Industry review of long train operation and in-train force limit

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Industry Review of Long Train Operation and In-Train Force Limit

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report. Prices are given in Canadian dollars unless otherwise noted, and may have been converted from foreign currencies at the time of writing.

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As the part of NRC’s efforts aiming to develop guidelines for the safe operation of long trains in Canada, the present study focuses on the following aspects:
• Review derailments identified by the TSB as having been related to long trains and in-train forces;
• Simulation of long, mixed goods trains to better understand longitudinal in-train forces;
• Review industry standards and practices related to controlling in-train forces and managing long trains;
• Recommendation of the draft in-train force limit based on the review.</td></tr>
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EXECUTIVE SUMMARY

In the search for increased efficiency the railroads have been changing operations towards the use of longer trains. Longer trains require less crew per ton of freight transported, reduce the number of train slots taking up a position on the infrastructure, reduce scheduling conflicts ("train meets" on line), and reduce the number of times that crossings are blocked by trains. Fuel consumption is improved with longer trains though reduced wind resistance per car and through reduced idling times when one train must stop to let another pass. Long trains are seeing expanded use across Canada, especially along the country's busiest traffic corridors.

But while the advantages of long trains are considerable, they are not without added cost and risk. Longer, heavier trains require more locomotive power which, for conventional trains with head-end power, increases the draft and buff loading required to accelerate and decelerate the train. As well, as trains negotiate curves and grades, slack in the couplers causes longitudinal train action to arise, resulting in significant forces between cars as the train stretches and compresses. Large in-train forces damage track and cars, couplers and lading, and in severe cases large in-train forces can be a primary or secondary contributor to derailments.

The increase in train length and weight has also been accompanied by a change in accident statistics. In the decade from 1999 to 2009, trains involved in main track derailments saw a 40% increase in mass, a 26% increase in length, and a 20% increase in the number of cars involved. As well, since 2000 the Transportation Safety Board (TSB) has investigated at least 14 derailments where in-train forces have been a causal or contributing factor to the derailment.

Given the industry trend towards operating longer trains, Transport Canada (TC) has committed to develop new guidelines for safe operation of long trains on the Canadian rail network. At the request of Transport Canada, the National Research Council Canada (NRC) has been contributing to the development of the guidelines, through the work summarized in this report and in other related projects. The approach is to build the guidelines based on a review of previous work, the industry best practices, and in-train force limits that govern the risk level.

Factors contributing to a higher derailment risk due to in-train forces are car weight, distribution of loaded and empty cars in a train, type of coupler, total train length, positioning of locomotive power, and train handling. The derailment risk due to in-train forces are of greatest concern in track areas having numerous curves and where there are rapid changes of grade. These characteristics apply to much of the mountain territories in Canada's western provinces and several other areas within Canada.

Industry-generated best practices for train marshalling are currently based on train length and tonnage [1]. Operating practices of the individual railroads for distributed power, train make-up rules and train handling procedures all have a central role in reducing the in-train forces. However, there is no common, industry-wide practice and minimal science-based guidelines or limits to guide the development of safe operating practices for long trains.

In order to avoid the development of prescriptive guidelines that might constrain flexibility and productivity, limits for the allowable in-train buff (compression) and draft (tension) forces can be determined based on two primary failure mechanisms; wheel/rail derailments and knuckle failures, respectively. From these force limits, it would then be possible to generate the best and most suitable practices for the marshalling and operation of long trains over a specific section of track.

As the part of NRC's efforts aiming to develop guidelines for the safe operation of long trains in Canada, the present study focused on the following aspects:

- Review derailments identified by the Transportation Safety Board (TSB) as having been related to long trains and in-train forces;
- Review industry and railroad standards and practices related to controlling in-train forces and managing long trains;
- Recommendation of the draft in-train force limit based on the review.

The following summaries and conclusions have been drawn from the present study:

(1) From the review of fourteen TSB reports it is found that:

- All of the derailed trains are mixed goods trains;
- Most of the first derailed cars are empty cars, except for two yard locomotives;
- 9 of the 14 (64%) derailed trains are longer than 8,000 feet;
- In half the cases, the use of non-standard large swing angle couplers contributed to the initiation of the derailment;
- Estimates for in-train forces that were the primary cause of the derailments were:
    - -135, -175, -200, -200, -216, -250 and +225kips;
- An empty car in a long train connected to a car with large swing angle couplers is one of the main risks for a derailment caused by in-train forces;
- Simulation of two derailment scenarios was undertaken using longitudinal train dynamics software.
- The simulations showed that in-train forces are dependent on train makeup as described by the Association of American Railroads (AAR) Train Makeup Manual (TMM), and that handling practices and the use of distributed power (DP) play an important role in controlling in-train forces.

(2) The trailing tonnage method and guidance of AAR Train Makeup Manual published in 1992 are still used by the industry as basis for train marshalling rules. The key points of the TMM are summarized as follows:

- Limit allowable trailing tonnage behind an empty car;
- The trailing tonnage limit is determined by draw bar force limit, grade, curving resistance and rolling resistance;
- Draw bar force limit is determined as 38.9% of car weight divided by coupler angle;
- Coupler angle is determined by degree of curve, together with car lengths, truck centers and coupler lengths of two adjacent cars;
- Under buff condition, the lateral bolster-to-track free play (gap) will increase the coupler angle compared to the draft loading case.

(3) Based on the review of the AAR Train Makeup Manual and the current AAR Manual of Standards and Recommended Practices (MSRP), the draft (pull-apart) limits were identified for different material grade of coupler knuckles as:

- Grade C (AAR TMM 1992): accepted working limit of 250,000 lbs
- Grade E (AAR TMM 1992): accepted working limit of 300,000 lbs
- Current AAR MSRP: 400,000 lbs

Given that older cars equipped with knuckles made of Grade C and Grade E materials are still in use, it is recommended that a limit of 250,000 pounds be used as the pull-apart force limit if the knuckle material grade and service condition is unknown for a train. However, the limit to permanent deflection corresponding to the knuckle material can be used as the pull-apart limit in the situation where all the knuckles in a train are known as recently manufactured with high material grade.

(4) CP began using rules-based software, called TrAM, to adjust train makeup starting in 2003. TrAM is a set of comprehensive, territory specific, marshalling rules and supporting computer tools designed to permit the efficient use of distributed power. The use of the TrAM system has allowed CP to introduce longer and heavier trains without a subsequent increase in derailments, as seen by the fact that of the 14 derailments cited by the TSB as involving in-train forces, only one was a CP train.

(5) Prior to 2004 CN had no publically available rules for train makeup to control in train force. CN has historically followed the AAR TMM rules, and applied experience in operating its trains over specific territories to set local written and verbal guidance for train makeup. However, beginning in 2004, following on recommendations set out by TSB, CN began implementing restrictions on specific routes to control in-train forces through train length restrictions and marshalling practices. CN also began using more DP and began applying increasingly restrictive rules on routes that had historically resulted in coupler failures and derailments. By 2010 CN had instituted a series of train makeup and handling guidelines across Canada.

(6) A summary of the train handling best practises as used by CN and CP was undertaken. General and common practices were identified through a review of example practices provided by CN and CP. These include (but are not limited to):
- Forward planning based on characteristics of territory and train;
- Priority of using throttle manipulation and dynamic brake;
- Limit of using high dynamic brakes;
- Control train action by gradual handling and properly adjusting slack;
- Placement of DP to reduce forces and improve air brake control;
- Limits on placement of long empty cars, cars with specialty couplers.

(7) The review of TSB reports and industry standards and practices has highlighted that estimating, predicting, or controlling longitudinal in-train forces is not a simple task. The experience of BHP railroad in Australia in operating extremely long trains supports this conclusion. It was also noted that more research into the measurement of in-train forces and the study of coupler fatigue is needed.

(8) The AAR Tran Makeup Manual was the start of instituting an industry-wide method of estimating and controlling in-train forces. The CP TrAM system and the CN rules-engine go beyond what the Train Makeup Manual set out, but are proprietary methods, instituted using computer software. Both systems have allowed the respective railroads to increase train lengths and weights on appropriate routes. However, given the accidents that occurred between 2000 and 2010, the increase in train length and weight has not occurred without errors from which the railroads learned valuable lessons. Therefore, a new industry wide guideline for the safe operation of long train needs to be developed.

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1 INTRODUCTION

In the search for increased efficiency the railroads have been changing operations towards the use of longer trains. Longer trains require less crew per ton of freight transported, reduce the number of train slots taking up a position on the infrastructure, reduce scheduling conflicts ("train meets" on line), and reduce the number of times that crossings are blocked by trains. Fuel consumption is improved with longer trains though reduced wind resistance per car and through reduced idling times when one train must stop to let another pass. In addition, when long trains include distributed locomotive power the improved air pressure control in the brake lines reduces unintended parasitic brake drag, while the improved distribution of in-train forces reduces curving resistance - both further improving fuel economy. In the extreme cases, these long trains can extend to over four kilometres in length and contain 150 cars or more[1]. Long trains are seeing expanded use across Canada, especially along the country's busiest traffic corridors.

But while the advantages of long trains are considerable, they are not without added cost and risk. Longer, heavier trains require more locomotive power which, for conventional trains with head-end power, increases the draft and buff loading required to accelerate and decelerate the train. As well, as trains negotiate curves and grades, slack in the couplers causes longitudinal train action to arise, resulting in significant forces between cars as the train stretches and compresses. Large in-train forces damage track and cars, couplers and lading, and in severe cases large in-train forces can be a primary or secondary contributor to derailments.

The increase in train length and weight has also been accompanied by a change in accident statistics. In the decade from 1999 to 2009, trains involved in main track derailments saw a 40% increase in mass, a 26% increase in length, and a 20% increase in the number of cars involved [TSB March 17 2010]. As well, since 2000 the Transportation Safety Board (TSB) has investigated at least 14 derailments where in-train forces have been a causal or contributing factor to the derailment.

Given the industry trend towards operating longer trains, Transport Canada (TC) has committed to develop new guidelines for safe operation of long trains on the Canadian rail network. In 2011, Transport Canada engaged in a project to increase the level of safety on rail networks via improvements in train marshalling practices, based on modeling of in-train forces. Several reports summarize the modeling results [2] [3], however the project was terminated before the contractor was able to generate guidelines for managing forces associated with long trains in curved territories. At the request of Transport Canada, the National Research Council Canada (NRC) has worked on the development of the guideline. The approach is to build the guidelines based on a review of previous work, the industry best practices, and in-train force limits that govern the risk level.

Factors contributing to a higher derailment risk due to in-train forces are car weight, distribution of loaded and empty cars in a train, type of coupler, total train length, positioning of locomotive power, and train handling. The derailment risk due to in-train forces are of greatest concern in track areas having numerous curves and where there are rapid changes of grade. These

[1] In North America trains with 150 cars or more are not commonly seen in regular operations. In Australia and Brazil, and in some captive operations in North America, trains with up to 350 cars have been operated routinely.

characteristics apply to much of the mountain territories in Canada's western provinces and several other areas within Canada.

Industry-generated best practices for train marshalling are currently based on train length and tonnage [1]. Operating practices of the individual railroads for distributed power, train make-up rules and train handling procedures all have a central role in reducing the in-train forces. However, there exist no common industry-wide practices and minimal science-based guidelines or limits to guide the development of safe operating practices for long trains. Given the vast number of permutations of car types, train lengths, types of locomotives and track profiles, it may not be economically practical to devise best practices to adequately address all the possibilities.

In order to avoid the development of prescriptive guidelines that might constrain flexibility and productivity, the objective of this study is to develop performance based limits on in-train forces. Limits for the allowable in-train buff (compression) and draft (tension) forces can be determined based on two primary failure mechanisms; wheel/rail derailments and knuckle failures, respectively. From these force limits, it would then be possible to generate the best and most suitable practices for the marshalling and operation of long trains over a specific section of track.

Since the publication of the Train Makeup Manual [4] by the Association of America Railroads (AAR) in 1990s, the operational environment including typical train length and tonnage have changed considerably. Accordingly, the industry has developed various rules to guide safe operation of longer trains. A successful example of their implementation is the Train Area Marshalling (TrAM) system developed by Canadian Pacific Railway [5] and the Marshalling Rules Policies developed by CN [6].

In this phase of study, existing approaches for implementing in-train force limits will be reviewed through the examination of relevant Transportation Safety Board (TSB) derailment reports, a review of published reports and literature on industry practices to control in-train forces, and a review of the relevant industry recommended practices, guidelines and rules (such as CP's TrAM and CN's Marshalling Rules Policies) through discussions with the major Canadian railroads.

2 Review of Derailments Involving In-Train Forces

2.1 TSB Report Review

The Transportation Safety Board of Canada (TSB) Railway Investigation Report R10T0056 [7] summarizes 13 previous derailments involving in-train forces. These reports were reviewed to identify the causes of the derailment; i.e. string-lining, jackknifing, curvature, in-train force level, coupler angle, or other causes.

The reports reviewed were:

1. R00W0106 [8]
2. R01M0061 [9]
3. R01T0006 [10]
4. R02C0050 [11]
5. R02W0060 [12]
6. R05D0039 [7][2]
7. R05C0082 [13]
8. R05V0141 [14]
9. R06W0085 [7][3]
10. R07D0009 [15]
11. R07T0110 [16]
12. R07T0323 [17]
13. R09T0092 [18]
14. R10T0056 [7]

Table 1 summarizes the identifying information concerning the derailments. Of the 14 derailments identified by the TSB as involving high in-train forces, 13 involved CN trains and 1 involved a CP train. The derailments span the time frame from 2000 to 2010, and take place in Ontario, Alberta, and British Columbia. It should be noted that the derailments listed in Table 1 do not represent all the main-line derailments that occurred in the time period from 2000 to 2010, or the most costly derailments in terms of property damage or casualties: they are derailments identified by the TSB as having had in-train forces as a factor in the cause or on the outcome of the derailment.

[2] A full engineering report for R05D0039 was not issued. A summary of the event is given in Appendix B of TSB report R10T0056.
[3] A full engineering report for R06W0085 was not issued. A summary of the event is given in Appendix B of TSB report R10T0056.

Table 1: Summary of TSB Accident Reports Reviewed.

TSB Investigation Report No.	Train	Mile Marker	Subdivision	Location	Accident date	TSB Report Date
R00W0106	CN Train E20531-15	Mile 154.4	Redditt	White	16 May 2000	2002
R01T0006	CN Train M-310-31-15	Mile 143.00	Kingston	Mallorytown	16 January 2001	2003
R02W0060	CN Train E-201-31-24	Mile 251.3	Redditt	Winnipeg	26 April 2002	2003
R01M0061	CN Train M-306-31-05	Mile 178.67	Napadogan	Drummond	06 October 2001	2004
R02C0050	CN Train A-442-51-08	Mile 52.1	Camrose	Near Camrose	08 July 2002	2004
R05C0082	CP Train 277-26	Mile 69.2	Red Deer	Near Bowden	27 May 2005	2007
R05D0039	CN Train M31031-02	n/a		Coteau, QC	02-Mar-05	2005
R05V0141	CN Train A4715-05	Mile 56.6	Squamish	Garibaldi	05 August 2005	2007
R06W0085	CN Train M30041-26	n/a		Armstrong, ON	27-May-06	2006
R07D0009	CN Train M-31031-10	Mile 99.13	Drummondville	Drummondville	12 February 2007	2008
R07T0110	CN Train M36321-26	Mile 264.94	Kingston	Cobourg	28 April 2007	2008
R07T0323	CN Train M-38461-29	Mile 9.30	Halton	Malport	30 October 2007	2008
R09T0092	CN Train M36231-20	Mile 247.20	Kingston	Brighton	21 March 2009	2010
R10T0056	CN Train M37631-30	Mile 1.40	York	Pickering	30 March 2010	2011

2.2 Main Findings

Table 2 summarizes the key aspects of interest as described in the TSB reports. The reports were grouped into four scenarios described as follows:

- High buff forces resulting in jack-knifing derailment.
- High draft forces resulting in string-lining derailment on curves.
- Equipment failures or malfunctions of equipment on the train (i.e. couplers).
- The train is placed into emergency brake by the locomotive engineer (i.e. grade crossing collision).

