Advantage

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Contents

Development of guidelines for descending steep grades: British Columbia coastal off-highway truck applications

Abstract

The increase in forest road grades on the coast of British Columbia has led to hauling safety concerns. To investigate this issue and to develop guidelines for hauling on these steep grades, the Forest Engineering Research Institute of Canada (FERIC) installed instrumentation on a coastal off-highway truck to measure braking energy requirements during typical steep grade descents. FERIC used the data to develop a computer model for predicting brake performance for steep grade descents and to develop descent guidelines for several operating conditions.

Keywords

Forest roads, Gradients, Logging trucks, Haul operations, Safety, Models and simulation, British Columbia.

Author

Séamus P.S. Parker, Western Division

Introduction

Forest road grades on the coast of British Columbia have been increasing in recent years. This trend is primarily a result of roads being built on ridges and stable benches whenever possible to avoid sensitive unstable slopes. Steeper roads also allow for reduced road requirements when accessing mountainous terrain, which reduces the environmental impact in terms of site occupancy and contributes to reduced road construction costs. In addition, increased engine retardation capabilities have enabled steeper road grades to be safely descended. Road grades often exceed 20% and in some cases 25%—levels that can seriously impact hauling safety.

The increased prevalence of steep road sections has raised safety concerns for WorkSafeBC (Workers' Compensation Board of British Columbia). In many instances, it has prohibited hauling on steep pitches until corrective action could be taken to address the safety concern, through either road modification or the drafting of safe operating procedures. In these situations, FERIC has often been approached by WorkSafeBC and the forest industry to assist in developing the descent procedures.

Safe descent of steep forest roads depends on many factors, including braking capacity, brake adjustment, brake thermal characteristics, road surface traction, descent speed, hauling configuration, payload, grade, grade length, and horizontal road alignment. These factors, while generally understood, require further study and quantification to sufficiently address safety concerns when descending steep forest roads. Therefore, FERIC, WorkSafeBC, and several major forest companies agreed to develop descent guidelines for a variety of situations. In 2003, a steering committee was formed to direct research in this area, with the primary objective of developing guidelines for descending steep forest roads.

In September 2003, a runaway crash occurred on a steep forest road (26% grade) with an off-highway "fat"[1] truck (Figure 1), which resulted in a fatality. In September 2005, WorkSafeBC issued an official guideline that separated the hauling requirements into two categories: grades less than 18% and grades greater than 18%.[2] This separation was based on the assumption that reasonably maintained equipment is designed for grades up to 18%, which is the maximum allowable grade specified in British Columbia (B.C. Ministry of Forests 2002). On grades above 18%, a risk assessment must be conducted prior to hauling on these grades and a safe descent procedure with specific conditions for haul suspension must be developed.

Typically on road grades less than 18%, most of the retardation is accomplished by engine/driveline retarders. As road grades exceed 18%, the demand on the service brakes is increased, resulting in increased brake temperatures. The service brake (S-cam actuated drum brake) performance deteriorates at elevated temperatures due to drum expansion and a reduction in the friction level of the brake lining. Variability in brake systems (adjustment levels, friction materials, air valves, and plumbing) can result in unbalanced braking which can further increase brake temperatures. Therefore, the service brake temperatures must be minimized to provide sufficient braking capacity in an emergency such as in the event of a driveline failure. To accomplish this, specific driving and truck/road maintenance procedures will be required when descending grades of greater than 18%. In addition, it may be necessary to develop specific road design standards for steep grades so that sufficient relief is provided between steep road sections to allow time for adequate cooling of the service brakes.

Figure 1. Loaded off-highway "fat" truck configuration.

The 2003 fatality and the ensuing WorkSafeBC guideline and enforcement focused FERIC's research on developing guidelines that could be used to assist the forest industry when conducting risk assessments on grades greater than 18%. The guidelines presented in this report are intended for coastal "fat" trucks which carry significantly higher payloads than highway trucks hauling off-highway loads. Descent guidelines for highway trucks will be developed in the future.

Objectives

- Evaluate brake retardation power of coastal "fat" trucks under typical operating conditions.
- Determine the key parameters influencing the safe descent of steep grades and evaluate the sensitivity of these parameters.
- Develop specific guidelines for descending steep grades for coastal "fat" trucks, which can be used when conducting risk assessments.

1 "Fat" refers to the width of the truck. These trucks are designed exclusively for off-highway applications and are typically equipped with 3.34 m wide axles (compared with 2.59 m axles for highway legal trucks).

2 G26.2-2 from OHS Guidelines Part 26 – Forestry Operations, WorkSafe BC (Workers' Compensation Board of British Columbia).

Forest Engineering Research Institute of Canada (FERIC)

Find us Online! www.feric.ca

Eastern Division and Head Office
580 boul. St-Jean
Pointe-Claire, QC, H9R 3J9

(514) 694-1140
(514) 694-4351
admin@mtl.feric.ca

Western Division
2601 East Mall
Vancouver, BC, V6T 1Z4

(604) 228-1555
(604) 228-0999
admin@vcr.feric.ca

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Methodology

Evaluation of retardation levels

In the fall of 2004, FERIC installed instrumentation to measure retardation levels on a Pacific P-16 5-axle off-highway log hauling configuration operating at Hayes Forest Services Limited's Franklin River Division (located near Port Alberni, B.C.). Retardation, vehicle speed, road grade, and individual brake lining temperature were measured for 35 descents. Prior to each descent, the brake adjustment levels were measured and adjusted if necessary. Brake retardation power was estimated for three components: driveline, service brakes, and rolling resistance. This information was categorized into low, medium, and high speed classes (<20 km/h, 20–35 km/h, and >35 km/h, respectively) to identify trends. This exercise identified that descents involving pitches of greater than 18% grades only occurred at speeds of less than 20 km/h.

Descent guidelines and their application

The descent guidelines were prepared through the application of a computer model developed and validated with the test data (Parker 2006). This model was applied to determine the critical operating parameters required to safely descend a range of traction conditions and brake configurations. For each of these operating conditions, the maximum payload and descent speed were determined for a range of descent scenarios under which the trucks can be safely operated. In this analysis for safe operation, the trucks were required to stop within 50 m following a driveline failure. These descent scenarios are characterized by the following parameters:

- Grade (%) of pitch where driveline failure occurs
- Length (m) of pitch
- Distance (km) of descent prior to pitch
- Average grade (%) of descent prior to pitch

The major parameters influencing the descent guidelines and their relative sensitivity were reviewed using the guidelines for a 3 km descent on an 18% grade.

Results and discussion

Evaluation of retardation levels

The 35 descents monitored in this study were summarized into the three speed classes (Table 1). The low-speed class represented the descents on the block access roads on the steeper grades, the medium-speed class represented descents on branch roads, and the high-speed class represented mainline descents. Overall, the average road grades were very low and the descent distances were relatively short. The summarized data illustrated an inverse relationship between descent speed and average grade, with descent speed reduced on steeper road grades. The rolling resistance as a percent of vertical load was reduced on higher-speed descents since these descents typically occur on the permanent compacted roads.

