1: States Allowing Weights in Excess of the Federal Limits

Pounds	Truck Tractor and 2 Trailing Units	Truck Tractor and 3 Trailing Units
86,400	New Mexico	
90,000	Oklahoma	Oklahoma
95,000	Nebraska	
105,500	Idaho, North Dakota, Oregon, Washington	Idaho, North Dakota, Oregon
110,000	Colorado	Colorado
115,000		Ohio
117,000	Wyoming	
120,000	Kansas, Missouri	Kansas, Missouri
123,500		Arizona
127,400	Indiana, Massachusetts, Ohio	Indiana
129,000	Arizona, Iowa, Nevada, South Dakota, Utah	Iowa, Nevada, South Dakota, Utah
131,060		Montana
137,800	Montana	
143,000	New York	
164,000	Michigan	

Source: 23 CFR 658, Appendix C.

METHODOLOGY

Vehicle Configurations

Six different vehicle configurations were analyzed as part of this research. As shown in Table 2, these vehicle configurations were estimated to account for nearly 94 billion vehicle miles traveled (VMT) in the year 2000 and comprised more than 81 percent of the VMT accumulated by combination vehicles.[9] By far, the five-axle configuration (5-axle) accumulated the majority of VMT among combination vehicles and served as one of the baseline vehicle configurations used in this study. A double configuration (DBL), which is used predominantly in less-than-truckload operations, served as the other baseline configuration in this study.[10]

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[9] Combination vehicles, as opposed to single unit vehicles, are comprised of a tractor with one or more trailers.

[10] "Less-than-truckload" refers to the segment of the trucking industry that picks up small shipments of freight (i.e., less than a truckload) and consolidates this freight for transportation to another location where it is redistributed and delivered.

Table 2: Estimated 2000 VMT by Select Vehicle Configuration And Operating Weight Groups

Vehicle Configuration[1]	Percentage of Year 2000 VMT by Operating Weight					Year 2000 VMT (million)
	45 - 60,000	65 – 80,000	85 - 100,000	105 - 120,000	125 - 140,000	
5-axle (CS5T)	27%	33%	10%	<1%	0	81,069
Double (DS5)	32%	43%	6%	0	0	5,263
6-axle (CS6)	22%	24%	26%	5%	1%	6,049
RMD (DS7)	23%	21%	28%	14%	3%	632
TRPL (TRPL)	11%	29%	37%	15%	5%	126
TPD (DS8+)	23%	21%	28%	14%	3%	759

1) The configurations listed are included in the categories shown in parenthesis in the HCAS.
Source: 1997 Federal Highway Cost Allocation Study, Appendix C, Table C-8

The two baseline configurations were modeled at 60,000 pounds GVW as well as at the existing maximum federal limit of 80,000 pounds GVW. The 5-axle was comprised of a 3-axle sleeper cab with a tandem axle 53-foot semitrailer powered by a 400 horsepower Cummins engine. The vehicle's tare weight, or weight of the equipment without cargo, was 32,000 pounds. Approximately 63 percent of the 5-axle VMT in year 2000 was estimated to occur on rural roads.[11]

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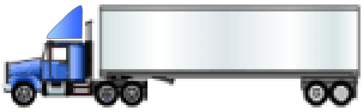
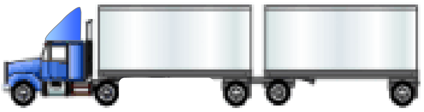
[11] U.S. Department of Transportation, *Federal Highway Cost Allocation Study – Final Report*, p. II-10 (August 1997).

The DBL was comprised of a 2-axle day cab, two 28-foot single-axle trailers, a single-axle dolly connecting the two trailers, and powered by a 400 horsepower Cummins engine. The vehicle's tare weight was 35,500 pounds. Approximately 60 percent of the DBL VMT in year 2000 was estimated to occur on rural roads. Examples of these baseline vehicles are shown in Figure 1.[12]



5-axle Tractor-Semitrailer



Double

Figure 1: Baseline Vehicle Configurations

In addition to the baseline vehicles, four higher productivity vehicles (HPVs) were also modeled over the typical route. HPVs, which include LCVs, can operate at GVWs greater than the current federal maximum while still conforming to federal axle weight and bridge formula limits.[13] As opposed to the federal axle limits, the Bridge Formula controls the distribution of the vehicle's load while on the Interstate System. For some configurations, compliance with the federal maximum GVW restricts the full application of the Bridge Formula.[14]

The HPVs analyzed in this study include a six-axle tractor-semitrailer (6-axle), a Rocky Mountain double (RMD), a triple trailer combination (TRPL) and a turnpike double (TPD). The 6-axle was comprised of a 3-axle sleeper cab with a three-axle 53-foot semitrailer powered by a 450 or 500 horsepower Cummins engine. The vehicle's tare weight was 34,500 pounds. Approximately 59 percent of the 6-axle VMT in year 2000 was estimated to occur on rural roads. This configuration, as well as the other HPVs, is shown in Figure 2.

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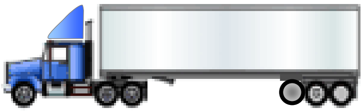
[12] Although not shown in Figures 1 or 2, sleeper cabs were modeled for the 5-axle, RMD and TPD configurations while day cabs were modeled for the DBL and TRPL configurations. The various cab types reflect those most commonly associated with the selected configurations. The sleeper cab weighed 3,500 pounds more than the day cab.

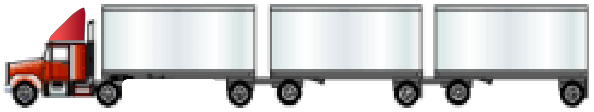
[13] In addition to federal maximum GVW and axle limits, vehicles must conform to the weight distribution limits specified under the Federal Bridge Formula. *See* 23 USC §127.

[14] See: Western Highway Institute, How to Apply Formula B for Vehicles in Regular Operation, Technical Report 1-75 (1975).

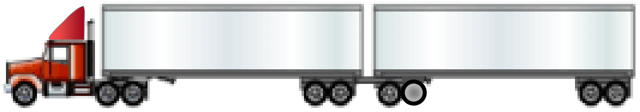


6-axle Tractor-Semitrailer

Rocky Mountain Double



Triple Trailer Combination



Turnpike Double

Figure 2: Higher Productivity Vehicle Configurations

The RMD was comprised of a 3-axle sleeper cab, one 48-foot tandem-axle semitrailer, one 28-foot single-axle semitrailer, a single-axle dolly connecting the two trailers, and powered by a 400, 450 or 500 horsepower Cummins engine. The vehicle's tare weight was 43,500 pounds. Approximately 60 percent of the RMD VMT in year 2000 was estimated to occur on rural roads.

