NJ TRANSIT CONTRACT NO. 13-007
BRIDGE AND RAILWAY ENGINEERING

HOBOKEN TERMINAL BUMPER BLOCK INSPECTION TRACK 5 REHABILITATION RECOMMENDATION

SUBMITTED TO:
NJ TRANSIT

SUBMITTED BY:
HNTB CORPORATION

DECEMBER 15, 2017

HNTB

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EXECUTIVE SUMMARY

In September of 2016, the bumper on Hoboken Terminal Track 5 was impacted by a 4-car locomotive-pushed train traveling at approximately 21 mph. The incident resulted in complete failure of the bumper, which was overridden by the cab car, as well as damage to the train, concourse and station building. The subject Task Order requires HNTB to analyze the existing terminal-track bumper blocks at Hoboken Terminal and, for any bumpers that are not rated to at least 10 mph, to make recommendations for new or rehabilitation options.

This report makes a recommendation to replacing all existing fixed bumpers with a 10-mph sliding friction bumper designed for a deceleration rate of 0.15 g. The bumper should be installed to allow the greatest practical slide length as shown in Table 1. The contingency length beyond what is required to stop the train provides an additional factor of safety.

Use of a bumper with a lower design speed would not protect against trains operating at the normal timetable speed of 10 mph. Use of a higher design speed results in loss of platform capacity or requires use of a deceleration rate above 0.15 g. At or below 0.15 g, it is expected that the typical standing passenger can remain standing without holding on to the train. Above 0.15 g, the likelihood of passenger injury increases. See Section 5.0 for additional discussion of deceleration rates.

HNTB is working with Rawie through their North American distributor H.J. Skelton to determine the appropriate model of sliding friction bumper for use at Hoboken Terminal. Delivery terms are typically four months from receipt of final technical approvals. Installation of the bumper is expected to cost approximately $100,000, including procurement of the bumper and relocation of the signal and insulated joint (IJ) at the end of the track. If Buy America requirements apply, the cost increases to approximately $120,000. These unit costs assume multiple bumpers are ordered at one time.

Drawings of example sliding friction bumpers provided by Rawie are shown in Figure 1 and Figure 2. Figure 1 shows a 12-shoe bumper without auxiliary rails. Figure 2 shows a 20-shoe element with auxiliary rails. All bumpers suppled for the Hoboken project would be built with a head designed for NJ TRANSIT's push-pull and EME equipment, similar to what is currently on Track 15, shown in Appendix A.

Track length and design consist lengths are addressed in Section 3.0 and Section 4.0. A discussion of impact force and deceleration rates is included in Section 5.0 and Section 6.0. A discussion of existing bumpers structural analysis is included in Section 6.0.

Table 1 Proposed Hoboken Terminal Bumpers and Track Capacity

TRACK	TRACK LENGTH	NO. COACHES	NO. FRICTION SHOES	10 MPH STOPPING DISTANCE	CONTINGENCY LENGTH	DECEL. RATE
1	344	2	10	25	24	0.14
2	607	5	10	46	11	0.07
3	605	5	10	46	9	0.07
4	666	6	20	27	4	0.13
5	667	6	20	27	5	0.13
6	844	8	20	34	5	0.10
7	843	8	20	34	4	0.10
8	1,096	11	28	32	4	0.11
9	845	8	20	34	6	0.10
10	840	8	28	24	11	0.14
11	834	8	28	24	5	0.14
12	607	5	10	46	11	0.07
13	599	5	12	38	11	0.09
14	805	7	20	30	55	0.11
15 [NOTE 5]	793	7	20	30	43	0.11
16	856	8	20	34	17	0.10
17	856	8	20	34	17	0.10
18	936	9	20	37	9	0.09

Table Notes:

1. 10 mph stopping distance provide by Rawie; all bumper are 10 feet long
2. Consist length includes number of cars shown plus one locomotive
3. All lengths in feet
4. Contingency length assumes removal of existing bumpers
5. Track 15 requires relocating existing sliding friction bumper

