A “Brake Free” Descent

Modeling Safe Descents for Large Trucks on Steep Slopes

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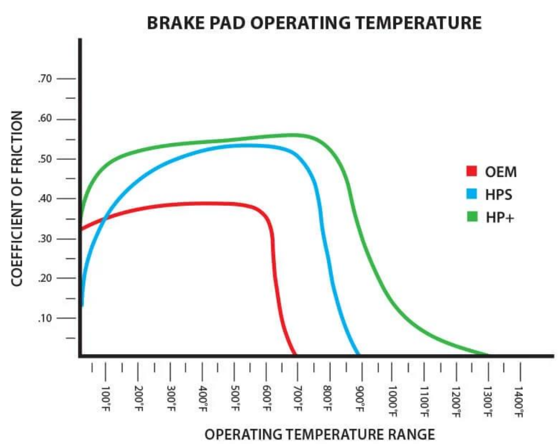
Introduction

A common point of failure for Class-8 vehicles occurs on long descents, often along mountainous roadways. During a descent, engaged service brakes convert the truck’s kinetic energy into heat. As service brakes are applied, they heat up. As the brake temperatures exceed 500°F they reach a point where the braking friction ‘fails’ and there is no braking power. In some cases, the brake drums/pads/discs expand and lose effectiveness, contributing to brake fade. When brake fade occurs, trucks can and do, accelerate out of control. Engine braking is shown to play a critical role in safely increasing descent speeds without increasing reliance on service braking and the accompanying risk of brake fade.

The safest solution and one supported by large truck OEMs as well as CDL training manuals is to transit steep descents using only gear selection and engine braking so that the service brakes remain at or near full braking capability (near cold brakes) should an emergency braking situation occur. The manuals do state that the driver should not use any higher gear for the descent than he used for the climb and preferably 1 gear lower. This recommendation is only valid if the driver has actually ‘gone up the hill’ in recent memory.



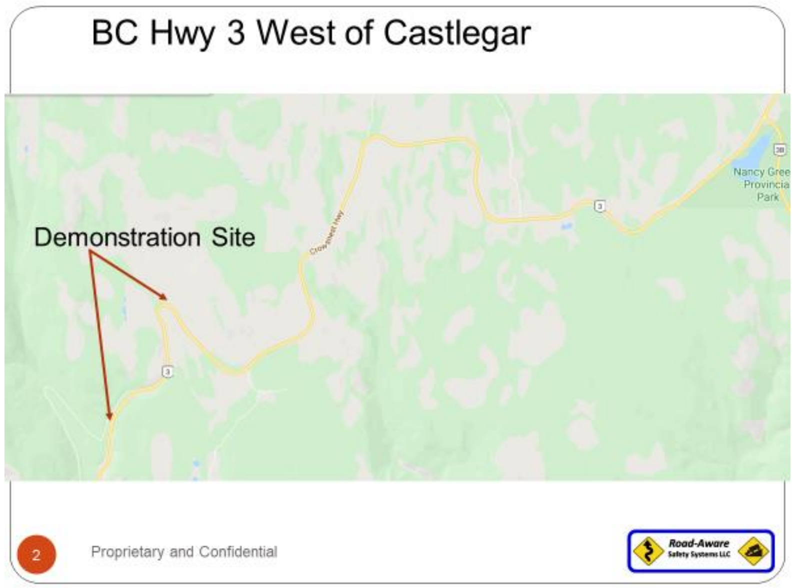
Hawke Brakes

Other than these general recommendations there is nothing that provides the driver with a recommended safe descent speed based on the tractor-trailer specification, load type and weight, engine braking, number of braking axles plus, slope % and distance.