The TRPL was comprised of a 2-axle day cab, three 28-foot single-axle trailers, two single-axle dollies connecting the two rear trailers, and powered by a 400, 450 or 500 horsepower Cummins engine. The vehicle's tare weight was 47,500 pounds. Approximately 75 percent of the TRPL VMT in year 2000 was estimated to occur on rural roads.

The TPD was comprised of a 3-axle sleeper cab, two 48-foot tandem-axle semitrailers, a tandem-axle dolly connecting the two trailers, and powered by a 450, 500 or 600 horsepower Cummins engine. The vehicle's tare weight was 50,000 pounds. Approximately 58 percent of the TPD VMT in year 2000 was estimated to occur on rural roads.

Based on each vehicle's operating weight, the appropriate size of engine was matched to each configuration. The specifications for each of the modeled engines conformed to EPA's exhaust emission standards effective January 2007 of 0.01 grams per brake-horsepower-hour (g/bhp-hr) for PM and averaging 1.2 g/bhp-hr for NOx.[15] These new engine emission standards are 90 percent less for PM and average 50 percent less for NOx than the previous standards.

ATRI also contacted leading equipment manufacturers to determine equipment weights and dimensions for each configuration.[16] The following table provides summary information for each vehicle configuration.

Table 3: Vehicle Configuration Summary

Vehicle Configuration	Number of Axles	Engine Size[a] (HP)	Trailer(s) Length (Feet)	Trailer(s) Capacity (Cu. Ft.)	Tare Weight[b] (lbs)
Baseline Vehicles					
5-axle	5	400	53	4,040	32,000
DBL	5	400	28/28	4,200	35,500
Higher Productivity Vehicles					
6-axle	6	450/500	53	4,040	34,500
RMD	7	400/450/500	48/28	5,750	43,500
TRPL	7	400/450/500	28/28/28	6,300	47,500
TPD	9	450/500/600	48/48	7,300	50,000

a - Size of engine is dependent upon the vehicle's load. See Appendix A for more details.
b - Tare Weight refers to the vehicle's total weight when empty.

Route

A generic route was selected over which to model the operation of each vehicle configuration. Typical of many truck operations, including line-haul and many point-to-point shipments, a route was selected that minimized distances between the pick-up and drop-off locations and the highway system.[17] As a result, the majority of route mileage represents highway operations.

The route was modeled as a non-stop trip of more than 400 miles between two locations. The reverse of each trip was also modeled. In order to minimize any

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[15] NOx and PM are two pollutants produced during the combustion of fossil fuels. NOx is a contributor to summertime ozone formations, or smog, while PM is generally associated with urban haze.

[16] Vehicle weights can vary substantially among configurations due to variations in equipment weight as well as features.

[17] Line-haul is a term used by the less-than-truckload segment to describe the transportation of freight between cities after pick-up and consolidation and before redistribution and delivery.

differences caused by elevation changes along the route, all data are averaged based on the roundtrip.

A maximum cruise speed of 65 mph was modeled for the entire trip. Low speed, start-stop operations represented less than 1 percent of the total mileage and, therefore, were not assessed as part of this modeling effort. As the maximum cruise speed could not be sustained during certain assents, the average speeds ranged from 5 to 11 percent lower than the maximum cruise speed and varied by configuration.[18] An illustration of the route is provided in Figure 3.

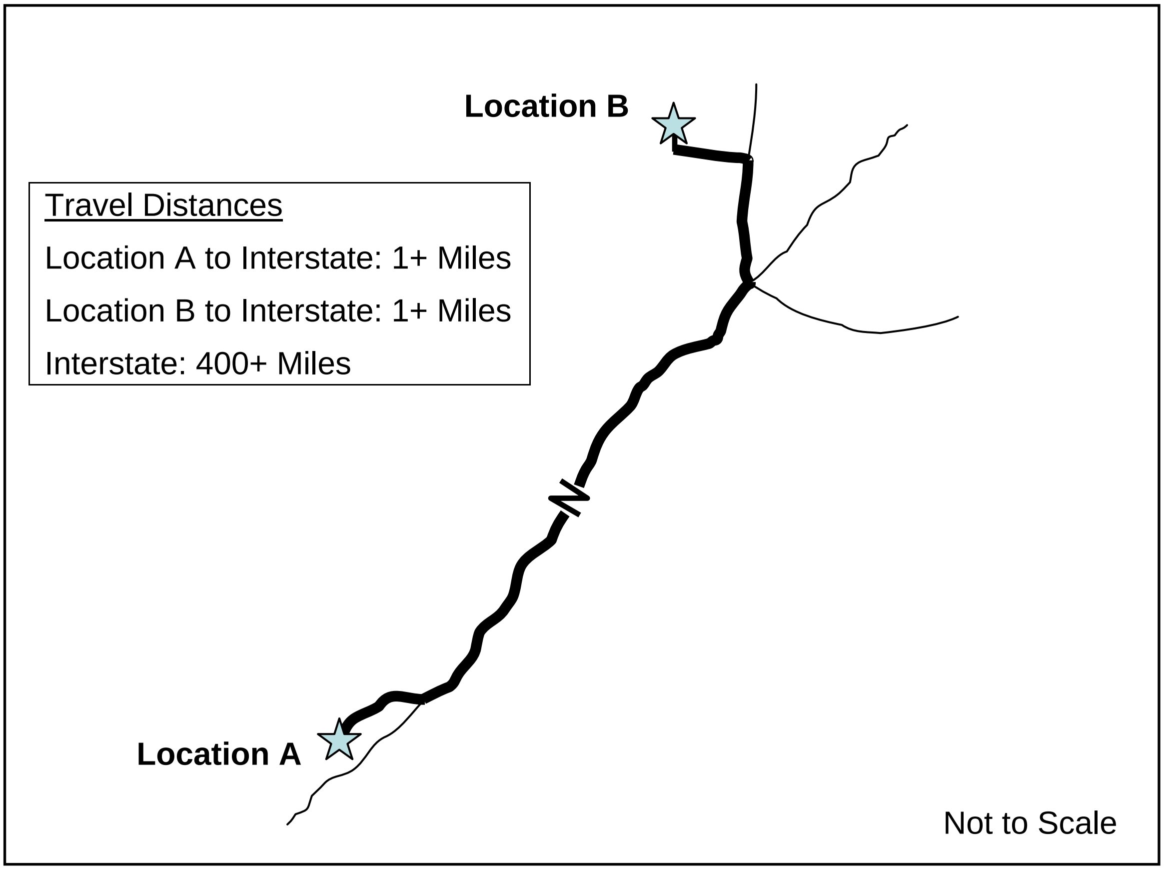

Figure 3: Illustration of Generic Route

ENERGY EVALUATION

Using Cummins' Vehicle Mission Simulation (VMS) model, fuel consumption was estimated for each vehicle configuration and GVW and averaged for each roundtrip over the modeled route. Each VMS run produced an estimate of the fuel burned for each trip as well as a detailed map showing how much fuel was burned at various speeds and loads.