The low-speed descent retardation power components are illustrated in Figure 2. Except for descents 11b and 14a, the total retardation power was between 350 and 500 kW. The service brakes generally accounted for the lowest power absorption in the range of 10 to 20%, whereas the driveline (engine brake and transmission retarders) accounted for the greatest power absorption (35–55%). Rolling resistance also represented a significant power component (30–50%). The highest average total power absorption of 575 kW occurred in descent 11b due to the higher average grade of 10.4% and many extended steep pitches up to 25%. The

Table 1. Descent summary

	Speed class (km/h)		
	<20	20–35	>35
Number of descents	12	12	11
Average distance (km)	2.2	1.2	1.8
Average speed (km/h)	14.6	28.3	44.8
Average road grade (%)	9.7	6.0	3.6
Maximum road grade (%)	27.0	22.0	14.5
Estimated rolling resistance (% of vertical load)	3.0	2.3	1.5

lowest average total power absorption of 261 kW occurred for descent 14a at a relatively low average grade of 6.3%. In both of these descents, the service brake power absorption was higher than for the other low-speed descents. This was due to the steep pitches in descent 11b, and because the engine brake was disengaged in descent 14a to demonstrate the impact of the engine brake and its effect on service brake temperatures.

The relatively low level of power required to retard the truck results from the relatively low average grades over long distances. However, the peak retardation power absorption (Figure 3) can be considerably greater due to steep grade pitches and substantial decelerations observed during testing. The peak retardation power was generally greater than 600 kW, with three instances where the peak power exceeded

Figure 2. Average retardation power breakdown for descent speeds less than 20 km/h.

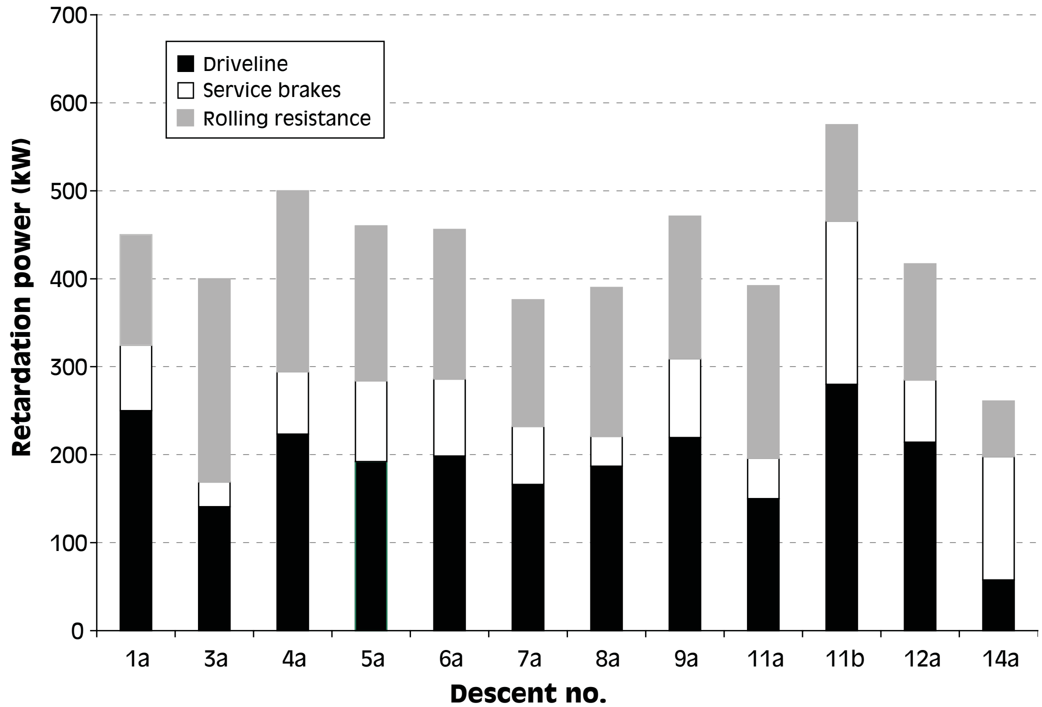
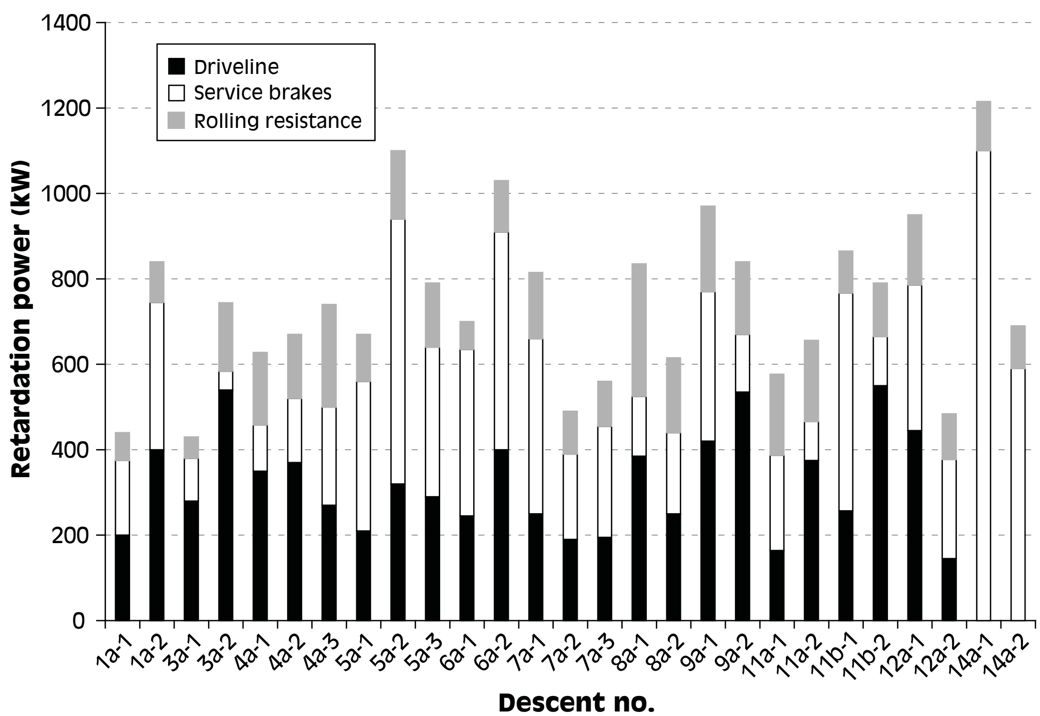


Figure 3. Peak retardation power breakdown for descent speeds less than 20 km/h.



1000 kW. The service brakes absorbed a marked increase in the proportion of the peak retardation power compared to the average descent conditions.

