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Analysis of Variables Influencing Towing Limits in Self-Propelled Rail Track Maintenance Equipment

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Abstract: The towing limits for self-propelled rail track maintenance equipment (SP-TME) are influenced by a multitude of factors, including the type and weight of the equipment, speed, braking capabilities, track and weather conditions, traction, engine power, driveline performance, coupler/towing link integrity, and safety regulations. This study investigates these variables to determine their impact on the towing limits of SP-TME. Unlike traditional rail vehicles, SP-TME possesses unique operational constraints and specifications, necessitating careful consideration of its independent mobility. An extensive analysis was conducted on the towing usage and overuse of SP-TME during travel mode, examining various scenarios that incorporate different combinations of trailing load, rail track grade, rail curvature, and weather conditions. These scenarios, ranging from normal to worst-case, aim to simulate demanding operational environments. The parameters evaluated include structural strength, traction, engine and driveline performance, wheel rolling and skidding, braking capabilities, trailing load, speed, and track and weather conditions. Results indicate that under normal and moderate conditions, the equipment can tow significantly higher loads than the defined base load. However, in special situations, such as negotiating tighter curves and steeper grades in adverse weather conditions, wheel skidding and locking emerge as limiting factors. Findings related to service and parking brake performance during steep grade descents, particularly when the trailer lacks independent braking capabilities, are also presented. Recommendations and cautions are provided to ensure safe and efficient operation of SP-TME under various conditions.

Keywords: Railroad vehicles; Towing strength; Finite element analysis (FEA); Towing limit variables; Self-propelled rail track maintenance equipment (SP-TME)

1 Introduction

Rail TME is crucial for ensuring safe, efficient, and reliable railway operations. These specialized machines are designed to handle a range of tasks, including track repairs and inspections. Track maintenance machinery refers to the equipment used in corrective or preventive modes to restore the rail track to an optimal position, promoting improved safety and a longer rail life. Some commonly used track maintenance machines include track leveling and surface equipment, tie and ballast maintenance equipment like tampers, stone blowers, track stabilizers, rail grinding equipment, tie equipment, ballast cleaners, and undercutters. Apart from conducting maintenance activities on rails, this equipment often needs to tow the other smaller equipment or trailers or be towed by other vehicles for transportation or rescue, which requires substantial towing strength to maneuver effectively along the railway lines. These machines are typically robustly built for safety, both for the track and the equipment itself. However, despite their sturdy construction, these machines encounter certain limiting variables that affect their towing capabilities, impacting their overall efficiency and performance. The towing limit for rail vehicle-TME depends on various factors: the type of equipment, equipment weight, speed, braking, track conditions, weather conditions, traction, engine power, driveline performance, coupler/towing link, strength, performance and safety regulations [1–15]. These variables collectively determine the towing limits for rail vehicles, and adherence to these limits is crucial for safe and efficient railway operations. In SP-TME, the concept of towing limits varies from the traditional sense since these machines can move independently; because of operational constraints and specifications that need to be observed to ensure safe and efficient functioning. Deciding on the appropriate tow vehicle trailer rating is a critical aspect of safe and efficient towing. The vehicle's capacity to tow a trailer is determined by its manufacturer and is usually specified in the owner's manual or on a sticker placed on the vehicle. The example sticker/decal is shown in Figure 1. The driveline performance in pulling the equipment and load behind, the braking of equipment for safe stopping distances, and the strength of the towing structure are the major aspects that influence equipment towing, which are explored in this study.

Rail curves and grades add resistance for rail vehicles to move; rail equipment must overcome these resistances to start or continue moving. The most important train resistances are curve resistance and grade resistance, expressed in terms of pounds of force per ton of weight carried by the train per degree of curve or grade, respectively [1–3, 13]. Curve resistance depends on the curve radius, track gauge, rail condition, and the characteristics of the rolling stock. It is well known that a vehicle running on a curve experiences lateral acceleration, resulting in high lateral forces that cause curve resistance [10–16]. When differences in track level cannot be avoided, gradients are used. However, these gradients cannot be too steep, considering the maximum available adhesion force between the driven wheels and the rails [1, 13, 14].