These different scenarios are colour coded in Table 2. Table 3 summarizes the train length, weight, and other pertinent details for each derailment. Table 4 summarizes the common characteristics of the derailments. The details regarding the TSB derailment reports and how they are classified are discussed in the following sections.

Table 2: Summary of TSB long train derailment reports since 2000: accident details

TSB Report #	Report Date	derailment speed	terrain	grade	curvature	draft or buff	estimated in-train force (kips)	coupler angle (rotation from centreline, degrees)	speed (reduction/ increase/ constant)	associated TSB reports	number of derailed cars
		mph		percent							cars
R00W0106	16-May-00	41	undulating	-0.5	mild S-curve	buff	n/r	n/r	reduction	no report	19
R01M0061	06-Oct-01	38	ascending	0	S-curve	buff	n/r	n/r	reduction	no report	15
R01T0006	16-Jan-01	45	undulating	-0.7 to +0.7	S-curve	buff	n/r	n/r	reduction	LP 022/2001	26
R02C0050	08-Jul-02	25	descending	-0.7	6	buff	n/r	9.2 to 10.3	reduction	no report	15
R02W0060	26-Apr-02	17	undulating	-0.5	tangent	buff	n/r	n/r	reduction	no report	8
R05D0039	02-Mar-05	stopping	n/r	n/r	tangent	buff	n/r	n/r	reduction	no report	16
R05C0082	27-May-05	13.7	flat	-1	tangent	buff	255	19	reduction	LP 057/2005 LP	24
R05V141	05-Aug-05	22	ascending	2	12	draft	n/r	n/r	constant	no report	9
R06W0085	27-May-06	stopping	n/r	n/r	curve	buff	n/r	n/r	reduction	no report	26
R07D0009	12-Feb-07	31	undulating	+0.4 to +0.8	tangent	draft	444	8	constant	LP 023/2007	8
R07T0110	28-Apr-07	46	undulating	-0.35	1.19	buff	135	30	reduction	no report	22
R07T0323	30-Oct-07	15	flat	0	0	buff	175	13	reduction	no report	31
R09T0092	21-Mar-09	50	undulating	bottom of sag	tangent	draft	200 to 250	8	constant	LP 017/2010	6
R10T0056	30-Mar-10	23	undulating	0	tangent	buff	219	21	reduction	LP 045/2010	15

high buff loads
string-line derailment
pull apart: broken knuckle
crossing incedent

Table 3: Summary of TSB long train derailment reports since 2000: train details

No.	TSB Report #	Derailment Date	Train Length (ft)	Train Tonnage	Train Type	Loco #	Car #	Speed (mph)
1	R05C0082	27-May-05	5,050	4,512	Mixed	4	77	13.7
2	R02W0060	26-Apr-02	5,412	9,363	Mixed	3	85	17
3	R06W0085 (no report, see R10T0056)	27-May-06	5,479	9,175	Mixed	3	86	
4	R07D0009	12-Feb-07	7,006	10,815	Mixed	5	105	31
5	R07T0323	30-Oct-07	7,839	7,810	Mixed	4	131	15
6	R05D0039 (no report, see R10T0056 and R07T0323)	02-Mar-05	8,138	14,712	Mixed	3	137	
7	R01M0061	06-Oct-01	8,700	10,000	Mixed	3	130	38
8	R00W0106	16-May-00	8,800	9,440	Mixed	2	136	41
9	R09T0092	21-Mar-09	8,850	11,845	Mixed	3	137	50
10	R05V141	05-Aug-05	9,341	5,002	Mixed	7	144	22
11	R10T0056	30-Mar-10	9,383	12,166	Mixed	3	149	23
12	R01T0006	16-Jan-01	9,450	11,700	Mixed	2	149	45
13	R07T0110	28-Apr-07	9,602	9,000	Mixed	3	135	46
14	R02C0050	08-Jul-02	9,708	17,201	Mixed	5	154	25

Table 4: Summary of TSB long train derailment reports since 2000: common characteristics

No.	UDE	Non-standard Coupler		The first car(s) derailed	Primary Cause			Seceondary Cause		Curvature	Grade, %
		Yes	Swing angle (deg)		Longitudinal	Coupler force, kip	Lateral	Longitudinal	Coupler force, kip		
1		YES	38	Loco	Buff	-250.0	Rail rollover			0	-1
2				Empty 80' center beam	Jackknifing		Wheel lift			sharp curve, No 10 crossover	-0.5
3		YES	30	Light HZGX maintenance car	Jackknifing					curve	
4	YES			59' empty tank & loaded 93' autorack	Pull-apart		N/A	Jackknifing	-444.0	0	+0.4 to +0.8
5		YES	13	Empty new dump car	Jackknifing	-175.0	wheel climbing			0	0
6		YES	13	Dump car	Jackknifing					0	
7	YES				Unknown		N/A	Jackknifing	-1000.0	S-curve	0
8				Empty tank	buff		Wheel climbing			shallow	-0.5
9	YES			Loaded tank and empty flat	Pull-apart	225.0	N/A	Jackknifing	-1500.0	0	ottom of sag
10				Empty center beam	String lining	-200.0	Car rollover			12	2
11		YES	42	Loco	Jackknifing	-216.5	Track panel shift			0	0
12	YES				Unknown			Jackknifing	-1150.0	S-curve	-0.7 to +0.7
13		YES	30	Light HZGX maintenance car	Jackknifing	-135.0	Wheel Lift			1.19	-0.35
14		YES		Empty hopper	buff	-210.0	Car rollover			6	-0.7

The following general conclusions can be made:

1. Train Length
    a. Nine (64%) of the 14 derailed trains are longer than 8,000 feet.
    b. Five (36%) of 14 less than 8,000 feet.
2. Train Types
    a. One hundred percent involve mixed trains with some empty cars.
    b. No unit trains and no fully loaded trains were involved.
3. The estimated in-train forces (for primary cause) are -135, -175, -200, -200, -216, -250 and +225 kilo-pounds (kips).
4. Most of the first derailed cars are empty (center beam, tank, hopper, dump car, maintenance car) except for two yard locomotives.
5. Half (7 out of 14) involve non-standard, large swing angle couplers under buff loading.
6. One derailment is a string lining case on 12 degree curve, but 5 other similar cases are mentioned in the TSB report (4 of these derailments involves undesired emergency braking).
7. Four out of 14 involve an undesired emergency braking (UDE); two were generated by broken knuckles and two by unknown reasons. Three of these cases are related to undulating terrain.

2.2.1 *High buff forces resulting in jack-knifing derailment*

The TSB reports that describe this derailment scenario are:

- R00W0106 [8]
- R01T0006 [10]
- R02C0050 [11]
- R02W0060 [12]
- R05D0039 [7]
- R05C0082 [13]
- R06W0085 [7]
- R07T0110 [16]
- R07T0323 [17]
- R10T0056 [7]

In all of these derailments, the train is progressing on a down-grade or undulating terrain when the locomotive engineer begins train handling procedures to lower the train speed using only the dynamic brake (DB) or the locomotive (independent) air brake, but not the train air brake. When the DB is applied, high retarding forces may be developed (as high as 98,000 lbs per locomotive) which can result in high buff loads progressing through the train. If there was slack in the train before the DB application, the run-in of trailing cars as the slack is taken up can cause large dynamic buff loads as the draft gear is loaded to maximum compressive travel.

This is not unusual and typically the train speed is reduced to manage the forces. However, in some of the cases where the train derailed, the train consist also contained one or more specialty cars with couplers that have larger than normal drawbar swing angles. As well, train marshalling has typically placed the loaded cars trailing empty cars, creating a situation where the majority of the train tonnage trails a long empty car. The result is that the high buff loads, in some cases combined with drawbar jack-knifing, caused a wheel to climb or a rail to roll over, initiating a derailment. In all cases listed above, the first car to derail is either a specialty car with non-standard couplers or a long empty car, with that car being located behind the locomotives or leading a large group of heavy loaded cars.

Also typical of these derailments is that following the initial derailment due to high buff loads, an undesired emergency brake event (UDE) occurs originating at the first derailed car. The resulting in-train forces that develop during the emergency braking period are exacerbated by poor marshalling practices that place blocks of loaded cars trailing empty cars, which causes more cars to derail than may have otherwise. Other factors that influence the severity of the derailment are whether the engineer bailed off the locomotive emergency brake and if the end-of-train braking system was applied (in cases where a manual application is required to initiate an EOT brake application).

2.2.2 *High draft forces resulting in string-lining derailment on curves*

A TSB report that describes this derailment scenario is:

- R05V0141 [14]

In derailments of this type, the train is progressing on an upwards-grade through sharp curves of more than 10 degrees. Normal train handling procedures, such as an increase in throttle to maintain speed, to negotiate the increasing grade and sharp curves cause high draft loads which create a string-lining situation at one of the curves. The draft forces are translated into lateral loads at the coupler that cause a wheel to climb or a rail to roll over on the low rail of the curve. This initial derailment may then cause an undesired emergency brake application which results in more cars derailing. As well, due to poor marshalling practices, loaded cars may have been placed trailing empty cars, possibly causing more cars to derail than otherwise would have. Only one derailment of this type was identified by the TSB.

2.2.3 *Equipment failures or malfunctions*

The TSB reports that describe this derailment scenario are:

- R07D0009 [15]
- R09T0092 [18]

In derailments of this type, the train is progressing following normal operating procedures when an equipment failure causes an undesired emergency brake event (UDE). A UDE may initiate at any point in the train when the brake pipe is broken or ruptured. When this occurs, the rapid decrease in brake pipe pressure propagates from the point of separation forwards and backwards along the train, causing the cars to initiate emergency braking in sequence outwards from the separation point. High in-train buff forces can then develop in the trailing portion of the train as the leading cars are in a state of full brake application while the cars trailing are decelerated only by the coupler forces generated by cars ahead of them.

If an EOT device is present, it will not automatically be activated to initiate emergency braking from the rear of the train, as it would be if the emergency braking sequence had been started at the locomotive. As a result, high in-train forces may develop as the cars in the trailing portion of the train take up available slack and fully engage the draft gears of the leading couplers before the braking system has been able to develop full brake retarding force [19]. Marshalling of loaded cars at the rear of the train may also have an effect on the severity of the subsequent derailment.

2.2.4 *Collision prevention by engineer*

A TSB report that describes this derailment scenario is:

- R01M0061 [9]

In this type of derailment the train is placed into emergency brake by the locomotive engineer as an attempt to prevent striking a person or vehicle on the track. A train placed into emergency braking should not derail, but in some cases the derailment that follows is due to high in-train buff forces exacerbated by poor marshalling practices that placed a string of loaded cars trailing either empty cars or cars with specialty couplers. During the derailment the engineer may or may not bail off the locomotive emergency brake, which will further affect the in-train forces. As well, if present, the EOT brake device may or may not be initiated by the engineer.

In-train forces that develop during emergency braking should not be high enough to cause equipment failure (e.g. broken coupler) and a subsequent derailment. However, high longitudinal loads can develop as a result of very sudden slack-action as the full-braking force progresses from the lead car to the end of the train. As the emergency brake signal progresses to the rear of the train, the draft gear become fully loaded as slack is taken up, and high forces can be generated. These forces can be reduced if the emergency brake signal is also started from the rear of the train using an EOT emergency brake application device, known in Canada as a Train Information and Braking System (TIBS) device. Having the rear of the train commence emergency braking at close to the same time as the front of the train reduces the stopping distance and in-train forces compared to emergency stops here a TIBS device is not used [19].

The high in-train buff forces that may result during an emergency brake application can cause a derailment in the same manner as discussed previously – the coupler angle, combined with the car lengths and curvature of the track form a kinematic condition that transfers a portion of the longitudinal force laterally. This lateral force is usually not high enough to cause any undue effects under normal operations, however when high enough, and given the right combination of coupler, car length, weight, and track curvature, may be sufficient to cause a wheel or truck to be pushed off the rails.

2.3 Summary of TSB Reports of Interest

A review of 14 relevant TSB derailment reports was undertaken to learn what effects in-train forces had on these derailments.

It was found that two derailments were caused by coupler failures due to improper manufacturing methods. One derailment was due to a collision and UDE at a grade crossing. Ten derailments are suspected to have initiated due to high in-train buff forces, in combination with curved track, long empty cars, and non-standard couplers. A selection of these derailments was used as a basis for modelling high in-train buff forces. One derailment was due to high string-lining forces occurring while climbing significant grade while travelling on sharp curves. This derailment was used as a basis for modelling high in-train draft forces.

2.3.1 *Summary of Observations*

From the reports reviewed it is concluded that there are five main factors contributing to derailments caused by high in-train forces for long trains:

1. Operating on undulating terrain.
2. Operating on terrain with sharp curves (curves greater than 5 degrees).
3. Inclusion of specialty cars with higher than normal coupler swing angle or truck center spacing.
4. Poor train marshalling that places empty or lightly loaded cars ahead of groups of heavily loaded cars.
5. Sub-optimal train handling, that includes the excessive use of dynamic braking to control speed, or sudden changes in throttle and brake settings without allowing time for train slack to adjust.

3 INDUSTRY PRACTICE OF OPERATING LONG TRAINS

3.1 Introduction

Canadian Pacific (CP) and Canadian National (CN) are Class 1 railways with headquarters in Canada that operate throughout Canada and the US. These companies follow the regulations set out by TC, the guidelines published by the AAR, and their own internal rules for safely and efficiently operating trains.

Since the early 1990s the rail industry has increased train lengths and weights in an effort to improve efficiency and reduce costs. At about the time when these longer trains began to enter service, the AAR issued the Train Make-Up Manual (TMM) [1], an update to the recommendations put forward in the Track Train Dynamics (TTD) (AAR Report R-185) [20]. These manuals presented recommendations on marshalling and handling to prevent excessive in-train forces, but the railroads themselves were responsible for implementing a process or procedure to safely marshal and operate trains on their systems.

This environment of self-regulation with respect to train length and makeup allowed the railroads to gradually increase train lengths and weights and to introduce the use of distributed power (DP) into their systems. However, as the average train length increased so did the number of accidents involving longer trains. The Transportation Safety Board (TSB) notes that between 2000 and 2010 they had investigated at least 14 derailments where in-train forces were a causal or contributing factor, and that from 1995 to 2010 the average length of train involved in a main-line derailment had increased by 25 percent [21].

After analyzing the results of hundreds of investigations the TSB developed the Watchlist in 2010. The Watchlist is a list of safety issues investigated by the TSB that pose the greatest risk to Canadians. As issues are addressed or resolved, they are removed from the Watchlist. In response to the increase in accidents involving longer and heavier trains, the TSB issued in its first Watchlist[4] a recommendation that "railways need to take further steps to ensure the appropriate handling and marshalling of longer/heavier trains. Detailed risk assessments are required whenever operating practices change. [22] "

The railways also noted that derailments due to in-train forces were increasing and in response developed improvements to their train marshalling and handling practices. These practices, once put into effect, appeared to have reduced the frequency of main line derailments due to in-train forces, and in response the TSB removed the longer/heavier trains item from the 2012 Watchlist [23] [24].

The following sections summarize the CP and CN approaches to train marshalling and handling.

[4] added to the Watchlist in August 2010. http://www.tsb.gc.ca/eng/surveillance-watchlist/rail/2010/rail_2.asp

3.2 CP Train Marshalling

Canadian Pacific (CP) developed and implemented its own train marshalling process and tools beginning in 2003 [25]. The project evolved over a ten year span into a complete train marshalling process called Train Area Marshalling (TrAM). Every train, regardless of its length, tonnage and destination is screened through this process to ensure compliance with all marshalling requirements before travelling on to a main line. TrAM was first introduced across CP on December 15, 2003 and in the US Operations on August 1, 2004.

CP implemented TrAM as it recognized that different track profiles and combinations of heavy ascending or descending grades with high degree of curvature raised the necessity to consider different train marshalling techniques for different train types (e.g. uniform bulk, uniform Intermodal or mixed manifest trains).

TrAM is a comprehensive set of train marshalling rules and supporting computer tools designed to permit the efficient use of Distributed Power (DP) beyond the traditional use in bulk trains. TrAM also applies marshalling restrictions in a territory-specific manner to avoid restrictive marshalling rules where they are not required, and to apply consist specific rules dependant on the territory and the cars in the consist.