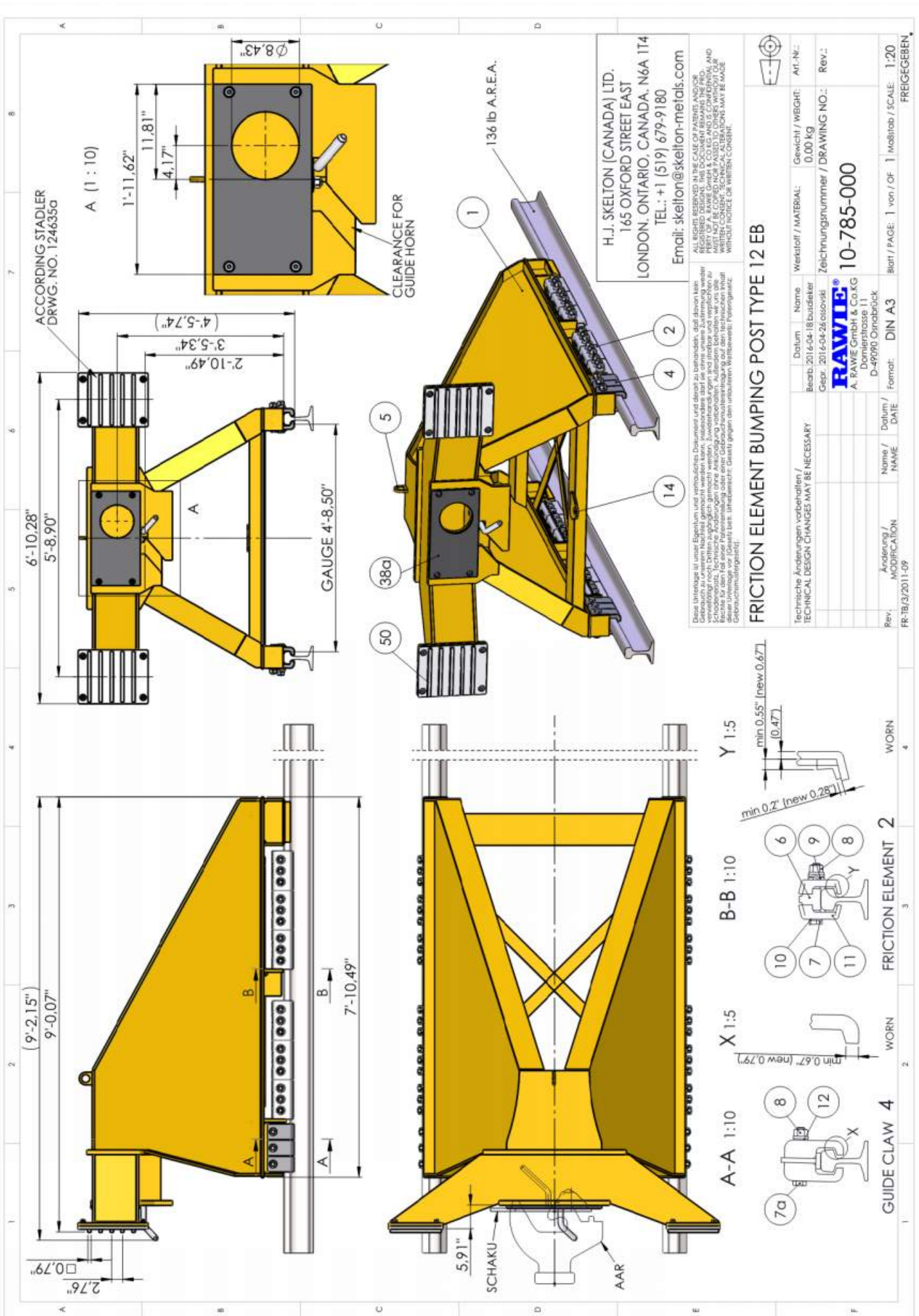

Figure 1 Example 12-shoe sliding friction bumper

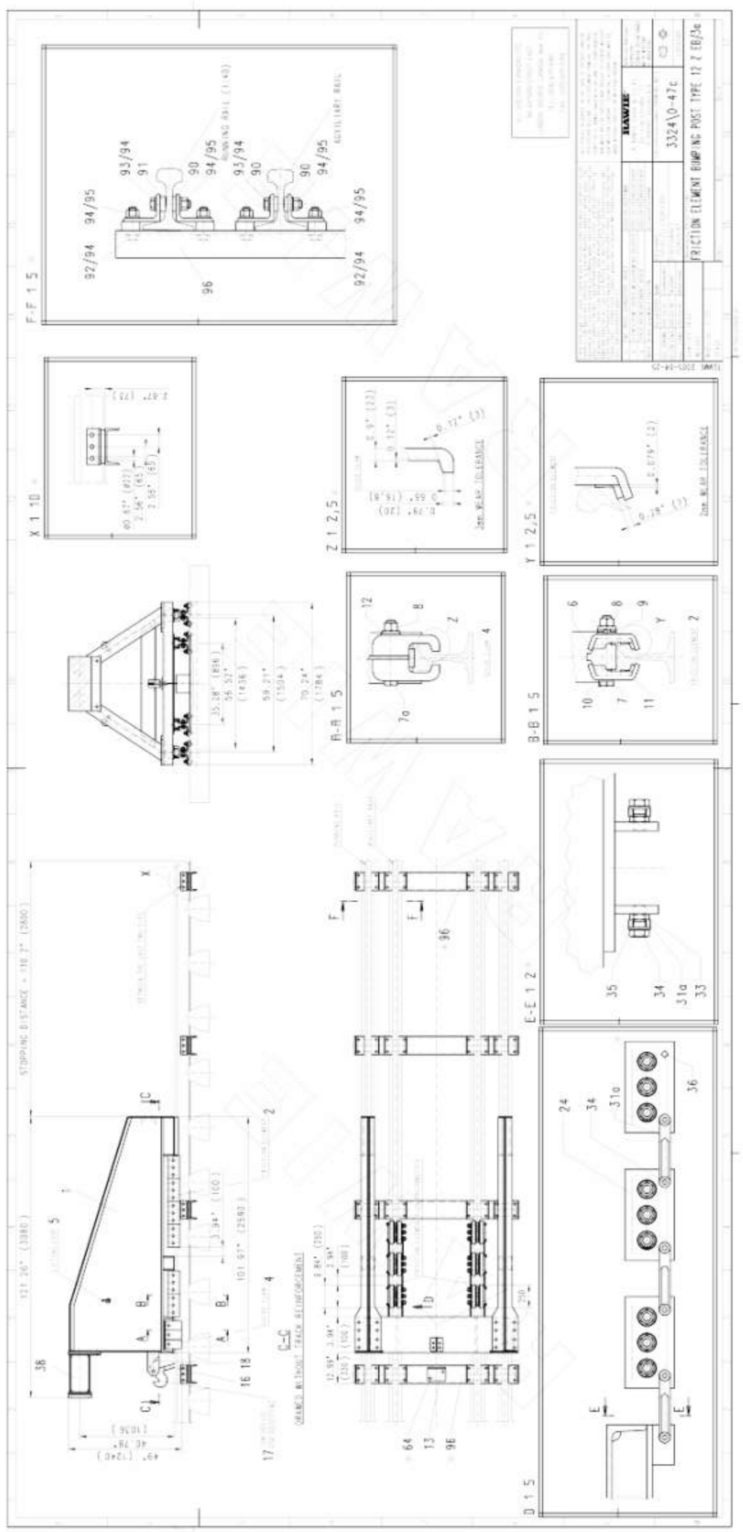

Figure 2 Example 20-shoe sliding friction bumper with auxiliary rails

1.0 Background

Hoboken Terminal includes NJ TRANSIT commuter rail and light rail, PATH, ferry and bus service. A central passenger concourse connects each of the services to each other, to the station building, and to the local street system. NJ TRANSIT commuter trains platform on 18 parallel platform tracks all of which stub end at the passenger concourse. Four additional non-revenue tracks stub-end at or near an extension of the concourse that connects the HBLRT station with the rest of the terminal.