Figure 1. Example decal

Rail cars, equipment, and locomotives are engineered to negotiate curves and grades within specific limits. While they are designed to handle certain grades efficiently, navigating steeper gradients and tight curves might affect their speed, stability, and efficiency and cause wear on both the equipment and the tracks. In the United States, mainline railroads commonly feature curves of 1 or 2 degrees and gradient or slope for railroad tracks of around 2-2.2%. However, certain lines and mountain regions necessitate tighter curves of 5–10 degrees and steeper grades, reaching up to 3.3%. The design standard for the sharpest curve limit on railroad tracks typically ranges between 9 and 10 degrees, measured in terms of the degree of curvature or degree of curve and steepest grade, to 3.3% in United States mainline railroads [9]. The study presented explores the towing limiting variables of the machine across diverse track scenarios, encompassing grades up to 3.3% and curves of up to 10 degrees.

The braking system of a railway vehicle is distinct from that of road vehicles, with pneumatic braking playing a crucial role in the complex braking systems of railway vehicles. Unlike road vehicle braking, the operation of pneumatic brakes involves a series of interconnected components, contributing to the safety and efficiency of train travel. However, despite their efficiency, pneumatic brakes may require significant braking distances, emphasizing the need for careful consideration of stopping distances in railway operations to ensure safety. This study includes checks on parking braking and pneumatic service braking in scenarios described in detail in the methods and results sections, ensuring safer maneuvering and stopping distances when towing loads. The third aspect, structural strength [4–8, 12, 13], is verified by performing structural analysis and buckling analysis on the equipment and tow links using various towing and grade forces for normal to steep grade situations.

Compared to other on/off-road vehicle industries and rail freight/passenger cars, the TME industry has limited published research. The significance of this study lies in its comprehensive analysis of the parameters and variables that affect these machines when navigating steep grades, tight curves, misuse/overuse, wheel rolling, wheel skidding, and adverse weather conditions while towing loads. The research provides valuable insights into the factors that limit towing performance. This understanding is crucial for optimizing the safe and efficient travel of equipment on rail tracks. Sections 3, 4, and 5 discussed in detail the three major aspects: structural strength, machine performance, and braking capabilities that affect towing limits. The findings contribute to formulating guidelines for speed control and friction enhancement, thereby enhancing safety in rail equipment and infrastructure. Section 6 in the conclusions and comments summarizes these insights.

2 Method, Assumptions, and Parameter Selection

2.1 Validation Process

Establishing towing limits involves considering various factors: equipment type, design and safety requirements, customer specifications, braking capabilities, traction, engine and driveline performance, structural necessities on mainframe strength, and the tow link/coupler strength. The aim was to assess the existing equipment capacity for unforeseen towing situations, potential overuse, or misuse, particularly when handling higher loads than designed. The steps typically involved in determining the SP-TME's towing limits encompass several key stages:

-Define towing load requirements and criteria for the equipment under design.

-Select or design the necessary coupler link.

-Design the equipment mainframe for towing loads based on established criteria or the selected coupler type, if that dictates the maximum towing load [3–8, 12, 13].

-Conducting in-depth evaluations of the mainframe's strength concerning towing and coupler loads. These assessments focus on the tow hitch or structural areas, ensuring compliance with designed or regulatory loads [3, 7, 8, 12].

-Analyzing and evaluating the coupler link to assess buckling tendencies due to compression loads during towing or when in contact with other trailer cars or equipment.

-Performing traction, engine, and driveline performance calculations under various track and weather conditions. This ensures sufficient traction, available power for traction, and driveline component performance for handling the required and additional towing loads [1, 2, 10–13].

-Evaluating braking safety for equipment towing loads. This involves calculating service braking, panic braking, and parking brake effectiveness on the steepest grades and permitted speeds, considering worst-case scenarios where reliance on the main propelled equipment's braking is necessary due to the absence of braking arrangements on the towed trailer car.

-Determining towing limits by integrating analyses and performance calculations across all variables and constraints affecting towing operations.

Figure 2 illustrates the critical stages of the validation process, aiding in understanding the complex interactions and criteria considered.