Following the implementation of TrAM in 2003, CP's train designs grew progressively longer and heavier which required the use of DP in more than one location in the train, known as multiple remotes. This change in practice triggered the design, development and implementation of an enhanced version of TrAM, known as TrAM 2, which was implemented in July 2009. TrAM 2 built on the more than five years of experience gained by CP operations in train marshaling knowledge using TrAM. The introduction of Multiple Distributed Power (MDP) Train models has enabled CP to extend the application of DP from 7000 feet on bulk trains to 14,000 feet on intermodal MDP trains.

Description of TrAM [25]
The TrAM process takes into account the in-train forces that develop in a train during operations. In describing the TrAM process, CP states that in-train forces can arise from three distinct causes (parameters):

1. Longitudinal forces: These are forces resulting from locomotive throttle modulations, train resistance (due to grade, curve and rolling resistance), and acceleration/deceleration of the train. They are divided into draft (run-out) and buff (run-in) forces, where draft causes tension forces in couplers and buff causes compression forces.
2. Slack Action forces: These are sudden/instantaneous in-train forces resulting from changes in the steady-state draft/buff conditions of the train. They arise from the relative motion that takes place between cars as they take up or free up the slack that exists in standard friction draft gear. Although these forces are essentially longitudinal forces, they arise due to dynamic effects, not steady state throttle, braking, or drag force effects. Slack forces can potentially be extremely high, especially in situations where draft gear travel is taken up and the draft gear travels limits are reached.
3. Lateral forces: Lateral forces due to in-train forces are caused by the combination of the longitudinal in-train force, track curvature, the coupler angle and length, and the length of two adjacent cars [1]. This force is in addition to the wheel-rail forces that occur as a freight car passes through a curve. Lateral forces due to curving at under or overbalance speed are not accounted for in TrAM.

Locomotive throttle, train braking, dynamic braking (DB), and locomotive placement when using distributed power (DP) affect each of the three force mechanisms, either directly or indirectly. On tangent track, excessive longitudinal draft and buff forces may not lead to high lateral forces but can lead to coupler knuckle failure or damage to the freight car structure. On curves, draft and buff forces create lateral loads that can cause derailment due to string-lining (excessive draft) and jack-knifing (excessive buff).

String-lining occurs when excessive draft forces cause a low weight car to be pulled towards the inside of a curve. Jack-knifing occurs when excessive buff forces cause a low weight car to be pushed to the outside of the curve. In both situations the lengths of the cars, the lengths of the couplers, and the car weights all factor into development of lateral loads, creating loading conditions where the lateral to vertical load ratio (L/V) exceeds the allowable limit for the track.

The American Association of Railroads (AAR), through various field tests and derailment investigations, has determined the following threshold limits for L/V ratios:

- L/V > 0.82 (wheel lift impending)
- L/V > 0.75 (wheel may climb worn rail)
- L/V > 0.64 (poorly restrained rail may overturn)

In general, these increased risk L/V loading situations are most likely to happen on sharper curves with empty cars under higher than normal buff and draft forces. Identifying the conditions under which these situations are expected to occur is a focus of the TrAM process. To analyze this situation, TrAM uses the coupler angularity relationship developed by the AAR in the Train Makeup Manual [1].

Rules Governing TrAM [25]

The rules used by TrAM to keep in-train buff and draft forces to acceptable levels, ultimately keeping the estimated L/V ratio to 0.82 or lower, are applied to the trains in a territory-specific manner. The TrAM rules are applied differently based on the severity of track profile, train make-up and vehicle characteristics. To achieve this, the CP network is divided into 5 “Areas” (Area 1 through Area 5) for the purposes of train marshalling. The division of the network is based on track profile, including characteristics such as grade, curvature, and undulations. Area 1 is the least restrictive, while Area 5 is considered the most restrictive.

Area	Typical most extreme Physical Characteristics in Area
1	1.35% ascending grades, with 5 degree curves 1.26 descending grades, with 5 degree curves
2	0.75% ascending and descending grades (undulating), with 10 degree curves
3	1.3% ascending grades, with 6 degree curves 1.7% descending grades, with 11 degree curves
4	1.3% ascending grades (undulating), with 8 degree curves 1.0% descending grades (undulating), with 8 degree curves
5	2.3% ascending grades, with 11 degree curves 1.7% descending grades, with 11 degree curves

TrAM Requirements [25]

Given the five area designations, CP then identified requirements that must be taken into consideration when devising train marshaling rules. These requirements are as follows:

1. Trailing Car Tonnage (TCT)

- Applied mainly to mixed trains.
- TCT is the total weight of all cars following any car in a train (up to a remote locomotive).
- TCT is applied to cars behind a remote locomotive as it would be for a conventional train.
- TCT is applicable mainly to light or empty cars, or cars longer than 65 feet.
- The TCT limits vary with TrAM Area 1 through 5 for any given car.
- TCT is important to prevent derailments caused by excessive L/V due to high draft and buff forces.

2. Threshold Tonnage
   - Maximum train tonnage that can be handled without the possibility of causing a TCT violation. It differs by TrAM area.
   - By adjusting the train makeup through re-positioning of cars that exceed TCT limits (i.e. empty cars or long cars) the Threshold Tonnage for a train can be increased for a given set of cars. Therefore, by readjusting the train makeup, the Threshold Tonnage of the train can be increased without compromising the TrAM L/V limits.

3. Draft forces
   - Maximum draft forces behind each locomotive are considered to prevent train separations and damage to track structures.
   - Factors that are accounted for are: tractive effort of the driving wheels, grade, trailing tonnage, and train resistance forces
   - Does not account for dynamic (slack action) forces.
   - Train sectioning and remote locomotive placement is done such that at any point on the train the maximum draft force cannot exceed the haulage capacity of 2 AC locomotives.

4. Buff forces
   - Calculated for the cars directly ahead of the remote locomotives.
   - Train sectioning and remote locomotive placement is done such that at any point on the train the maximum buff force cannot exceed the haulage capacity of 1 AC locomotive.

5. Remote zone
   - The cars directly ahead of a remote locomotive are designated the ‘remote zone’.
   - The remote zone consists of 5 cars ahead of a single remote locomotive or 10 cars ahead of two remote locomotives.
   - The remote zone must meet minimum weight requirements.
   - The remote zone effectively ‘cushions out’ the in-train forces generated by the remote locomotives.
   - Empty cars and combinations of short and long cars are monitored and controlled in the remote zone.

6. Maximum train length to last remote locomotive
   - For remote locomotive operation the last locomotive must remain within a minimum distance from the lead (controlling) locomotive.
   - This restriction is to ensure that if radio contact is lost with the last locomotive, that air pipe signals (from the lead locomotive) will reach the last locomotive within an acceptable time. This is required so that during the application of the train brakes the remote unit would drop to idle with only the command from the air brake system. This is to prevent the remote unit from staying ‘on-throttle’ and pushing on the end of the train while the head-end is braking – a situation that would create excessive buff forces.

7. Dynamic Brakes
   - The combined DB force for the locomotives must not exceed 200,000 pounds.
   - For DP trains, if the tonnage between locomotive sections is not sufficient (to limit longitudinal forces) this limit may be exceeded: in these situations a reduced DB setting can be defined and the locomotive engineer can be prompted to not exceed this DB setting.

8. Distributed Power
   - The correct combination of lead and remote consists is checked.
   - Maximum distances between locomotive consists is monitored.
   - The requirement to reduce or cut out DB is monitored.
   - Remote zone weight/length requirements are monitored.
   - The requirement for a minimum percentage of train weight in each train section is monitored.

9. Long Car & Short Car Combinations
   - For cars over 65 feet long, the length of adjoining cars is monitored and considered.
   - The system calculates a ‘car length factor’ (CLF) which is the greater of the two length differences between one car or platform and adjoining cars or platforms.
   - Cars with high CLFs can handle lower TCT than a string of uniform length cars (due to the kinematics of car-coupler geometry).

10. Ascending Grade Weight Zone
    - Light/empty cars near the head-end, under high traction conditions such as ascending a grade, could develop high L/V values.
    - To prevent high L/V’s, the head-end 10 to 15 cars must meet minimum weight requirements.

11. Cushion Drawbars or End of Car Cushioning Devices (EOCCDs)
    - Cushion drawbars, or EOCCDs, can create situations where excessive slack action occurs under normal train operating conditions, especially when multiple cars with EOCCDs are marshalled as a block.
    - Simulation studies commissioned by CP have shown that:
      - long groups of cars (70 cars) with EOCCDs can create very high in-train buff forces during full service brake stops, but that shorter groups of cars (30 to 40 cars) with EOCCDs will create more acceptable levels of in-train forces.
      - There is an increase in buff and draft loads with an increasing number of EOCCDs.
      - that doubling the number of cars with EOCCDs results in 100 times the number of draft force cycles with 70kip peaks.
    - To control in-train forces, CP has unit blocks with EOCCDs are split by remote locomotives, or by blocks of conventional cars, where possible keeping blocks of cars with EOCCDs to less than 40.
    - Empty cars adjacent to blocks with EOCCDs are avoided.

3.3 CN Train Marshalling

The description of CN train marshalling rules presented in this section is summarized from correspondence between Robert Leblanc of CN and the authors [26]. A summary of the timeline of changes to CN marshalling practices as described in TSB reports prior to 2010 is presented in Appendix A.

CN marshalling rules cover a diverse mix of equipment and operating considerations. Because of this operational diversity, marshalling information is rationally segmented into various operating documents according to the various user groups that are responsible for marshalling awareness and/or compliance. These documents include [26]:

- time tables;
- General Operating Instructions (GOI);
- Locomotive Engineering Operating Manual;
- System Special Instructions;
- Regional Special Instructions;
- Availability of a Train Marshalling Job Aid [27] for certain regions;
- and various documents are routinely used by conductors, locomotive engineers, RTC, Yard Masters, etc.

As well, CN report that some important train marshalling instructions and rules are intentionally not published in the operating documents that are required to be carried by operating personnel, such as train crews. They state that while placing train marshalling rules in these documents may serve to provide some external visibility, in many cases it is impractical to expect train crews to properly interpret and/or comply with complex and often multi-variable marshalling requirements that are more suitably dealt with by computer systems when the train is being built at origin.

Given this background, in 2010 CN undertook a comprehensive review of train marshalling practices, including a benchmarking exercise of industry best practices. This exercise resulted in CN implementing new train marshalling policies and practices in key operating train corridors using a risk-based approach and a multi-phased implementation plan. These marshalling rules have since further evolved and the implementation has been expanded to nearly all of CN mainline tracks. Related to this, CN also made several marshalling awareness presentations to Transport Canada and the Transportation Safety Board [28]. The changes reported by CN that took place following this review are as follows:

- Specific train marshalling rules were developed to reduce in-train and track-train forces, based on science, experience, benchmarking with other railroads, and a review of historical incident root-causes, including analyses in TSB reports.
- The effectiveness of these marshalling rules was verified and supported by reviewing historical incidents in the context of the proposed rules, including all of those listed in the TSB Brighton incident report (R09T0092).
- A CN 'rules engine' was developed to review marshalling rules compliance on an historical basis, thereby identifying priority locations and trains, and allowing a review of train designs to facilitate improved marshalling.

- CN's operations information system (SRS) was enhanced with the functionality to flag marshalling rule compliance, thereby notifying operating personnel of a marshalling issue before the train is assembled.
- A daily automated train marshalling report was developed and implemented to measure day-to-day performance and provide visibility into compliance with CN train marshalling Rules 1, 2 and 2A.

3.3.1 *Marshalling Rules*

CN has provided the authors with a document entitled *CN Marshalling Rules & Policies Overview (Nov 2014)* [6] which provided a consolidated summary of various CN marshalling rules in effect at that time. CN stated that these general rules may be augmented with more restrictive marshalling rules as required in specific corridors based on experience, train performance, topography, risk, derailment analysis, and other potentially unique issues of concern. These additional restrictions may include (but are not limited to) the following examples:

- Dangerous Goods (GOI - TDG)
- Dimensional loads (GOI 3.10)
- Passenger equipment moving on freight trains (GOI 3.14)
- Spine cars or skeleton cars (GOI 3.16)
- 2-axle cars (GOI 3.16)
- Open top loads (GOI 3.17)
- Cars handling CWR (GOI 3.19)

As an example of the rules described by CN, the generalized train length and tonnage policy described by CN is shown in Table 5, and the general marshalling rules that apply to conventional manifest trains hauling more than 8,000 tons and to Distributed Power (DP) trains hauling more than 9,500 tons is shown in Table 6.

The *CN Marshalling Rules & Policies Overview (Nov 2014)* also lists detailed rules governing the placement and length of:

- Intermodal equipment in trains greater than 6,000 feet long,
- Distributed power (DP) marshalling requirements and locomotive placement, and
- Territory specific marshalling rules.

Table 5: CN Generalized Train Length and Tonnage Restrictions [6]

	Intermodal:		Manifest:		Bulk:	
	Non DP:	DP:	Non DP:	DP:	Non DP:	DP:
Feet	12000	14000	10000	12000	10000	12000
Tons	12000	14000	14000	20000	18000	24000

Notes: a) length also restricted by siding infrastructure
b) in addition to the above, additional local restrictions may apply
c) authorized length / tonnage may deviate from above limits on specially designated trains

Table 6: CN Marshalling Policy: Manifest Trains [6]

Rule 1: Tail End Heavy	• no more than 33% of train weight in rear 25% of train length
Rule 2: Empty Block Stability	a) Head-end Portion: no more than 8000 tons on a conventional train (DP train 10,000 tons) may be marshalled behind a solid block of 10 or more consecutive light cars that are entirely positioned within the head-end 20 positions, and; b) Remaining Portion: no more than 10,000 tons on a conventional train (DP train 10,000 tons) may be marshalled behind a solid block of 10 or more consecutive light cars anywhere in train, exclusive of the head-end 20 positions.
Rule 2A: Empty Block Stability *(Winnipeg – Chicago Corridor)*	a) For a train powered by a single locomotive in the head-end consist, the first five (5) positions of the train must not be occupied by cars weighing 45 tons or less. Preferably, the head-end 5 cars would be loads. b) For a train with two or more powered locomotives in the head-end consist, the first ten (10) positions of the train must not be occupied by cars weighing 45 tons or less. Preferably, the head-end 5 cars would be loads.
Rule 4: Excessive Cushion Cars	• maximum of 120 cushioned cars

In addition to specific train marshalling initiatives, CN has also implemented newly available technologies that are expected to enhance safety and to help reduce risk. These are as follows:

- CN has reported that the majority of high horsepower road locomotives are now equipped to automatically send a radio command to the SBU associated with the head-end IDU whenever the controlling lead locomotive experiences an emergency brake command, whether operator initiated or due a trainline UDE, conductor emergency valve, etc.
- CN has reported that it has installed Locotrol Distributed Power (DP) technology to assist in managing in-train forces and lateral forces in curves. As of 2014 CN has over 560 DP-equipped locomotives in the fleet, or equivalently 47% of the road locomotive fleet (3,000 HP or greater). This number is planned to increase to over 741 DP locos (57%) over the next two years. Also, CN expects to continue to expand the use of the DP asynchronous control that allows for the head-end and DP remote locomotives to be operated at different throttle settings. This form of independent control provides enhanced command of in-train forces on challenging terrain.
- CN has reported that it has begun operations using Trip Optimizer (TO) technology, an intelligent auto-pilot control system that automatically determines optimal throttle settings on locomotives. The technology is interactive with the topography and adjusts to slow orders. In addition to being an environmental enhancement through reduced fuel consumption, Trip Optimizer controls throttle or dynamic brake adjustments to reduce in-train forces, minimizing the likelihood of train separations or damage to goods. CN

reports that by the end of 2014, Trip Optimizer was operational on over 275 CN locomotives.

- CN has reported that it has begun operations using Wi-Tronix remote monitoring capability that allows operational data being streaming to the locomotive event recorder to be monitored and/or collected for timely analysis of train handling rules compliance. A variety of key train handling rules are monitored in real-time and an email alert is automatically sent out to notify designated stakeholders when a compliance exception occurs. By the end of 2014, CN expects to have over 1,200 road locomotives equipped with Wi-Tronix technology.
- CN has reported that it has developed an in-house system called Locomotive Engineer Performance Profile (LEPP). LEPP is a performance score-carding system that uses train handling data from the Wi-Tronix remote monitoring equipment to assess and rank driver proficiency as well as compliance with critical train handling rules. LEPP provides visibility into driver proficiency on an ongoing basis as well as identifying marginal performers in an objective and consistent manner, which allows targeted actions to be taken, such as additional training, coaching, mentoring, etc, to help address suboptimal train handling in a timely manner.