A Long Steep Slope

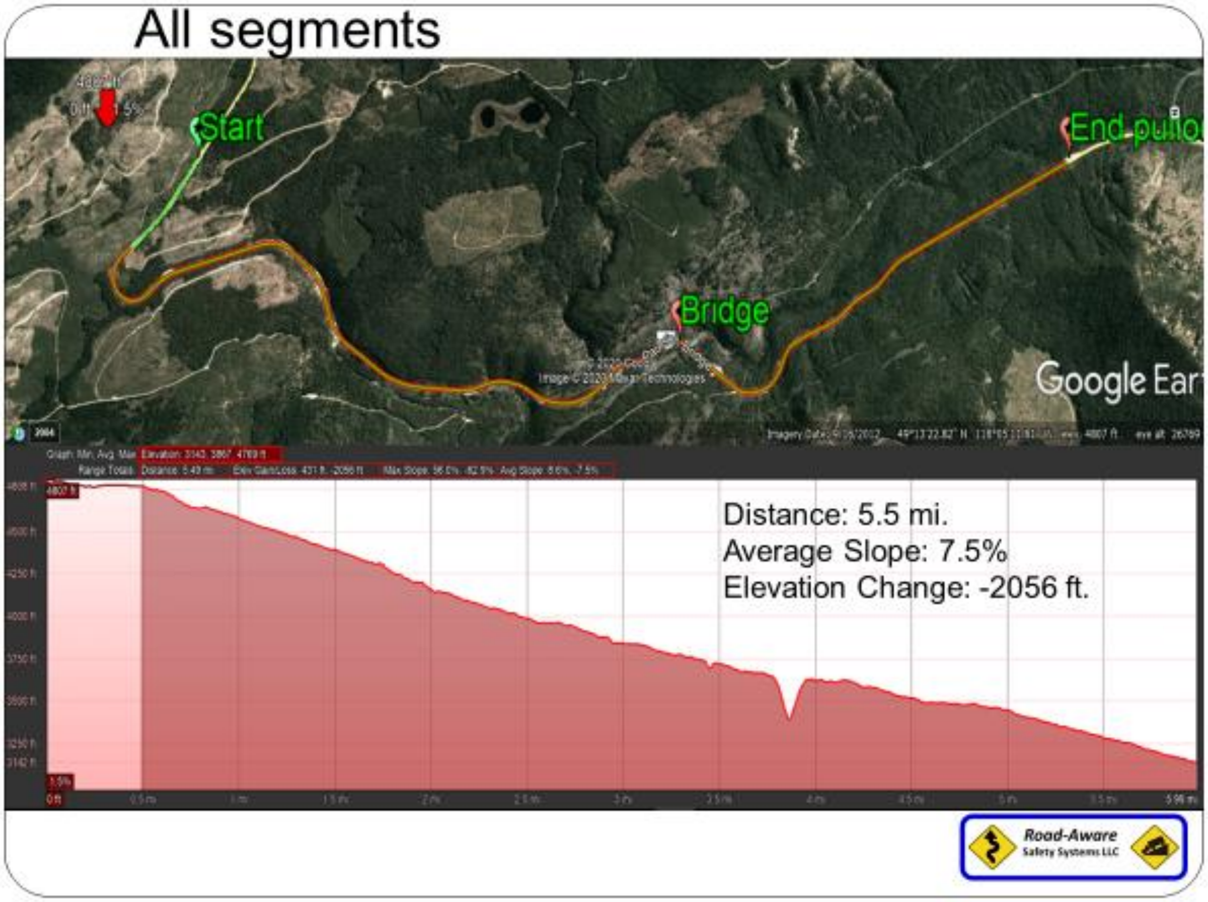
A demonstration was designed to show that a fully loaded semi could descend a long steep slope using only gear selection and engine braking. In addition, a braking model was applied to the slope and three configurations of tractor-trailers to show the potential impact of speed and use of service brakes on brake temperatures and braking distances.

The slope chosen is on British Columbia Highway 3 also known as The Crowsnest Highway. The slope started at a west bound pullout about 20.5 mi/33kms west of the junction of BC Hwy 3 and BC Hwy 3B. The road is downhill, over the Paulson railway bridge to another pullout about 5.5 miles (8.5 kms) west from the start point.



Start point: 49°09'50.6"N 118°06'01.1"W   End Point: 49°13'23.2"N 118°05'12.9"W

The elevation change between the start point and the end pullout is about -2056 ft (-617 m) with a 7.1% slope (simple rise over run) between the start and end points. Google Earth provides a slightly different approach to slope calculation and gives a 7.5% slope between the same points.



This slope can also be broken into 6 separate legs, each with a 'local' slope contributing to the overall slope of the run.

	Length mi / km	Slope %	Elevation Change ft / m
All Legs	5.5 / 8.5	7.5	-2056 / -617
Leg 1	0.3 / 0.5	8.2	-132 /-40
Leg 2	2.1 / 3.2	7.7	-831 / -249
Leg 3	0.65 / 1.0	7.2	-235 / -71
Leg 4	0.24 / 1.4	4.8	-57 / -17
Leg 5	0.78 / 1.2	5.3	-188 / -56
Leg 6	0.96 / 1.5	6.0	-309 / -93

Driving the Slope

"The point of the exercise was to use no service brake at all, and we accomplished that."

In early March 2020 Jim Park, Equipment Editor for Heavy Duty Trucking magazine and Professional Driver Trainer, Andy Roberts, Mountain Transport Institute in Castlegar, British Columbia, set out to drive down a long, steep slope while not using the truck's service brakes at all.

Mountain Transport Institute Ltd. is situated in the best terrain to build mountain driving skills. Castlegar is located within one hour of 4 different mountain passes. MTI mountain driver training provides a weeklong immersion into the intricacies of handling heavily loaded trucks in the mountains and is offered with loaded tridem trailers or loaded super "B" trailers. "In our opinion the correct way to descend steep grades and any hill for that matter is to select the correct gear and proceed down the hill without the use of the vehicles service brake system" MTI.

Students are taught proper procedures for ascending and descending long mountain grades. Instruction includes methods to complete difficult downhill downshifts when the wrong gear has been selected for descending a grade, as well as methods for identifying sharp curves ahead of time and proper procedures for dealing with them.

Making the descent "brake free "without using (or using minimally) service brakes, pick a gear and stay there, using the engine brake (compression release brake, Jacobs Brake, Jake Brake) to manage descent speed provided a unique data set not commonly available.