The peak service brake temperatures increased with speed as illustrated in Table 2, as the high-speed descents occurred towards the end of the haul when the brake temperatures had increased with time. The increase in temperatures for the trailer brakes was greater than that for the drive brakes due primarily to the larger air brake chambers present on the front trailer axle. More importantly, during the steep grade descents (at low speeds), the peak service brake temperatures did not exceed 125°C and 205°C for the drive and trailer axles, respectively (Figure 4). The high service brake temperatures for descents 6a and 14a occurred where low levels of water cooling were utilized. The high service brake temperature for descent 11b was due to the steeper average grade.

Similarly, the difference in temperatures within axle groups was greatest for the trailer at the highest speed because of the differently-sized brake chambers between the front and rear trailer axles. Ideally, the brake temperature differential should be less than 30°C for the drive axles and less than 50°C for the trailer axles. However, variations in brake adjustment, lining friction, heat transfer from the lining and drum, shoe and S-cam geometry, and air pressure can result in these observed temperature differences where the individual service brakes do a disproportionate amount of work.

An example of the brake lining temperature throughout the descent is shown in Figure 5 for descent 11b. In this example, one of the front trailer brakes, trailer 1R,[3] does the majority of the work while the rear trailer axles absorb a relatively low level of energy. The drive axle brakes are relatively well-balanced with temperatures within 25°C of each other. Brake temperature has a significant influence on braking capacity. Therefore, service brake temperatures need to be carefully

Table 2. Service brake temperature summary [a]

	Speed class (km/h)		
	<20	20–35	>35
Drive axle temperatures (°C)			
Peak	79–110	86–124	119–147
Differential between brakes	30–47	36–68	63–82
Trailer axle temperatures (°C)			
Peak	69–135	85–129	130–173
Differential between brakes	34–77	54–82	82–115

[a] Ranges represent 95% confidence limits.

[3] Number and letter indicate axle number and whether wheel is on the right or left side.

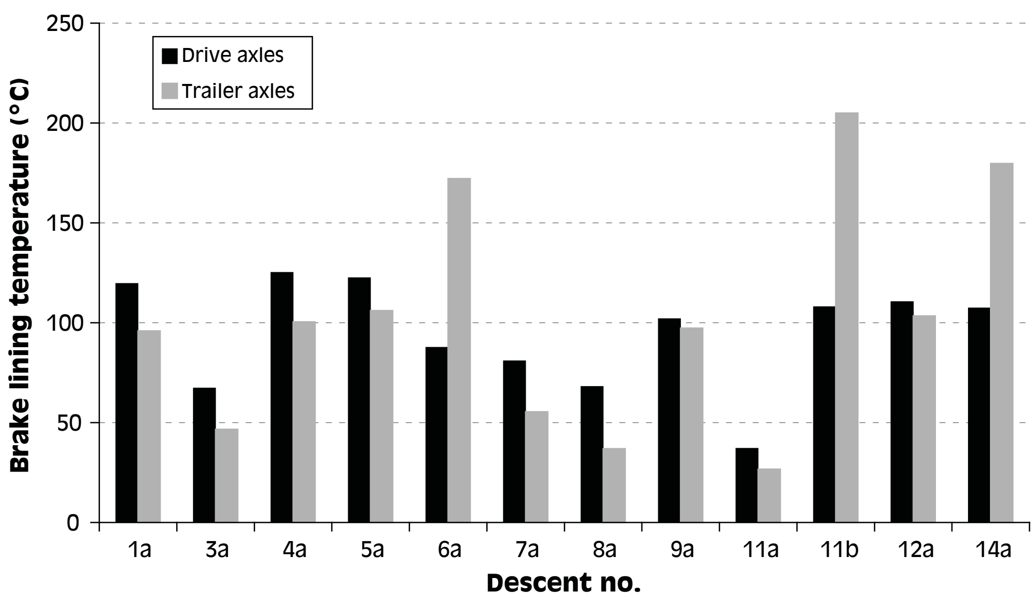


Figure 4. Peak service brake temperatures for descent speeds less than 20 km/h.

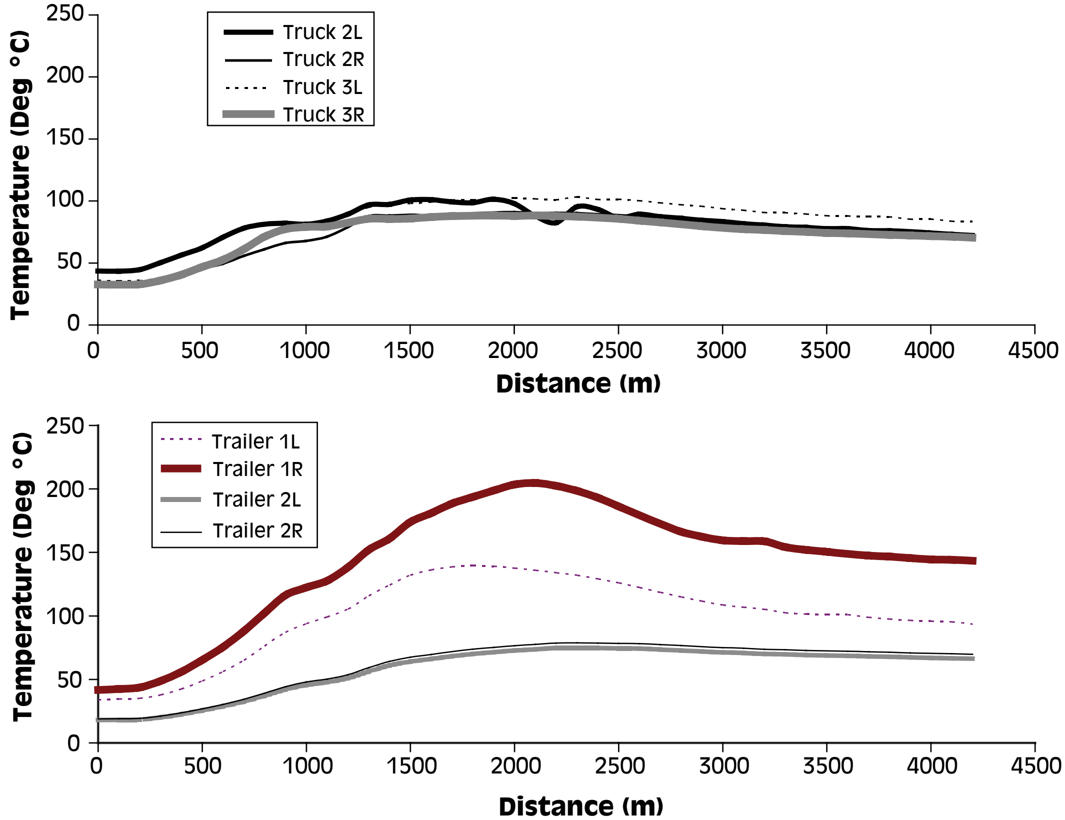


Figure 5. Brake lining temperature profile for descent 11b.

