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Performance and cost-effectiveness of air disc brakes and air drum brakes for truck semi-trailers in different road and speed conditions

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Abstract: This study uses TruckSim™ to model disc brakes and drum brakes on a fully loaded truck semi-trailer to study the performance of each brake type as downgrades and speeds vary. The brake performance is measured based on braking distance. A simplified economic comparison based on life cycle cost analysis to determine which road and vehicle conditions give rise to the cost-effectiveness of disc brakes is performed. The studies suggest that disc brakes shorten braking distances by 10-20%. They also suggest that the percentage reduction in braking distance as speed increases and downgrade gets steeper is approximately 12-19%. Evidence is provided that trucking companies operating their vehicles in steep terrain and at high speeds with disc brakes could benefit from 12-80% in long-term cost savings. Finally, at the societal level, by preventing crashes arising from rear-end collisions and runaway truck incidents, disc brakes save at least $649 million annually.

Keywords: GSRS, braking systems, grades, speeds, life cycle cost analysis, brake torque capacity

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1. Introduction

Even though trends in truck safety have generally improved over the last decade, truck-related fatalities are still concerning. Trucks are usually highly vulnerable to crashes on steep downgrades because of brake failure and subsequent truck runaway crashes. This is attributable to the high Kinetic - heat energy conversion rate at the brakes, increasing the probability of a brake fade due to heating and, ultimately, crashes due to runaway events. Many Wyoming Highways go through mountainous terrain, resulting in severe downgrades, which create challenging situations for truck drivers. Such impacts of dangerous terrain on Wyoming truck crashes were quite frequently reported by previous studies (Haq, Zlatkovic, & Ksaibati, 2019; Alrejjal, Farid, & Ksaibati, 2021; Alrejjal & Ksaibati, 2022; Alrejjal, Farid & Ksaibati, 2022).

In response to this, the Wyoming Department of Transportation, WYDOT, has implemented safety interventions such as reduced speed limits but has had a negligible impact on truck crash rate. An antidote to this scenario of truck crashes on downgrades has been the rating of grade severity. These severity ratings summarize the degree of hazard present and communicate this to the driver to take extra precautions. Grade severity rating studies have evolved from the Bureau of Public Roads, BPR, Hykes, and Lill's grade rating systems. These systems presented disadvantages related to oversimplification, largely because they failed to account for truck and environmental characteristics. Eventually, the Federal Highway Administration, FHWA sponsored a study to develop a Grade Severity Rating System, GSRS. The GSRS is based on a brake temperature model, which predicts the brake system temperature at the bottom of the grade. This system improved over previous GSRS systems by incorporating truck and environmental conditions, such as initial brake temperature, ambient temperature, brake cooling, heating factors, and downgrade characteristics. The GSRS produced a Weight Specific Speed, WSS sign assigning different descent speeds for different truck weight categories. This greatly simplified the driving task and was thus considered an enhancement over previous systems (Moomen, Apronti, Molan & Ksaibati, 2018).

The FHWA GSRS model enhanced truck safety on downgrades by providing the driver with explicit instructions on what to do instead of being required to evaluate information under different conditions. Regardless, since this new development, trucks have seen an exhaustive change in their design. Specifically, in 1989, Bowman re-evaluated the GSRS model and determined that some modifications were required to account for fuel conservation measures. These measures were introduced for trucks about a decade after the GSRS was developed (Bowman & Coleman, 1989).

The deployment of fuel conservation measures on truck designs has reduced the aerodynamic drag of trucks. This can be attributed to reduced frontal areas, airfoils, and streamlined designs. The industry has replaced the bias ply design of tires with radial tires. Engine friction, which also provides resistance to the truck's forward motion, has declined significantly over the past decade. These enhancements have reduced the non-braking forces available to retard truck motion and have thus applied a greater load on braking systems (Moomen, Apronti, Molan & Ksaibati, 2018). Consequently, this has led to longer stopping distances, directly contradicting the Federal Motor Vehicle Safety Standard (FMVSS) rule of reducing the stopping distance of trucks by 30% by the year 2013 (Gary & Aaron, August 2013). This has necessitated more advanced braking systems.

The main braking systems of the truck available to resist these greater loads are referred to as service brakes, and they typically execute when the brake pedal is depressed. There are two types of service brakes. These are drum brakes and disc brakes. A **drum brake** is a round drum with a set of shoes strategically inserted into it. The drum brake revolves alongside the wheel, and when the brake pedal is depressed, the shoes are forced against the sides of the drum, and the wheel is slowed. On the other hand, a **disc brake** incorporates a saucer-shaped metal rotor revolving along with the wheel. On applying pressure to the brake pedal, the brake pads are squeezed against the disc by a caliper. As more pressure is applied to the brake pedal, the wheel is slowed, eventually bringing the truck to a halt. Disc brakes and drum brakes exhibit different advantages and disadvantages. For instance, disc brakes generate higher braking torques and apply faster braking force, leading to shorter stopping distances. Secondly, due to exposure to air, disc brakes cool better, making them resistant to brake fade.

On the other hand, drum brakes tend to expand away from the friction material (shoe) when they get hot. Thirdly, disc brakes perform better under wet conditions because they are exposed to the air and can sling water off quickly (Les Schwab, 2020). Despite these advantages of disc brakes over drum brakes, disc brakes tend to be more expensive than drum brakes.

Figure 1 and 2 illustrate a typical drum brake and disc brake, respectively.

Figure 1: Drum brake

Source: www.dreamstine.com

Figure 2: Disc brake

Source: www.alamy.com

A recent study recommended disc brakes for fleets that frequently travel over mountain passes (Moomen & Ksaibati, 2020). This recommendation is supported by studies that have found that air disc brakes may improve large truck stopping distance by 30% and, as a result, minimize high-speed large-truck striking rear-end collisions by as much as 43.2% (Camden, Medina-Flintsch, Hickman, Miller & Hanowski, 2017). This study attempts to investigate this recommendation and guides the speed and grade levels that maximize the cost-effectiveness of disc brakes. The new brakes will also reduce the Kinetic- heat energy conversion rate so they can handle higher speeds without experiencing brake fade. One major accompaniment of this development will be upgrading the GSRS to predict higher maximum speeds. As a result, drivers will not trivialize the suggested values.

1.1. Market penetration rates for disc brakes and drum brakes

Drum brakes are the oldest braking mechanisms with a maximum adoption rate in North America owing to their low cost compared to air disc brakes. North America has an adoption rate of approximately 80–85% for drum brakes in heavy-duty vehicles Air Brake System Market – Global Forecast to 2025. (The Air Brake System, 2020).

It is projected that market penetration for Air Disc brakes (ADBs) might reach 50% by 2021 in North America (Disc Brake, www.alamy.com). The air disc brake system (Disc brake) market was estimated to be $4.5 billion in 2018 and is projected to reach $5.6 billion by 2025 at a CAGR (Compound annual growth rate) of 3.31% during the forecast period (Air Brake System Market, 2020). The only air disc brake approved for all major truck and trailer Original Equipment Manufacturers and OEMs in North America is the ADB22X, with a market penetration rate of nearly 90% (Bendix Spicer Foundation Brake, 2020). More than 80 % of commercial trucks in Europe already use air disc brakes. The complete shift to air disc brakes in North America may require 10 to 15 years (Marlowe, 2020).

Table 1 lists the components of air brake drums, their respective quantities in a unit braking system, the unit, the extended price of each set of components, and summarizes the total cost. The quote was obtained from TransWest truck trailer Recreational Vehicles and applied to 70-80% of trucks.