3.4 General Train Handling Practices

Train handling has long been recognized by the railroads as having a significant effect on in-train forces. CN, in its *Locomotive Engineer Operating Manual* (CN-LEOM), and CP, in its *General Operating Instructions* (CP-GOI), both have sections detailing recommended train handling practices.

Sections of these operating manuals and instructions are discussed in the TSB derailment reports where train handling was considered to be an issue in the cause or severity of the derailment. Those train handling procedures are considered to be most relevant to the control of in-train forces, and are summarized in this section.

Overview of General Guidelines
In general, the railroads understand that proper handling of trains of any length is required to prevent broken equipment or derailments due to excessive draft or buff forces that can arise due to excessive throttle, braking, or ‘slack action’ forces.

For example, CP in the CP-GOI provide guidance on the use of the DB and the throttle in Section 16, entitled Train Handling, which states [13];

- When changing from motoring to DB when the train is in motion, pause for ten seconds with the throttle in IDLE.
- When moving into the braking zone, pause at the minimum braking position long enough to adjust train slack, then move the handle slowly within the braking zone to obtain the desired braking effect.
- After releasing the DB in preparation for applying power, the throttle must be advanced with care to ensure gradual adjustment of train slack.
- When governed by temporary speed restriction, when DB factor of the lead locomotive consist is 14 or greater, the DB handle MUST NOT be placed in a position higher than No. 5 for approximately one half mile prior to the beginning of, or when the locomotive is moving over any temporary speed restriction. Note: The train air brakes and DB may be used to comply with the speed restriction.

Pertinent sections of the CN-LEOM have been summarized in several TSB reports ([16], [17], [18], and [29]) with the most recent summary available in R10T0056 [7]. From these reports, some examples of the general guidelines specified by CN can be summarized as follows:

- Locomotive engineers should have a thorough knowledge of the physical characteristics of the territory they will be operating and use this knowledge and good judgement to ensure proper train handling techniques.
- Locomotive engineers must utilize "forward planning" in consideration of territory profiles, planned stops, required speed adjustments and slack control, avoiding aggressive use of the locomotive throttle and train braking systems.
- Throttle manipulation must be used as the primary means of controlling the train.
- Dynamic brake must be fully utilized as the initial braking force.
- Make only incremental/gradual throttle and brake adjustments
- Select and adjust the throttle, dynamic brake, and air brake in a manner which minimizes in-train and track-train forces; and
- Allow slack to gradually adjust within the train before increasing throttle, dynamic brake, or air brake applications.

Variations of the procedures listed above that are in use by CN and CP are used by the railroads as a way to control train slack action and in-train forces. However, the procedures may be different or altered slightly depending on the region of operation and the train make-up, and as such a comprehensive listing or review of all the pertinent procedures is beyond the scope of this report.

Use of Dynamic Brake

The CN and CP guidelines display a preference to using the DB for initial braking effort, although both guidelines acknowledge that the DB must be used with caution, and that throttle, air brake, and DB applications must be performed with appropriate care and time delays to allow the train to take up slack to minimize in-train forces due to slack motion.

The favoured use of the DB over the air brake is for several reasons:

- Repeated reductions in brake pipe pressure without sufficient time allowed to re-charge the system pressure can lead to a complete loss of the air brakes. The use of DB for continuous brake retarding force eliminates the need for continuous or repeated use of the air brakes in many operational situations, helping the train to maintain service brake capability on long descents.
- The application and release of the air brakes is delayed for cars at the rear of the train, or for cars furthest from a locomotive providing the air brake signal. This delay in the release of the brakes can result in some cars have brakes that 'drag' when the train is under positive throttle and accelerating. This situation increases fuel use and component wear. The use of DB eliminates this possibility.
- Use of the air brakes rather than the throttle or DB for speed control causes wear of the brake shoes and the wheel treads.

The CN-LEOM states that the use of DB is effective in slowing the train for planned stops, speed restrictions and speed control, and that when DB is available it must be used as the first means of initiating required train braking forces. When DB is in use, the automatic air brake may be required to provide additional braking effort, although there is no limit on the amount of time spent in DB mode. As with most braking and throttle actions, the DB application is to be gradual and incremental, allowing the slack to bunch against the locomotive consist.

The use of DB is an excellent method of speed control, but it is capable of generating high in-train and track-train forces which, in the case of head-end motive power, concentrates the brake retarding force at the head-end of the train. Therefore there are limits to the amount of braking which should be applied using DB and to avoid excessive force it may be necessary to use a combination of DB and automatic brake, and/or to implement speed control tactics further in advance.

Also to be considered when using DB is that due to the design and nature of the electric traction motors used in locomotives, the maximum DB retarding forces occur in the 5 to 30 mph speed range (for any DB setting). Therefore, extra care must be exercised in this speed range so as to not develop excessive DB retarding forces.

The use of DB can lead to high in-train forces even with careful use, even where train slack has been taken up. The excessive buff forces that can be generated using the DB may result in a derailment or gradual deterioration of the track structure, particularly if the forces occur at a turnout, a crossover, within a sharp curve or at a track irregularity. Because of these possibilities, operators are instructed to exercise extreme caution when making bunched stops or decreasing speed, giving due consideration to grade, curvature and weight distribution of the train consist, and to exercise care when using DB without train air brakes to effect a slowdown or stop.

The proper use of DB is especially critical when three or more locomotives are at the head-end of the consist. For example, both CN and CP have rules restricting the number of head-end locomotives with operative DB, depending on whether the locomotives are alternating current (AC) or direct current (DC) powered locomotives[5]. Along with the number of axles with active DB, there may also be restrictions on the use of the DB depending on track conditions. For example, to avoid train handling problems, the CN-LEOM describes the following DB restrictions:

- For 1 or 2 locomotives in a consist there are no DB restrictions.
- For 3 or more locomotives in a consist the DB use is restricted to a maximum of 500 Amps when the head-end is entering a turnout, crossover or curve, until at least half the train has passed through.

As an example of the procedures applied with the use of DB, the CN-LEOM describes the main steps in applying DB as follows:

- When changing from power to DB, reduce the throttle to IDLE one position at a time, pausing briefly in each throttle position. Once the throttle is in IDLE, wait 10 seconds, then move the DB handle to SET-UP position. The pause allows current in the traction motor fields to dissipate, prevents a surge of retarding force, and allows the train slack to adjust.
- To initiate dynamic braking, advance the DB handle past SET-UP in small, incremental moves, allowing the slack to bunch against the locomotive consist.
- Once the slack is bunched against the locomotive consist, make further adjustments of the DB handle in a smooth and steady manner, allowing at least 30 seconds in progressing to maximum braking effort.
- If the wheel slip or brake warning light illuminates, reduce the dynamic braking effort until the light extinguishes. If the light remains illuminated, stop the train and inspect the locomotive consist.

[5] High horsepower (4,400 hp) AC locomotives are capable of generating up to 98,000 pounds of DB braking effort per locomotive.

- To prevent slack from running out when coming to a final stop, gradually apply the independent brake. The DB handle may be moved to the OFF position once the independent brake becomes effective. The train brakes may also need to be applied to prevent the slack from running out when stopping on an ascending grade.

4 REVIEW OF INDUSTRY STANDARDS

4.1 Introduction

The previous section reviewed the practices that CN and CP use to manage train make-up and handling to suit their particular regions.

This section will review the generally accepted railroad industry rules and practices as suggested by the Association of American Railroads (AAR) in the Train Make-Up Manual [1], and review the load limits placed on the design of railcar components in the AAR Manual of Recommended Standards and Practices (MSRP) [30]

4.2 AAR Train Make-up Manual

The Train Make-up Manual (TMM) is an updated version of previously published guidelines that were part of a report published by the AAR in 1979 called Track Train Dynamics (TTD) (AAR Report R-185 [20]). The TTD research program resulted in the first industry wide train make-up guidelines that were written to control in-train forces though the regulation of trailing tonnage, use of head end and helper locomotives, and the placement of critical car combinations in the train according to TTD principles.

As trains became longer and the use of distributed power increased, the guidelines outlined in the 1979 TTD report required updating. The Vehicle Track Systems (VTS) Program, a collaborative effort involving the AAR member railroads, the AAR, the RAC-TC, and the FRA, worked to update the guidelines that were then published as the Train Make-up Manual. As stated in the abstract of Report R-802, the TMM is “intended to be a source of information for considerations such as train size and car placement, that relate to the make-up of trains” [1].

Section 2.0 of the TMM presents general train make-up guidelines, and recommends for unrestricted interchange service trains that meet the following conditions:

1. Total train weight is less than 4000 tons, <u>and</u>,
2. Maximum gradient is less than 2.0%, <u>and</u>
3. Maximum curvature is less than 8 degrees

Of note is that these conditions do not specify a maximum length. This means that there is a possibility for a relatively long train to be created that passes these rules. For example a 4000 ton train with 2 locomotives, pulling all empty cars could be upwards of 100 cars long. If the empty cars were all over 90 feet long the potential exists to create a train more than 9000 feet long.

For trains that do not meet these criteria, the reader is referred to Section 5.0 of the TMM, which outlines a series of calculations along with tables that allow the reader to calculate allowable trailing tonnage values for a selected car. These calculations require an understanding of the forces involved in train handling.

Section 3.0 of the TMM summarizes the main forces involved: the train resistance forces (grade, curving, rolling, and acceleration), tractive effort forces, and braking forces. Equations describing tractive effort for a given speed and horsepower rating are presented, accounting for rail adhesion. Braking forces are estimated, allowing for dynamic braking of locomotives, for the automatic air brake of rail cars, and the independent brake of locomotives.

Section 4 of the TMM summarizes the steady state forces that develop within a train that are applied for a relatively long period of time, such as during a long climb ascending grade, or retardation using dynamic brakes. Transient in-train forces generated when draft gear slack limits are reached are also discussed, describing how these forces are typically present in track with crests, sags, and undulating terrain.

Section 5 of the TMM presents the detailed make-up guidelines. The system presented follows two methods, where:

a) Method 1: used for steady state operation, assuming no acceleration. Tables (and plots) of trailing tonnage per ton of long car weight are presented for 92-to-38, 92-to-44, and 92-to-58 foot long car combinations[6].
b) Method 2: used for starting, accelerating, decelerating or stopping trains. Tables (and plots) of trailing tonnage per ton of long car weight are presented for 92-to-38, 92-to-44, and 92-to-58 foot long car combinations for ascending grades and for descending grades with 250 kips of DB force.

In total nine tables, with accompanying plots, are presented to be used to calculate allowable trailing tonnage (TT). As well, tables are presented for converting long-short car combination lengths to those differing from the three combinations used in the TT tables.

Section 6 describes special car cases, such as multiple platform cars, single axle cars, cars with increased lateral truck clearance, long cars with 43 inch couplers, long car combinations in turnouts, end-of-car cushioning devices (EOCCD), and slack considerations.

Section 8 describes locomotives and the placement of helper locomotives to achieve the lowest drawbar force. At the time of publication of the TMM, distributed power was not widely used even though the benefits of using DP were understood.

Section 10 presents the trailing tonnage force calculations that were used to generate the table presented in Section 5. The method assumes that a safe lateral load at the wheel is an L/V value of 0.82 or less. The calculation then uses this load limit to arrive at the load generated at the bolster, and ultimately the longitudinal load required to exceed this safe L/V limit.

4.3 AAR Manual of Standards and Recommended Practices

The AAR publishes the Manual of Standards and Recommended Practices (MSRP) to guide the rail industry in the building of cars and components that can be used on the railroads in full interchange service. The MSRP has very detailed rules and recommendations regarding the design and testing of all aspects of freight cars in order for the cars to be freely used and repaired on an exchange basis throughout the railway network anywhere in North America.

The sections of the MSRP that are related to longitudinal in-train forces are reviewed in the following sections.

[6] 92-38 refers to a 92 foot long car coupled to a 38 foot long car.

4.3.1 Pull Apart Force Limits

Freight cars operating on the North American railroads must be built to a common standard to enter interchange service. The design parameters are documented in the AAR Manual of Standards and Recommended Practices (AAR-MSRP). With respect to longitudinal in-train forces the design standards for the five major components that interact to form the car-to-car connection between freight cars are of interest. These are the:

1. coupler knuckle body,
2. coupler body (drawbar),
3. coupler yoke,
4. draft gear, and
5. draft gear pocket (in the car body)

AAR-MSRP Section M-211-00, 4.2.2.1.3 specifies that the coupler knuckle to have no more than 0.03” permanent set at 400,000 lb test load, and minimum ultimate strength of 650,000 lb.

AAR-MSRP Section M-211-00, 4.2.2.1.3 specifies that the coupler body is to have no more than 0.03” permanent set at 700,000 lb test load, and have minimum ultimate strength of 900,000 lb.

AAR-MSRP Section M-205-00, 4.3 specifies that coupler yokes must display no more than 0.03” deflection after 750,000 pounds of test load, and must have a minimum ultimate strength of 900,000 pounds. (page B-15, section 4.3).

AAR-MSRP Section B specifies the design limits for draft gear. Draft gear are energy absorbing devices, and must withstand a prescribed load over a prescribed amount of travel, depending on draft gear type and use. When a draft gear has been loaded to the maximum design travel limit, it is in a “bottomed” condition and will transmit longitudinal loads between the yoke and draft gear pocket directly (without any cushioning effect)[7].

AAR-MSRP Section M-1001 Section 4.4.13 specifies the design loads for the draft gear pocket of the car body. Three load conditions are given:

1. Draft forces of 350,000 lb. AAR M216 describes the fatigue spectrum limit load of 350,000 pounds, therefore it is assumed that the load limit specified in this section is also the fatigue design load, as it is lower than the design ultimate load of the coupler knuckle.
2. Static compression forces of 1,000,000 pounds.
3. Impact compression of 1,250,000 pounds.

Table 7 summarizes the design loads for the coupler components, for the requirements set forth in the current version of the AAR-MSRP as of 2010. The coupler knuckle is designed to fail at the lowest load, and therefore acts a “fuse” in the system, having an ultimate load (to failure) that is below the permanent-set load for the coupler body and yoke.

[7] For the purpose of this study, the details of the draft gear operation are not important.

Table 7: AAR-MSRP load limits for coupler components (2010)

	load at maximum permanent set of 0.03 inches (lb)	minimum ultimate load (lb)
knuckle	400,000	650,000
coupler body	700,000	900,000
coupler yoke	750,000	900,000

As the knuckle is designed as the weak link in the train system in draft conditions, the draft in-train force limit is determined by the strength of knuckle. In 1992, when the AAR Train Makeup Manual [1] was published, there were two coupler system materials in use in North America, classified as Grade C and Grade E steel. According to the AAR Train Makeup Manual, couplers made of the Grade C material have an accepted working limit[8] of 250,000 pounds in draft, and couplers made of the Grade E material have an accepted working limit of 350,000 pounds. The ultimate design load was stated as 300,000 and 400,000 pounds for the Grade C and Grade E materials respectively. Based on discussions between the NRC and industry it was agreed that old cars equipped with knuckle made of these two materials are still in use at this time.

The current AAR-MSRP standard (as of 2010) as shown in Table 7 indicates that load at maximum permanent set of 0.03 inches is 400,000 pounds. Following the AAR TMM rules where the permanent set limit is used as the working limit, the current material grade has a draft limit of 400,000 pounds.

Table 8 is a summary of the knuckle force limits for different grades of knuckle steel used in North American since 1990s that may currently be in service, showing the load limits that produce permanent deflections and ultimate strengths.

Table 8: Load Limits to Permanent Set and Ultimate Strength of Different Knuckle Materials

Knuckle material grade	Load at maximum permanent set (pounds)	Ultimate Strength (pounds)
Grade C (1992)	250,000	300,000
Grade E (1992)	300,000	400,000
AAR MSRP 2010	400,000	650,000

Coupler Fatigue

In normal operation the knuckle assembly is subjected to many loading and unloading cycles due to train action and motion. For this reason, a coupler knuckle assembly must pass a fatigue test as outlined in AAR-MSRP Section S, Specification M-216 before the final design is allowed to be used in interchange service. This test is in addition to the knuckle bodies meeting the ultimate and permanent set loading condition described above.