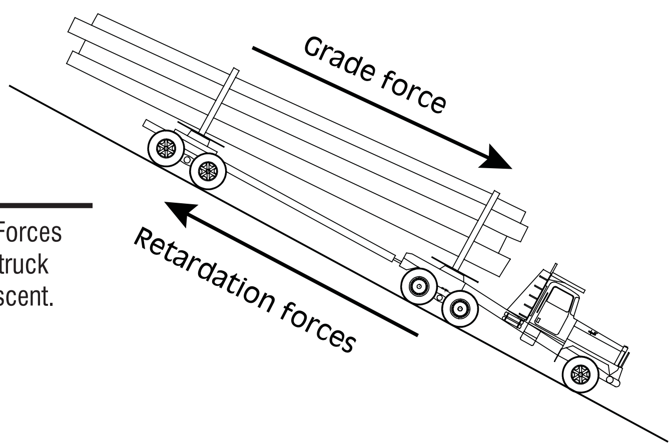


Figure 6. Forces acting on truck during descent.

managed to ensure brake performance is optimized. Brake adjustment and the condition of linings are also important factors influencing brake performance, with a well-adjusted brake having a considerable increase in brake capacity relative to a brake at its adjustment limit. Care should be taken to ensure that all brakes are adjusted to similar levels so that the brakes contribute equally, thereby reducing the chance of brakes overheating and subsequently fading.

Descent guidelines and their application

The physics of steep grade descents

Safe descent of steep grades depends on the careful management of many parameters and their interaction with each other. As a truck descends a grade, the grade force due to gravity propels the truck downwards which can potentially cause the truck to accelerate to unsafe speeds unless the retardation forces generated at the tire/road interface are sufficient to counteract the grade force (Figure 6). When the retardation forces equal the grade force, a steady speed is maintained. In order to stop the truck on this grade, the retardation forces must exceed the grade force and this margin will determine the rate of deceleration. The magnitude of the grade force is directly proportional to the grade and truck mass. At increased grades and loads, an increase in the retardation forces is required to safely descend the grade.

The retardation forces generated at the tire/road interface are dependent on many factors including the individual wheel service brake capacity, driveline retarder capacity, rolling resistance, load distribution, and traction level of the road surface. The traction level (or coefficient of friction) of the road surface limits the retardation force acting at the tire/road interface. The maximum grade that a truck can descend is determined by the brake capacity in combination with the surface traction, as illustrated in Figure 7.

At very low traction levels (snow/ice), the maximum descent grade is limited to 13% when the truck is equipped with only drive and trailer service brakes because above this grade, the truck is unable to develop sufficient braking forces on the road surface to overcome the grade force. Traction levels can be improved on low-friction surfaces through the use of chains, which would extend the operating range under these conditions. However, with "fat" trucks, chains are seldom used because hauling is usually suspended on low-friction surfaces.

At higher traction levels, greater braking forces may be developed to the point that the service brake capacity becomes the limiting factor, allowing the truck to descend grades of up to 30%. The use of steering axle brakes increases the braking force available and allows the maximum descent grades to be further increased. These grade limits must be observed because when there are insufficient retardation forces to counteract the grade force, the truck will accelerate to an unsafe speed and potentially "run away."

The primary source of retardation is generally provided by the driveline retarder, with the service brakes assisting as required. The theoretical power requirements for a "fat" truck loaded with a 100 tonne payload at a descent speed of 10 km/h are illustrated in Figure 8 as a function of road grade. The driveline retarder has sufficient capacity to accomplish all the retardation requirements up to a road grade of approximately 12%. However, in practice, the service brakes are used together with the driveline retarder to provide the necessary retardation. As grades exceed 12%, the service brakes are essential to provide the necessary retardation to maintain the 10 km/h descent speed. The "fat" truck has sufficient heat dissipation properties to absorb up to 200 kW of braking power over a long period, when water cooling is available. This means that in this example, the truck can safely descend grades of up to 17% with water cooling. This maximum sustained grade level is approximately the same as that stipulated in the Forest Road Engineering Guidebook of 18% (B.C. Ministry of Forests 2002). This example demonstrates the importance of developing

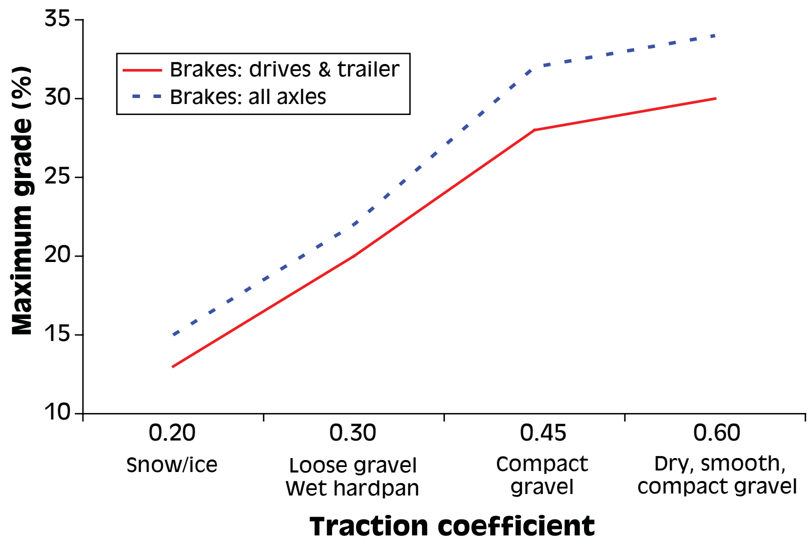


Figure 7. The influence of traction on maximum descent grades.

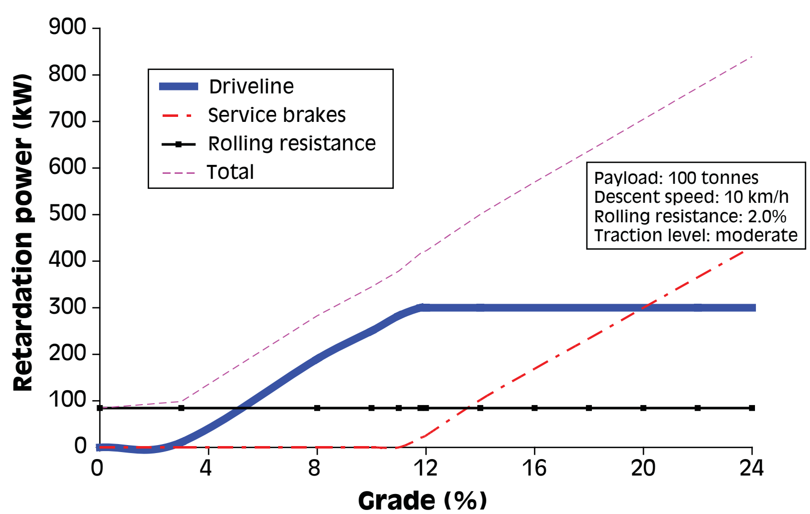


Figure 8. Retardation power distribution versus grade.

descent guidelines, particularly when the grade exceeds this level over long distances.