Table 1: Air brake drum/ shoe package cost for 75% of trucks

ID	Description/ Ref Number	Quantity	Price($)	Extended Price($)
1	KIT MERITOR EXT SVC	4	49.94	199.76
2	4707Q SHOE PAIR CORE	4	35.52	142.08
3	BRAKE DRUM 16.5 X 7.0 BAL.	4	102.79	411.16
4	SEAL	4	47.20	188.80
5	GASKET	4	2.44	9.76
6	1/2 X 36 '' HOSE	4	12.02	48.08
7	A/S 28SPL 5.5 CS56040	4	74.24	296.96
8	USA 3030 BRAKE CHAMBER NO CLEV	4	56.80	227.20
9	TRAILER ABS ECU/MODULATOR VA	1	786.54	786.54
	Total Parts			$ 2,168.26
	Total Core Charges			$ 142.08
	Subtotal			$ 2,310.34
	Total Tax			$ 196.38
	Quote Total			**$ 2,506.72**

Source: © TransWest Truck Trailer RV

Table 2 lists the components of air disc brakes for a typical truck, their respective quantities in a unit braking system, the unit and extended price of each set of components, and summarizes the total cost. The quote was obtained from TransWest truck trailer Recreational Vehicles but is still generalizable to other trucks since the components of braking systems are typically the same irrespective of the brand of the truck on which it is used.

Table 2: Air disc brake cost for a typical truck

ID	Description/ Ref Number	Quantity	Price($)	Extended Price($)
1	BRAKE PADS	2	195.60	391.20
2	KIT, SPARE	1	1066.22	1066.22
3	CORE	1	499.50	499.50
4	AIR DISC BRAKE SPARES KIT	1	1047.58	1047.58
5	AIR DISC BRAKE SPARES KIT-Core	1	499.50	499.50
6	ROTOR ASY 2XV 197.5 430MM CO	4	237.62	950.48
7	SEAL	4	47.41	188.80
8	VALVE ABS/RELAY CO	1	426.64	426.64
	Total Parts			$ 4,070.82
	Total Core Charges			$ 999.00
	Subtotal			$ 5069.92
	Total Tax			$ 430.94
	Quote Total			**$ 5,500.86**

Source: © TransWest Truck Trailer RV

As is evident, drum brakes cost only about 45.7% of the price of disc brakes. These standard costs of disc brakes and drum brakes will be relevant in conducting the economic life-cycle cost analysis for both types of brakes. These costs are, however, retail prices, and thus initial fitment costs might be lower in new production vehicles.

2. Literature review

The literature review generally revealed minimal background studies surrounding the subject matter (measuring the performance of disc and drum brakes with variation in road and vehicle characteristics). However, existing literature focused on mechanical applications and provided some insights and guidance into the brake system modeling process and economic analysis.

The first study focused on the jackknife stability and interactions between the tractor with air-disc brakes and the trailer, which had air-disc or air-drum brakes. The brakes were either electronically or pneumatically controlled. The tradeoff between the vehicle equipped with disc and drum brakes was discussed. Simulation results showed that a tractor with disc brakes had more excellent jackknife stability (Zagorsky, 2020). Building on this study, the influence upon jackknife stability of higher performance brakes on the prime mover while keeping traditional pneumatically controlled s-cam drum brakes on the trailer was studied. Electronically controlled braking systems (ECBS) disc brakes were directly compared to those equipped with s-cam drum brakes. Results showed that the simulated presence of the ECBS disc brakes on the tractor results in no degradation of the performance of the rig in terms of jackknife stability while braking in turn (Dunn & Heydinger, 2003).

Further studies involved simulations of a typical 4X2 heavy commercial vehicle with a pneumatic brake system equipped with a drum brake. The response time of the system and the transient torque with drum brakes were examined. The same layout on replacing with equivalent disc brakes showed better torque characteristics. The vehicle exhibited better stopping distance by replacing the drum brake with a disc brake (Mithun, Mariappa & Gayakwad, 2014).

In the drive to reduce the dry stopping distance required for heavy trucks, it is unavoidable to increase the effectiveness of the foundation brake systems. Concerning just the foundation brakes, the vast majority of current tractor and trailer brakes are of the s-Cam and Drum type. However, air Disc brakes and larger sized s-cam brakes are commercially available alternatives that produce higher output. This warrants a comparative study between drum brakes and disc brakes. The goal is to improve the effectiveness of the brake system while retaining or enhancing vehicle stability during braking. A study highlighted the results of stopping tests at 97 km/h (60mph). It investigated the dry surface-stopping performance of semi-trailers and the stability of combination tractor-semitrailer rigs (Abdi & Molan, 2015).

Because of increased speed limits at the state level, the National Highway Transportation Safety Administration, NHTSA has implemented additional testing of heavy trucks at higher test maneuver entry speeds. Test results were presented from three vehicles, a Class 7 school bus, a Class 8 truck tractor, and a Class 8 straight truck. Results were discussed for full treadle straight-ahead stops from 97 km/h (60 mph), 113 km/h (70 mph), and 121 km/h (75 mph). Each vehicle was tested with two different brake configurations; (i) air-disc brakes on the steer axle and s-cam brakes on drive axles (ii) Traditional s-cam brakes on all axles. Comparisons reveal that vehicles in the hybrid configuration exhibited superior stopping performance to the vehicles equipped with traditional s-cam brakes (Zagorski, 2005)

In terms of investigating the cost-effectiveness of braking systems, a study found that in 2015, large trucks (trucks with a gross vehicle weight rating of more than 4536 kg (10,000 lb)) were involved in 414,958 crashes, resulting in 116,000 injuries and 4,067 fatalities (Federal Motor Carrier Safety Administration, 2016). Associated costs of each crash component were also computed from these statistics. The American Automobile Association, AAA Foundation for Traffic Safety performed research to provide scientifically based estimates of the societal benefits and costs of air disc brake systems as one of four emerging technologies that would serve as countermeasures to reduce these crashes (Camden, Medina-Flintsch, Hickman, Miller & Hanowski, 2017).

3. Materials and methods

The commercial vehicle simulation package, TruckSim™ 2020, was used to model and simulate a fully loaded truck semi-trailer (80,000 lb). TruckSim™ is a well-known multibody simulation package developed by Mechanical Simulation Corporation (MSC) and used for simulating the acceleration, braking, ride, handling, and rollover of medium to heavy trucks, buses, and tractor-semitrailers (Applications in the Simulation of Truck Dynamics, 2020).

The TruckSim multibody vehicle dynamics software established the driver-vehicle-road dynamic simulation modeling. Three main components were assigned in the software; the driver control model, the vehicle model, and the three-dimension road-building model. A typical five-axle tractor-semitrailer was used to evaluate the stability performance on curved roadways at various operating speeds. Regarding the truck deceleration, the braking forces were applied on a dry road surface, so the tire-pavement friction was constant. Bonneson measured the variation in deceleration using an instrumented vehicle and suggested that the usual deceleration upon the curve's entry should be 3 ft/s^2 (0.91 m/s^2). Several studies use real field experiments and high-fidelity simulation tests examining the location of the highest lateral acceleration. Three locations were considered; at the curve's beginning, middle, and end. The results showed that the lateral acceleration is maximized at the beginning of the curve. The brakes are applied at the curve's entry point since the maximum lateral friction is developed at this curve location. Hence, the simulation model achieves a deceleration value at the curve's entry point by mimicking a human driver intermittently applying and releasing the brakes.