[8] It is assumed that the “accepted working limit” as reported in the TMM corresponds to the load at maximum permanent set of 0.03 inches of deformation as reported by the current MSRP.

The fatigue test requirements for types E and F couplers are described in Section 4.4 and 4.5 of AAR-MSRP Section S, Specification M-216. Figure 1 reproduces the input load spectrum, from Figure 4.1 of Specification M-216. To be approved, the average life of four knuckles tested must exceed 600,000 cycles with no individual knuckle exhibiting a life below 400,000 cycles. The maximum force range in the fatigue spectrum is given as 283,000 pounds, with a total of 1058 cycles occurring in each spectrum. From the requirement, it is seen that to reach the minimum of 400,000 cycles the spectrum must be repeated fully a minimum of 378 times, with the peak load occurring 1,512 times. Also note that 54 load cycles in the spectrum have peak loads over 200,000 pounds.

Table 4.1 Knuckle fatigue test load cycles

Segment	Number of Cycles (Sinusoidal Form)	Total Elapsed Cycles	Cycle Load Range (Min to Max)[a/]
1	4	4	18–283 kips
2	2	6	18–265 kips
3	7	13	18–245 kips
4	10	23	18–227 kips
5	31	54	18–209 kips
6	77	131	18–189 kips
7	65	196	18–171 kips
8	73	269	18–154 kips
9	89	358	17–133 kips
10	105	463	17–115 kips
11	129	592	17–97 kips
12	187	779	17–79 kips
13	279	1058	15–59 kips

[a/] ±5% margin of error on minimum loads
±2% margin of error on maximum loads

Figure 1: Knuckle fatigue test load cycles (Table 4.1 from AAR-MSRP Specification M-216)

In normal operation, when fatigue cycles are accumulated in service, the eventual fatigue failure of a component typically happens at loads that are below the maximum load experienced by the component up till that time. This is because fatigue crack initiation and growth occurs as loading cycles occur and as damage is built up. The peak loading cycles cause a crack (or cracks) to form but do not lead to complete failure. The cracks continue to grow at force levels that are lower than the peak loads experienced by the component in the past (or during testing). Thus, for currently manufactured knuckles, where the load to reach ultimate failure (in one cycle) is 650,000 pounds, and permanent set is 400,000 pounds, the peak load that occurs during the fatigue test is 283,000 pounds, approximately 56% lower than the ultimate strength of the coupler. For a coupler that has reached the design fatigue limit in terms of number of cycles, or critical crack growth, the load to cause failure in this condition may be lower than either of these loads, so that for a 'worn out' coupler the final pull-apart failure load is unknown but can be expected to be lower than 400,000 pounds or even 283,000 pounds.

This reality of an in-service coupler having an unknown failure load leads to the conclusion that a reasonable assumption must be made in setting draft-force limits for longitudinal in-train forces. New coupler knuckle designs are expected to meet deformation, ultimate, and fatigue load requirements, while older in-service coupler knuckles experience an unknown number of cycles, with an unknown range of loads. Given these facts, and considering that older knuckles will have accumulated fatigue damage over the course of operation, it is not unreasonable to use the load at permanent set (or “accepted working limit”) as an operating limit for the draft force. In the AAR TMM, the lowest “accepted working limit” of 250,000 pounds, for Grade C couplers, was used as the upper limit of draft in-train forces.

Based on the above review of coupler knuckle permanent set, ultimate strength, and fatigue test loadings, it is recommended that:

- 250,000 pounds be used as the pull-apart force limit if the knuckle material grade and service condition is unknown, and;
- The limit to permanent deflection corresponding to the knuckle material in use[9] be used as the pull-apart limit in the situation where all the knuckles in a train are known as recently manufactured with high material grade.

For example, the pull-apart limit of 250,000 pounds can apply to nearly all mixed service trains in Canada, where freight cars of various ages and conditions are present. On the other hand, a pull-apart limit of 400,000 pounds can be applied to captive fleets or fleets with well documented car specifications and conditions where all cars are using the materials currently specified by the AAR MSRP.

Summary

The design load limits for a car system are compared in Figure 2 below, where the components with the highest force level requirements are to the left of the graph. The use of the coupler knuckle as a ‘fuse’ in the system is evident from this chart.

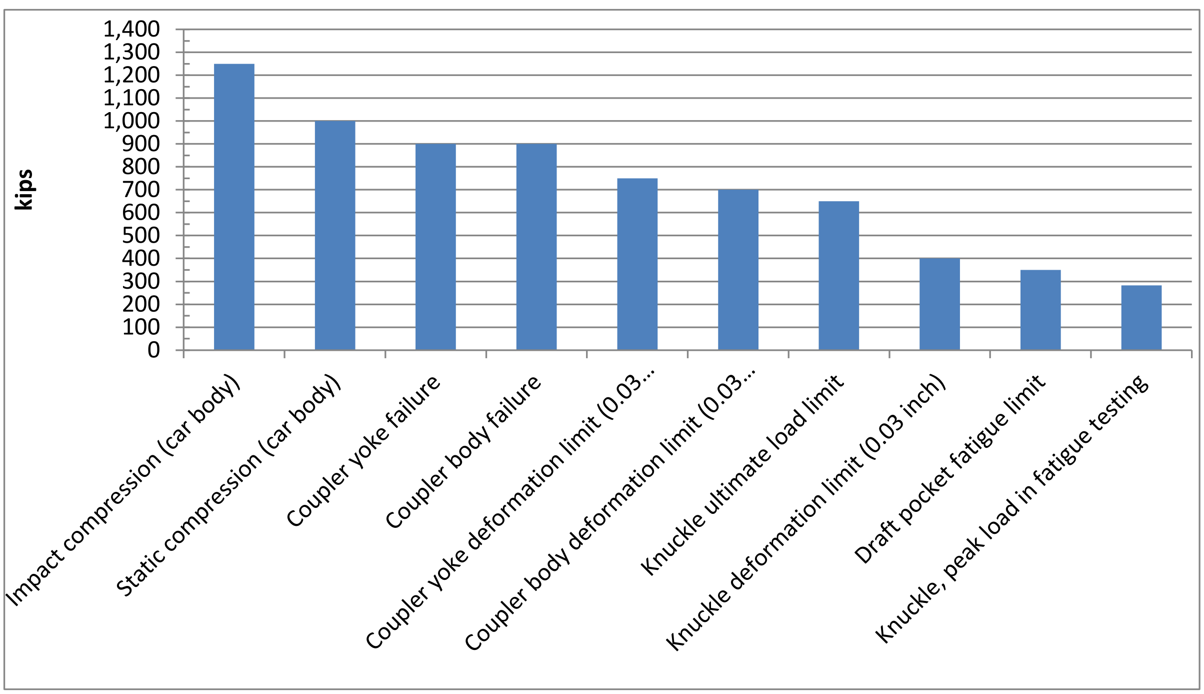

Figure 2: Comparison of current AAR-MSRP load limits for freight car components.

[9] 400,000 pounds for current manufactured couplers in general service. Unit trains may use other specified materials.

4.3.2 In-train forces in long trains: BHP Iron Ore experience.

The BHP Iron Ore company in Australia has been operating with extremely long trains for nearly two decades [31] [32]. As of 2001, the BHP-Billiton Iron Ore company was operating 220 car (2.5 km long) to 330 car trains on a daily basis. In July of 2001 the company ran a single 640 car train to break a record for the longest train. During that record breaking run the train broke two couplers, highlighting the need for control of in-train forces when running these extremely long trains.

The iron ore trains are made up of identical loaded ore cars bringing ore to a port, with an empty-car train returning to the mine. In these operating conditions the main concern is to monitor and control the in-train forces to prevent broken coupler components, and reduce track loading to increase track life. The BHP trains, as a captive fleet, are able to run these very long trains for the following reasons:

- All the cars are either empty or loaded: the mixing of empty and loaded cars within a train is not a concern;
- All the cars are identical: there are no long-short car combinations;
- Distributed Power is used as standard operating practice;
- The terrain is flat to mildly undulating;
- Inspection of coupler components takes place on a regimented routine of every 300 trips.

The initial findings reported in 2001 concluded that coupler failure was due to corrosion fatigue failure of the coupler body. There was no relation between coupler age or service life, "indicating [that] variability in material properties, and/or surface quality and/or operational factors were responsible." Couplers with 12-15 months of service were showing signs of fatigue cracking, although the majority of failed couplers had been in service between 6 to 10 years. Metallurgical analysis presented strong evidence that corrosion fatigue was the main cause of failure, but that in some case coupler materials did not fully meet specifications for impact or strength criteria.

The measurement of in-train forces, in cooperation with Monash University [32] concluded that the measurements allowed the BHP railroad to:

- evaluate different train configurations;
- mitigate risk by identifying operations which cause high compressive forces capable of causing wheel climb derailments;
- develop and use load spectra to develop component life comparison;
- validate the effectiveness of Electrically Controlled Pneumatic (ECP) brakes;
- tune and validate in-train force models.

The authors found that in-train forces vary between different drivers, lines, car positions within a train, and locations along a track, and therefore measuring in-train forces was the most reliable way to study in-train forces. Also noted was that knowledge of distribution of coupler slack was a key aspect in managing in-train forces.

Through the measurement of in-train forces, the BHP operators have determined that when travelling over undulating terrain small differences in train handling, such as the time of application of the air brake, DB, or throttle, can cause significant differences in the peak in-train forces: the 2013 article noted a difference in peak forces of 331 and 154 kips for similar trains operated under slightly different operating conditions.

It must be noted that although the BHP experience in routinely operating extremely long trains may not have a comparative equivalent in Canada, the lessons the railroad has learned through the study of operations, measurement of in-train forces, and investigations into the causes and prevention of coupler failure are transferable to the Canadian situation and warrant further attention.

4.3.3 Coupler Angle Limits

Allowable coupler angles specified by the AAR Standard M-1001, section 2.1.4.4.1 [30] are reproduced in Figure 3 below. The maximum contour angle between centerlines is defined by AAR Standard M-1001, section 2.1.4.4.2 [30], and is reproduced in Figure 4 below.

Table 2.1 Horizontal curve data for standard coupler arrangements

Coupler Design Yoke Design Arrangement Standard[a/]	Maximum Coupler Lateral Angle[b/]	Maximum Coupler Lateral Displacement at Coupling Line C (in.)[b/]	Effective Coupler Length L[c/] (in.)	Length of Shank[d/] (in.)
E60C, Y40A, S-239	7°	3.47	28.46	21.50
E61B, Y30A, Striker S-2018	9°	4.53	28.94	16.94
E67B, Y41A, S-241	8°	4.63	33.28	25.00
E68B, Y45A, S-243	13°	9.67	43.00	31.00
E68B, Y49A, S-244	13°	9.67	43.00	31.00
E69A, Y45A, 15° Striker	15°	15.53	60.00	48.00
F70C, Y45A, Striker S1C (former)	10°	5.08	29.25	17.25
F70C, Y45A, S-245	13°	6.58	29.25	17.25
F79C, Y45A, S-247	13°	9.67	43.00	31.00
F79C, Y49A, 13° Striker	13°	9.67	43.00	31.00
F73A, Y45A, 15° Striker	15°	15.53	60.00	48.00

NOTES:

a/ Where no arrangement standard exists, strikers are shown.
b/ Lateral tabular values shown are maximum coupler displacements. Lateral values may be reduced, providing cars can negotiate the required curves specified in paragraph 2.1.4.2.1.
c/ Length from coupling line to intersection of coupler centerline with car centerline.
d/ Length from coupler horn to butt or pivot point of coupler.

Figure 3: AAR-MSRP Standard M-1001, Section 2.1.4.4.1: Coupler Lateral Angle

Table 2.2 AAR standard couplers
Maximum contour angle between coupler centerlines

Coupler Combination	Contour Angle α	
	Horizontal	Vertical
E and E	13.50°	4.75°
E and F	8.00°	3.25°
E and H	6.50°	2.00°
F and F	3.75°	2.00°
F and H	1.75°	0.75°
H and H	0°	0°

Figure 4: AAR-MSRP Standard M-1001, Section 2.1.4.4.2: Coupler Contour Angle

4.4 Wear Limits for Coupler Components

The 2011 AAR Field Manual of Interchange Rules 16, 17 and 18 describes the rules and conditions that must be met for the interchange use of coupler components. To be used in interchange service, the components must be compatible, and as such the Manual describes wear limits (minimum dimensions) for coupler components that must be met. The wear limits are measured using contour limit gages. Should a coupler component not meet the wear limit it is condemnable and must be removed from service.

The Field Manual does not describe or detail any force limits or force limit test procedures for allowing a coupler component to remain in service. All decisions regarding the removal from service of a coupler component are made using measuring aids (contour limit gages), visual inspection for excessive cracks and wear, and measurement of key dimensions.

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5 IN-TRAIN FORCE EVALUATION BY DYNAMIC SIMULATION (TEDS): RECREATION OF DOCUMENTED ACCIDENT EVENTS

5.1 Simulation of Two Derailment Cases Caused by High In-Train Forces

The TSB derailment reports R05V0141 [14] and R02C0050 [11] describe accidents where it was concluded that longer trains and train marshalling, such as long-short car combinations and/or groups of heavy cars trailing groups of light cars, played a role in the severity of the derailment or was potentially the cause of the derailment. To better understand the in-train forces that can be produced under these situations, and to learn what the effects of corrective actions are on these forces, the two accident situations were studied using TEDS software.

In both cases the train make-up, track geography and operating conditions were replicated as closely as possible to those reported in the TSB reports and the supplemental TSB Engineering reports. The two situations and the results are described in the following sections.

5.1.1 *Case 1: R05V0141 - String-lining Derailment.*

A string-lining derailment occurred on a section of mountainous region track near Squamish, British Columbia on the 5th of August 2005. Nine cars derailed, one of which was loaded with caustic soda which spilled into the Cheakamus River.

The track in this region is winding with a continuous climb: maximum measured grades of 2.2% combine with repeated reverse curves between 6 to 12 degrees of curvature. The train derailed in a track section with a 12 degree curve on a grade of 1.97%. Figure 5 shows the elevation profile and track curvature, as used by TEDS, over the mile of track where the derailment occurred.

The analysis simulated the train running along the section of track where the derailment occurred. The positioning of locomotive power was examined in its relation to the coupler forces and truckside L/V between the cars where the derailment took place.

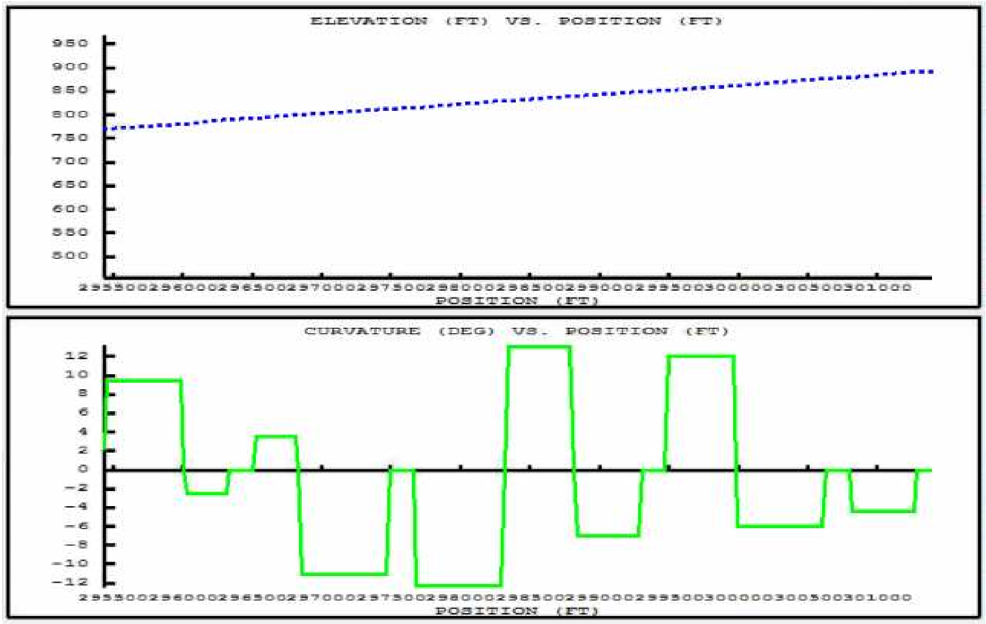

Figure 5 – Case1: Track curvature and elevation, MP 56-57, Squamish Subdivision

The train model used in the analysis consisted of 151 cars of 6 types: locomotives (7), box cars (1), tank cars (3), bulkhead flat cars (6), and gondola cars (134). The consist had a total length of 8,293 feet and a train weight of 4,794 tons. There were 5 locomotives at the head end of the train and 2 locomotives located at positions 113 and 114 in the consist. Figure 6 shows the car lengths and Figure 7 shows the car weights along the consist.