The measured levels of retardation (Figure 2) are higher than predicted in the theoretical example of Figure 8 due to higher descent speeds measured during testing. These higher speeds (14.6 km/h average compared to 10 km/h) were possible since the average grade was less than 10%. In practice, the service brakes assist retardation even at grades of less than 12%.

Descent guideline overview

Descent guidelines have been developed that recommend maximum speeds (Appendix I) and loads (Appendices II and III) for a range of different conditions. These are the two parameters that can be most easily controlled to influence the service brake duty cycle and thereby manage brake temperatures to ensure good braking performance. Other parameters influencing brake performance are the distance and average grade of the descent prior to the critical pitch, and the length and grade of the critical pitch itself. These parameters are included in the maximum load descent guidelines in Appendices II and III.

The interaction of the many parameters influencing maximum recommended payload are illustrated in Figures 9 to 11 for one descent scenario: a 3 km, 18% grade followed by critical pitch exceeding 18%. As discussed previously, traction level and the use of steering axle brakes has a major influence on payload capacity and the grade that can be safely negotiated. For this descent scenario, on a low-traction surface with brakes on the drive and trailer axles, the maximum pitch that can be safely descended is 20% with a maximum payload of 100 tonnes (Figure 9). On the same low-traction surface, the use of steering axle brakes extends the payload capacity to 115 tonnes on a 20% pitch, and extends the operating range to a 22% pitch.

On moderate traction surfaces, the operating range is extended to pitches up to 28%, particularly when trucks are equipped with steering axle brakes. The length of the

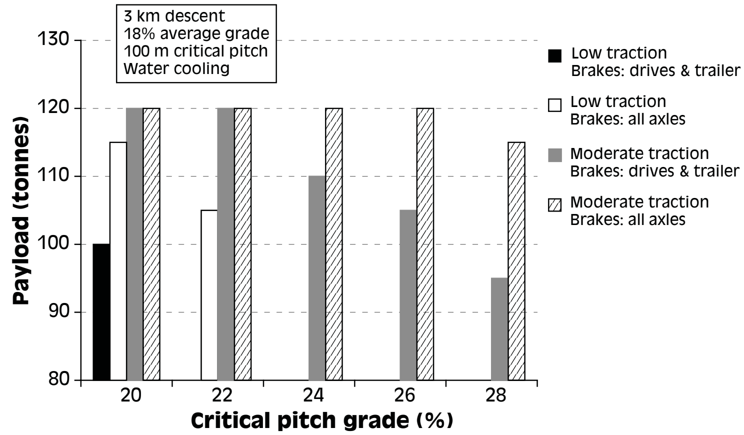


Figure 9. Maximum recommended payloads for a range of conditions (3 km descent on 18% average grade followed by 100 m pitch of steeper grade).

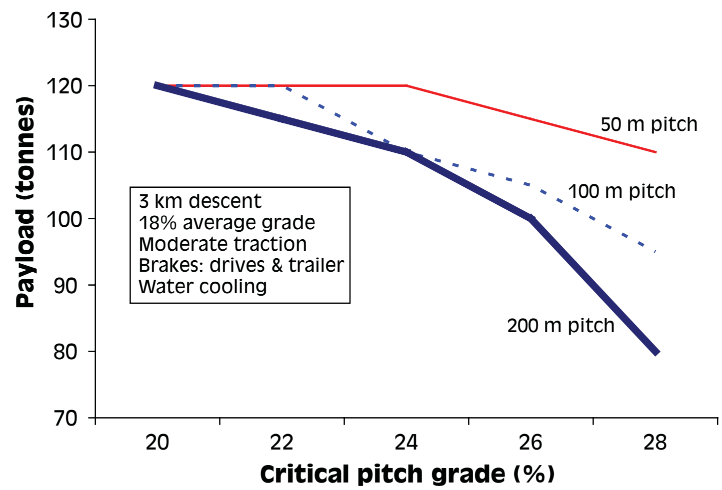


Figure 10. The influence of pitch length on maximum recommended payload (3 km descent on 18% average grade).

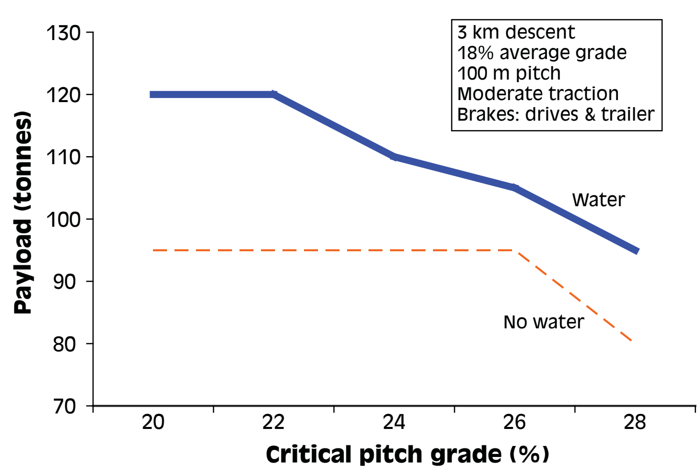


Figure 11. The influence of water cooling on maximum recommended payload (3 km descent on 18% average grade).

pitch also influences payload capacity, with payloads being reduced at increased pitch lengths (Figure 10). The use of water to cool the brake drums during these steep grade descents is important in maximizing payload capacity (Figure 11), and highlights the need to reduce payloads during winter periods when water application is not recommended because this may ice the road at temperatures less than 3°C and reduce traction level.

Sample application of descent guidelines

The application of these guidelines can be best understood by reviewing a sample descent profile (Figure 12) for a typical coastal off-highway "fat" truck equipped with service brakes on the drive and trailer axles and water available for cooling the brakes. The speed and maximum loads are determined separately (Tables 3 and 4, respectively). The speed may be varied throughout the descent, with the sample descent divided into three speed sections (Table 3).

The 10 km/h speed for the road section containing the steep pitches (km 1 to km 2.45) is dictated by the steepest pitch and worst case traction condition. The maximum speeds before and after this section are higher due to the lower grades. To determine the maximum load for this descent, each critical pitch must be evaluated separately. The initial 7% road section is not included in the calculation of the cumulative distance prior to the pitch because the service brake temperatures remain low under these conditions, particularly with water cooling the brakes, and therefore brake performance will not deteriorate. The average grade prior to the pitch is a weighted average.

The tables in Appendices II and III are used to determine the loads for critical pitches 1 and 2, respectively, based on their different traction conditions. The distances and average grades are rounded up to the next highest level in the tables. In the case of critical pitch 1, the distance prior to the pitch

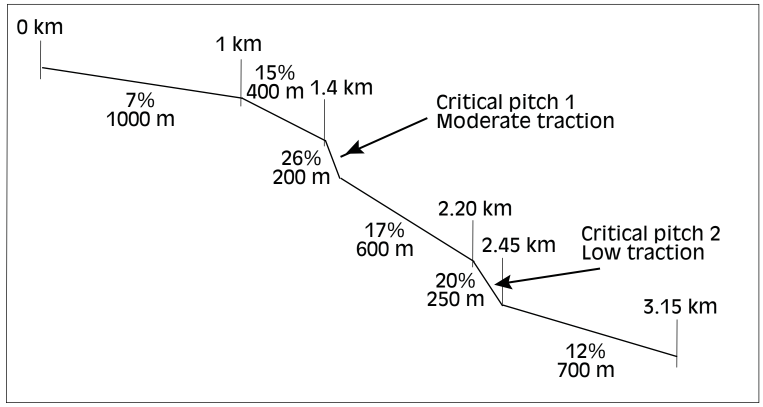


Figure 12. Sample descent profile.