Simulation studies were conducted using TruckSim in order to study the variation of the air disc brake and air drum brake performance with different downgrades (3%, 6%, and 9%) and at different speeds (81 km/h (50 mph), 97 km/h (60 mph), 113 km/h (70 mph) and 129 km/h (80 mph)). These ranges were chosen because they cover most of the road and vehicle characteristics that trucks will typically travel along the mountainous downgrades of North America.

3.1. Modelling

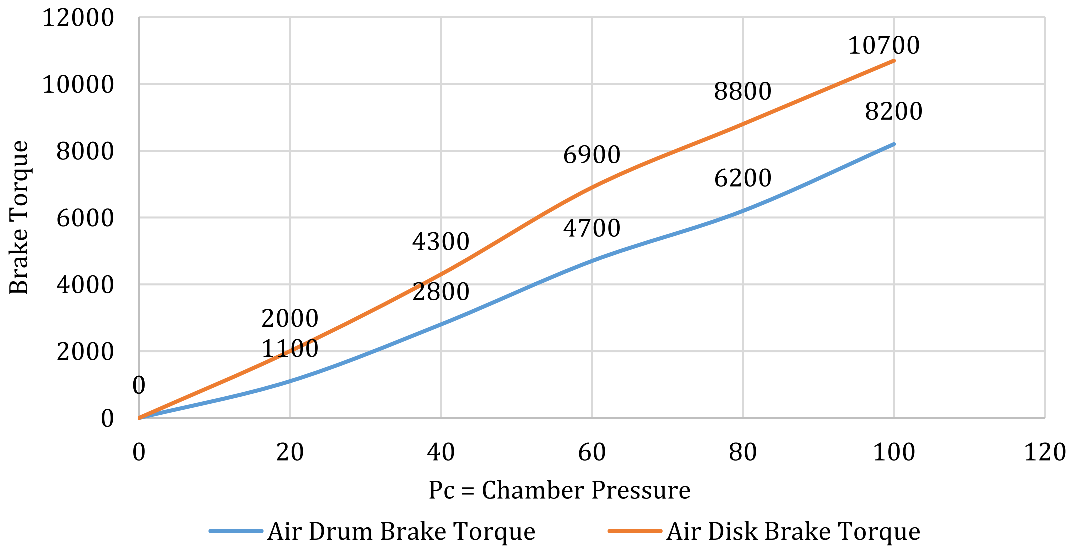
Disc brakes and drum brakes have several differences. For these simplified simulation studies, their modeling was differentiated primarily based on their brake torque capacity and cooling characteristics.

3.1.1. Brake torque capacity

To model the brake torque capacities of the disc brake and drum brake, respectively, quadratic model outputs for both brake torques were plotted against chamber pressure at speeds of 32 km/h (20 mph), 80 km/h (50 mph), and 97 km/h (60 mph). These were based on experimental data at 5443 kg (12000 lb) Gross Axle Weight Rating, GAWR, actuated by a 1.9 m^2 (20 in^2) brake chamber (Zagorski, 2003).

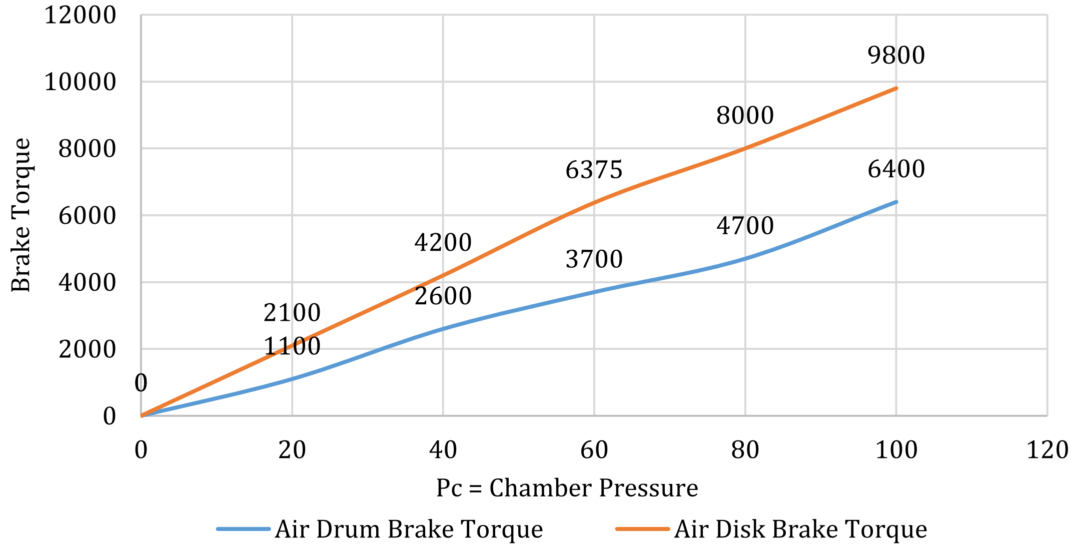
The plots are shown in Figures 3, 4, and 5.

Figure 3: Steer Axle Air Drum Brake & Air Disc Brake Torque vs. Pressure at 32 km/h



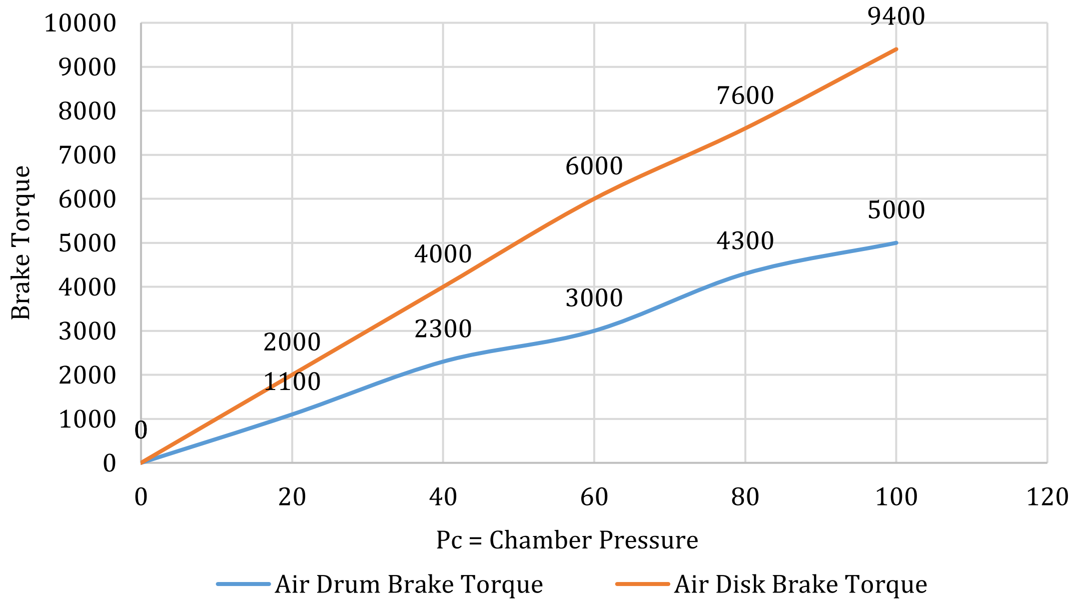
Source: Dunn, 2003

Figure 4: Steer axle air drum brake & air disc brake torque vs. pressure at 80 km/h



Source: Dunn, 2003

Figure 5 Steer axle air drum brake & air disc brake torque vs. pressure at 97 km/h



Source: Dunn, 2003

The ratio of the slopes of the torque pressure curves for Figure 3 is 1.6, for Figure 4 is 1.3, and for Figure 5 is 1.86. Thus, the ratio of the slopes of the torque-pressure curves of disc brakes to drum brakes for the given speeds range from 1.3-1.8. Since the brake torque produced is limited to the brake torque capacity, selecting the default brake torque capacities provided by Trucksim for the simulation (10KNm and 7.5 KNm) would be reasonable. The former models disc brake behavior, and the latter models drum brake behavior. This is because the ratio of these brake torque capacities is approximately 1.3, which is quite conservative. This selection is also supported by commercially available disc brakes manufacturers tout a potential increase in effective braking torque of 20% over existing drum brakes (Dunn, 2003). A sample screenshot from the Trucksim simulation is shown in Figure 6 below.