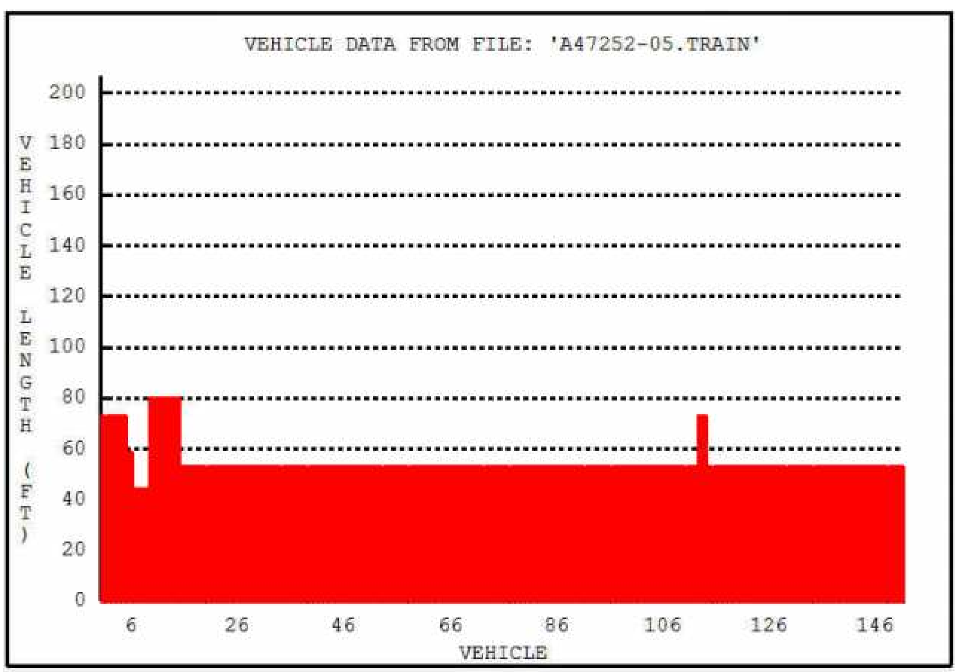

Figure 6 – Case 1: Vehicle lengths

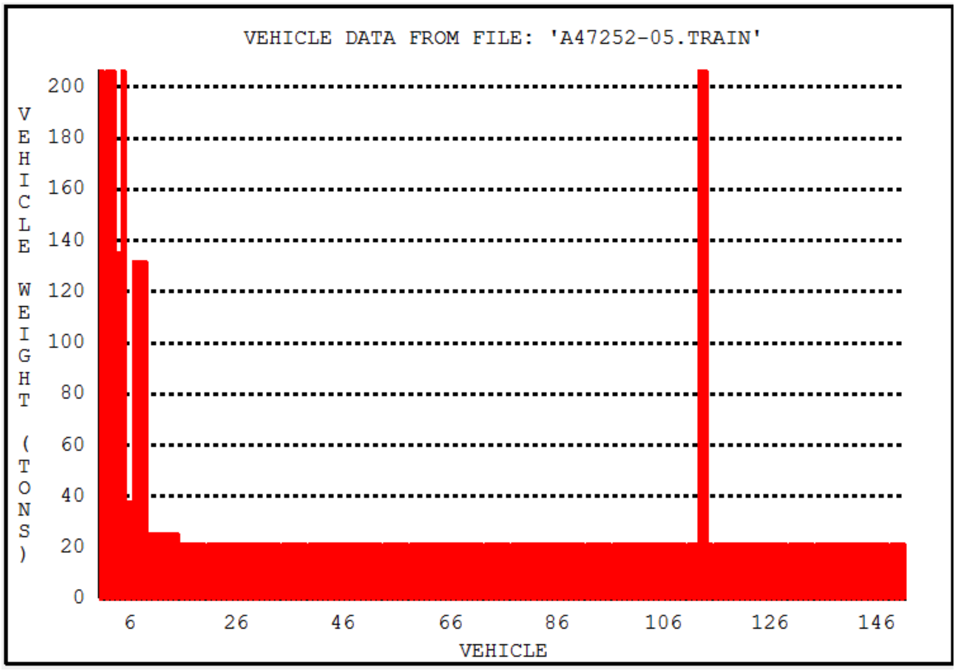

Figure 7 – Case 1: Vehicle weights

The operation of the train called for the first 3 locomotives at the head end of the train to be operating along with the locomotives in positions 113 and 114. Due to mechanical issues, the train proceeded with 4 locomotives providing power from the head end of the train and the locomotives in positions 113 and 114 inactive. The derailment of this train occurred between cars 9 and 10, making this the location of interest for the two cases of locomotive power.

5.1.1.1 Case 1, Study 1: Original Derailment Scenario

When the derailment occurred, four locomotives at the head end of the train were providing all of the power. The coupler force between cars 9 and 10 from Mile 56-57 in this operational scenario is shown below in Figure 8. The average coupler force between the short car 9 and much longer car 10 is approximately 182,500 lbs. The plot in Figure 9 shows the truckside L/V across this same section of track.

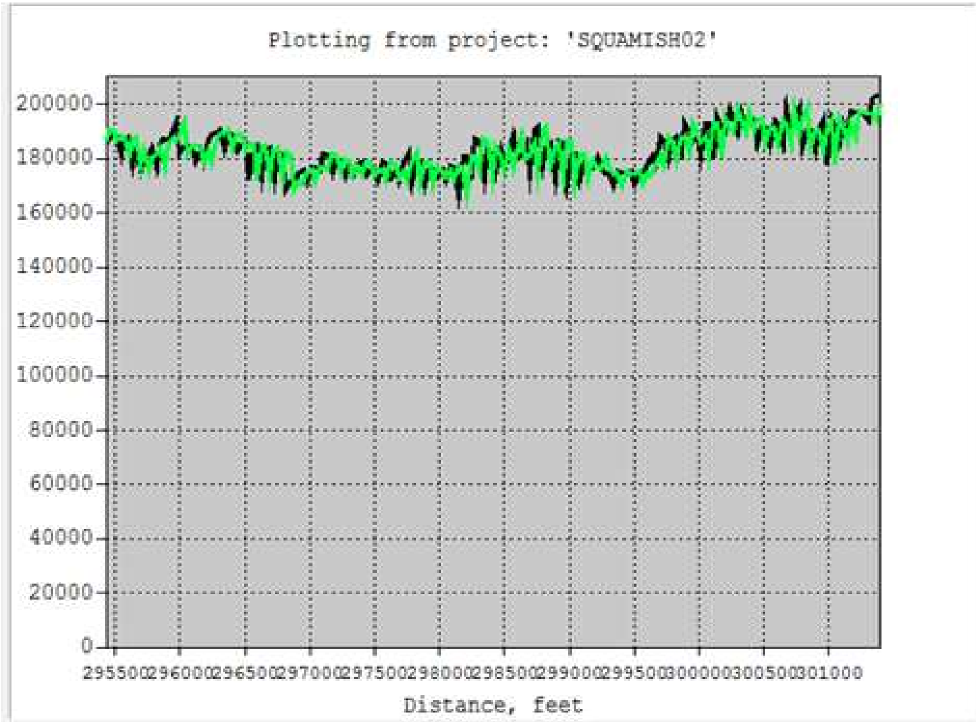

Figure 8 – Case 1, Study 1: Car 9 aft coupler force (green) and Car 10 fore coupler force (black) in pounds

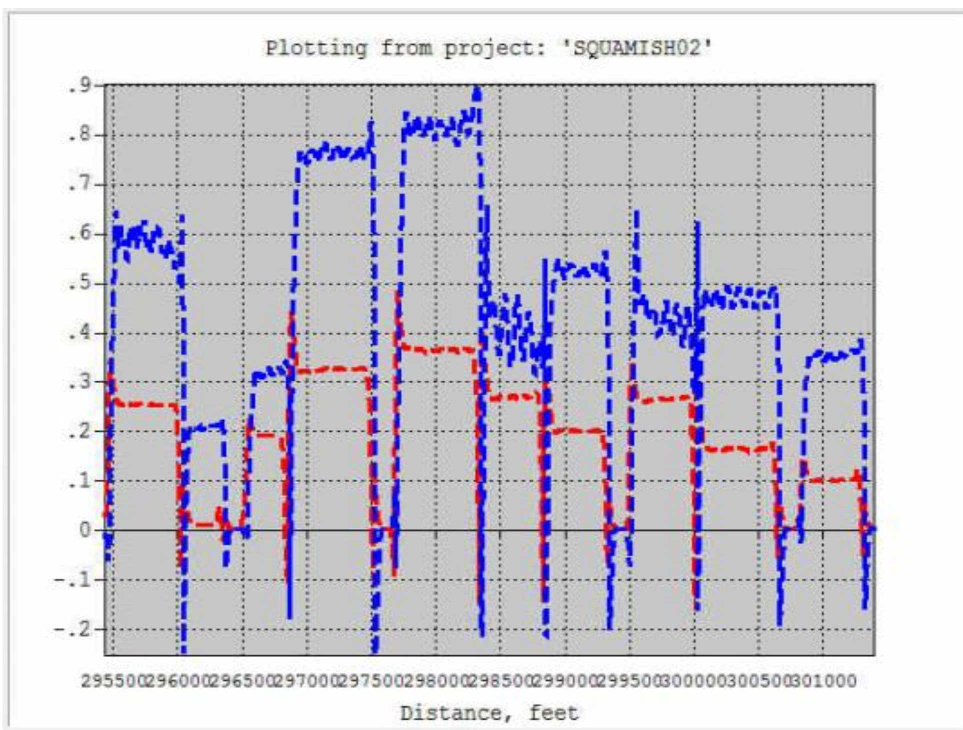

Figure 9 – Case 1, Study 1: Right truckside L/V for truck B on car 9 (red) and truck A on car 10 (blue)

The right truckside L/V is shown for truck B on car 9 (red) and truck A on car 10 (blue). The L/V for car 10 in this scenario reaches approximately 0.9 putting it at a severe risk of a wheel climb derailment.

5.1.1.2 Case 1, Study 2: Intended Operational Procedure (DP)

The intended operation of this train called for the first 3 locomotives at the head end of the train to be powered along with the locomotives in positions 113 and 114. A TEDS model of this configuration was built and simulated over the same section of track as the derailment scenario.

Figure 10 below shows the coupler force between cars 9 and 10 from Mile 56-57. The plot in Figure 10 shows an average coupler forces between cars 9 and 10 of approximately 86,700 lbs. Figure 11 shows the truckside L/V ratio across this same section of track. The maximum truckside L/V for this analysis is 0.55 and occurs on the leading truck of car 10.

This analysis shows the effect that the positioning and application of locomotive power can have on coupler forces and L/V in a consist. In Case 1, which simulates the derailment conditions, the maximum calculated truckside L/V of 0.9 is well above the L/V of 0.6 that is considered to be hazardous by the Federal Railroad Administration. In Case 2, the maximum truckside L/V of 0.55 is much lower and falls below the hazard threshold. Distributed power operation in these simulations more than halved the average coupler force between Cars 9 and 10.

These values indicate that had the train been operating with the positioning of locomotive power as planned, this derailment would likely have been avoided.

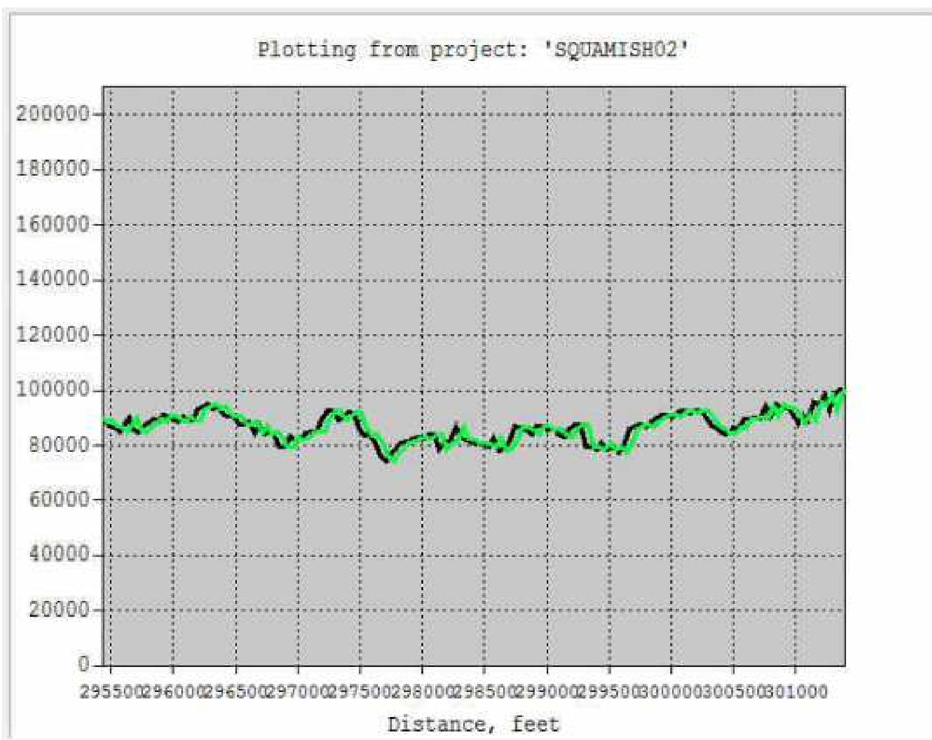

Figure 10 – Case 1, Study 2: Car 9 aft coupler force (green) and Car 10 fore coupler force (black) in pounds

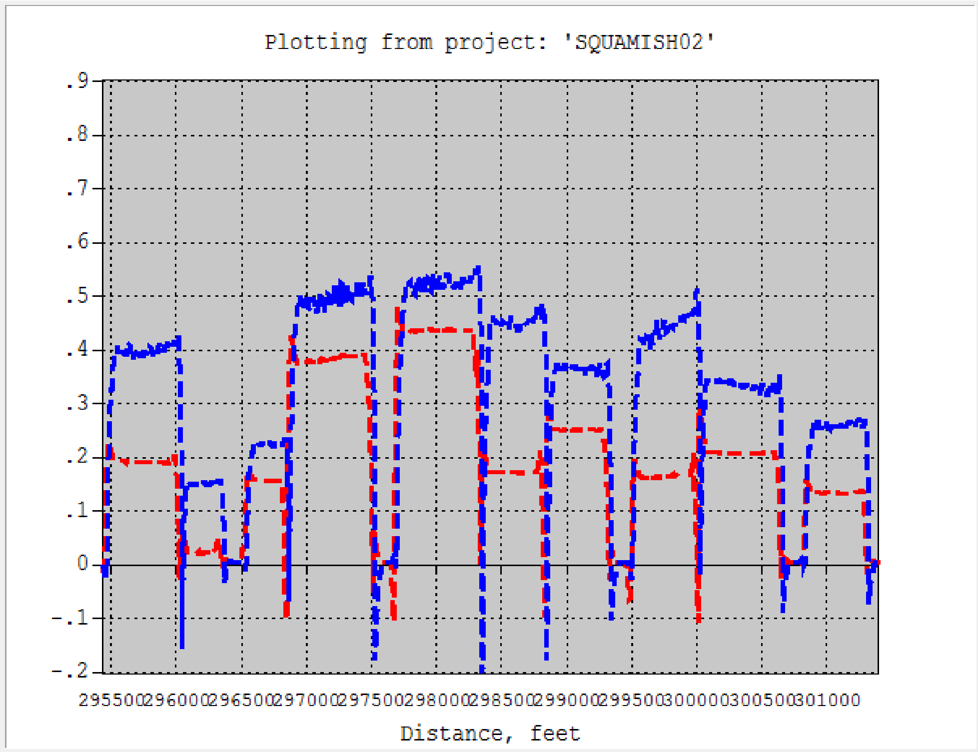

Figure 11 – Case 1, Study 2: Right truckside L/V for truck B on car 9 (red) and truck A on car 10 (blue)

5.1.2 *Case 2: R02C0050 - High Buff/Lateral Load Derailment*

A second derailment case was simulated using TEDS, in this case a train running along a section of track in Camrose, AB, where a derailment occurred. Train marshalling practices and the effect they have on the coupler forces between the cars where the derailment took place are examined.