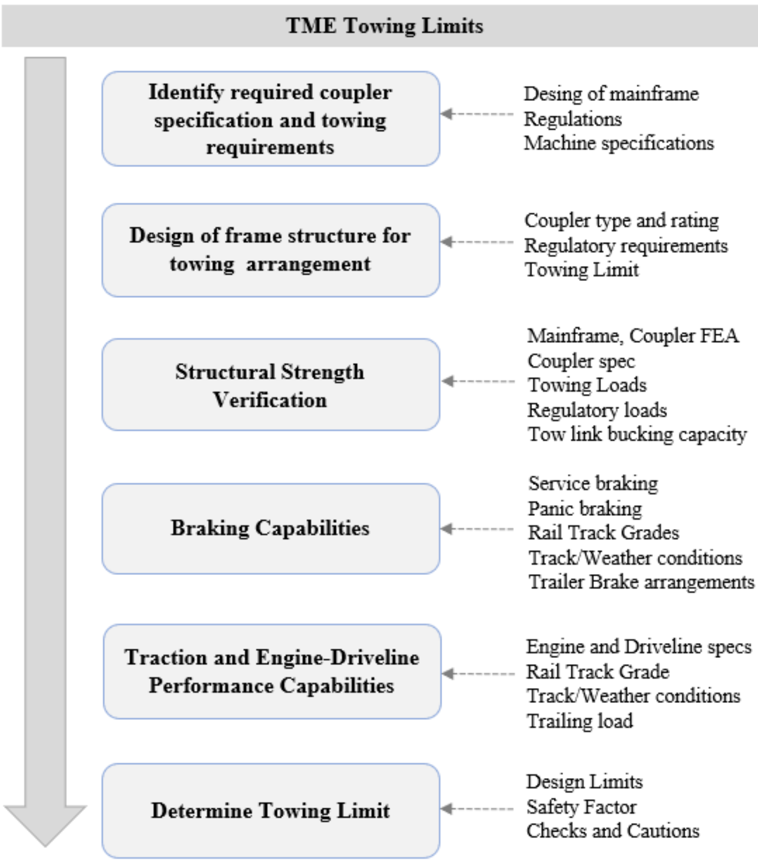

Figure 2. Validation process

2.2 Assumptions and Parameter Selection

-The maximum grade and sharpest curves were selected from typical mainline rail curves in the United States. Speed variations were done based on rail equipment max speed (30 mph), and available driveline modes.

-Three scenarios of trailing loads, with a 35,000 lb base load and two additional overload scenarios, were created to assess the potential overuse or misuse of the equipment across a range of track grades and rail curves, from typical, moderate, to worst-case scenarios.

-Several scenarios, incorporating different combinations of trailing load, rail track grade, rail curve, and weather conditions, were analyzed. These scenarios ranged from normal and moderate to worst-case scenarios, aiming to simulate demanding situations.

-The rail-wheel conditions were assumed to be dry for strength calculations, as this worst-case scenario yields higher loads on the towing structure. The towing forces on the structure were calculated accordingly for a maximum 3.3% grade.

-For traction and braking capabilities, wet conditions were used as they represent the worst-case scenario in these calculations. Wet conditions result in reduced traction force, the possibility of wheel skidding, and longer stopping distances during braking.

-Grade, curve, and rolling resistance are references from the American Railway Engineering and Maintenance-of-Way Association (AREMA) [2, 10–13].

-Driveline and braking system parameters used as shown in Section 4 and 5 are from parts/machine specifications.

-Power to accessories is assumed to be 15% in traction calculations. Overall drive system efficiency is considered at 85% in traction and performance calculations. The linkage efficiency is considered at 85% in braking calculations.

-For worst-case scenarios in braking and stopping distance calculations; it is assumed that there are no separate brakes on the trailer or trailing car.

-The effect of dynamic retarding force is not considered to have a worst-case scenario to check braking just with the pneumatic service brake capabilities.

-All the calculations, analysis, and checks were done in travel mode. The working equipment and attachments are in stored/travel mode.

3 Results: Strength Limits

3.1 Equipment Frame Strength

The equipment mainframe structure was analyzed for towing trailer loads. The strength evaluation was done for two load scenarios: 1) When the equipment traverses the highest grade with the maximum trailer load, with the wheels in rolling; and 2) In a rare but possible scenario where the equipment breaks down on an incline, causing the trailer equipment wheels to lock, causing the wheels to slide and not roll. This situation of wheel sliding generates exceptionally high towing forces, necessitating an assessment of the structural strength under this extreme load condition. Such an occurrence, more of a rescue situation than a typical towing scenario, also places immense forces between the wheel and rail track due to the lack of rolling motion. Such conditions, though atypical, demand scrutiny due to the extraordinarily high forces exerted, particularly on dry tracks, warranting verification of the towing structure's strength under these extreme loads. Figure 3 illustrates the parameters used in calculating the towing load.