Figure 6: Truck semi-trailer descending a downgrade in Trucksim simulation (©Trucksim mechanical simulation)

3.1.2. Cooling characteristics

Cooling rates and hence the cooling coefficient has been found to depend on the shape and size of the disc or drum. Experimental results show that the cooling rates of front brakes are about 20 % higher than the rear brakes and that front discs are incredible about 25 % more quickly than the corresponding drum size recommended for the exact vehicle (Newcomb & Millner,1965). Although these are values pertaining to the umbrella term of "vehicles," thus implying that they apply to passenger vehicles, it should be noted that they apply (with some variation) to heavy trucks as well.

Simulations were run for the disc brake and drum brake with a 0.7 MPa (101.53 psi) constant full brake application force for 15 s. The deceleration is constant at 3.4 m/s^2 (11.2 ft/s^2). Braking distance values were obtained for each combination of grade and speed for both brakes by identifying the station value corresponding to a zero longitudinal speed value in the TruckSim output.

4. Results and discussions

4.1. Evaluating the performance of disc and drum brakes with respect to braking distance

Stopping distance is the distance required to stop a vehicle in motion completely. This typically consists of the following:

(i) The distance required to respond to a hazard (perception-reaction time/distance), and

(ii) The time required for the brakes to bring the vehicle to a stop (braking distance).

Perception-reaction distance can be affected by drugs, alcohol, distractions, tiredness, environment, and other conditions. On the other hand, the braking distance is affected by brakes, tires, weather conditions, road conditions, and weight (Road Safety, n.d.).

Stopping distance,

$$S = 1.47ut + u^2/(30\{\frac{a}{g}\} + G) \quad (1)$$

where,

u = Initial velocity when brakes are applied (m/s)

G = Grade (%)

t = time to perceive/react (s)

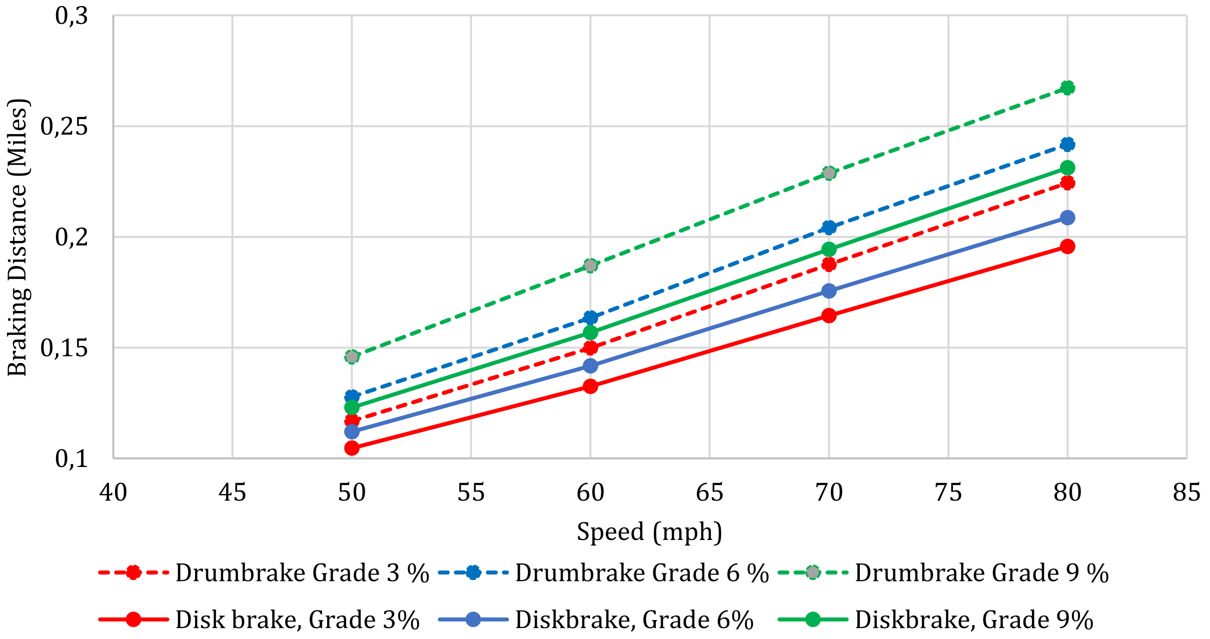
a = Vehicle deceleration (ft/s^2)

g = Acceleration due to gravity (9.8 m/s^2 or 32.2 ft/s^2).

Stopping distance values from the simulation excludes perception-reaction distance and simply breaking distance values.

Figure 7 shows the variation of Speed and Grade with braking distance for a drum brake and disc brake. These plots were obtained from the TruckSim output.

Figure 7: Variation of speed and grade with braking distance for drum brake and disc brakes



The plot shows a linear relationship between braking distance and speed, with braking distance increasing with speed regardless of grade or brake type. On average, the braking distance increases by 23% for every 16 km/h (10 mph) increase in speed, regardless of grade or brake type. In addition, it is suggested from the plots that disc brakes shorten braking distances by 10-20 %. According to past studies, 'The braking distance depends on how fast the vehicle traveled before the brakes were applied and is proportional to the square of the initial speed. Even small speed increases mean significantly longer braking distances (Sokolovskij, 2007).

In mathematical terms, assuming d = braking distance, u = initial speed and
k = proportionality constant; $d \propto u^2$,

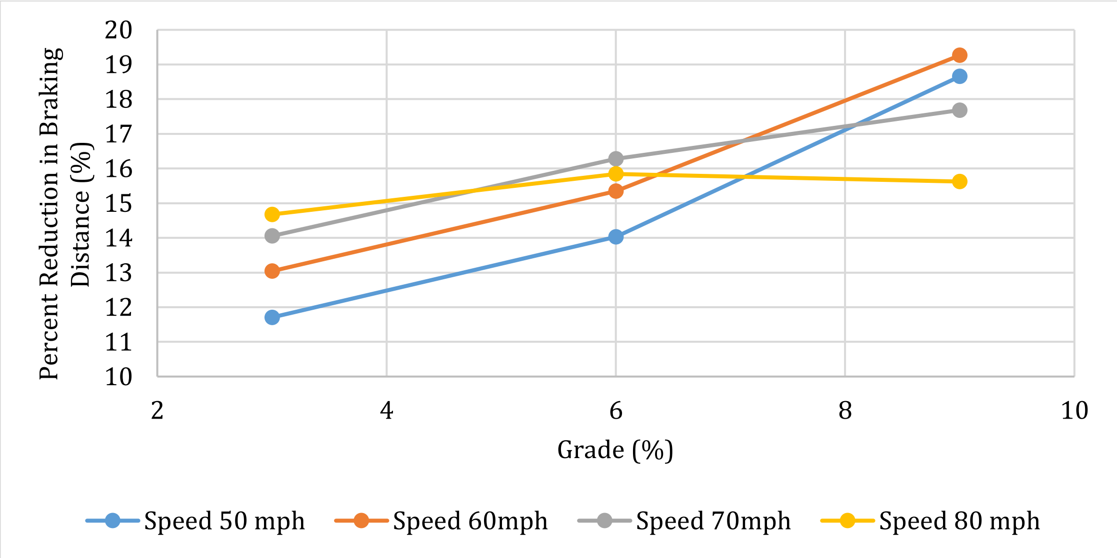
$$\text{Thus, } d = k * u^2 \tag{2}$$

Assessing percentage changes in braking distance with a 16 km/h (10mph) increase starting from an initial speed of 80 km/h (50 mph) within the pre-defined relevant range;