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[18] See Appendix A for average speeds.

The VMS model is used primarily to compare component changes within a vehicle's specification. The model is comprised of two fundamental parts. The "static" performance calculations, such as engine and vehicle speeds, are based on gearing and tire size, gradeability and startability. This information is independent of the route being run. The second part of the model is the performance en route and accounts for the fuel burned, the duty-cycle of the engine, the number of shifts and other route-related factors.

The route simulation is based on steady-state engine performance data from test cell data corrected for standard day at sea level conditions in accordance with Society of Automotive Engineers practices. Some of the performance data, such as vehicle aerodynamics, tire friction, etc. is assumed based on average industry numbers. Therefore, the performance data will tend to produce optimistic performance numbers when compared to actual vehicle test data. It has been demonstrated, however, that when used for comparative purposes (i.e., comparing different vehicle specifications), differences between simulation runs translate favorably to differences between real vehicle performance on a percentage basis.

Payload Impacts

Operating vehicles at heavier GVWs provides the opportunity to increase the amount of freight carried by each vehicle. When modeling the 5-axle configuration at the maximum 80,000 pounds GVW allowed under federal law, the empty weight of the vehicle took up 40 percent of the available GVW, leaving 48,000 pounds for additional payload. Similarly, the empty weight of the DBL configuration at 80,000 pounds GVW took up more than 44 percent of the available GVW, leaving 44,500 pounds for additional payload. Through the use of HPVs, in most cases, payload weights can be increased at a higher rate than the weight of the additional equipment needed to transport the added freight (i.e., axles, dollies and trailers).

As shown in Figure 4, the following payload weight increases were observed when compared to the 5-axle configuration at 80,000 pounds GVW.

- At 97,000 pounds GVW, the 6-axle configuration accommodated a payload weight increase of 30 percent;[19]
- At 100,000 pounds GVW, the TPD accommodated a payload weight increase of 4 percent while the RMD accommodated an increase of 18 percent;

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[19] The 6-axle configuration at 97,000 pounds GVW conforms with existing axle weight limits; however, under the federal Bridge formula this configuration is limited to approximately 90,000 pounds GVW.

- At 120,000 pounds GVW, the TPD accommodated a payload weight increase of 46 percent while the RMD accommodated an increase of 59 percent; and
- At 140,000 pounds GVW, the TPD accommodated a payload weight increase of 88 percent.

In addition, the following payload weight increases were observed when compared to the DBL configuration at 80,000 pounds GVW.

- At 100,000 pounds GVW, the TRPL accommodated a payload weight increase of 9 percent; and
- At 120,000 pounds GVW, the TRPL accommodated a payload weight increase of 51 percent.

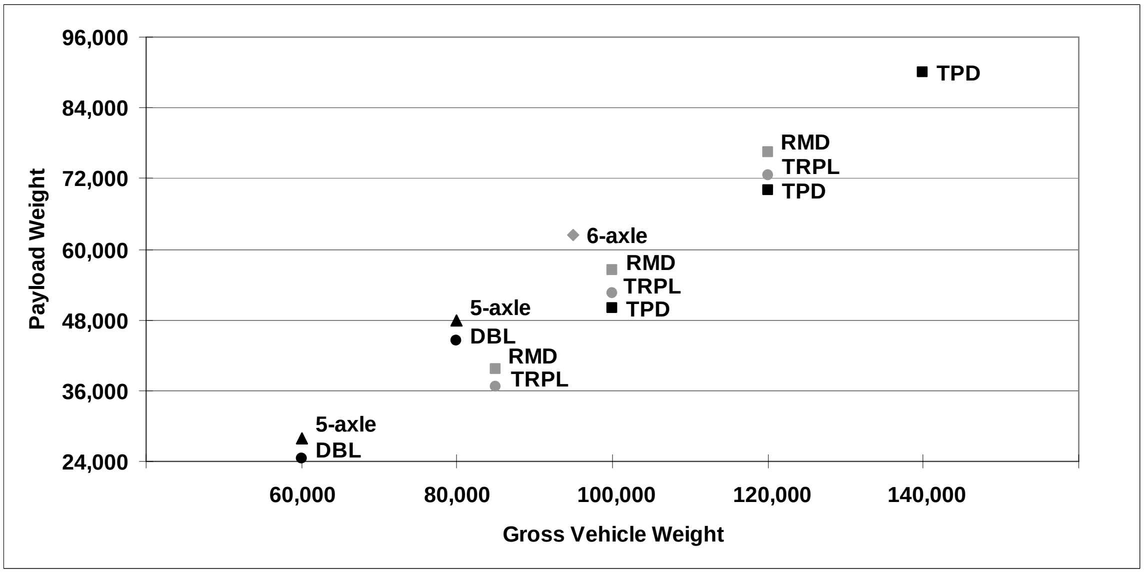

Figure 4: Payload Impacts

In addition to being limited by operating weight, trucks can also be limited by the volume of freight carried (i.e., cube-limited). To assess the impacts of operating HPVs in cube-limited operation, a capacity comparison was made between the 5-axle and DBL configurations operating at 60,000 pounds GVW and the longer combination vehicles (LCVs). At 60,000 pounds GVW, the 5-axle vehicle can be loaded to a maximum freight density of 6.9 pounds per cubic foot (PCF) with a payload of 28,000 pounds. Extrapolating this density to the cubic feet available to LCVs results in the RMD operating at 83,175 pounds GVW with a payload capacity of 39,675 pounds (42 percent more capacity) and the TPD operating at 100,370 pounds GVW with a payload capacity of 50,370 pounds (80 percent more capacity).

Similarly, the DBL at 60,000 pounds GVW can be loaded to a maximum freight density of 5.8 PCF with a payload of 24,500 pounds. Extrapolating this density to the cubic feet available in the TRPL results in an operating weight of 84,040 pounds GVW with a payload capacity of 36,540 pounds (49 percent more capacity).