Table 3. Speed guidelines for sample descent

Road section (km)	Traction level (minimum)	Distance (m)	Maximum grade (%)	Condition [a] (Table I-1)	Maximum speed (km/h) [a]
0–1.00	moderate	1000	7	C	25
1.00–2.45	low	1450	26	A	10
2.45–3.15	moderate	700	12	C	18

[a] From Appendix I.

Table 4. Load guidelines for sample descent

Critical pitch				Road section preceding pitch [a]		Maximum load (tonnes)
Location (km)	Distance (m)	Grade (%)	Traction	Distance (m)	Grade (%)	
1.40	200	26	moderate	400	15.0	120
2.20	250	20	low	1200	17.8	100

[a] Road section preceding pitch is the total cumulative distance and weighted average of the grade.

(400 m) is rounded up to 0.5 km. In the case of critical pitch 2, the distance is rounded up to 1.5 km, the average grade is rounded up to 18%, and the pitch length is rounded up to 300 m. The resulting maximum loads are 120 and 100 tonnes for critical pitches 1 and 2, respectively, resulting in a maximum load for the descent of 100 tonnes due to the low traction on pitch 2. If the first critical pitch had a low traction level, then no loads could be hauled down this road. Conversely, if critical pitch 2 had a moderate traction surface, then a maximum load of 120 tonnes could be hauled.

This example illustrates the importance of surface traction when descending steep grades. Therefore, measures should be taken to maximize surface traction through road construction and maintenance as well as haul scheduling. On steep road sections, roads should be built using the appropriate material, be drained appropriately, and maintain a smooth compact surface. In addition, hauling on steep grades should be scheduled during periods when traction levels are maximized.

To simplify the application of these guidelines, FERIC has developed a spreadsheet tool to output the critical values.

The maximum load recommended in the guidelines is 120 tonnes and is based on existing practices as well as stability considerations. To maintain acceptable stability levels, the load height should not exceed 6.4 m (21 ft.) and the manufacturer vehicle weight ratings should be considered when determining load sizes. Experience has shown that these log truck configurations were designed to withstand significant loading. A good maintenance and inspection program should be in place to monitor the condition of the critical vehicle components.

Occupational health and safety regulators in British Columbia and Alberta have investigated the issue of exceeding manufacturer vehicle weight ratings. Both provinces concluded that exceeding manufacturer vehicle weight ratings was not the primary issue relating to the safety of log hauling, particularly on private road networks. Therefore, regulations limiting vehicle loads to manufacturer specifications have been loosely applied to log trucks. In Alberta, for example, the industry is required to prepare a hazard assessment for transporting loads in excess of rated capacities based on broad hazard categories (Alberta Human Resources and Employment 1999).

Conclusions

On steep grade (low-speed) descents, data from the on-board monitoring system indicated that the service brakes generally account for the lowest power absorption (10–20%) whereas the driveline accounts for the greatest power absorption (35–55%). Rolling resistance also represents a significant power component (30–50%). The highest average total power absorption measured on low-speed descents was 575 kW, resulting from the high average grade of 10.4% with many extended steep pitches up to 25%.

The relatively low level of measured power required to retard the truck results from the relatively low average grades over long distances. However, the peak retardation power absorption was considerably greater resulting from a combination of steep grade pitches and large decelerations to control speed. The peak retardation power was generally greater than 600 kW, with instances that exceeded 1000 kW. Appropriate gear selection and careful speed control can reduce the peak retardation requirements even on relatively steep pitches. The lowest peak retardation levels of less than 500 kW occurred when the lowest gear was engaged throughout the pitch, thereby keeping the speed below 10 km/h.

The measured peak service brake temperatures generally occurred during the high-speed (>35 km/h) descents which typically occurred at the end of the haul. The measured peak brake lining temperatures on the steep grade (low-speed) descents were 150°C and 205°C, respectively, for the drive and trailer axles; these were well below the maximum allowable lining temperature of 350°C.

Surface traction level is the most critical and limiting factor affecting steep grade descents. The maximum grade that a truck can descend is determined by the brake capacity in combination with the surface traction. At very low traction levels (snow/ice), the maximum sustained descent grade is limited to 13% when the truck is equipped with only drive and trailer service brakes. In these very low traction conditions, the grade can be extended to 15% for pitches less than 50 m in length. The low traction operating range could be extended if chains were to be used under these conditions. At higher traction levels, greater braking forces may be developed to the point that the service brake capacity becomes the limiting factor, allowing the truck to descend grades of up to 30%. Therefore, measures should be taken to maximize surface traction through road construction and maintenance as well as haul scheduling.

Safe descent of steep grades depends on the careful management of many parameters and their interactions with each other. The descent guidelines that FERIC developed in Appendices I, II, and III take all of these parameters into account. The parameters that can most easily be controlled to ensure safe descents are loads and speeds. Other parameters influencing brake performance are the distance and average grade of the descent prior to the critical pitch, as well as the length and grade of the critical pitch itself. As grades and length of grades increase, service brake temperatures increase and impact brake performance. Accordingly, each haul needs to be evaluated based on these many parameters. A maximum load can then be determined for the haul as well as maximum speed levels for specific road sections along the haul route.

Implementation

- Forest operations planners should conduct a review of their existing road networks utilizing the developed guidelines and method described in this report to identify critical road sections requiring speed and load limits. Maximum speeds on critical road sections should be identified.
- A maximum load size will need to be determined for each harvesting block and communicated to loader operators and truck drivers. There are currently no truck scales available for coastal "fat" trucks. Therefore, load weights and volumes should be monitored on each block to develop site-specific load conversion factors to ensure that the maximum loads are adhered to. If the load weight conversion factor is unknown, then smaller loads should be hauled until the conversion factor is established. FERIC is currently investigating the development of on-board weigh scales for these types of trucks, which will assist in determining load weights.
- To maintain acceptable stability levels, the load height should not exceed 6.4 m (21 ft.). When determining maximum load size, manufacturer vehicle weight ratings should be considered. Experience has shown that these log truck configurations can withstand loading above these weight ratings. However, it is important that a good maintenance and inspection program is in place to monitor the condition of the critical vehicle components.
- The descent guidelines should be provided to forest road engineers to assist them in road layout and design. FERIC has developed a spreadsheet-based tool to simplify the application of the guidelines.
- All steep roads should be constructed with the best material available to maximize traction. These roads should be compacted sufficiently prior to use and maintained to ensure a smooth compact surface.