For u1 = 80 km/h (50 mph), d1 = $(50)^2$ k = 2500k
Next, u2 = 97 km/h (60 mph), d2 = $(60)^2$ k = 3600k
Therefore, change in braking distance = (abs (d2- d1)/d1)*100 = (3600k – 2500k)/2500k = 44 %
For u3 = 113 km/h (70 mph), d3 = $(70)^2$ k = 4900k
Therefore, change in braking distance = (abs (d3- d2)/d2)*100 = (4900k – 3600k)/3600k = 36 %
For u4 = 129 km/h (80 mph), d4 = $(80)^2$ k = 6400k
Therefore, change in braking distance = (abs (d4- d3)/d3)*100 = (6400k – 4900k)/4900k = 30 %

On average, the percentage improvement in braking distance is (44 + 36 + 30)/3 = 37 %, which relatively approximates the value obtained during prior studies and is exactly equal to this value (30%) from the conservative viewpoint. This implies that the Trucksim output, due to limitations associated with simplifications in the modeling process, could not capture this nuance and hence the smaller average improvement in stopping distance (15%) suggested via simulations. Disc brakes consistently produced shorter braking distances regardless of grade and speed. This information is summarized in Figure 8.

Figure 8: Percent reduction in braking distance for using disc brakes over drum brakes with varying speed and grade



At 81 km/h (50 mph), disc brakes produced a 12% reduction in braking distance over drum brakes at a 3% downgrade. This reduction increased to 14% and 18% at 6% and 9% downgrades at the same speed, respectively. At 97 km/h (60 mph), disc brakes produced a 13% reduction in braking distance over drum brakes at a 3% downgrade. This reduction increased to 15% and then 19% at 6% and 9%, respectively. At 113 km/h (70 mph), disc brakes produced a 14% reduction in braking distance over drum brakes at a 3% downgrade. This reduction then increased to 16% and 17% at 6% and 9%, respectively. Finally, at 129 km/h (80 mph), disc brakes produced a 15% reduction at a 3% downgrade. This reduction increased to 16% each for a 6% and 9% downgrade, respectively.

The plot indicated in Figure 8 suggests that there is an increase in percentage reduction, 12-19 % in braking distance as the downgrade gets progressively steeper as drum brakes are replaced with disc brakes, but it is not entirely clear from the output whether this percent reduction increases with speed at constant grades. Furthermore, this improvement will minimize high-speed large truck striking rear-end collisions by up to 43.2% (Camden, Medina-Flintsch, Hickman, Miller & Hanowski, 2017). Furthermore, grade and braking distance output derived an inverse linear relationship. There was an average increase of 8.5% in braking distance with every 3% decrease in downgrade regardless of the speed for disc brakes and an increase of 11% in braking distance for every 3% decrease in a downgrade for drum brakes. This supports the notion that disc brakes apply more braking force faster, resulting in shorter braking distances.

4.2. Evaluating the cost-effectiveness of disc brakes and drum brakes

As demonstrated in the simulation, disc brakes shorten braking distances by 10- 20%. The components of braking systems deteriorate for a number of reasons ranging from driving habits and stopping habits to braking quality. However, all things being equal, brake life is directly related to the braking distance traveled when brakes are partially or fully applied. This implies that shorter braking distances would use up the brake life over a longer period than longer braking distances. This implication is intuitive but would require empirical studies to substantiate it. Thus, they will require less disc brake replacements over the lifetime of the semi-trailer for which it is used. However, disc brakes are about two times costlier than drum brakes. In addition to that, brake pads, the limiting component in disc brakes, require replacement every 30,000-70,000 miles (Baxter, 2020). On the other hand, brake shoes, which are the corresponding limiting component in drum brakes, require a shorter replacement span of 15,000- 30,000 miles (Louis Motorcycle Clothing, 2020) (Rx Mechanic, 2020). Thus, disc brakes would only be more cost-effective over the lifespan of a given semi-trailer within a particular range of specified parameters, including grade, speed, lifespan, and cost.

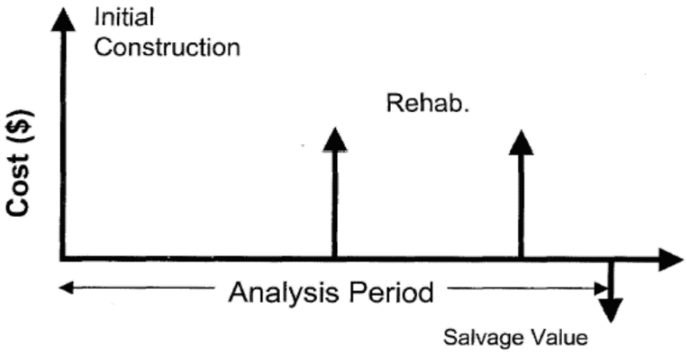
In order to investigate this range, a life-cycle cost analysis was conducted for a disc brake and drum brake over the lifetime of a semi-trailer, assuming each brake type would be equipped with the same type of brake after its useful life had expired. The Life Cycle Cost is generally given by

$$\text{NPV} = \text{Initial Cost} + \sum \text{Future Cost} * [(1/(1+i)^n] \text{ ,} \quad (3)$$

where
NPV = Net Present Value, $
n = Time of Future Cost, Years
i = Discount Rate, %

A diagrammatic representation of the life cycle cost/expenditure flow diagram is given in Figure 9.

Figure 9: Expenditure flow diagram



A number of simplifying assumptions were made in this investigation, inclusive of which are:

- The brake wear, which is practically contributed to both by partial and full application brakes, will be assumed to be caused only by full brake applications.
- The brake lifespan is determined by the wear, which the brake will cumulatively accrue through the braking distance resulting from full application brakes.
- There will be exactly one full application brake per mile of vehicle distance traveled.
- Maintenance costs are excluded from the analysis. The entire brake is replaced when the limiting component wears down. This applies to both discs and drums.
- The vehicle will travel a maximum of 650 miles per day (Big Rig Pros, 2020)
- The average useful life of a semi-trailer is 15 years (Soard Becca, 2017).
- The inflation rate, which will be used to discount future expenses, is 4% (Laurence, 2014).

A sample calculation for the life-cycle cost of drum brakes over the life span of a semi-trailer at a downgrade of 9% and a speed of 97 km/h (60 mph) based on the simplifying assumptions above is included in Tables 3 and 4.