As discussed above, through the operation of the HPVs analyzed in this study, for weight-limited carriers, per vehicle payload weight increases ranging from 4 to 88 percent were observed through the addition of axles or additional trailers and dollies. For cubed-limited carriers, per vehicle payload weight increases ranging from 42 to 80 percent were observed through the addition of trailers and dollies.

Fuel Economy Impacts

As opposed to the payload weight increases discussed above, operating vehicles at higher GVWs may require the use of larger engines which, combined with the additional weight, decreases fuel economy on a miles-per-gallon (mpg) basis. As shown in Figure 5, for both the 5-axle and DBL configurations, an average round-trip fuel economy of 5.4 mpg was estimated when operated at 80,000 pounds GVW over the modeled route. In comparison, at 100,000 pounds GVW, average fuel economy decreases ranging from 11 to 15 percent were estimated.[20] At 120,000 pounds GVW, average fuel economy decreases ranging from 20 to 22 percent were estimated while at 140,000 pounds GVW, average fuel economy decreased an estimated 30 percent.

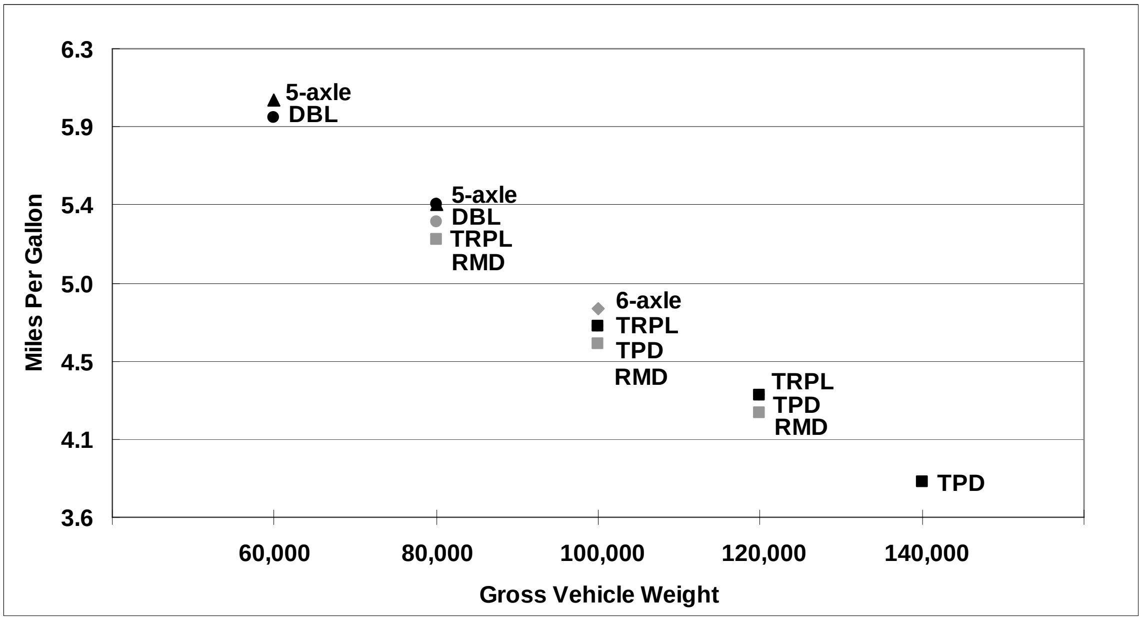

Figure 5: Fuel Economy Impacts

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[20] For modeling purposes, the 6-axle configuration was analyzed at 100,000 pounds GVW.

For the cube-limited operations, average round-trip fuel economies of 5.9 and 6.0 mpg were estimated for the DBL and 5-axle configurations, respectively, when operated at 60,000 pounds GVW over the modeled route. At 80,000 pounds GVW, average round-trip fuel economy decreased by an estimated 13 percent for the RMD compared to the 60,000 pound 5-axle configuration and by 10 percent for the TRPL compared to the 60,000 pound DBL configuration.[21] At 100,000 pounds GVW, fuel economy decreased by an estimated 22 percent for the TPD compared to the 60,000 pound 5-axle configuration.

As shown in Figure 5, fuel economy was fairly consistent at each of the modeled weights. Regardless of the configuration or number of axles, there was a fuel economy difference of less than 5 percent at each of the respective GVWs. This seems to indicate that the vehicle's GVW and size of engine were the dominant factors in determining fuel economy with rolling resistance associated with the number of axles and vehicle configurations having less of an effect on fuel economy.

Energy Impacts

A comparative measure of the energy efficiency of each vehicle configuration can be expressed as ton-miles per gallon. Ton-miles per gallon (TM/gal) is a metric which multiplies the freight tonnage of a shipment by the number of miles traveled and divides by the number of gallons of fuel consumed during the trip. This methodology enables a consistent comparison to be made between vehicle configurations operating over a common route at different payload weights and fuel economies. A higher degree of energy efficiency is associated with a higher TM/gal rating.

Based on this methodology, as shown in Figure 6, at 80,000 pounds GVW, the 5-axle configuration achieved 129 TM/gal while the DBL, due to its lower payload weight capacity, achieved 119 TM/gal. At 97,000 pounds GVW, the 6-axle configuration achieved a 17 percent increase in TM/gal while at 100,000 pounds GVW, the RMD achieved a 1 percent increase in TM/gal compared to the 80,000 pound 5-axle.[22] The TRPL at 100,000 pounds GVW achieved a 3 percent increase in TM/gal compared to the 80,000 pound DBL.

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[21] For modeling purposes, the cube-limited RMD and TRPL were modeled at 80,000 pounds GVW even though their actual GVW was 83,175 and 84,040 pounds, respectively; while the TPD was modeled at 100,000 pounds GVW even though its actual GVW was 100,370 pounds.

[22] As fuel consumption was not modeled at 97,000 pounds GVW, straight-line extrapolation was used to determine estimated fuel consumption at this GVW.