Three runs were made down the slope in two different power units, one with a manual transmission the other with automatic transmission and two different trailers with different load weights. The first run was with the Volvo tractor hauling a loaded tandem (two-axle) trailer providing a GVW (Gross Vehicle Weight) of 80,000 lb / 36,287 kg. For the Volvo's second run, the tandem trailer was swapped for a loaded three-axle trailer that provided a GVW of 102,500 lb / 46,493 kg. See chart below.

Drivers	Jim Park	Andy Roberts	Braking Axles
Tractors			
Volvo[1] Automatic Transmission	X		3
Freightliner[2] Manual Transmission		X	3
Trailers			
Tandem Trailer 80,000 lb / 36,287 kg	X		2
Three-axle Trailer[3] 102,500 lb / 46,493 kg	X	X	3

[1]Volvo D13 (500 hp/1850 lb-ft) with 12-speed <u>automatic,</u> iShift transmission. Engine Brake Rating 500 hp @ 2200, 350 hp @ 1500 rpm.

[2]Freightliner DD15 (560 hp/1850 lb-ft) with an 18-speed <u>manual</u> transmission.

[3] This trailer was a four-axle unit, but the rearmost axle was up and not used so only 3 braking axles on this trailer were available during the demonstration.

Volto Tractor Trailer unit

Freightliner Tractor

Volvo Tractor and Quad Axle Trailer showing 4th axle raised

Drivers descended safely in all three runs using only proper gear selection, full use of engine braking and, minor applications of the service brakes, to maintain a +/-1900 rpm for engine safety. In general, the units were able to maintain a 30 mph (50 kph) descent speed in all three runs.

Each run was video recorded, with the driver providing comments and observations during the descent.

Comments from Run 1-1 video by Jim Park, Volvo Tractor and Tandem Trailer GVW 80,000 lbs.

2:12	this fools people, the sign says 7% (a posted highway sign) but it's not immediately 7% a bit slow to start with
2:54	in 6th gear can toggle between 2 (Medium) and 3 (High) on engine brake, full range in the gears 30 km/h
4:16	too low gear, give her another one up to 7th with EB 3 (jake high)
5:25	upshift to 8th, EB 3 50 km/h
6:34	engine brake high rpm not burning any fuel at all
7:17	8th gear EB 2 nice and stable.
9:00	stop for the bridge, brakes cold, could have had to slow down for slower traffic
10:00	6% grade off the bridge, crept up to too high a gear, had to downshift, brakes cold, easy to recover

11:15	8th gear, coasting, starting to get steeper
12:30	upshift to 9th EB 3
12:50	should always be in the highest possible gear with the engine brake in 2 or 3
	Note: Run 1-1 ended 5 minutes past 12:50 and the End Pullout.
14:45	11th coasting 80 km
15:15	start downshifting to 8th, 30 km corner coming up
17:50	slick little downshift
20:30	read the road and consider weight distribution and tire condition for traction

Comments from Run 2-1 video by Jim Park, Volvo Tractor and Tri-axle Trailer GVW 102,500 lbs.

1:15	7^{th} gear EB 1, flat part of the hill
1:40	EB 2 1400 rpm
2:20	EB 2 1700 rpm 40 kph
2:45	EB 3 decelerating, will be good for the steeper part of the hill
3:05	can toggle between EB 2 and 3 1900 rpm 45 km
3:30	EB 3, on the steeper section 1900 with slight deceleration
4:00	2000 rpm, not quite 50 kph
4:15	2100 rpm but holding, if it does push beyond that a quick brake application would not be a big deal
4:30	light brake application brough time back below 2000 rpm, can feel the extra weight
6:15	steep segment is 8%
6:45	made three light brake applications to keep it under 2200 rpm
7:15	Construction zone ahead, could be sweating now if you had to stop
9:00	stop for the bridge
11:30	7th gear EB 1 maybe a little slow for this section, EB off to see how fast it picks up speed.
12:15	What went wrong last time? Thought it was flat enough, but it got steep sooner than expected
13:30	7th gear the advertised grade is slightly less than we're on. Sign says 6%.
14:00	40 km 1750 7th gear
14:30	How fast should I be going, road's flat, but there are curves or truck traveling slower than we are or a crash or rockslide.
15:15	You need to keep your brakes always cool enough to be able to come to a full stop immediately.

Comments from Run 4-1 video by Andy Roberts, Freightliner Tractor and Tri-axle Trailer GVW 102,500 lbs.