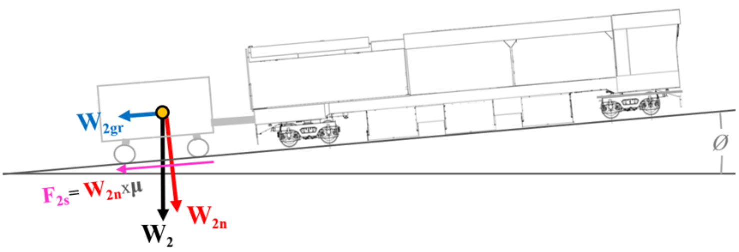

Figure 3. Equipment trailing load on grade

-W_2: Trailer Weight: 1) 35000 lb, 2) 45000 lb, 3) 43000 lb;

-Rolling Resistance of bearings: 0.005 lb/lb;

-W_{2gr}: Trailer weight force along grade;

-W_{2n}: Trailer weight force normal to track;

-Ø=Grade=3.3%;

-Materials: Plates: A572 gr50 (Yield=50 KSI, UTS=65 KSI) and Tubes: A500 gr. B (Yield=50 KSI. UTS=58 KSI);

-Friction coefficient, wheel-rail (dry), μ= 0.25.

The FEA models were generated in Ansys mechanical software using higher-order solid tetrahedral elements with an average element size of 0.35 inches (see Figure 4). The induced stress levels below 85% of material yield strength or 67% of ultimate tensile strength, whichever is less stress, were considered safe in evaluating the structure for various towing proof loads [5–8].

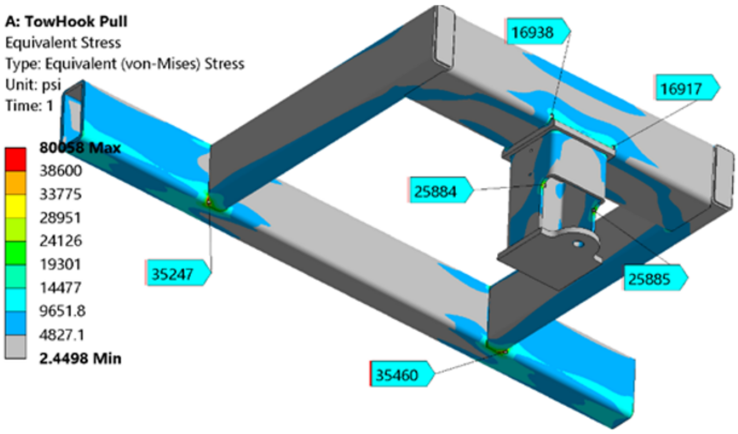

Figure 4. Von-mises stress on mainframe

Table 1. Stress results for different tow loads

Trailing Weight lb	35000		45000		43000	
Track Grade =3.3%	Tow Load lb	Stress psi	Tow Load lb	Stress psi	Tow Load lb	Stress psi
Rolling × 1.25	1662	5893	2136	7574	2089	7408
Breakdown Wheels Locked	8745	31010	11250	39893	10750	38120
Panic Braking (0.05g) 30mph-600ft	3079	10918	3959	14039	3783	13415

The stress levels for the various applied loads are under material yield limits, so the analysis was done for the 10,000 lbf tow load, and stress results were linearly interpolated for the other loads given in Table 1. Push and pull load cases were analyzed separately. Panic braking tow load is calculated based on vehicle equipment speed of 30 mph and stopping distance of 600 ft. Table 1 summarizes the stress results of wheel rolling, wheel sliding, and panic-breaking situations in 3.3% grade. Each of the rolling, sliding, and panic braking scenarios was evaluated for three different towing load values: current capacity and overcapacity. The strength analysis results indicated that the equipment mainframe structure is strong enough for an additional tow load than the rated load.