Each of these stub-ended tracks are protected by a bumper block to prevent trains from overrunning the end of the track and entering the passenger concourse. There are four types of bumper blocks including five concrete, twelve structural steel, one sliding friction type and four rail-mounted fixed bumpers. The Track 5 structural steel bumper was damaged and has been removed, therefore, eleven of the structural steel bumpers were inspected. The other revenue track bumpers were inspected by HNTB and will be rated and included in the analysis.

2.0 Inspection Summary

During the week of March 20, 2017, HNTB inspected each of the existing bumping blocks and the last 100 feet of each revenue terminal track. HNTB also measured the length of each platform and the distance to the departing insulated joints (IJs) at the west end of the platform. The bumper on Track 5 was damaged and removed from the facility and was not inspected. Photo 1 shows the east end of Track 5 after removal of the bumping post. Photo 2 shows ballast and track that was installed in place of the former bumper.

Photo 1 – East End of Track 5, taken March 21, 2017

Photo 2 – Track 5 Ballast added, taken May 31, 2017

2.1 Track Inspection Summary

The tracks at Hoboken Terminal are constructed with crossties and ballast. Most use composite crossties outside the bumper area. At the structural steel bumpers, the track is typically supported by timber block ties in ballast – the structure of the steel bumpers prevents installing crossties for the last nine feet of track approaching the bumper. Typically, rail is bolted ±78-foot strings of 132 RE but other sections were noted including 140 RE, 136 RE and 131 RE. Each track except Track 19 has a pair of insulated joints in advance of the bumper; both field-applied poly insulated joints and factory boned insulated joints were found.

The height of the bumper head relative to the track varies significantly throughout the terminal. The original steel bumpers were designed for a 5-inch rail section to be strapped to the foundation of the bumper. The concrete bumpers were built with the running rails embedded in the concrete. Over time, the elevation of the tracks west of the bumpers has been lowered (tracks under canopy) or in some cases raised (tracks outside canopy) and the change in rail section has also affected the height of the bumper relative to the top of rail.

Various conditions exist however. In general, the track 15 feet west of the bumper is generally much lower than the track at the bumper. In these cases, there may be a ramp in the track profile up to the bumper. In an impact these sudden changes in track elevation may contribute to overriding of the bumper.

In addition to the insulated joints, there are impedance bonds, traction power return or cross bonding cables, signals and track wires at the east end of each track. The cables for this equipment enter a transverse duct bank that crosses Tracks 2 through 14 at a point approximately 9 to 12 feet west of the bumper. In some cases, the concrete portion of the duct bank impedes placement of crossties or lowering of the track.

2.2 Bumper Inspection Summary

The purpose of the inspection was to determine overall bumper condition for structural analysis and confirm as-built dimensions from the provided reference documents. Field investigation was limited to visual inspection utilizing simple hand tools for quantifying component sizes and material deterioration. The inspection rating at each track is included in Table 2.

The eleven steel bumping posts have similar levels of deterioration including multiple steel members/plates exhibiting severe corrosion, severe pack rust, and severe section loss from train plow impacts. Four of these steel posts appear to have been impacted by trains as evidenced by vertically split cast-iron striking surfaces, deformed steel angles/plates/rivet heads near the striking surface and observable tilting. The bumper on Track 5 was damaged and removed from the facility and was not inspected.