0:46	calculating the right gear, based on the Volvo comparing 12-speed to 18-speed
1:35	starting in 5th gear direct
2:15	rpm 2000, EB on 2 switch up to EB 3 45km
3:07	1800 rpm and coming up on the steep part, jake is pulling us down but maybe not enough
3:40	we have a few rpm to play with but the needle is climbing a little quicker
4:00	40 kph 1800 rpm
4:30	2050 rpm 50 kph
4:44	quick brake application to get it down below 2000 rpm

6:10	grade flattened out a little, knocked it back to EB 2 1700 rpm
7:50	turn on the engine fan, 75 hp of draw there, might have done that rather than the brake application
9:30	wait for red light at the bridge
12:00	6th gear, level off the bridge, not as steep
13:55	here we go, 6% versus 8% on the steeper part, and we have gone up a full gear. (6th)
14:00	probably too much, should have given it a half-gear 5th od)
14:30	55 kph, 1750 rpm EB 3
14:52	1900 rpm turn on the fan, rpm drops slightly, just enough to prevent the up shift.

Braking Models by RoadAware Safety Systems

RoadAware Safety Systems developed software that uses algorithms to examine segments of road and calculate safe speeds for tight corners and steep descents. These calculations are tailored to each power unit (Class-8), trailer type and load based on the user's input before starting a route. The descent physics model examines the force of gravity, rolling resistance, aerodynamic drag, internal resistances, engine braking, and service braking to determine the amount of braking power that must be supplied by the service brakes to maintain a constant speed during descents. The braking power and vehicle speed are then used to calculate the temperature of brakes, the accompanying effective braking capacity, and braking distance of the vehicle. The model operates on the assumption that the tractor-trailer maintains a constant speed during each leg of the descent (typically 0.5-3.0 mi/0.3-4.5 km segments). It is also assumed that the brake load is evenly distributed amongst all drums/rotors. An Excel model utilizes these equations to generate the maximum speed at which the vehicle, under certain conditions, could navigate a given descent within the thresholds of 'safe' driving. The model does not take into account the transmission gear selection or the RPM limitations of the engine, which the driver will choose based on their experience and company policies.

The descent model also highlights the advantages of coupling advanced 3D mapping with vehicle engineering algorithms.

This descent strategy shifts the focus away from stopping distance and places it on minimizing service brake usage during a descent by effectively utilizing the engine braking capabilities of the tractor. In this way, the speed at which the engine brake can provide enough braking power so that the service brakes maintain >80% of their effective braking capability throughout the descent are calculated. As the semi moves down slope, the model behaves like a continuous piecewise function where the final values of the previous leg define the initial conditions of the following leg.

In the models below, a brake capacity is calculated for speeds of 20, 25, 30, 35 and 40 mph down the 6 Legs of the slope. Each Leg is calculated based on its slope and length of the Leg. In addition, engine braking settings are applied to the target speed.

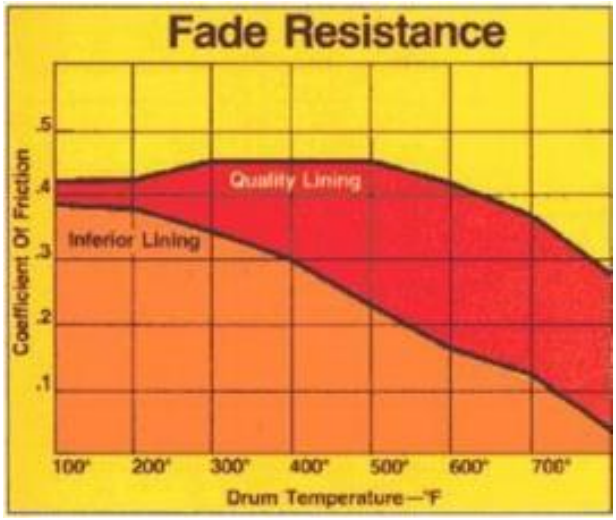
Brake Temperatures

Perhaps the most complicated aspect of the descent model is predicting the heat transfer coefficient from the brakes to the environment. Brake temperature calculations include the initial temperature, the ambient conditions, the material properties and volume of the brakes, braking power, heat dissipation, and time. Two other pieces are needed to complete the brake temperature equation: estimates of brake properties (density, surface cooling area, specific heat, and volume), and heat transfer coefficients.

Braking Capacity

Brake effectiveness is directly tied to the coefficient of friction between the brake pads and rotor, or brake lining and drum. There is limited publicly available information quantifying the relationship between the coefficient of friction and brake temperature aside from that published by manufacturers of racing grade brake systems

Coefficient of Friction vs Drum temperature



Examining the chart, the coefficient of friction can be represented by a system of equations so that the calculated temperature of the brake drum can be determined. In establishing the full braking potential, the system can be modified to return an effective **braking capacity**, expressed as a percentage of the maximum braking potential. By substituting the brake temperature at the end of each leg, the remaining braking capabilities of the tractor-trailer can be determined and used in conjunction with the maximum possible braking force, to determine the vehicle's available braking force and estimated stopping distance once the remaining braking force is applied. Note that the effective braking capacity is different for the front and rear brakes. This causes the tractor to maintain a meager amount of braking power in the two front brakes, even after all other brakes have burned out.

Braking Distance

The U.S. Department of Traffic published helpful data regarding the stopping distances of a tractor-trailer applying the maximum braking capabilities of the vehicle. In this study, a 42,840 lb tractor-trailer equipped with 6 brakes stopped from 60 mph with an average deceleration a=19.6 ft s^{-2}. It can be determined that each brake exerted a stopping force of 139,944 lb_f. The 139,944 lb_f of braking force is assumed reasonable and accurate.