Table 3: Sample calculation for lifespan of drum brake before requiring replacement (Downgrade 9%, Speed 97 km/h (60 mph))

Average lifespan of drum brakes	(35,000) 56,300	Miles km
Number of full application brakes/mile	1	
Stopping distance for drum brake per full application brake	(0.19) 0.3	Miles km
Stopping distance for drum brake per mile (0.19 x 1)	(0.19) 0.3	Miles km
Number of miles traveled per day	(650) 1047	Miles km
Stopping distance for drum brake per day (650 x 0.19)	121.53 196	Miles km
Number of days drum brake lasts (35,000/121.53)	287.99	days
Number of years drum brakes last before requiring replacement (287.99/ 365)	0.79	years
The average useful life of a semi-trailer (15 years) (15 x 365)	5475	days
Unit Cost of Drum Brake	$2,506	

Table 4: Life-cycle cost analysis for drum brake during the available service life of a truck semi-trailer (Downgrade 9%, Speed 97 km/h (60 mph)).

Year	0	0.79	1.58	2.37	3.16	3.95	4.74
Expense	-2506	-2429.5	-2355.4	-2283.5	-2213.8	-2146.3	-2080.8
Year	5.53	6.32	7.11	7.9	8.69	5.53	9.48
Expense	-2017.3	-1955.8	-1896.1	-1838.3	-1782.2	-2017.3	-1727.8
Year	10.27	11.06	11.85	12.64	13.43	14.22	15
Expense	-1675.1	-1624.0	-1574.4	-1526.4	-1479.8	-1434.7	130.312
Total	**$36,418**						

Cost comparisons are computed for four scenarios of braking systems. These include:

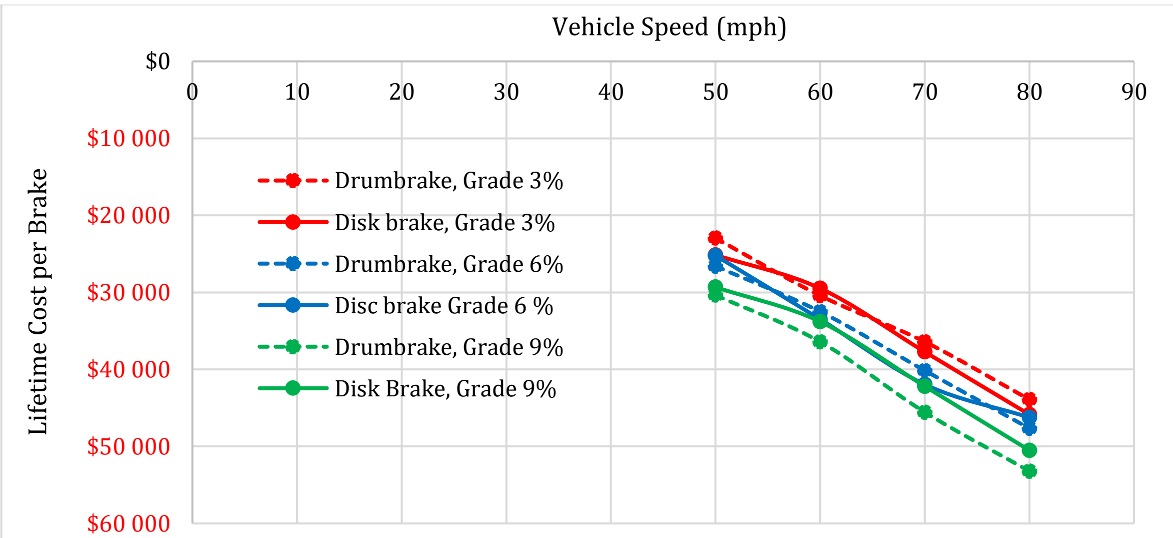
- Scenario 1 (Maximum Drum brake lifespan, Maximum Disc brake lifespan)
- Scenario 2 (Maximum Drum brake lifespan, Minimum Disc brake lifespan)
- Scenario 3 (Minimum Drum brake lifespan, Minimum Disc brake lifespan)
- Scenario 4 (Minimum Drum brake lifespan, Maximum Disc brake lifespan)

The results for each scenario are displayed in Figures 10, 11, 12 and 13

Scenario 1 (Maximum Drum brake lifespan, Maximum Disc brake lifespan)

In Figure 10, Scenario 1, disc brakes were found to be the more cost-effective option as the downgrades got steeper.

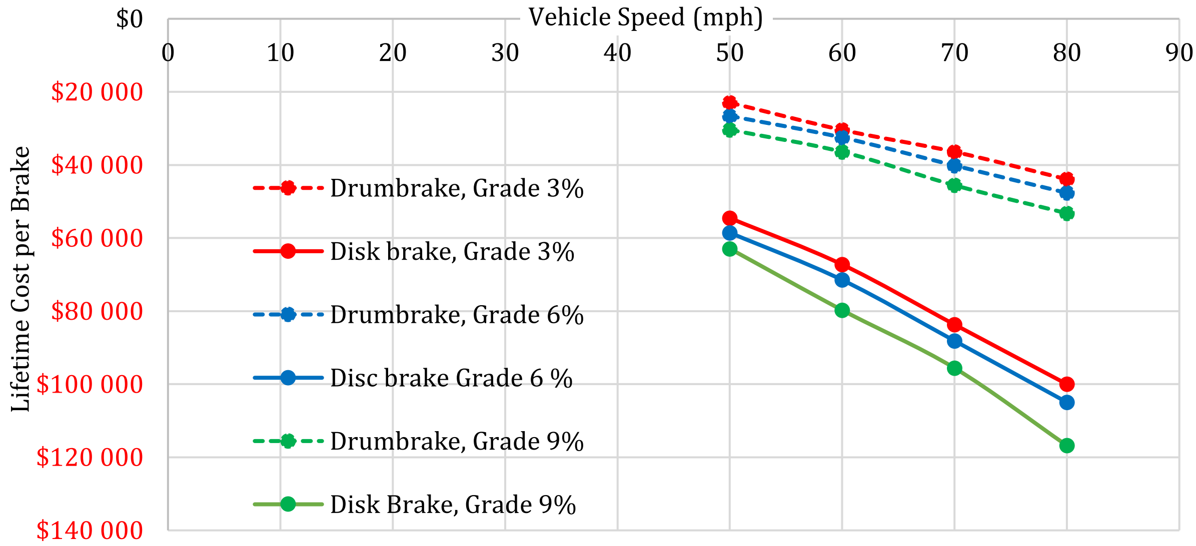
Figure 10: Variation of average lifetime cost for braking systems with speed at different grades, Scenario 1. (Maximum drum brake lifespan, maximum disc brake lifespan)



At a 3% downgrade, disc brakes are cost-effective at only 60 mph, whereas they are cost-effective at both 50 mph and 80 mph at a 6% downgrade. However, they are cost-effective at all speeds at a 9% downgrade. Therefore, it can be concluded that as downgrades get steeper, disc brakes become more cost-effective over a wider speed range.

Scenario 2 (Maximum Drum brake lifespan, Minimum Disc brake lifespan):

Figure 11: Variation of average lifetime cost for braking systems with speed at different grades, Scenario 2. (Maximum Drum brake lifespan, Minimum Disc brake lifespan



In Figure 11, Scenario 2 clearly shows that disc brakes are significantly not the cost-effective option regardless of the speed when the lifespan of drum brakes is maximized, whereas disc brakes are minimized.