- Hauling on steep grades should be scheduled during periods when surface traction is maximized, and the road condition should be monitored to ensure that the traction level is maintained. Hauling should be suspended if minimum traction levels are not achieved (e.g., wet or snow-covered surfaces).
- Steering axle brakes should be maintained and utilized on these trucks to improve retardation levels. Ideally, these brakes should be plumbed through the treadle valve to ensure that they are used when required.
- The service brakes should be properly maintained and adjusted frequently to ensure that the air chamber stroke does not exceed 3.8 cm (1.5 in.) when operating on steep grades. Brake temperatures should be monitored to identify brakes that are under- or over-braking and adjusted accordingly or, if necessary, serviced to maintain balanced braking. FERIC should investigate the feasibility of developing a remote brake temperature monitoring system which could alert drivers when individual brakes are under- or over-braking.
- The main findings of this study and descent guidelines should be presented to the main stakeholders (i.e., drivers and forest operations planners) through workshops in cooperation with the BC Forest Safety Council through its Forestry TruckSafe program.

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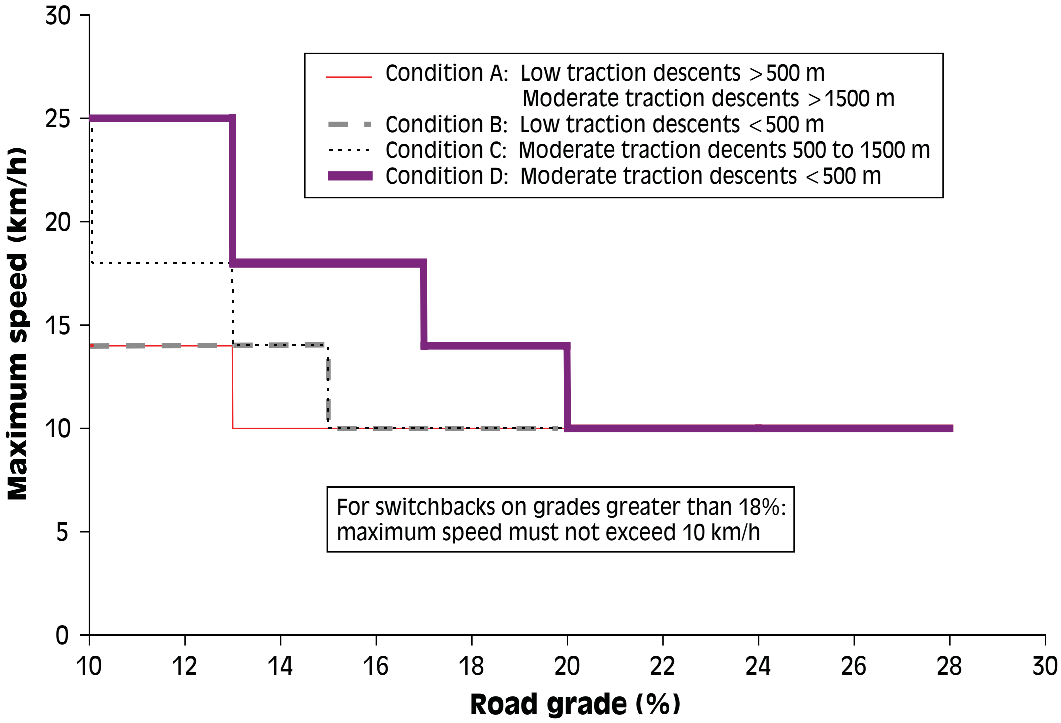
Appendix I

Coastal off-highway log truck configurations (5-axle)



Appendix II

Maximum payload (tonnes) guidelines for steep grade descents for coastal off-highway truck configurations (5-axle) [a]

Low traction (loose gravel or wet hardpan, coefficient of friction = 0.30)

Cumulative distance prior to pitch (km)	Average grade prior to pitch (%)	Critical pitch grade (%)	[√] service brakes - drive and trailer axles [ ] service brakes - all axles (incl. steers) [√] engine brake [√] water cooling Critical pitch length				[√] service brakes - drive and trailer axles [ ] service brakes - all axles (incl. steers) [√] engine brake [ ] water cooling Critical pitch length				[ ] service brakes - drive and trailer axles [√] service brakes - all axles (incl. steers) [√] engine brake [√] water cooling Critical pitch length				[ ] service brakes - drive and trailer axles [√] service brakes - all axles (incl. steers) [√] engine brake [ ] water cooling Critical pitch length			
			50 m	100 m	200 m	300 m	50 m	100 m	200 m	300 m	50 m	100 m	200 m	300 m	50 m	100 m	200 m	300 m
0.5	15	20	120	120	120	115	120	120	120	115	120	120	120	120	120	120	120	120
		22	120	-	-	-	120	-	-	-	120	120	120	120	120	120	120	115
		24	110	-	-	-	110	-	-	-	120	-	-	-	120	-	-	-
		26	-	-	-	-	-	-	-	-	105	-	-	-	105	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.5	18	20	120	120	120	115	120	115	120	120	120	120	120	120	120	120	120	120
		22	115	-	-	-	115	-	-	-	120	120	120	120	120	120	120	115
		24	-	-	-	-	-	-	-	-	120	-	-	-	120	-	-	-
		26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.5	21	22	-	-	-	-	-	-	-	-	120	120	115	115	120	120	115	115
		24	-	-	-	-	-	-	-	-	110	-	-	-	110	-	-	-
		26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.5	24	24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5	15	20	120	115	110	110	120	115	110	110	120	120	120	120	120	120	120	120
		22	120	-	-	-	120	-	-	-	120	120	120	120	120	120	115	115
		24	110	-	-	-	110	-	-	-	120	-	-	-	120	-	-	-
		26	-	-	-	-	-	-	-	-	105	-	-	-	105	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5	18	20	115	105	105	100	110	105	105	100	120	120	120	120	115	115	115	115
		22	100	-	-	-	90	-	-	-	120	115	115	105	115	115	115	105
		24	-	-	-	-	-	-	-	-	120	-	-	-	115	-	-	-
		26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5	21	22	-	-	-	-	-	-	-	-	90	90	90	90	80	80	80	80
		24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.5	24	24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.0	15	20	120[b]	115[b]	110[b]	95[b]	95[b]	90[b]	80[b]	75[b]	120[b]	120[b]	120[b]	120[b]	105[b]	105[b]	105[b]	105[b]
		22	120[b]	-	-	-	95[b]	-	-	-	120[b]	120[b]	100[b]	100[b]	105[b]	105[b]	100[b]	100[b]
		24	110[b]	-	-	-	-	-	-	-	120[b]	-	-	-	105[b]	-	-	-
		26	-	-	-	-	-	-	-	-	105[b]	-	-	-	105[b]	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.0	18	20	110[a]	100[b]	90[b]	90[b]	-	-	-	-	115[b]	115[b]	115[b]	115[b]	70[c]	70[c]	70[c]	70[c]
		22	-	-	-	-	-	-	-	-	115[b]	105[b]	100[b]	90[b]	70[c]	70[c]	70[c]	70[c]
		24	-	-	-	-	-	-	-	-	115[b]	-	-	-	70[c]	-	-	-
		26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.0	21	22	-	-	-	-	-	-	-	-	75[c]	75[c]	75[c]	75[c]	-	-	-	-
		24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.0	24	24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

[a] No value indicated by "-" means that there is no safe payload for that application. [b] Loads valid for 3.0 km or longer. [c] Descent distance must not exceed 3.0 km.