The American Association of State Highway and Transportation Officials (AASHTO) regularly publishes a handbook regulating aspects of road and highway design. The equation used to determine the stopping distance of a vehicle once brakes are applied, is the stopping force divided by vehicle mass yielding the effective braking capacity This is included as a variable determining the stopping distance of the tractor-trailer.

Modeling BC Highway 3 Descent

In the models below, front and rear brake temperature, brake capacity and braking distance are calculated for downhill speeds of 20 (32 kph), 25 (40 kph), 30 (48 kph), 35 (56 kph) and 40 (64 kph) mph down the 6 Legs of the slope. Each Leg is calculated based on its % slope and length of the Leg. In addition, generic High, Medium, and Low engine braking settings are applied to the target speed.

Engine Specifications:	
Engine Brake Power (hp)	
Off	32
Low	180
Med	285
High	390
MX11 values used	

A 100% Brake Capacity indicates that at the given descent speed and engine brake setting, the unit can make the descent with no further braking support. In the braking models for each of the 80k and 102.5k GVWs, the use of the Low EB setting cannot maintain a 20 mph descent speed. The 20 mph Brake Capacity chart shows the 80k unit ending the run at 76% capacity and 47% for the 102.5k unit indicating that use of the service brake is required to maintain the descent speed, in addition to the engine brake at the Low setting. The impact is seen in the increase in front and rear brake temperatures to over 300°F.

The model shows that as Brake Capacity decreases, Braking Distance does not necessarily increase, but Brake Temperatures do increase. Brake temperatures over 500°F result in loss of brake friction (brake fade) and increase in possible brake or tire fire.

In the 80k GVW unit at 30 mph with Engine Brake setting at Med, the Brake Capacity is above 75% and Braking Distance near 150ft but, the trailer brakes are starting to heat up as the service brakes are needed to keep speed. At 30 mph the Braking Capacity is above 75% but the brakes continue heating. At 40 mph Brake Capacity is below 70%, the Braking Distance is near 200ft and Brake Temperature is pushing 500°F. At 40 mph with the High Engine Brake setting, the Braking Distance is reduced, and Brake Temperatures drop.

At the 102.5k GVW the charts show that at 30 mph at the High EB setting, Brake Capacity decreases to near 75% as the model requires service brake application to maintain the descent speed. Both drivers commented on the need for service brake or engine fan application to reduce engine rpm below 2000.

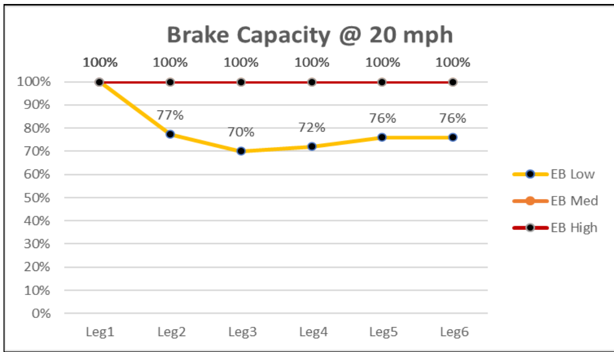
Summary

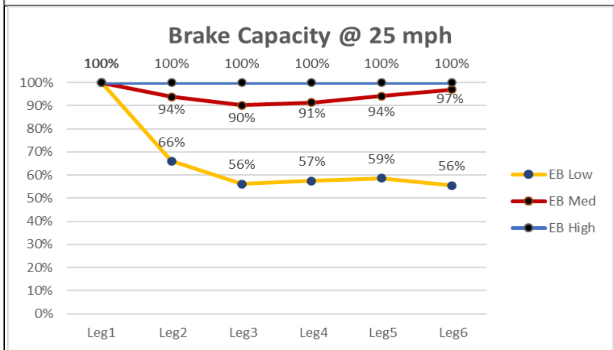
The RoadAware Braking Model and actual driver experience match well. The model shows that the 80k GVW unit at 30 mph/50 kph a driver can descend the hill using only the engine brake and have 100% Brake Capacity in EB High and over 75% Brake Capacity using the EB Medium setting. The drivers showed that this descent could be easily accomplished “brake free” using only a little of the Braking Capacity and creating a safe descent profile.

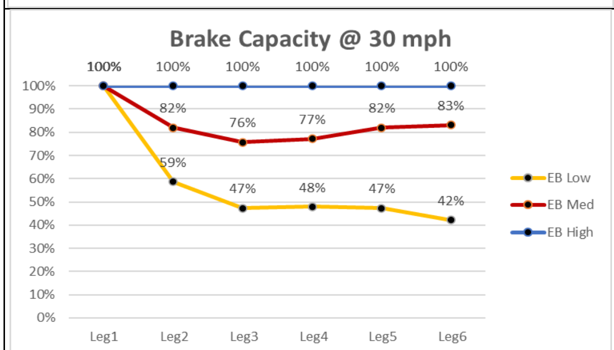
With the heavier 102.5k GVW unit at 30 mph/50 kph, the drivers had more difficulty maintaining a safe engine speed of 1900 rpm without additional speed adjustments via the service brakes. While the drivers were able to successfully negotiate the descent at 30 mph, a 25 mph descent speed may be a safer “brake free” target.