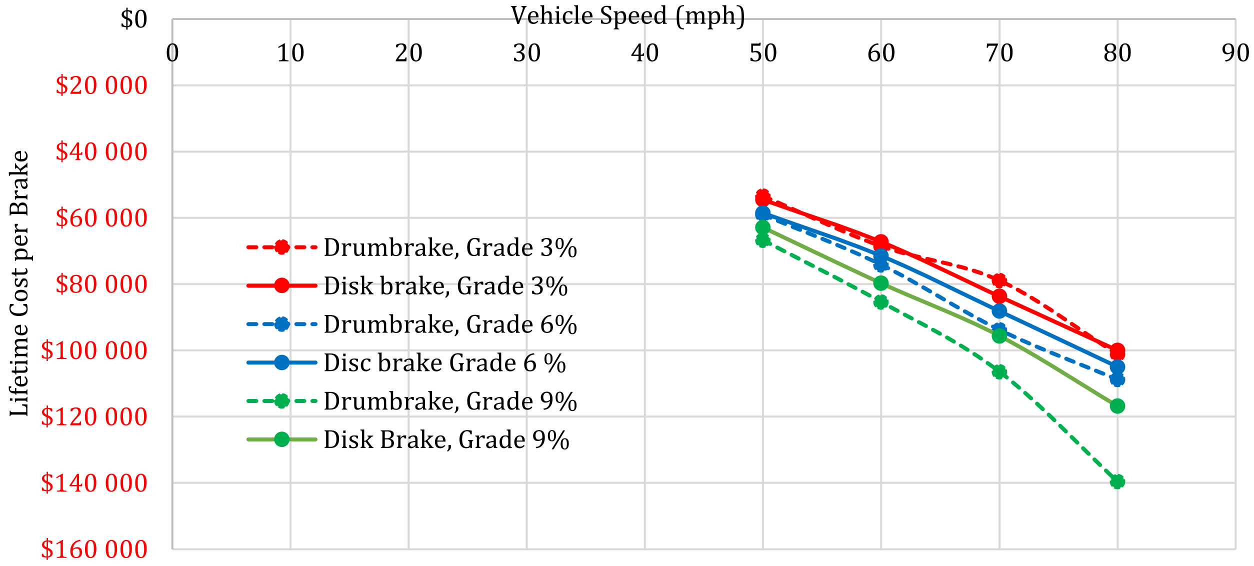
This is an obvious conclusion because the longer the lifespan of drum brakes, the fewer the number of brake replacements required, and for each replacement, the cost is about half the cost of the disc brake. Another observation is the fact that the slope of the disc brake curves for every grade level is about twice those for drum brake curves. This implies that the average lifetime cost doubles for every 16 km/h (10 mph) increase in speed for disc brakes compared to drum brakes.

Scenario 3 (Minimum Drum brake lifespan, Minimum Disc brake lifespan):

In Figure 12, Scenario 3 minimizes the lifespan of both disc brakes and drum brakes. It is clear that disc brakes are the more cost-effective option for every speed level as the grade steepens, besides the outlier for drum brakes at 3% and at 113 km/h (70 mph).

The magnitude of cost-effectiveness also increases with speed level as the grade steepens. This implies that disc brakes not only provide increasing reductions in stopping distances as the grade steepens but are also the cheaper option over the lifespan of the semi-trailer if the terrain presents steep downgrades or requires higher speeds or a combination thereof.

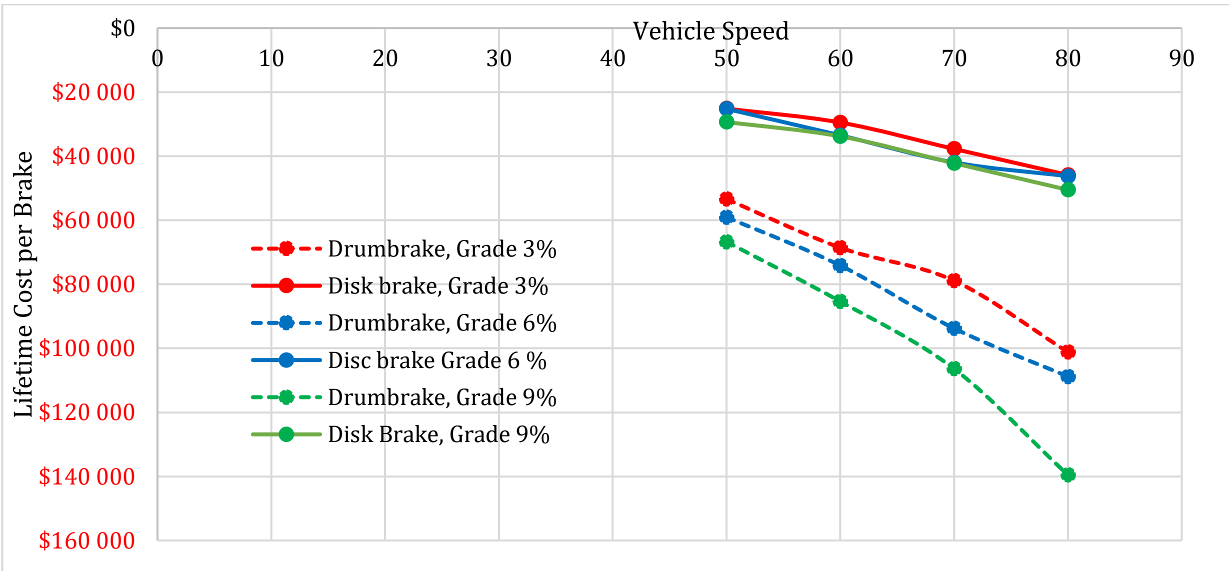
Figure 12: Variation of Average lifetime cost for braking systems with speed at different grades, Scenario 3. (Minimum Drum brake lifespan, Minimum Disc brake lifespan)



Scenario 4 (Minimum Drum brake lifespan, Maximum Disc brake lifespan):

In Figure 13, Scenario 4 occurs when drum brake lifespan is minimized, whereas maximizing disc brake lifespan. The curves indicate that disc brakes are significantly more cost-effective at every speed level and for every grade percentage.

Figure 13: Variation of Average lifetime cost for braking systems with speed at different grades, Scenario 4. (Minimum Drum brake lifespan, Maximum Disc brake lifespan)



This finding is significant because despite the fact that a maximum disc brake lifespan requires fewer brake replacements, each replacement costs about twice the amount an equivalent drum brake would require. Because these two parameters are inversely related, it is not intuitively obvious which braking system will be more cost-effective. It is also important to observe that the slope of the drum brake curves for each grade is more than twice those for disc brake curves, and this slope seems to increase with increasing grade. This implies that the average lifetime cost doubles for every 16 km/h (10 mph) increase in speed for drum brakes compared to disc brakes, and this cost increment becomes higher, the steeper the grade. This observation should inform trucking companies that if they intend to operate their vehicles in terrain with steep downgrades and at high speeds, they will generate the highest return on their investment if they use disc brakes instead of drum brakes. Quantitatively, this would range from 12% to 80% cost savings.

4.3. Safety and societal implications of using disc brakes over drum brakes

Disc brakes prevent truck crashes in two main ways; reducing stopping distance and providing resistance to brake fade, hence truck runaway.

Studies have shown that air disc brakes may improve large-truck stopping distance by 30%, thereby reducing high-speed large-truck striking rear-end collisions by 43.2% (Camden, Medina-Flintsch, Hickman & Hanowski, 2017). This means preventing as many as 2,411 crashes, 1,447 injuries, and 37 deaths annually (assuming the brakes are fitted on existing and new trucks). The annual cost of crashes that air disc brakes may prevent is approximately $1,077,209,477. 'The societal costs of crashes include medical and emergency costs, environmental and fuel costs, the cost of property damage, costs associated with lost productivity due to roadway congestion, and monetized quality-adjusted life-year, QALY' (Camden, Medina-Flintsch, Hickman, Miller & Hanowski, 2017).