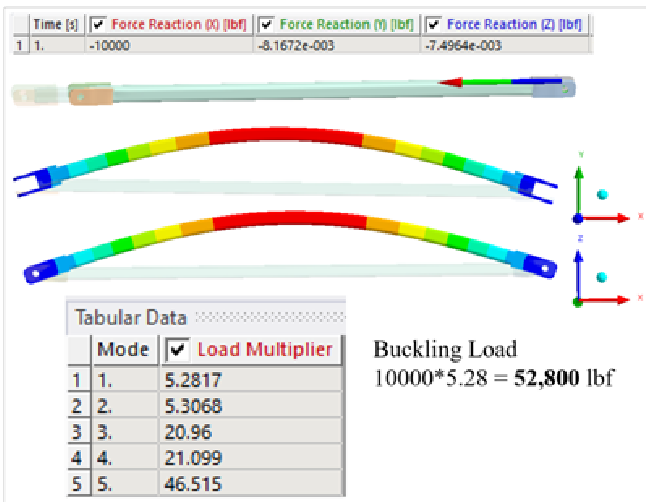

Figure 5. Critical buckling load

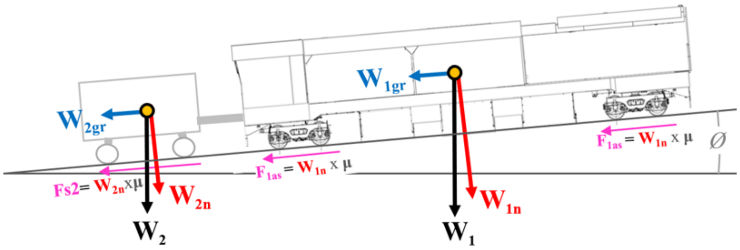

Figure 6. Equipment schematic for traction, engine driveline performance on grade in self-transport mode

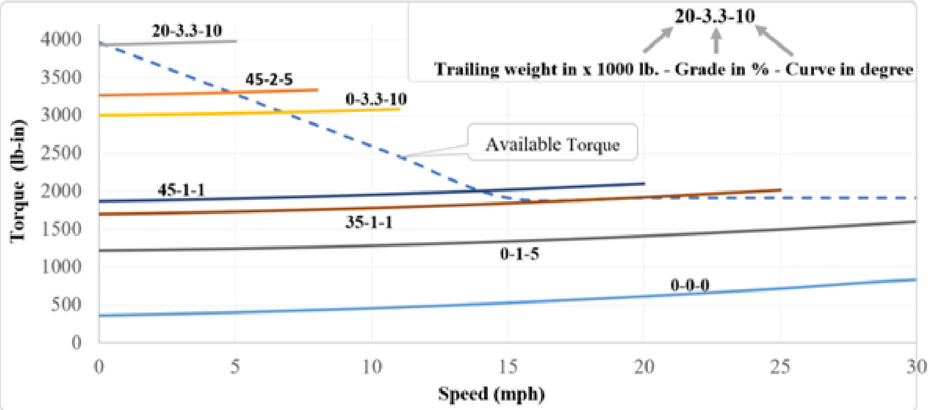

Figure 7. Torque available vs required in high gear

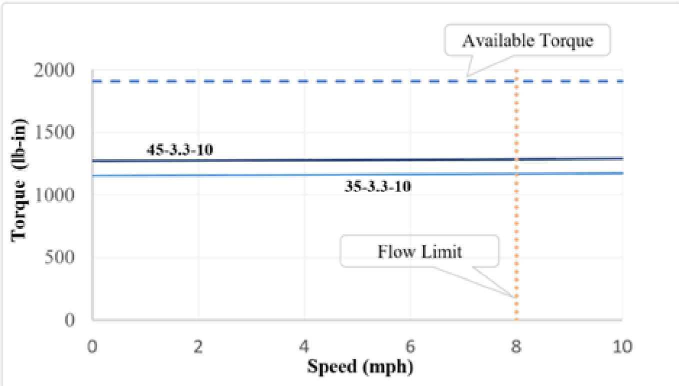

Figure 8. Torque available vs required in low gear

Case:05

	Traction, Driveline Parameters		
1	Total Weight (Equipment+Trailer)	110000	lb
2	Machine weight	65000	lb
3	Trailing Vehicle weight	45000	lb
4	No of drive axle	2	
5	Weight on Front Axle (Powered)	29300	lb
6	Weight on Rear Axle (Powered)	35700	lb
7	Wheel Radius	14.0	in
8	Engine Power	250	HP
9	Engine rpm set	2200	rpm
10	Power to accessories ≈ 15%	38	HP
11	Available HP for traction- Travel	213	HP
12	Flow -Drive Pump @eng speed	58.61	gpm
13	Drive Pump Qty	2	
14	Drive Motor Qty	2	