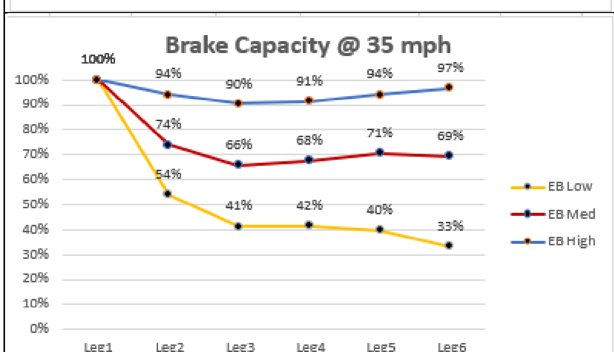
The model shows that drivers can unknowingly impact brake temperatures and increase braking distances by increasing descent speeds by as little as 5 mph (8 kph). The Braking Model shows that at 30 mph, engine braking itself would have difficulty maintaining speed and a 90% plus Brake Capacity. At the end of the run, +75% Brake Capacity in EB High and +50% Brake Capacity in EB Medium remained. The EB Medium Front Brake Temperature is calculated to be +400 °F and Rear Brake Temperature of +500 °F resulting in a Braking Distance of nearly 200 ft. While this descent was made “safely”, additional requirements for braking without given time for the brakes to cool, may put the rig in jeopardy.

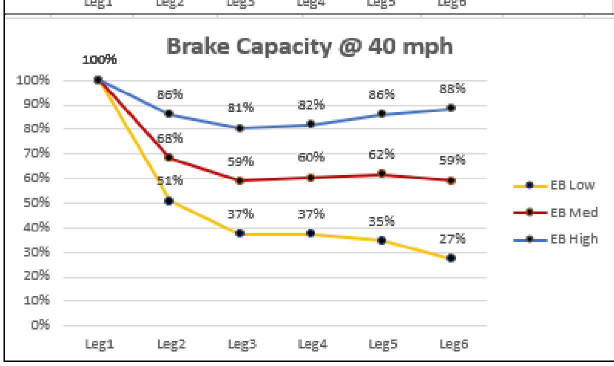
Brake Capacity Model for **80,000 GVW with 5 axles**: 3 front 2 rear, 2 brakes each axle.