Figure 12 shows the TEDS elevation profile and track curvature over the mile of track in which the derailment occurred. The track model used in this analysis consisted of a descending 0.7% grade which then entered a 6 degree curve.

The train was powered by 3 locomotives at the head end. Directly behind the powered locomotives were 2 unpowered yard switching locomotives. The initial derailment of this train occurred at a lightly loaded aluminum hopper car, located in position 6 directly behind the yard switching locomotives.

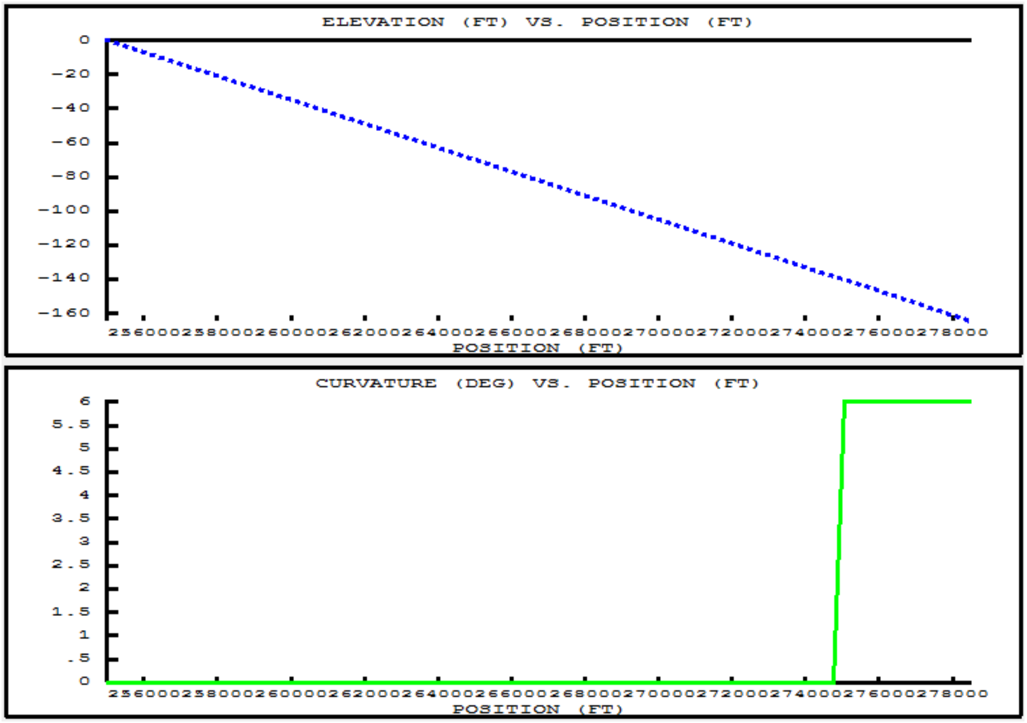

Figure 12: Case 2 Track model for the derailment location (MP 52.1, Camrose Subdivision)

5.1.2.1 Case 2, Study 1: Derailment Scenario

The consist used in the analysis had 159 cars of 4 types: locomotives (5), covered hopper cars (2), bulkhead flat cars (151), articulated 3 pack (1). The train had a total length of 11,166 feet and a weight of 17,260 tons. There were 5 locomotives at the head end of the train, with the first 3 providing the motive power, followed by 2 yard switching locomotives. This consist had empty or lightly loaded cars positioned behind the locomotives and loaded cars at the rear of the train. Figure 13 shows the car weights along the consist.

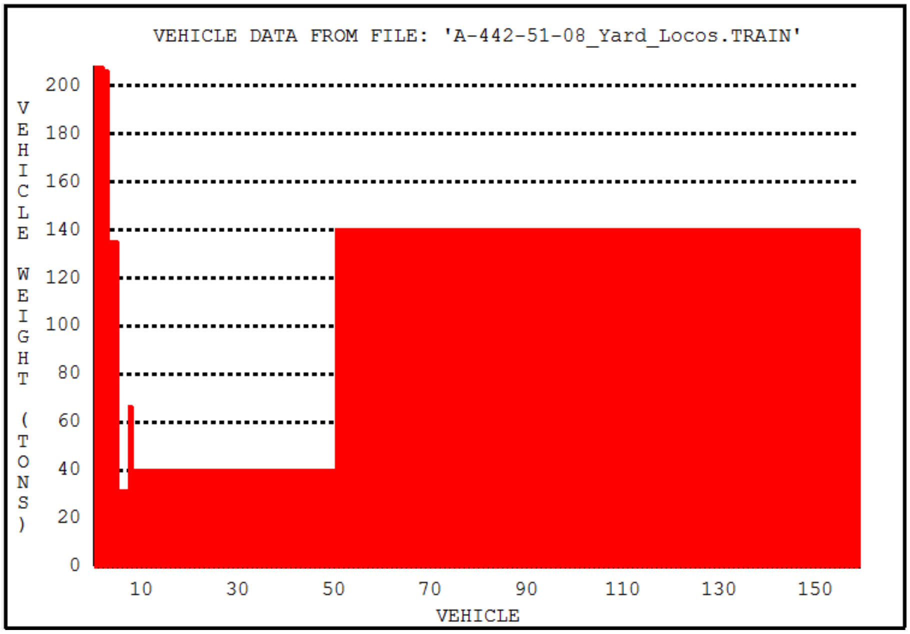

Figure 13: Case 2, Study 1: Car weights of original consist

When the derailment occurred, the 3 locomotives at the head end of the train were using dynamic breaking to maintain the train speed at 25 mph. The yard switching locomotives in positions 4 and 5 were not equipped with alignment control couplers, permitting a draw bar angle as large as 19 degrees. The coupler force between cars 5 and 6 across the mile of track where the derailment occurred in this scenario is shown in Figure 8, where an average of approximately 210,000 pounds of buff (compressive) force is observed.

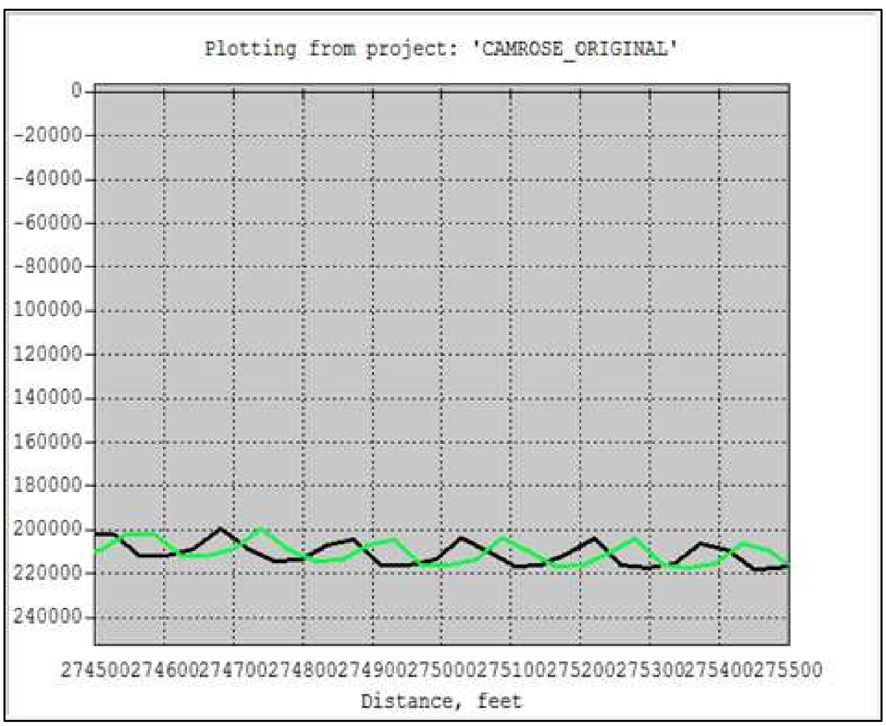

Figure 14: Case 2, Study 1: Car 5 aft coupler force (green) and Car 6 fore coupler force (black) (pounds)

The translated lateral force with a draw bar angle of 19 degrees is calculated as follows:

$F_{tl} = F_{in} \sin\alpha$
$F_{tl} = 210000 \times \sin19° = 68,369$ lbs

The L/V ratio for this car can now be calculated:

$L/V = 2\ F_{tl}/W$ (where W is the car weight)
$L/V = 2 \times 68369 / 44000 = 3.1$

The calculated L/V of 3.1 is well in excess of the 0.82 L/V ratio required for a rollover of the rail, as calculated in the Transportation Safety Board engineering report LP114/02.

5.1.2.2 Case 2, Study 2: Modified Consist

The consist used in this analysis has been modeled to have the loaded cars behind the locomotives, with the empty and lightly loaded cars at the tail end of the consist, shown in Figure 15. The hopper car that derailed behind the yard switching locomotive in Case 1 is now in position 113. The yard switching locomotives have been moved to the rear of the consist in positions 158 and 159.

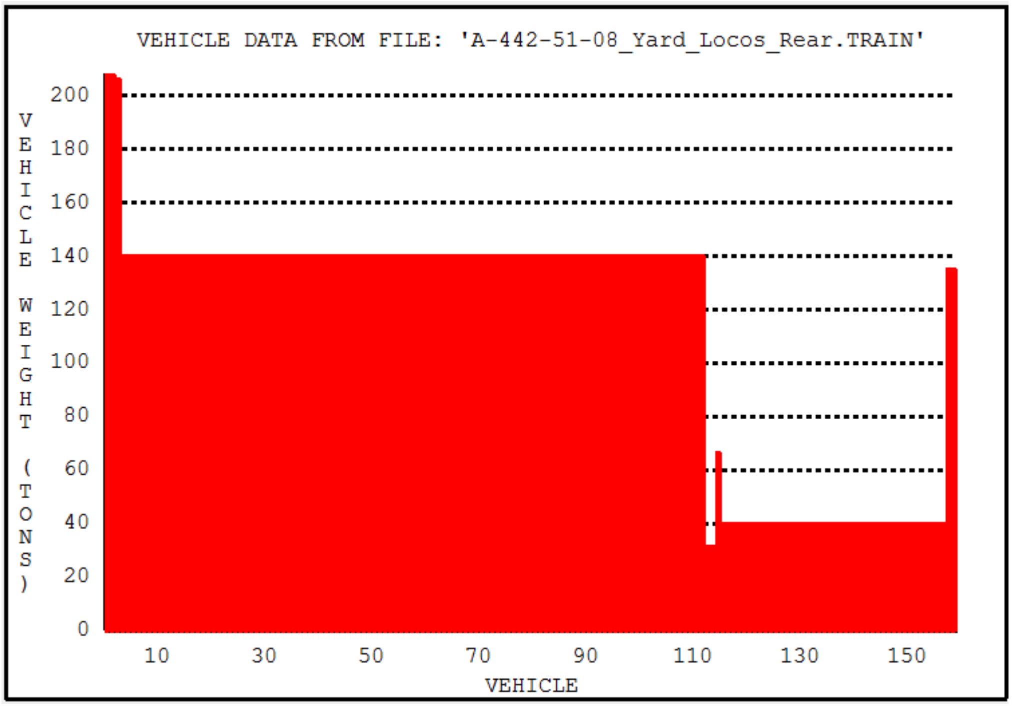

Figure 15: Case 2, Study 2: Car weights of the modified consist

The locomotives at the head of the consist are equipped with alignment control couplers, limiting the draw bar angle to 8 degrees. The coupler force between cars 3 and 4 across the mile of track where the derailment occurred is shown in Figure 16. It is unchanged from the previous derailment scenario, averaging about 210,000 pounds buff.

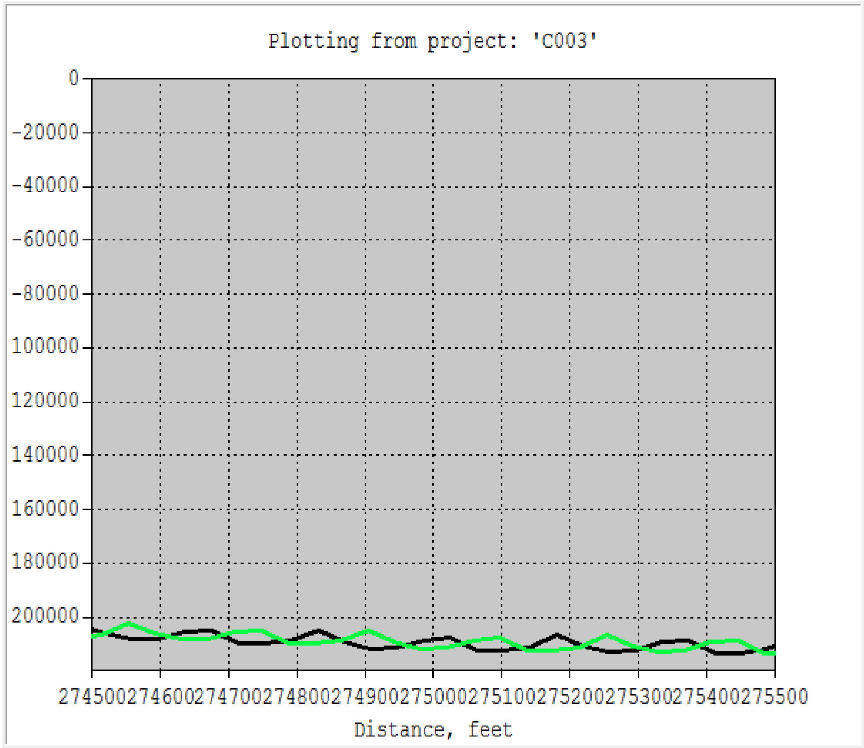

Figure 16: Case 2, Study 2: Car 3 aft coupler force (green) and Car 4 fore coupler force (black) (pounds)

At this location the draw bar angle is now restricted to 8 degrees and the translated lateral force is calculated as follows:

$F_{tl} = F_{in} \sin\alpha$
$F_{tl} = 210000 \times \sin 8° = 29{,}226$ lbs

The L/V ratio for this car can now be calculated:

$L/V = 2\ F_{tl}/W$ (where W is the loaded car weight)
$L/V = 2 \times 29226 / 280000 = 0.21$

The calculated L/V of 0.21 indicates that the loaded car located behind the locomotives is not in danger of a derailment. The coupler forces at the hopper car that derailed in Case 1 are shown in Figure 17 for its new location (car 113) in this consist.