Our study yielded approximately 15% improvement in large-truck braking distance by using air disc brakes. A thorough literature review yielded no empirical relationship between percent improvement in braking distance and annual crash cost savings, and so assuming, rather conservatively, a linear relationship between the two parameters, the savings gained by the use of air disc brakes is expected to be halved based on our results; $538,604,738 since the 30% reduction obtained from previous studies yields cost savings of $1,077,209,477 (Camden, Medina-Flintsch, Hickman, Miller & Hanowski, 2017).

In terms of crashes due to brake fade avoided, current data is scarce, but a 1981 study for the National Highway Traffic Safety Administration (NHTSA) estimated that runaway truck incidents totaled 2,450 per year, incurring costs of nearly $37 million at that time (Chairman, Roy, Tabb, Van, Walton, Robertson & Macgregor, 1992). This scenario is conservative given that there has been a 14% reduction in fatal crashes partly because air disc brakes have penetrated the market since the early 1980s. Thus, in reality, more annual savings are likely to be achieved. Nevertheless, if the total number of runaway trucks had remained 2,450, in today's dollar terms, this would cost $110,174,252.61 due to inflation. Therefore, by preventing crashes arising from rear-end collisions and runaway truck incidents, society may save at least $649 million annually.

4.4. Investigating the impact of disc brakes on speed limits

Approximately 84% of states in the US post vehicle speed limits between 105- 120 km/h (65 - 75 mph).

Consequently, Bendix Commercial Vehicle Systems has conducted tests of disc-braked and drum-braked vehicles at legal speeds up to 120 km/h (75 mph). At higher legal speeds, test results proved that Bendix air disc brakes exhibited even more pronounced performance advantages than drum brakes.

During the side-by-side testing, data showed that the Bendix air disc brake-equipped truck's stopping distances were 93 m (305 ft) to 99 m (325 ft). This range of stopping distance is particularly relevant because, during nighttime driving, low-beam headlights provide only 170 m (350 ft) of visibility. It should be noted that this value ordinarily would depend on the reflectivity of the object being viewed. The drum brake-equipped truck stopped in the range of 137 m (450 ft) to 158 m (518 ft) initially when cold, but as the drums heated up, the stopping distances became progressively longer. Eventually, the stopping distance for the hot drum brake-equipped vehicle exceeded 229 m (750 ft) (Bulk Transporter, 2004). This indicates that at higher legal speeds, air disc brakes provide approximately a 35% reduction in stopping distance when cold and up to 58% reduction when hot compared to drum brakes. This has a significant impact on crash statistics and associated cost savings.

The opposite case can be made for recommending higher speed limits when equipping fleets, especially in mountainous regions, with air disc brakes. The reduced stopping distances and the significant reduction in susceptibility to brake fade would allow trucks to travel safely at higher speeds than would be the case if they were using drum brakes. This is a key reason the current GSRS requires updating; to reflect the capacity for higher maximum descent speeds.

5. Conclusions and recommendations

The study suggested that braking distance increased by 23% for every 16 km/h (10 mph) increase in speed regardless of grade or brake type. It also suggested that disc brakes shorten braking distances by 10-20 %. Furthermore, it suggests an increase in the percentage reduction in braking distance by 12-19 % as speed increases and the downgrade gets steeper. This implies that disc brakes were more likely to keep the stopping distance within FMVSS requirements for truck uses requiring high speed and steep grades. According to past studies, 'The braking distance depends on how fast the vehicle traveled before the brakes were applied and is proportional to the square of the initial speed. That means even small speed increases mean significantly longer braking distances' (Dunn, 2003). This fact exposes the extent of simplification and limitations in our modeling process because the results of our study maintain a constant improvement of 23% in braking distance with every 16km/h (10 mph) increase in speed irrespective of the speed in the speed range under consideration as opposed to the analysis performed based on equation (2).

It was also determined from the cost analysis that when both drum brakes and disc brakes maximize their lifespan, disc brakes become progressively more cost-effective with steeper downgrades. Moreover, as drum brake lifespan approaches its maximum value while simultaneously minimizing disc brake lifespan, for every 16 km/h (10 mph) increase in speed, the average lifetime cost for disc brakes doubles over that for drum brakes. As both drum brakes and disc brakes approach their minimum lifespan, it is observed that disc brakes are the more cost-effective option for every speed level as the grade steepens. The magnitude of cost-effectiveness also increases with speed level as the grade steepens. This implies that disc brakes both provide increasing reductions in stopping distances as the grade steepens and are the cheaper option over the lifespan of the semi-trailer if the terrain presents steep downgrades or requires higher speeds or a combination thereof. Finally, as drum brakes approach their minimum lifespan and as disc brakes approach their maximum lifespan, for every 16 km/h (10 mph) increase in speed, the average lifetime cost more than doubles for drum brakes compared to disc brakes, and this increase in cost becomes higher, the steeper the grade. This observation should inform trucking companies that if they intend to operate their vehicles in terrain with steep downgrades and at high speeds, they will generate the highest return on their investment if they use disc brakes instead of drum brakes. Quantitatively, this would range from 12 % to 80 % cost savings.

At the societal level, equipping all combination Unit Trucks with disc brakes conservatively prevents 1206 crashes, 724 injuries, and 19 deaths annually due to a stopping distance reduction of 15% instead of the 30% obtained in prior studies, which saves society $538,604,738. Assuming a very conservative case in which the total number of runaway trucks has remained at 2,450 since 1981, inflation would result in an extra annual cost of $110,174,252.61. Therefore, by preventing crashes arising from rear-end collisions and runaway truck incidents, society may save at least $649 million annually.

The following are some recommendations based on the findings of this study:

- TruckSim's brake model is quite simplistic, and by implementing an external model (e.g., via Simulink) in future studies, the user can take into account speed effects. That is, different torque levels based on vehicle entry speed, ability to study/model temperature effects such as brake fade and include more sophisticated Anti-Lock Brake system (ABS) models as was accomplished by Ashley Dunn in his Ph.D. dissertation.
- In the economic analysis, one of the simplifying assumptions was that the brake wear would be assumed to be a function only of full brake applications. More studies are required to determine the actual contribution of partial brake applications to brake wear.
- Maintenance costs for both braking systems should be investigated and included in the life cycle cost analysis instead of merely disposing of the braking system when its critical limiting component wears out.
- Training the drivers, managers, and maintenance personnel (labor costs) on the disc brake's capabilities and use should be quantified and included in the life cycle cost analysis.
- Future researchers should investigate the performance and range of cost-effectiveness of a hybrid braking system that combines both drum and disc brakes to compare to the analysis conducted in this paper.

- Relative expenses associated with realigning brake pad and brake shoe out-of-adjustment scenarios associated with the overall assembly being installed incorrectly or getting jarred out of proper position due to aggressive riding, accidents, or crashes should be included in the cost analysis.

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Data availability

Some or all data and models that support the findings of this study are available from the corresponding author upon reasonable request

Author contributions

The authors confirm their contribution to the paper: Study conception and design: K. Ksaibati, Vincent Ampadu; TruckSim Modelling and Simulation: Anas Alrejjal; Analysis and interpretation of results: Vincent Ampadu, K. Ksaibati; Draft manuscript preparation: Vincent Ampadu, K. Ksaibati. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Interest statement

The authors report no potential conflict of interest.

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