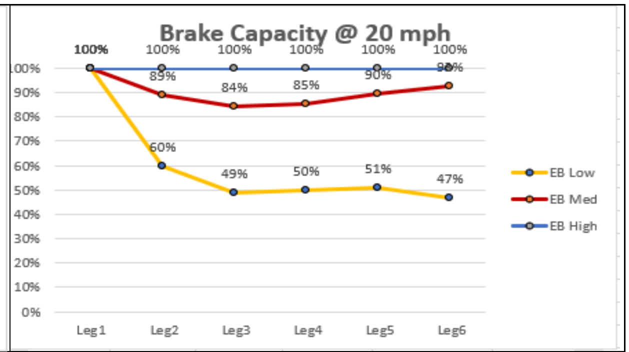


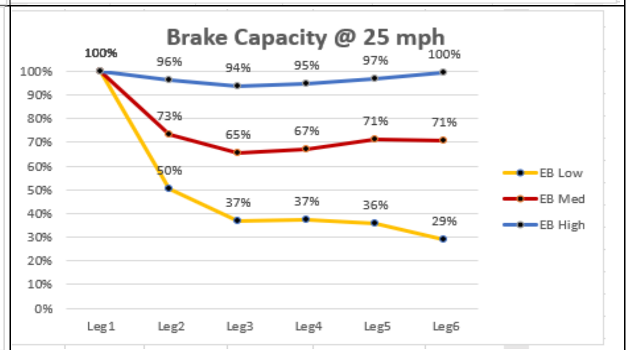


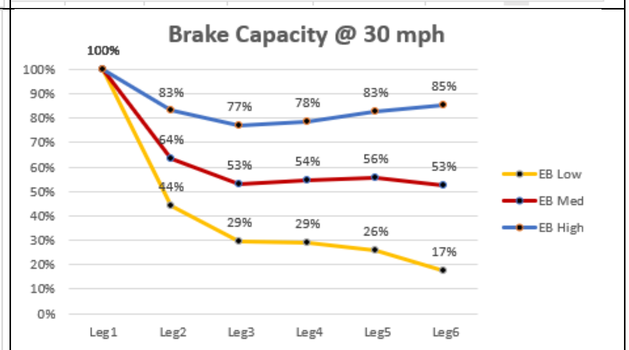


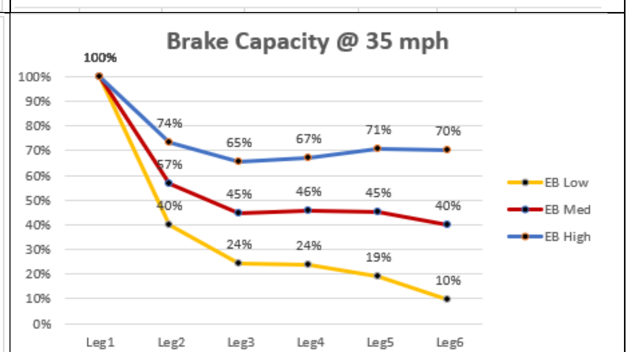


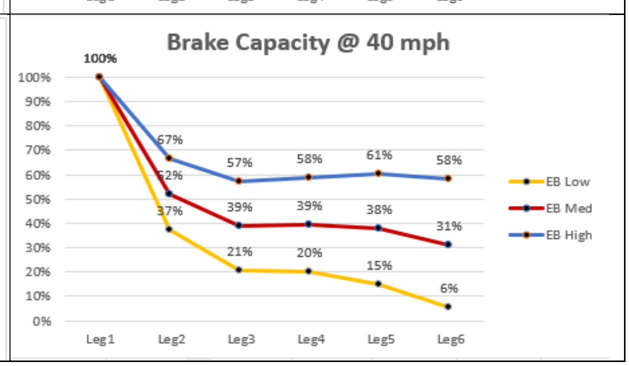
Brake Capacity Model for **102,500 GVW with 6 axles**: 3 front 3 rear, 2 brakes each axle.



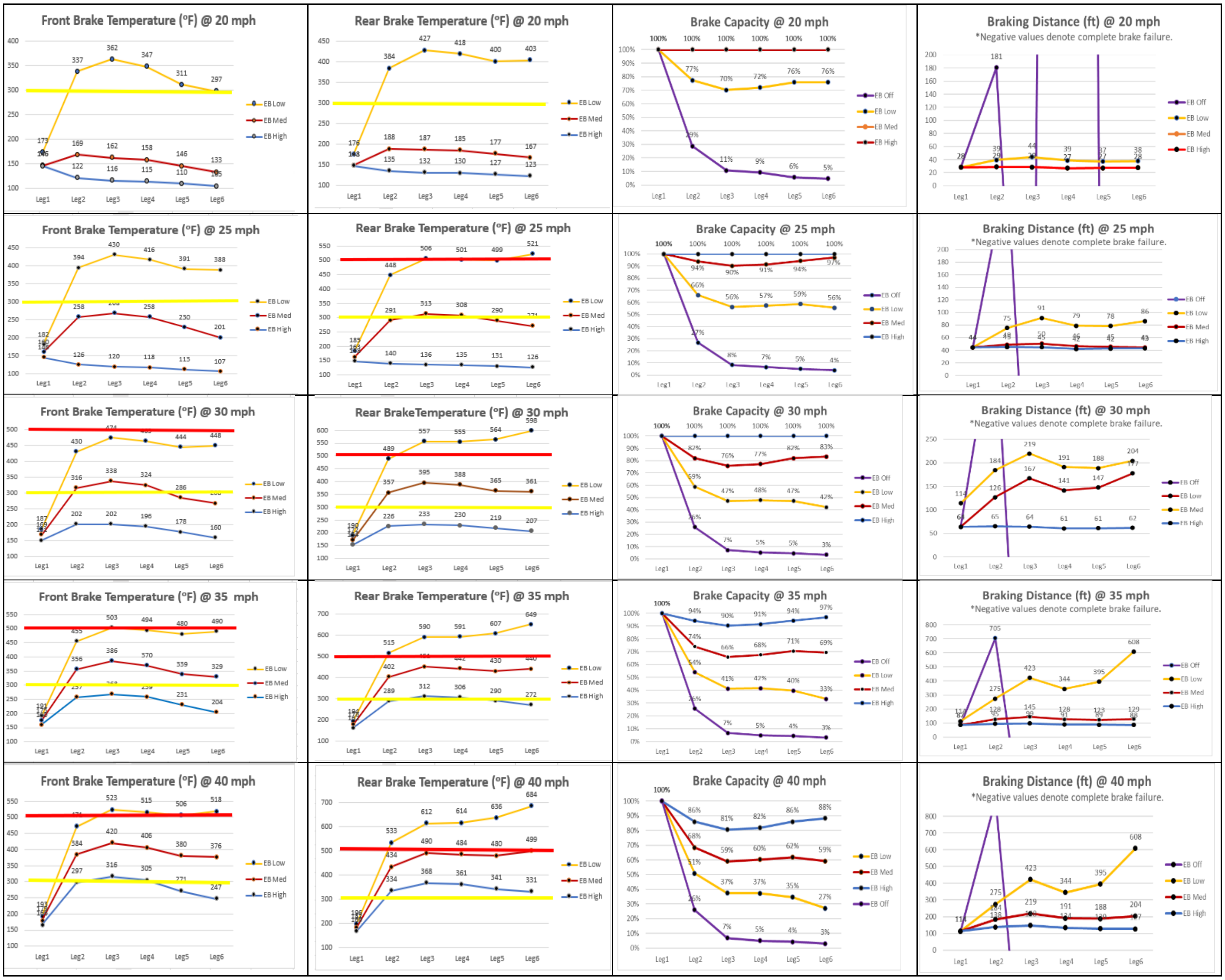








Braking Model for 80,000 GVW with 5 axles: 3 front 2 rear, 2 brakes each axle.