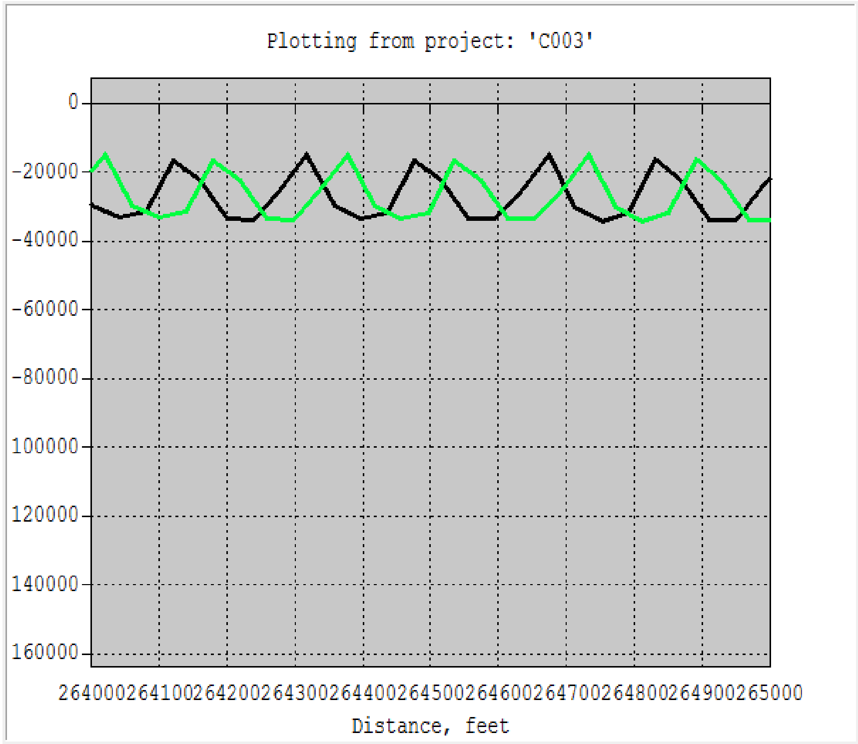

Figure 17: Case 2, Study 2: Car 113 aft coupler force (green) and fore coupler force (black) (pounds)

The average buff force at the light weight hopper car has now dropped over 85% from Case 1, from 210,000 to 30,000 pounds buff force. At this location the draw bar angle can only reach a maximum of 11 degrees, due to the E60 coupler on the hopper car, and the translated lateral force is calculated as follows:

$$F_{tl} = F_{in} \sin\alpha$$
$$F_{tl} = 30000 \times \sin 11° = 5{,}724 \text{ lbs}$$

The L/V ratio for this car can now be calculated:

$$L/V = 2\ F_{tl}/W \quad \text{(where W is the hopper car weight)}$$
$$L/V = 2 \times 5724 / 44000 = 0.26$$

The calculated L/V for the hopper car of 0.26 shows that in its new location in this consist, it is not at risk of a derailment.

This analysis shows the effect that train marshalling procedures can have on coupler forces and L/V in a consist. In Case 1, which simulates the derailment conditions, the maximum calculated L/V was 3.1, well above the L/V of 0.82 that is considered to be hazardous by the Federal Railroad Administration. In Case 2, the maximum calculated L/V was 0.26, suggesting that a derailment is unlikely under these conditions. The average coupler force on the hopper car that derailed in Case 1 decreased by 85% when it was placed towards the rear of the train.

Had the train been marshalled with the heaviest cars behind the motive power and the yard switching locomotives at the rear of the consist (where the non-alignment couplers would experience low longitudinal loads, this derailment could have been avoided.

5.2 Summary

TEDS was used to study the effects of train marshalling on in-train forces and the potential to prevent or reduce derailment severity. For the two accident situations studied, the recommended corrective actions, as outlined in the TSB reports, reduced the simulated in-train forces to levels which are acceptable and would not have precipitated a derailment.

The situations studied in this section represent only two selected accidents from the 14 that were identified by the TSB as having in-train forces as a primary or contributing cause. From these two situations the following conclusions can be made:

1. Marshalling of the train consist can have a significant effect on in-train forces;
2. Correct use of DP reduces in-train forces;
3. Incorrect use of, or failure to use DP, can result in extremely high in-train forces;
4. Care must be taken when special cars, and cars with large swing angle couplers are in a consist.

Railroads consider the two cases studied to be unusual situations: the trains were not typical of normal operations.

6 SUMMARY AND CONCLUSIONS

As the part of NRC's efforts aiming to develop a guideline for the safe operation of long trains in Canada, the present study focuses on the following aspects:

- Review derailments identified by the TSB as having been related to long trains and in-train forces;
- Review industry (AAR TMM and MSRP) and railroad (CN and CP) standards and practices related to controlling in-train forces and managing long trains;
- Recommendation of the draft in-train force limit based on the review.

A review of industry practices was undertaken to identify existing practices that are in use industry wide or are specific to the railroads themselves. The industry operates on a common set of standards and specifications set forth by the AAR within the Manual of Standards and Recommended and Practices (MSRP). As well, the AAR published the Train Makeup Manual (TMM) in 1992 to provide guidance to the North American railroads in controlling train forces through the adjustment of train makeup.

The following summaries and conclusions have been drawn from the present study:

(1) From the review of fourteen TSB reports it is found that:

- All of the derailed trains were mixed goods trains. No empty or loaded unit trains were involved.
- Most of the first derailed cars are empty (center beam, tank, hopper, dump car, maintenance car) except for two yard locomotives.
- 9 of the 14 (64%) derailed trains are longer than 8,000 feet.
- In half the cases, the use of non-standard large swing angle couplers contributed to the initiation of the derailment.
- Estimates for in-train forces that were the primary cause of the derailments were:
    - -135, -175, -200, -200, -216, -250 and +225kips.
- An empty car in long manifest trains (>8,000ft) connected to a car with large swing angle couplers is one of the main risks for a derailment caused by in-train forces.
- Simulation of two derailment scenarios was undertaken using train dynamics software TEDS. These simulations provided insight into the changes that can occur to in-train forces when consist and operational changes are made.
- The simulations showed that in-train forces are dependent on train makeup (as described by the AAR Train Makeup Manual), and that handling practices and the use of DP play an important role in controlling in-train force.

(2) The trailing tonnage method and guidance of the AAR Train Makeup Manual published in 1992 are still used by the industry as basis for train marshalling rules. The key points of the Train Makeup Manual are summarized as follows:

- Limit allowable trailing tonnage behind an empty car;
- The trailing tonnage limit is determined by draw bar force limit, grade, curving resistance and rolling resistance;
- Draw bar force limit is determined as 38.9% of car weight divided by coupler angle;
- Coupler angle is determined by degree of curve, together with car lengths, truck centers and coupler lengths of two adjacent cars;
- Under buff condition, the lateral bolster-to-track free play (gap) will increase the coupler angle compared to the draft loading case.

(3) Based on the review of the AAR Train Makeup Manual and the current AAR Manual of Standards and Recommended Practices, the following draft (pull-apart) limits are identified for different material grade of coupler knuckles,

Knuckle Material grade	Load at maximum permanent set (pounds)	Ultimate Strength (pounds)
Grade C (1992)	250,000	300,000
Grade E (1992)	300,000	400,000
AAR MSRP (2010)	400,000	650,000

Given that older cars equipped with knuckles made of Grade C and Grade E materials are still in use, it is recommended that a limit of 250,000 pounds be used as the pull-apart force limit if the knuckle material grade and service condition is unknown for a train. However, the limit to permanent deflection corresponding to the knuckle material can be used as the pull-apart limit in the situation where all the knuckles in a train are known to be recently manufactured with high material grade.

(4) CP began using rules-based software, called TrAM, to adjust train makeup starting in 2003. TrAM is a set of comprehensive, territory specific, marshalling rules and supporting computer tools designed to permit the efficient use of distributed power. The system also allows CP to marshal trains in a safer manner compared to randomly making train consists. The use of the TrAM system has allowed CP to introduce longer and heavier trains without a subsequent increase in derailments, as seen by the fact that of the 14 derailments cited by the TSB as involving long trains, only one was a CP train.

(5) Prior to 2004 CN had no publically available rules for train makeup to control in train force. CN has historically followed the AAR TMM rules, and applied experience in operating its trains over specific territories to set local written and verbal guidance for train makeup. However, beginning in 2004, following on recommendations set out by TSB, CN began implementing restrictions on specific routes to control in-train forces through train length restrictions and marshalling practices. CN also began using more DP and began applying increasingly restrictive rules on routes that had historically resulted in coupler failures and derailments. By 2010 CN had instituted a series of train makeup and handling guidelines across Canada.

(6) A summary of the train handling best practises as used by CN and CP was also undertaken. It is beyond the scope of this report to summarize all of the practices in use by CN and CP, as many of the practices are route specific and proprietary to the railroads. However, a general and common set of practices was identified through review of CN and CP provided examples of their practices. These include (but are not limited to):

- Forward planning based on characteristics of territory and train;
- Priority of using throttle manipulation and dynamic brake;
- Limit of using high dynamic brakes;
- Control train action by gradual handling and properly adjusting slack;
- Placement of DP to reduce forces and improve air brake control;
- Limits on placement of long empty cars, cars with specialty couplers.

(7) The review of TSB reports and industry standards and practices has highlighted that estimating, predicting, or controlling longitudinal in-train forces is not a simple task. The

experience of BHP railroad in Australia in operating extremely long trains supports this conclusion. It was also noted that more research into the measurement of in-train forces and the study of coupler fatigue is needed.

(8) The AAR Tran Makeup Manual was the start of instituting an industry-wide method of estimating and controlling in-train forces. The CP TrAM system and the CN rules-engine go beyond what the Train Makeup Manual set out, but are proprietary methods, instituted using computer software. Both systems have allowed the respective railroads to increase train lengths and weights on appropriate routes. However, given the accidents that occurred between 2000 and 2010, the increase in train length and weight has not occurred without errors from which the railroads learned valuable lessons. Therefore, a new industry wide guideline for the safe operation of long train needs to be developed.

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Appendix A: CN RESPONSES TO TSB RECOMMENDATIONS

Prior to 2010 CN had not publicly described the rules or systems in place for controlling train marshalling or handling with regards to controlling in-train forces. However, the responses CN had given concerning TSB recommendations and TC Notices were summarized in several of the TSB derailment reports that were reviewed. From these reports a timeline of activity by CN can be made as follows:

1. As of July 2003, as reported in TSB report R01T0006, CN has no constraints on trailing tonnage and length[10].
2. As of Jan 2004, as reported in TSB Report R01M0061, CN has 6% of locomotives with automatic synchronization of front and trail end emergency brake initiation. As well, the TSB has added in-train forces to the TSB Key Safety Issues List, and issued the TSB Recommendation R04-01 to TC that stated; *"Transport Canada encourage the railway companies to implement technologies and/or methods of train control to assure that in-train forces generated during emergency braking are consistent with safe train operation."* The implication is that TSB recommends that during emergency braking, in-train forces should also follow the TMM force rules.
3. In 2006 TSB issued RSA 02/06, "Marshalling of Long Merchandise Trains on CN's Kingston Subdivision". CN's response at that time was that it had in place an unwritten company practice to require trains having more than 25 empty multi-level or empty flat cars in a block to marshal the block to the end of the train.
4. In 2007 TSB issued RSI 14-07, RSA 08-07 and RSA 09-07. TC reported at that time that CN is working on a strategy to address tonnage distribution, however at that time it appears that CN did not have a train marshalling system in place that considers tonnage distribution.
5. As of May 2008, as reported in TSB Report R07T0110, the TSB was "concerned that, without buff force performance standards for rolling stock, cars with troublesome buff force behavior will continue to be marshalled in trains without appropriate restrictions." [16] As well TSB noted that for more than 7 years the TSB has highlighted train marshalling as a significant rail safety issue[11], and that the TSB had issued Recommendation R04-01 in Report R01M0061 in January of 2004. The TC response to the R04-01 was assessed as fully satisfactory in 2005.
6. March 2010: TSB Issues the *Watchlist* which includes a safety issue associated with the operation of longer heavier trains.[12] At that point in time (March 2010) TSB stated that "[although] the [TSB] is encouraged with recent CN initiatives, the initiatives are evolving and have not yet been widely implemented on the systems. Therefore the issue will remain on the *Watchlist* and the [TSB] will continue to monitor CN's progress".
7. On 07 April 2010, as reported in TSB Report R09T0092 [18], the TC Rail Safety Inspector issued a Notice under Section 31 of the Railway Safety Act to CN concerning failure to

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[10] Note from AST authors: perhaps other than what is recommended by the AAR TMM
[11] As reported in a conference paper by B. Tucker called "Trends in Transportation Safety – TSB Key Safety Issues", presented at the Canadian Transportation Research Forum, 02 November 2001.
[12] http://www.tsb.gc.ca/eng/surveillance-watchlist/rail/2010/rail_2.asp#n4

effectively manage in-train forces on freight trains operating on the Kingston Subdivision (KS). On 16 April 2010 CN responded with these corrective actions:

- CN will limit, on an interim basis, conventional trains to a maximum of 8500 feet and 12 000 tons.
- CN will monitor its train configurations for exceptional marshalling issues, such as large blocks of empties ahead of large blocks of loads.
- CN will begin implementing the use of distributed power trains of the KS (with the intent that all future KS trains will be DP trains).

8. On 25 May 2010 TC was satisfied with the measures outlined in CN's response to the April 2010 TC Notice [7].
9. TSB Report R10T0213 [29] states that in July 2010 CN began developing train marshalling rules primarily for conventional trains equipped with head-end power. The rules are based on industry practice and accident history and focused primarily on train weight distribution in an effort to minimize in-train forces.
10. As of 29 September 2010, the extent of the response by CN to controlling in-train forces, as reported in in TSB Report R09T0092 [18] is summarized as follows:
CN conducted a Break-in-Train Analysis and identified four undulating cluster locations on the Kingston Subdivision as problematic. CN is currently attempting to write train handling instructions or "scripts" for these areas based on in-train force simulations. To further address in-train forces, CN has put the following measures in place:
    - *It developed a new air hose and gasket to reduce air hose separations.*
    - *It tested trip optimizer software.*
    - *It improved detection and handling of equipment with non-alignment control couplers (April 2010).*
    - *It limited train lengths for both conventional and DP freight trains on the Kingston Subdivision (April 2010).*
    - *It implemented an intermodal train marshalling rule to restrict empty cars at the head end (July 2010).*
    - *It continued investment in locomotive DP technology that can reduce in-train forces. CN plans that, by the end of 2010, about 34 per cent of CN's road locomotive fleet will be DP–capable, increasing to 41 per cent by the end of 2012.*
    - *It implemented a series of marshalling rules primarily related to train weight distribution. The rules have been developed to reduce in-train and track-train forces and are based on science, experience, benchmarking with other railroads and a review of historical accident root causes including analyses in TSB reports.*
    - *It developed "Rules Engine" software to review marshalling rule compliance on a historical basis, to assist in identifying priority locations and trains and to review train designs to facilitate improved marshalling. The effectiveness of the marshalling rules has been verified and supported by reviewing historical accidents in the context of the proposed rules, including all the accidents listed in this TSB investigation report.*
    - *It modified its information system (Service Reliability Strategy or SRS) so that it flags marshalling rules compliance. SRS notifies operating personnel of marshalling issues and a daily automated report has been developed to measure performance to the marshalling rules.*
    - *It implemented a rule that limits tonnage trailing a block of 10 or more empty cars. This rule is presently in effect on the Kingston and Wainwright subdivisions and is being applied at distant terminals that build trains operating over these subdivisions. Initial*

results have yielded nearly a 50 per cent reduction in train separations on these subdivisions.

11. As of 26 October 2011 as reported in in TSB Report R10T0213 [29], CN had proposed the following train marshalling rules:
    1. Rule 1: Tail End Heavy: ensure that rear 25% of the train does not contain more than 33% of the train weight.
    2. Rule 2: Empty Block Stability: check for and limit solid blocks of light cars to 10.
    3. Rule 3: Check for and limit solid blocks of more than 20 loaded cars trailing a solid block of more than 20 light cars.
    4. Rule 4: Excessive EOCCD cars; limit trains to no more than 120 cars with EOCCDs..
    5. Rule 5: Excessive EOCCD cars on head-end: ensure that no more than 80% of non-EOCCD cars are in the rear 25% of the train.
    6. Rule 6: Long Car-Short Car: Check for and limit the coupling of cars greater than or equal to 79 feet to a car less than 47 feet in length.
    7. Additional Rules subject to train tonnage criteria will be customized to the territory.

TSB reported that CN began with partial implementation in December 2010, and implemented Rules 1, 2 and 4 on the Kingston and Wainwright Subdivisions with the goal of eventually implementing the marshalling rules system wide.

TSB removed the notice concerning the operation of longer, heavier trains from the 2012 Watchlist as the Board felt that *"the railway industry has made significant progress in the use and development of new technologies and strategies for operating longer, heavier trains with distributed power.*" [24] However, CN continued to develop and implement marshalling rules and other changes to their operations to decrease in-train forces, as described in Section 3.3 of this report.