Appendix III

Maximum payload (tonnes) guidelines for steep grade descents for coastal off-highway truck configurations (5-axle) [a]

Moderate traction (compact gravel or shot rock, coefficient of friction = 0.45)

Cumulative distance prior to pitch (km)	Average grade prior to pitch (%)	Critical pitch grade (%)	☑ service brakes - drive and trailer axles; ☐ service brakes - all axles (incl. steers); ☑ engine brake; ☑ water cooling — Critical pitch length				☑ service brakes - drive and trailer axles; ☐ service brakes - all axles (incl. steers); ☑ engine brake; ☐ water cooling — Critical pitch length				☐ service brakes - drive and trailer axles; ☑ service brakes - all axles (incl. steers); ☑ engine brake; ☑ water cooling — Critical pitch length				☐ service brakes - drive and trailer axles; ☑ service brakes - all axles (incl. steers); ☑ engine brake; ☐ water cooling — Critical pitch length			
			50 m	100 m	200 m	300 m	50 m	100 m	200 m	300 m	50 m	100 m	200 m	300 m	50 m	100 m	200 m	300 m
0.5	15	20	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		22	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		24	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		26	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		28	120	115	115	105	120	115	110	105	120	120	120	120	120	120	120	120
0.5	18	20	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		22	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		24	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		26	120	120	115	115	120	120	115	100	120	120	120	120	120	120	120	120
		28	120	115	105	100	120	110	105	95	120	120	120	120	120	120	120	120
0.5	21	22	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		24	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		26	120	115	115	115	120	115	115	115	120	120	120	120	120	120	120	120
		28	120	110	105	100	120	110	105	100	120	120	120	120	120	120	120	120
0.5	24	24	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		26	120	115	115	115	120	115	110	105	120	120	120	120	120	120	120	120
		28	120	110	100	100	115	105	100	95	120	120	120	120	120	120	120	120
1.5	15	20	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		22	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		24	120	120	115	115	120	120	115	115	120	120	120	120	120	120	120	120
		26	120	110	110	105	120	110	110	105	120	120	120	120	120	120	115	110
		28	120	100	95	90	120	100	95	90	120	115	115	110	120	110	105	105
1.5	18	20	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
		22	120	120	120	120	120	115	115	115	120	120	120	120	120	120	120	120
		24	120	120	115	115	120	110	105	105	120	120	120	120	120	120	120	120
		26	120	110	110	110	115	100	95	95	120	120	120	120	120	120	115	110
		28	120	100	95	95	110	95	90	85	120	115	115	110	120	110	105	105
1.5	21	22	110	110	110	110	105	105	105	100	120	120	120	120	100	100	100	100
		24	110	105	105	105	100	95	95	95	120	120	120	120	100	100	100	100
		26	105	100	95	95	95	90	85	85	120	115	115	110	100	100	100	100
		28	100	90	85	85	90	80	75	75	120	110	105	100	100	100	95	95
1.5	24	24	90	90	90	90	75	75	75	75	95	95	95	95	80	80	80	80
		26	90	90	85	80	75	75	70	70	95	95	95	95	80	80	80	80
		28	80	70	70	65	70	65	60	60	95	95	95	90	80	80	80	80
3.0	15	20	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]
		22	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	115[b]	115[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]
		24	120[b]	120[b]	115[b]	115[b]	120[b]	115[b]	110[b]	105[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]
		26	120[b]	110[b]	110[b]	105[b]	120[b]	105[b]	105[b]	95[b]	120[b]	120[b]	120[b]	120[b]	120[b]	120[b]	115[b]	110[b]
		28	120[b]	100[b]	95[b]	90[b]	120[b]	95[b]	90[b]	85[b]	120[b]	120[b]	120[b]	120[b]	120[b]	110[b]	105[b]	105[b]
3.0	18	20	120[b]	120[b]	120[b]	120[b]	95[c]	95[c]	95[c]	95[c]	120[b]	120[b]	120[b]	120[b]	105[d]	105[d]	105[d]	105[d]
		22	120[b]	120[b]	115[b]	115[b]	95[c]	95[c]	95[c]	95[c]	120[b]	120[b]	120[b]	120[b]	105[d]	105[d]	105[d]	105[d]
		24	120[b]	110[b]	110[b]	105[b]	95[c]	95[c]	95[c]	95[c]	120[b]	120[b]	120[b]	120[b]	105[d]	105[d]	105[d]	105[d]
		26	115[b]	105[b]	100[b]	100[b]	95[c]	95[c]	90[c]	85[c]	120[b]	120[b]	115[b]	115[b]	105[d]	105[d]	105[d]	105[d]
		28	110[b]	95[b]	80[b]	80[b]	95[c]	80[c]	75[c]	70[c]	120[b]	115[b]	110[b]	105[b]	105[d]	100[d]	95[d]	95[d]
3.0	21	22	100[b]	100[b]	100[b]	100[b]	75[e]	75[e]	75[e]	75[e]	110[b]	110[b]	110[b]	110[b]	80[f]	80[f]	80[f]	80[f]
		24	100[b]	100[b]	100[b]	100[b]	75[e]	75[e]	75[e]	75[e]	110[b]	110[b]	110[b]	110[b]	80[f]	80[f]	80[f]	80[f]
		26	100[b]	95[b]	90[b]	90[b]	75[e]	75[e]	75[e]	75[e]	110[b]	110[b]	105[b]	105[b]	80[f]	80[f]	80[f]	80[f]
		28	95[b]	85[b]	80[b]	80[b]	75[e]	75[e]	70[e]	65[e]	110[b]	100[b]	95[b]	95[b]	80[f]	80[f]	80[f]	80[f]
3.0	24	24	75[b]	75[b]	75[b]	75[b]	-	-	-	-	90[b]	90[b]	90[b]	90[b]	-	-	-	-
		26	75[b]	75[b]	75[b]	75[b]	-	-	-	-	90[b]	90[b]	90[b]	90[b]	-	-	-	-
		28	75[b]	70[b]	65[b]	-	-	-	-	-	90[b]	90[b]	90[b]	90[b]	-	-	-	-

[a] No value indicated by “-” means that there is no safe payload for that application. [b] Loads valid for 3.0 km or longer. [c] At descent distances greater than 3.0 km, load should not exceed 85 tonnes. [d] At descent distances greater than 3.0 km, load should not exceed 95 tonnes. [e] Descent distance must not exceed 3.0 km. [f] At descent distances greater than 3.0 km, load should not exceed 70 tonnes.