The five concrete bumping blocks exhibit varying extents of small to large spalls, fine to wide cracking, light to medium scaling, limited honeycombing, and limited hollow areas. The bumping block at Track 1 appears to be newer construction compared to the others.

Bolts/anchor rods attaching cast-iron/steel plate striking surfaces to both steel and concrete bumpers generally exhibit severe corrosion with full section loss and are severely deformed.

The sliding friction bumper appears to be new. The rail-mounted fixed bumper exhibits light to moderate steel corrosion and has multiple deformed components.

Table 2 Bumper Inspection Rating per Track

Location	Type	Inspection Rating	Location	Type	Inspection Rating
Track 1	Concrete	Good	Track 11	Steel	Poor
Track 2	Steel	Poor	Track 12	Steel	Poor
Track 3	Steel	Poor	Track 13	Steel	Poor
Track 4	Steel	Poor	Track 14	Concrete	Fair
Track 5	N/A	N/A	Track 15	Sliding Friction	Excellent
Track 6	Steel	Poor	Track 16	Concrete	Fair
Track 7	Steel	Poor	Track 17	Concrete	Fair
Track 8	Steel	Poor	Track 18	Concrete	Fair
Track 9	Steel	Poor	Track 19	Rail-Mounted	Fair
Track 10	Steel	Poor			

See Appendix A for a summary of inspection field notes for each track and inspection rating criteria.

3.0 Signal Preview Distance and Stopping Tolerance

For this evaluation, the term ‘stopping tolerance’ is used to describe the minimum desirable distance between the bumping post head and the coupler of the end car when a train is stopped at the designated stopping point at the end of the track. Based on operations observed during field inspections, trains are typically spotted approximately 10 to 15 feet from the face of the bumpers.

At the other end of the track, the term ‘signal preview distance’ is used to describe the minimum desirable distance from the west end of a train to the westbound departure signal. Engineers in locomotives, cab cars or EMU cabs must be able to see the signal in order to proceed out of the terminal. Both the geometry of the cab and the height and angle of the signal head limit how close the west end of the train can be to the signal.

The proposed minimum signal preview distance is 30 feet. This number should be confirmed by NJ TRANSIT operations department but is believed to be a workable number when balancing the extra track length needed to install energy absorbing bumping posts and the desire to maximize usable track length. It is possible that a reduction in this distance could be considered if the angle of the signal heads was adjusted.

Assuming a 15-foot stopping tolerance, the existing tracks have a signal preview distance of between 35 and 90 feet, with most tracks between 70 and 90 feet.

4.0 Design Consist and Track Length

NJ TRANSIT provided the weights and lengths of the design vehicles which are shown in Table 3. Consists were developed for each track based on these lengths. Each length consist assumes one locomotive, one cab car and a split between trailer cars with and without toilets as shown in Table 4.

HNTB measured the length of each track in the field between the face of bumper and the IJs at the westbound departure signal. The distance from the face of the existing bumper to the west face of the concourse was also measured. For each track, Table 5 shows the existing track length and the proposed track length assuming the existing bumpers are removed. The consist length and the remaining track available for signal preview, stopping tolerance and for a new bumping post is also shown.

Table 3 Design Vehicles

UNIT	EMPTY WEIGHT LBS	AW3 WEIGHT LBS	LENGTH FT
PL-42 AC LOCOMOTIVE	288,000	288,000	69.83
MULTI-LEVEL CAB CAR	139,250	189,740	85
MULTI-LEVEL TRAILER CAR (W/OUT TOILET)	132,990	187,275	85
MULTI-LEVEL TRAILER CAR (W/ TOILET)	134,880	186,690	85

Table 4 Design Consists

NO. COACHES	NO. CAB CARS	NO. W/ TOILET	NO. W/OUT TOILET	EMPTY WEIGHT LBS	AW3 WEIGHT LBS	LENGTH FT
2	1	0	1	560,240	665,015	240
5	1	2	2	962,990	1,225,670	495
6	1	2	3	1,095,980	1,412,945	580
7	1	3	3	1,230,860	1,599,635	665
8	1	3	4	1,363,850	1,786,910	750
9	1	4	4	1,498,730	1,973,600	835
11	1	5	5	1,766,600	2,347,565	1005

Note: Consist weights and lengths include one locomotive.