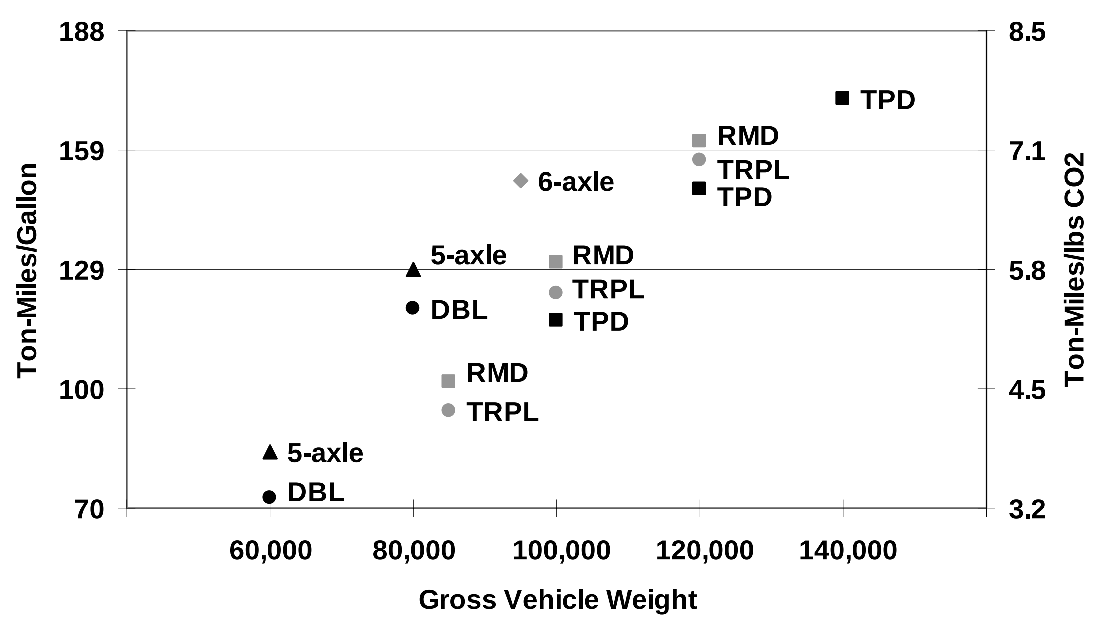

Figure 6: Energy Impacts:
Ton-Miles per Gallon and Ton-Miles per Pound of CO2

The lone exception to achieving higher TM/gal at higher GVWs was for the TPD at 100,000 pounds. The weight of the added trailer and dolly, compared to the 5-axle configuration, consumed approximately 18,500 pounds of the additional 20,000 increase in GVW. Consequently, the small increase in payload weight was offset by the additional fuel consumption which occurred at this GVW, resulting in a 10 percent decrease in TM/gal compared to the 80,000 5-axle configuration. While use of the TPD at 100,000 pounds GVW did not provide a TM/gal increase under the weight-limited scenario, as discussed later, an increase in TM/gal occurred when this configuration was analyzed under a cube-limited scenario.

At 120,000 pounds GVW, a 15 percent increase in TM/gal was achieved by the TPD and a 25 percent increase was achieved for the RMD compared to the 80,000 pound 5-axle. At this weight, the TRPL achieved a 31 percent increase in TM/gal compared to the 80,000 pound DBL. At 140,000 pounds GVW, the TPD achieved a 33 percent increase in TM/gal compared to the 80,000 pound 5-axle.

Table 4: Percentage Change in TM/gal – Weight-Limited Scenario

Configuration	Gross Vehicle Weight			
	97,000*	**100,000**	**120,000**	**140,000**
Compared to 5-axle @ 80,000 lbs GVW				
6-axle	17%	--	--	--
RMD	--	1%	25%	--
TPD	--	-10%	15%	33%
Compared to DBL @ 80,000 lbs GVW				
TRPL	--	3%	31%	--

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

As discussed earlier, for cube-limited operations, weight is not the limiting factor. Consequently, the TM/gal metric will be considerably lower for these types of operations than for weight-limited operations. As shown in Figure 6, at 60,000 pounds GVW, the 5-axle configuration achieved 84 TM/gal while the DBL achieved 73 TM/gal. At 83,175 pounds GVW and an equivalent freight density, the RMD achieved a 20 percent increase in TM/gal compared to the 60,000 pound 5-axle while at 84,040 pounds GVW, the TRPL achieved a 29 percent increase in TM/gal compared to the 60,000 pound DBL. The TPD at 100,370 pounds GVW and an equivalent freight density achieved a 39 percent increase in TM/gal compared to the 60,000 pound 5-axle.

Table 5: Percentage Change in TM/gal Cube-Limited Scenario

Configuration	Gross Vehicle Weight		
	83,175*	**84,040***	**100,370***
Compared to 5-axle @ 60,000 lbs GVW			
RMD	20%	--	--
TPD	--	--	39%
Compared to DBL @ 60,000 lbs GVW			
TRPL	--	29%	--

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

EMISSIONS EVALUATION

Carbon Dioxide Emissions

Carbon dioxide (CO2) is a greenhouse gas which is directly emitted when petroleum fuel is burned in an internal combustion engine. For diesel engines, approximately 22.2 pounds of CO2 is emitted into the atmosphere for each gallon of diesel fuel burned. Consequently, one option for reducing CO2 emissions is to become more efficient by consuming less fuel in relation to the amount of freight moved.

In order to make a consistent comparison between the vehicle configurations and operating weights analyzed in this study, the metric ton-miles per pound of CO2 emitted (TM/lbs CO2) was used to compare the various configurations. Since this metric is directly tied to fuel consumption, it mirrors the percentage changes indicated in the preceding discussion. In other words, the changes in fuel efficiency which were determined for operating the HPVs analyzed in this study translate directly into equivalent percentage changes in ton-miles per pound of CO2 emitted.

As shown in Figure 6 above, under the weight-limited scenario, TM/lbs CO2 ranged from 5.2 to 7.7 with increases in ton-miles for each pound of CO2 emitted occurring for nearly all of the HPVs analyzed at greater GVWs. In addition, under the cube-limited scenario, TM/lbs CO2 ranged from 3.3 to 5.3 with increases in ton-miles for each pound of CO2 emitted occurring for each of the LCVs studied at greater GVWs and nearly equivalent freight densities.

Oxides of Nitrogen and Particulate Matter Emissions

The following technique was used to estimate particulate matter (PM) and nitrogen oxides (NOx) emissions produced for the various trips. The technique simplifies the NOx and PM emissions calculation by noting that these emissions are quite uniform over the range of operation of the engine during the particular route analyzed. The figure below shows a typical torque curve for an engine.