	Machine, Driveline, Track Variables			
15	Gear Ratio (Travel) (m-w)	7	**High**	High or Low
16	Overall Drive system efficiency	0.85		
17	Travel Speed	17.00	mph	
18	Grade %	2.00	%	
19	Degree of curvature	5.00	deg	
20	Slip Force, μ=0.15	4395	lb	
21	Rolling Resistance Factor AREMA	10.00	lb/ton	
22	Grade Resistance Factor AREMA	20.00	lb/ton/%grade	
23	Curve resistance factor	0.80	lb/ton/curve deg	
	Calculations.travel			
24	Tractive Effort (travel)	3451	lb	
25	Power required (travel)	184	HP	check1
26	TE required per drive axle	1726	lb	check2
27	Torque required per drive motor	3451	lb-in	check3
28	Drive axle wt/TE ratio	19	>4	
29	Flow required per drive motor	58.27	gpm	
30	Total flow required - all drive motors	116.55	gpm	check4

Figure 9. Traction, driveline, track parameters and variables (snapshot from the calculation tool)

3.2 Buckling Strength of Coupler Link

The coupler link, or tow link, is the connecting element that transfers the tractive force from the rail maintenance vehicle to the equipment it is towing. Tow links are typically designed to handle the maximum anticipated tractive force and dynamic loads during transport towing. Buckling FEA was conducted on the coupler link between equipment and trailer weight. The FEA predicted critical buckling load of 52,800 lbf is found to be safe as it is higher than the estimated maximum and exceptional tow forces on the structure (see Figure 5).

The desired towing limit was 35000 lb, whereas the structural strength indicated that the machine could tow higher loads than that in normal wheel rolling situations on typical tight curves and steep grades. The special situation of wheel locking or wheel skidding limits the tow load to 43000 lb. However, the other variables such as traction, engine power, drive pump-motor performance, weather conditions, and braking safety investigated for the desired and higher towing loads are presented in Sections 4 and 5 of this paper.

4 Results: Traction, Engine, Drive Pump-Motor Performance

In this section, the equipment performance parameters, including traction, engine power, driveline performance, and vehicle speed, on various rail track grades and tight curves under varying towing loads are discussed. The engine power and torque generated directly impact the towing capacity (see Figure 6). Higher-powered engines with greater torque output allow the equipment to pull heavier loads effectively. However, limitations in engine power can restrict towing capabilities, especially when faced with steep gradients, sharp curves, challenging terrain, and wet track conditions.

The efficiency of the transmission system, including gears, axles, and drive shafts, as well as driveline parts like drive pumps and drive motors, plays a crucial role in translating engine power to the wheels. The equipment was evaluated for varying towing loads in high and low gear transmission on grades and curves shown in Figure 7, Figure 8, and Figure 9 and Table 2. The use of reduced speed and low gear enhances safety and control in maneuvers and stops by improving speed management, providing increased traction for starting on inclines, and aiding in precise maneuvers. This helps prevent wheel slippage and ensures safe deceleration during emergencies.

Table 2. Summary of traction, engine power, and capacities across conditions

Engine Power, Traction, Drive Parts					**Results**					
Case	**Gear**	**Grade %**	**Curve deg**	**Speed mph**	**35000 lb Trailer Wt.**		**40000 lb Trailer Wt.**		**45000 lb Trailer Wt.**	
					Yes/No	Reason	Yes/No	Reason	Yes/No	Reason
9	Low	3.3	10	9	Yes		Yes		Yes	
8	Low	3.3	10	10	Yes		Yes		No	Flow
7	Low	3.3	10	17	No	Power, Flow	No	Power, Flow	No	Power, Flow
6	High	3.3	10	17	No	Power, Torque, Flow	No	Power, Torque, Flow	No	Power, Torque, Flow
5	High	2	5	17	Yes		Yes		Yes	
4	High	1	5	24	Yes		Yes		Yes	
3	High	1	1	28	Yes		No	Flow	No	Flow
2	High	1	1	30	No	Flow	No	Flow	No	Power, Flow
1	High	0	0	30	Yes		Yes		Yes	