Scenario Conditions:		Brake Material Properties:		Engine Specifications:	
m, GVW (lb)	102500	c_R (Btu/lbF)	0.117	Engine Brake Power (hp)	
T_∞ (F)	85	V_R (ft^3)	0.28	Off	32
T_0 (F)	150	A_R (ft^2)	3.5	Low	180
Speed Limit (mph)	65	ρ_R (lb/ft^3)	441	Med	285
ρ_{air}(slug/ft^3)	0.0023769	ε_R	0.55	High	390
		# of brakes	12	MX11 values used	

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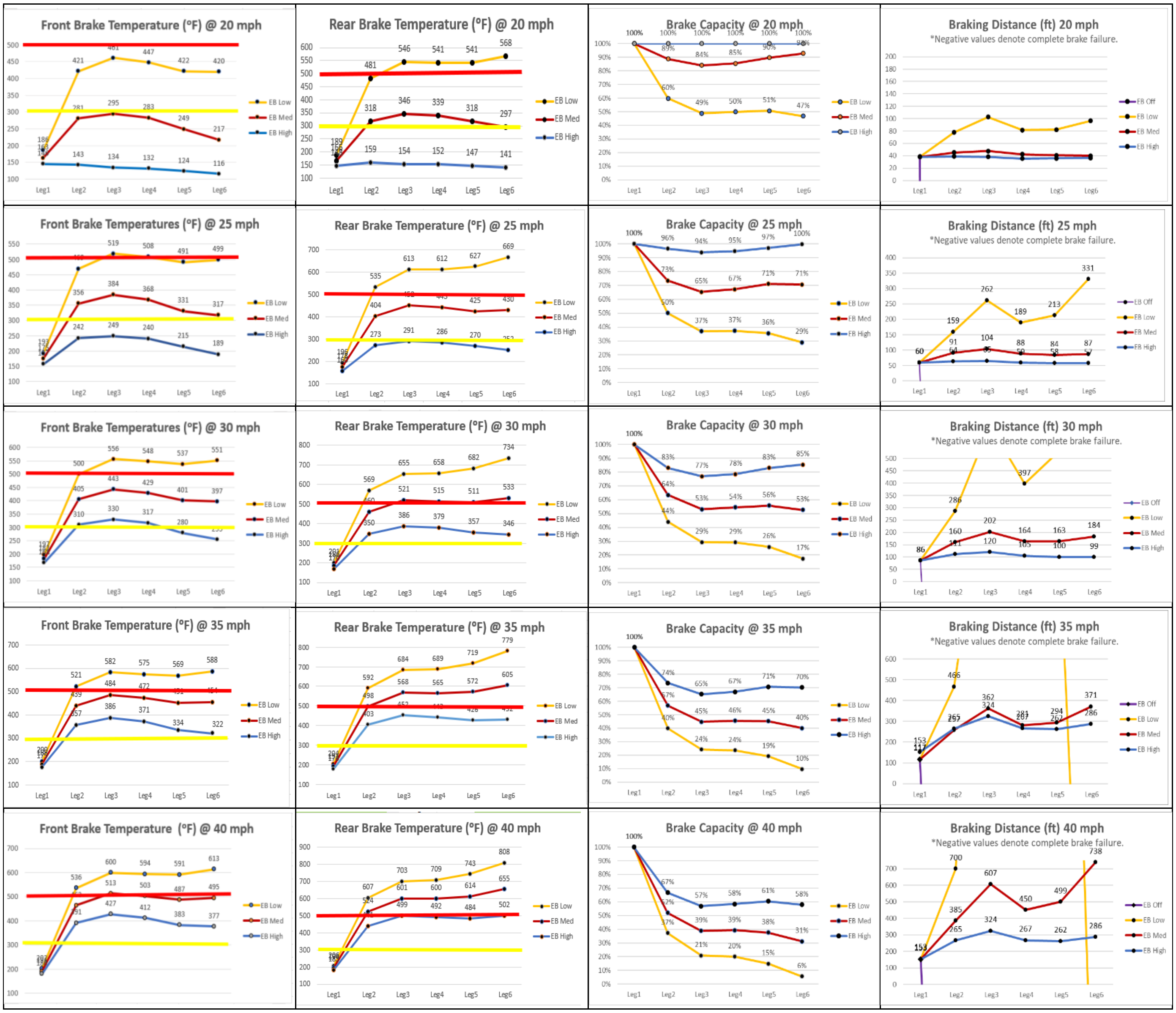

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