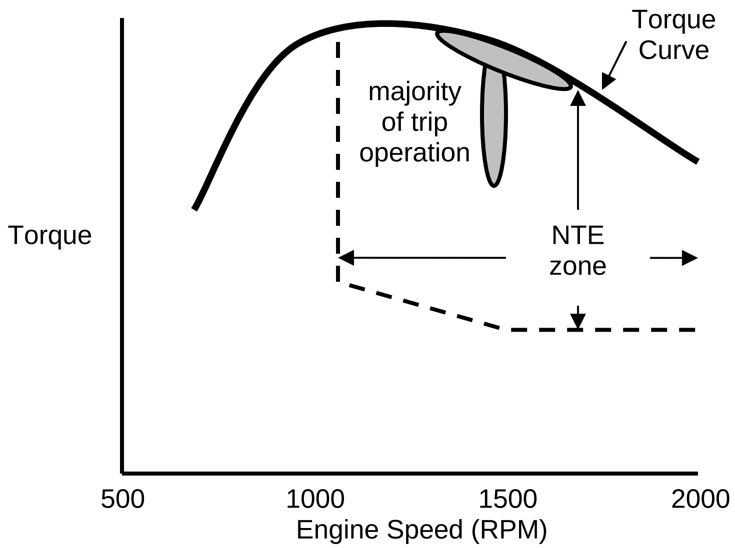

Figure 7: Typical Engine Torque Curve

The torque curve (the heavy line across the top of the figure) shows the maximum torque the engine is capable of producing. Within the region of operation of the engine, there is an area called the Not-to-Exceed (NTE) zone. This zone is defined by the EPA emissions test procedure. Inside the NTE zone, the emissions from the engine must not exceed 125 percent of the regulated level. Due to the constraints imposed by the NTE zone, the emissions of the engine will not vary widely when the engine is within the zone.

The shaded region shows a typical range of operation when a truck is cruising on a highway, generally between 55 to 65 mph. Since the trip which was simulated in this analysis is primarily a highway route, the majority of fuel was burned with the engine operating in this shaded region. As a result of the relatively small range of operation of the engine during the trip and the uniformity of the emissions over the actual operating range, a constant emissions rate (in grams of emissions per gallon of fuel burned) was assumed. Based on this assumption, the total emissions produced by the truck over the trip can be determined by multiplying the total fuel burned on the trip by the emissions rate.

The validity of this simplification was previously confirmed by doing a more detailed analysis for several of the trips.[23] For these trips, the operation of the engine was divided into 100 revolutions per minute by 25 horsepower bins. The percentage of the fuel burned during the trip in each bin was calculated and then multiplied by the actual emissions rate of the engine at that operating condition. The contributions from all of the bins were then summed to get a total emissions prediction for the trip. For the cases that were investigated in detail, the estimate

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[23] American Transportation Research Institute, *Energy and Emissions Impact of Operating Higher Productivity Vehicles* (September 2004).

of emissions using the more detailed approach were within 3 to 5 percent of the estimate using the simple, uniform emissions rate described above.

For the uniform emissions rate estimates, a NOx emissions rate of approximately 23 grams of NOx per gallon of fuel consumed was used. An appropriate emissions rate for PM for these trips would be approximately 0.11 grams per gallon.

Using the simplified methodology to estimate emissions per ton-mile produces emission impacts that mirror fuel consumption on a ton-mile basis. As discussed above, given the fairly constant range of engine emissions over the modeled route, emissions rates are expected to be fairly constant. Consequently, changes in emissions will be directly proportional to changes in fuel consumption.

Using this methodology, as shown in Figure 8, under the weight limited scenario, at 80,000 pounds GVW, the 5-axle configuration achieved 1,172 TM/gram of PM and 5.6 TM/gram NOx emitted while the DBL, due to its lower payload weight capacity, achieved 1,083 TM/gram of PM and 5.2 TM/gram NOx emitted. For cube-limited carriers, at 60,000 pounds GVW, the 5-axle configuration achieved 764 TM/gram PM and 3.7 TM/gram NOx emitted while the DBL achieved 660 TM/gram PM and 3.2 TM/gram NOx emitted.

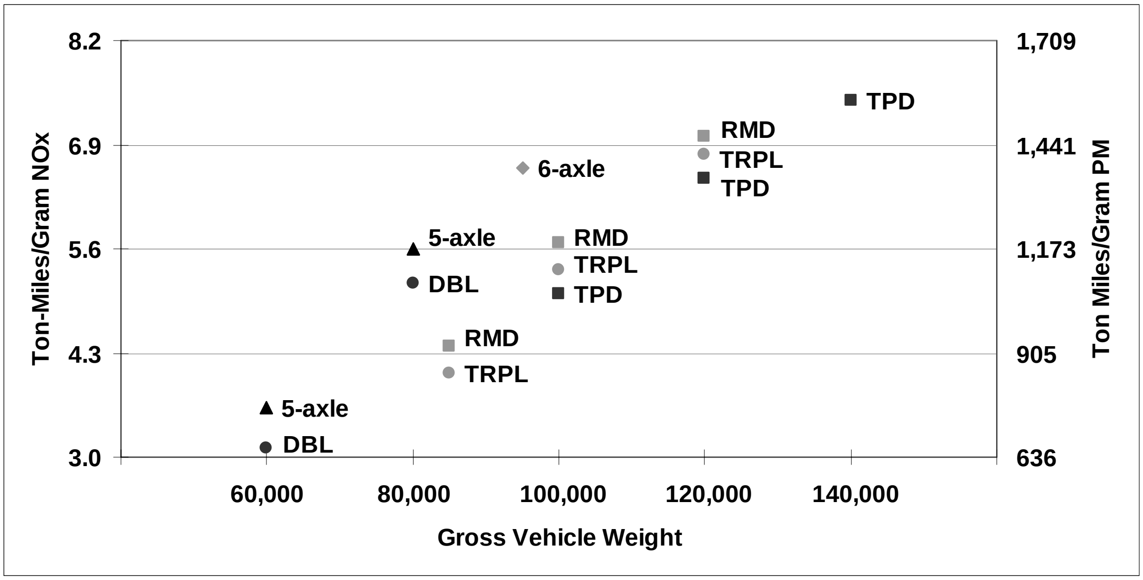

Figure 8: Ton-Miles per Gram NOx and PM

As these emission estimates reflect primarily highway operations, the same percentage changes in TM/gram of NOx or PM will occur through the use of HPVs as reported in the Energy Impact section. Routes involving more stop-and-go activities and less steady-state operations will not necessarily maintain this same relationship between NOx and PM emissions and fuel consumption.

However, for most highway operations, absent significant congestion, the steady-state engine operations will produce a fairly consistent NOx and PM emissions to fuel consumption relationship.

Examples of Energy and Emissions Impacts of HPVs

A shipment weighing 1,000 tons needs to be delivered to a destination 500 miles away. If the 5-axle studied in this report can be consistently loaded to 80,000 pounds GVW, it can carry a maximum payload of 24 tons. It will take 42 trips at this GVW to deliver the entire shipment. If average fuel economy is 5.4 mpg, the total amount of fuel required to deliver the entire shipment will be 3,889 gallons.