The towing strength is further influenced by the interaction between the wheels and the rail surface [1, 15, 16]. Adverse weather conditions, such as rain or snow, can affect the traction and grip of the equipment on the rails, consequently impacting towing capabilities. Some rail equipment is equipped with a sand arrangement to spray sand onto the rail surface, enhancing the friction between the rail and wheels. However, for calculation purposes, wet track conditions were considered to simulate worst-case scenarios. All results summarized in Table 2 and depicted in Figure 7 and Figure 8 pertain to scenarios involving wet track conditions. We developed an in-house calculation tool designed to evaluate the equipment based on the towing parameters discussed in this paper. Key parameters used in these calculations, cited from references [1–3, 9–13, 16–19], are illustrated in Figure 9, providing a detailed view of one specific scenario. Table 2 collates the results from various case studies, while Figure 7 and Figure 8 display torque vs. speed graphs that confirm the required torque as compared to the available torque across different gears, grades, and curves.

Several cases were created by exploring different combinations of parameters such as, transmission gear, grade, curve, vehicle speed. All such combinations were investigated for three trailing weights of 35000 lb, 40000 lb and 45000 lb. Apart from several check, four important checks have been performed to verify the limits; 1) Slip Force v Tractive Effort, 2) Power Required vs Power Available for Traction, 3) Torque Required vs Torque available at Drive Motor, and 4) Flow Required vs Maximum flow available from drive pump and at motor. Results indicated that the machine could tow the specified tow loads on 2% grade and 5-degree curve in high gear, with speeds up to 17 mph. The available power for traction, the flow required for drive pumps and motors, and the torque required become limiting factors when pulling heavy loads on higher grades and tighter curves. On typical mainline curves with curves of 1 or 2 degrees and grades around 2-2.2%, the equipment can pull a much higher load However, the strength calculations discussed in Chapter 3 limit the maximum towing capacity to 43,000 lb in an unconventional breakdown scenario on an incline. For scenarios involving higher grades and tighter curves, the equipment needs to be in low gear with reduced speeds to tow heavier loads. All three tow loads, up to 45,000 lb, can be towed on the steepest and tightest curves together in low gear by restricting the speed to 11 mph.

5 Results: Braking Capabilities

An in-house braking calculation tool was developed to verify the braking capabilities for the designed and increased towing loads. To consider the worst-case scenario, regular service braking and parking braking were analyzed on a 3.3% grade with allowable speeds, considering the trailer has no brakes of its own. Figure 10 illustrates how the equipment performs braking operations with a trailer under the specified conditions.

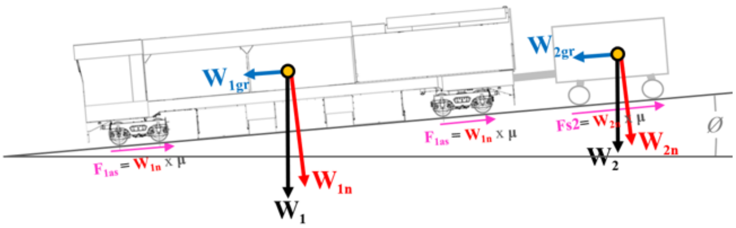

Figure 10. Equipment braking with trailer

	Parking Brake Parameters	
1	Total Weight (Equipment+Trailer)	110000 lb
2	Trailer Weight	45000 lb
3	Total Number of Axles	2
4	Number of brake shoes	6
5	Number of actuator cylinders per axle	2
6	Lever arm ratio	2.11
7	Linkage efficiency	0.85
8	Brake Actuator Force (Parking)	1910 lbf
9	Grade %	3.3%
10	Friction coefficient, wheel-rail, wet	0.15
11	Friction coefficient, shoe-wheel, wet	0.225
	Calculations Parking Brake	
12	Force of machine weight on grade	3628 lb
13	Adhesive Force	9745 lbf
	F.adhesive > F.machineWt, no sliding as long as brakes can hold	
14	Total Braking Force	4625 lbf
	F.braking > F.machineWt, parking brake can hold	
15	Safety factor	1.27
	FS >1.15, OK	

Figure 11. Parking brakes parameters

The parking brake parameters and results shown in Figure 11 are with one of the increased trailer loads scenarios checked. The overall results indicated that the parking brakes would not hold beyond ∼ 57,000 lb trailing weight on 3.3% grade in wet condition if there are no separate brakes on trailing car. Although the braking capacity is enough for up to 57,000 lb of trailing weight on a 3.3% grade, However, the tow hook strength limits the maximum trailing weight to 43,000 lb. There is enough adhesive force on the driving axles that indicates no wheel sliding would occur, and the total braking force is higher than the total weight force on the grade, so the parking brake can hold equipment at 3.3% grade with a trailing weight of 45000 lb.