Conversely, if a RMD can be consistently loaded to 120,000 pounds GVW, it can carry a maximum payload of 38.25 tons. It will take 27 trips at this GVW to deliver the entire shipment. If average fuel economy is 4.2 mpg, the amount of fuel required for the entire shipment will be 3,215 gallons.

In addition to making 15 fewer trips to deliver this hypothetical shipment, by consuming 674 fewer gallons of fuel, a 17 percent decrease in fuel consumption was achieved by the RMD. This decrease in fuel consumption equates to an equivalent percentage reduction in CO2 emissions, with nearly 7.5 fewer tons of CO2 being emitted into the atmosphere. Reductions in PM and NOx emissions will also be realized. Based on emission factors which represent steady-state engine operations, more than 34 fewer pounds of NOx and 0.16 fewer pounds of PM will be emitted into the atmosphere.

Cube-limited operations can similarly benefits from operating LCVs. A shipment encompassing 100,000 cubic feet being delivered to a destination 500 miles away would require 24 trips with a DBL having a freight capacity of 4,200 cubic feet. Assuming an average freight density of 5.8 pounds per cubic foot, the DBL would weigh nearly 60,000 pounds GVW. If average fuel economy is 5.9 mpg, the total amount of fuel required to deliver the entire shipment will be 2,034 gallons.

If a TRPL having a freight capacity of 6,300 cubic feet can be loaded to the same average freight density, it would weigh slightly more than 84,000 pounds GVW. It would require 16 trips at this GVW to deliver the entire shipment. If average fuel economy is 5.3 mpg, the amount of fuel required for the entire shipment will be 1,510 gallons.

In this instance, 8 fewer trips resulted in a fuel savings of 524 gallons with a corresponding decrease in CO2 emissions of 5.8 tons and reductions in NOx emissions of more than 26 pounds and PM emissions of nearly 0.13 pounds.

CONCLUSION

The results of this analysis provide a comparative estimate of the potential energy and emissions impacts of operating different vehicle configurations at various weights. Operating vehicles at heavier GVWs provides the opportunity to increase the amount of freight carried by each vehicle. Through the operation of the HPVs analyzed in this study, for weight-limited operations, per vehicle payload weight increases ranging from 4 to 88 percent were observed with the addition of axles or additional trailers and dollies. For cubed-limited operations, per vehicle payload weight increases ranging from 42 to 80 percent were observed through the addition of trailers and dollies.

As opposed to payload weight increases, operating vehicles at higher GVWs may require the use of larger engines which, combined with the additional weight, decreases fuel economy on a miles-per-gallon (mpg) basis. Fuel economy decreases ranging from 11 to 30 percent were found for the HPVs analyzed in this study under the weight-limited scenario while decreases ranging from 10 to 22 percent were found under the cube-limited scenario. Fuel economy was fairly consistent at each of the modeled weights. This seems to indicate that the vehicle's GVW and size of engine were the dominant factors in determining fuel economy with rolling resistance associated with the number of axles and vehicle configurations having less of an effect on fuel economy.

Using a comparative measure of the energy efficiency of each vehicle configuration, expressed as ton-miles per gallon (TM/gal), a consistent comparison between vehicle configurations operating over a common route at different payload weights and fuel economies was made.

At 97,000 pounds GVW, under a weight-limited scenario, a 6-axle configuration was found to achieve an increase in TM/gal of 17 percent. Other configurations, which included a Rocky Mountain double and a triple trailer combination, achieved an increase in TM/gal of 1 and 3 percent, respectively, at 100,000 pounds GVW. A turnpike double, at 100,000 GVW, experienced a decrease in TM/gal under the weight-limited scenario as a result of the added dolly and trailer accounting for most of the added weight. However, under a cube-limited scenario, this configuration achieved an increase in TM/gal of 38 percent due to the ability to add a greater volume of low density freight.

At 120,000 pounds GVW, under the weight-limited scenario, increases in TM/gal ranged from 15 to 31 percent. At 140,000 pounds GVW, an increase of 33 percent was observed. These percentage increases in TM/gal serve to illustrate the potential to increase fuel efficiency for most weight-limited operations.

Alternatively, for cube-limited operations, increases in TM/gal were found ranging from 20 percent for a Rocky Mountain double at 83,175 pounds GVW to 29 percent for a triple trailer combination at 84,040 pounds GVW to 39 percent at

100,370 pounds GVW for a turnpike double. These gains under the cube-limited scenario illustrate how increases in fuel efficiency may be achieved not only through increases in GVW but also through increases in vehicle length or a combination of the two.

The estimated fuel efficiency improvements found in this study translate directly into equivalent percentage improvements in TM/lbs of CO2 emitted. Consequently, the HPVs studied in this analysis generally increased environmental efficiency in terms of freight transported per unit of CO2 emitted.

Finally, as a result of the route consisting mainly of highway operations, the engines were able to operate primarily in a steady-state mode which produces emissions of PM and NOx which are fairly uniform to fuel consumption. Thus, improvements in environmental efficiency were also generally observed in terms of freight transported per unit of PM and NOx emitted.

APPENDIX A

Vehicle Data

At 60,000 pounds GVW:

5-axle	
Configuration:	6X4-2S
Engine:	Cummins ISX 400 ST
Average Horsepower:	211
Average Speed (mph):	62

DBL	
Configuration:	4X2-1S-2T
Engine:	Cummins ISX 400 ST
Average Horsepower:	213
Average Speed (mph):	62

At 80,000 pounds GVW:

5-Axle	
Configuration:	6X4-2S
Engine:	Cummins ISX 400 ST
Average Horsepower:	231
Average Speed (mph):	60

DBL	
Configuration:	4X2-1S-2T
Engine:	Cummins ISX 400 ST
Average Horsepower:	233
Average Speed (mph):	60

RMD	
Configuration:	6X4-2S-2T
Engine:	Cummins ISX 400 ST
Average Horsepower:	239
Average Speed (mph):	60

TRPL	
Configuration:	4X2-1S-2T-2T
Engine:	Cummins ISX 400 ST
Average Horsepower:	237
Average Speed (mph):	60

At 100,000 pounds GVW:

6-Axle	
Configuration:	6X4-3S
Engine:	Cummins ISX 450 ST & 500 ST
Average Horsepower:	253
Average Speed (mph):	60

RMD	
Configuration:	6X4-2S-2T
Engine:	Cummins ISX 450 ST & 500 ST
Average Horsepower:	261
Average Speed (mph):	60

TRPL	
Configuration:	4X2-1S-2T-2T
Engine:	Cummins ISX 450 ST & 500 ST
Average Horsepower:	258
Average Speed (mph):	60