	Inputs		
1	Total Weight	110000 lb	
2	Equipment Weight	65000 lb	
3	Trailer Weight	45000 lb	
4	Weigt on Front Axle (Powered)	29300 lb	
5	Weight on Rear Axle (Powered)	35700 lb	
	Service Braking	Front Axle	Rear Axle
6	Number of brake shoes per Axle	2	4
7	Lever (Rigging) Ratio	2.06	2.17
8	Linkage efficiency	0.85	0.85
9	Acutator Force	2163 lb	2163 lb
10	Retarding Force per Axle	1704 lb	3591 lb
11	Adhesive Force	4395 lb	5355 lb
	Retarding Force < Adhesive Force, OK	Check	Check
	Stopping Distance		
12	Total Retarding Force, All axles	5295 lb	
13	Weight force on grade	3628 lb	
14	Total Braking Effort	23343 lb-in	
15	Deceleration	5.85 in/s2	
16	Stopping Distance (with coast)	2073 ft	

Figure 12. Service brake parameters

Table 3. Stopping distance (service braking)

Speed mph	Grade %	Trailer Weight in lb					
		0	lb	35000	lb	45000	lb
30.0		457	ft	656	ft	713	ft
24.7	0.0%			457	ft		
23.6						457	ft
30.0		709	ft	1594	ft	2072	ft
19.7	3.3%			709	ft		
17.3						709	ft

Figure 11 and Figure 12 show the high-level parameters of parking and service braking used in checking the braking force and stopping distance with the maximum trailer load scenario at 3.3% grade. Due to the range of scenarios evaluated, Figure 11 and Figure 12 only include a snapshot of the larger calculation tool for maximum trailer load [4, 10–14, 20, 21]. Table 3 summarizes the results of the service braking tests both at base and with overuse of towing loads on level ground and a 3.3% grade. The stopping distance on braking increases significantly at higher speeds with an increase in trailing weight. The operator needs to use caution while towing trailing loads, lower the vehicle speed, or use the low gear for safe maneuvers or stops.

The effect of dynamic retarding force is not considered to have a worst-case scenario to check braking capabilities just with pneumatic service brake capabilities. Considering the worst-case scenarios, the braking capabilities of the equipment are enough for a higher tow load on the steepest grade, permissible speeds, and stopping distance.

6 Conclusions

The strength variables in the unconventional wheel locking scenario triggered by equipment breakdown on an incline impose a towing limit of 43,000 lb. While the occurrence of a non-rolling wheel situation is rare, it is a possibility. Under normal conditions, heavier loads could be towed on level tracks with typical curves of 1-2 degrees and 1-2% grades, with cautions about stopping distance during braking. The analysis of braking capabilities indicated a significant increase in stopping distance with higher towing loads at increased speeds. Stopping distance increases by 4.6 times on a 3.3% grade decline at 30 mph. For towing loads ranging from 35,000 to 45,000 lb, a reduction in speed of up to 40% is necessary to achieve the same stopping distance as when not towing any load. A reduced speed and/or the use of low gear are recommended for safe maneuvering or stopping when the machine is towing loads. The service braking force would not be enough to decelerate the machine for higher towing loads on 3.3% grade in wet conditions if there are no separate brakes on the trailing car. Parking brake calculations indicated safe up to 45000 lb trailing loads; the brakes would not hold at higher loads on 3.3% grade in wet conditions if there are no separate brakes on trailing cars.

The results summarized from the tables above collectively indicate that the equipment can tow a much higher load than the defined base load under normal and moderate conditions. The rare but possible wheel skidding or locking scenarios become the limiting factor in special situations based on strength calculations. It is evident that wet track conditions, steep grades, and sharp curves significantly reduce towing capacity. When towing loads in demanding situations where a combination of factors such as steep grades, sharp curves, and wet weather conditions pose significant challenges, careful handling and consideration are required to ensure safe operation. In such demanding situations, it is recommended to use low gear, maintain reduced speed, and utilize a sandbox to enhance wheel-rail friction.

Data Availability

The data used to support the findings of this study are available from the author upon request.

Conflicts of Interest

The author declares no conflicts of interest regarding this work.

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