TPD	
Configuration:	6X4-2S-4T
Engine:	Cummins ISX 450 ST & 500 ST
Average Horsepower:	260
Average Speed (mph):	60

At 120,000 pounds GVW:

RMD	
Configuration:	6X4-2S-2T
Engine:	Cummins ISX 450 ST & 500 ST
Average Horsepower:	282
Average Speed (mph):	59

TRPL	
Configuration:	4X2-1S-2T-2T
Engine:	Cummins ISX 450 ST & 500 ST
Average Horsepower:	274
Average Speed (mph):	58

TPD	
Configuration:	6X4-2S-4T
Engine:	Cummins ISX 450 ST & 500 ST
Average Horsepower:	277
Average Speed (mph):	58

At 140,000 pounds GVW:

Turnpike Double	
Configuration:	6X4-2S-4T
Engine:	Cummins ISX 600
Average Horsepower:	299
Average Speed (mph):	58

APPENDIX B

Data Tables

Table A: Payload Weight (Tons) by Configuration

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175	84,040	97,000	100,000	100,370	120,000	140,000
5-axle	14.00	24.00	--	--	--	--	--	--	--
DBL	12.25	22.25	--	--	--	--	--	--	--
6-axle	--	--	--	--	31.25	--	--	--	--
RMD	--	--	19.84	--	--	28.25	--	38.25	--
TRPL	--	--	--	18.27	--	26.25	--	36.25	--
TPD	--	--	--	--	--	25.00	25.19	35.00	45.00

Table B: Average Fuel Consumption (Gallons) by Configuration

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175	84,040	97,000	100,000	100,370	120,000	140,000
5-axle	69.8	78.0	--	--	--	--	--	--	--
DBL	70.7	78.3	--	--	--	--	--	--	--
6-axle	--	77.6	--	--	86.3*	87.8	--	--	--
RMD	--	80.5	82.1*	--	--	90.5	--	99.8	--
TRPL	--	79.6	--	81.6*	--	89.5	--	97.5	--
TPD	--	--	--	--	--	90.1	90.3*	98.5	110.3

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

Table C: Average Fuel Economy (MPG) by Configuration

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175	84,040	97,000	100,000	100,370	120,000	140,000
5-axle	6.0	5.4	--	--	--	--	--	--	--
DBL	5.9	5.4	--	--	--	--	--	--	--
6-axle	--	5.4	--	--	4.9*	4.8	--	--	--
RMD	--	5.2	5.1*	--	--	4.6	--	4.2	--
TRPL	--	5.3	--	5.1*	--	4.7	--	4.3	--
TPD	--	--	--	--	--	4.7	4.6*	4.3	3.8

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

Table D: Average Freight Ton-Miles per Gallon of Fuel

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175	84,040	97,000	100,000	100,370	120,000	140,000
5-axle	84	129	--	--	--	--	--	--	--
DBL	73	119	--	--	--	--	--	--	--
6-axle	--	--	--	--	151*	--	--	--	--
RMD	--	--	101*	--	--	131	--	161	--
TRPL	--	--	--	94*	--	123	--	156	--
TPD	--	--	--	--	--	116	117*	149	171

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

Table E: Average CO2 Emissions (Pounds) by Configuration

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175	84,040	97,000	100,000	100,370	120,000	140,000
5-axle	1,550	1,732	--	--	--	--	--	--	--
DBL	1,570	1,738	--	--	--	--	--	--	--
6-axle	--	--	--	--	1,916*	--	--	--	--
RMD	--	--	1,823*	--	--	2,009	--	2,216	--
TRPL	--	--	--	1,812*	--	1,987	--	2,165	--
TPD	--	--	--	--	--	2,000	2,005*	2,187	2,449

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

Table F: Average Freight Ton-Miles per Pound of CO2 Emitted

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175	84,040	97,000	100,000	100,370	120,000	140,000
5-axle	3.8	5.8	--	--	--	--	--	--	--
DBL	3.3	5.4	--	--	--	--	--	--	--
6-axle	--	--	--	--	6.8*	--	--	--	--
RMD	--	--	4.5*	--	--	5.9	--	7.2	--
TRPL	--	--	--	4.2*	--	5.5	--	7.0	--
TPD	--	--	--	--	--	5.2	5.3*	6.7	7.7

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

Table G: Average PM Emissions (Grams) by Configuration

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175*	84,040*	97,000*	100,000	100,370*	120,000	140,000
5-axle	7.7	8.6	--	--	--	--	--	--	--
DBL	7.8	8.6	--	--	--	--	--	--	--
6-axle	--	--	--	--	9.5	--	--	--	--
RMD	--	--	9.0	--	--	10.0	--	11.0	--
TRPL	--	--	--	9.0	--	9.8	--	10.7	--
TPD	--	--	--	--	--	9.9	9.9	10.8	12.1

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

Table H: Average Freight Ton-Miles per Gram of PM Emitted

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175	84,040	97,000	100,000	100,370	120,000	140,000
5-axle	764	1,172	--	--	--	--	--	--	--
DBL	660	1,083	--	--	--	--	--	--	--
6-axle	--	--	--	--	1,373*	--	--	--	--
RMD	--	--	918*	--	--	1,189	--	1,460	--
TRPL	--	--	--	855*	--	1,118	--	1,417	--
TPD	--	--	--	--	--	1,057	1,064*	1,354	1,555

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

Table I: Average NOx Emissions (Grams) by Configuration

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175	84,040	97,000	100,000	100,370	120,000	140,000
5-axle	1,605	1,794	--	--	--	--	--	--	--
DBL	1,626	1,801	--	--	--	--	--	--	--
6-axle	--	--	--	--	1,985*	--	--	--	--
RMD	--	--	1,888*	--	--	2,082	--	2,295	--
TRPL	--	--	--	1,877*	--	2,059	--	2,243	--
TPD	--	--	--	--	--	2,072	2,077*	2,266	2,537

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

Table F: Average Freight Ton-Miles per Gram of NOx Emitted

Configuration	Gross Vehicle Weight								
	60,000	80,000	83,175	84,040	97,000	100,000	100,370	120,000	140,000
5-axle	3.7	5.6	--	--	--	--	--	--	--
DBL	3.2	5.2	--	--	--	--	--	--	--
6-axle	--	--	--	--	6.6*	--	--	--	--
RMD	--	--	4.4*	--	--	5.7	--	7.0	--
TRPL	--	--	--	4.1*	--	5.3	--	6.8	--
TPD	--	--	--	--	--	5.1	5.1*	6.5	7.4

* Estimate based on straight-line extrapolation of fuel consumption data rather than actual modeling results.

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