Table 5 Track and Design Train Lengths

TRACK	EXISTING TRACK LENGTH	PROPOSED TRACK LENGTH	NO. COACHES	RESULTING LENGTH FOR SIGNAL PREVIEW, STOPPING TOLERANCE AND BUMPER OCCUPANCY
1	337	344	2	104
2	602	607	5	112
3	601	605	5	110
4	662	666	6	86
5	662	667	6	87
6	839	844	8	94
7	838	843	8	93
8	1091	1,096	11	91
9	840	845	8	95
10	833	840	8	90
11	826	834	8	84
12	602	607	5	112
13	595	599	5	104
14	799	805	7	140
15	769	793	7	128
16	850	856	8	106
17	850	856	8	106
18	930	936	9	101

Note: Proposed track length assumes removal of existing bumper and extension of track to west edge of concourse.

5.0 Bumper Forces and Deceleration Rate

Energy absorbing bumpers are recommended for revenue tracks on a passenger rail system. Train impacts with fixed bumpers generate high forces and conventional passenger equipment has limited capacity to absorb impact energy. For example, one study [1] found that the draft sill crush load of conventional railway equipment is 1,700,000 pounds which is attained after two inches of deflection. Even if a fixed bumping post could withstand this force, the sudden deceleration would cause injury to passengers and damage to the railcars. Also, as often happens with train collisions, the lead car may override a fixed bumper or one or more cars may derail due to the sudden release of the train's kinetic energy.

Energy absorbing bumpers are designed to stop a train at a controlled rate and provide a resisting force that is applied over a predetermined length. There are two common types of energy absorbing bumper: sliding friction and hydraulic.

The existing Rawie bumper on Track 15 is an example of a sliding friction bumper. Friction shoes clamp to the rail and resist sliding with a known force. By changing the number and spacing of friction shoes and the length of track behind the bumper, this type of bumper can be tailored to different train weights and speeds.

Hydraulic bumpers use a cylinder that slides with a known force. Different type and capacity cylinders are available to accommodate trains of different length and weight. Sliding friction bumpers typically can have a higher capacity than hydraulic bumpers because the stopping distance for hydraulic bumpers is limited to the length of the cylinder which is typically no longer than three to nine feet. Photo 4 shows a hydraulic bumper found in Chicago Union Station.

The hydraulic element can either be the primary means of absorbing energy mounted to a fixed foundation or it can be mounted to a sliding friction bumper. In the latter case, the hydraulic element can be designed to absorb energy from a low speed impact without sliding the friction elements. This is particularly useful for constrained terminal conditions where trains will routinely stop close to the bumper face; occasional low-speed impacts with the bumper can be accommodated without having to reset the friction elements. The bumping posts installed at NJ TRANSIT's Atlantic City terminal are an example of a combined sliding and hydraulic bumper and can be seen in Photo 5. Another example, from Boston, is shown in Figure 3.

Research did not show a correlation between specific deceleration rates and the level of injury expected to passengers within a train. The following sections provide a basis for the recommended design deceleration rate.

5.1 Stopping Distance Versus Force

To illustrate the effect of impact speed and stopping distance, Table 6 shows a range of initial speeds between 2.5 and 25 mph and stopping distances between 2.5 inches and 30 feet. The top section shows the resulting g-forces to stop a train under each condition. It should be noted that in this table, g-force is a function of the initial speed and the stopping distance only and is independent of the weight of the vehicle.

On the table, conditions that result in a deceleration above 0.3 g are marked with dark highlighting and those between 0.15 and 0.3 are marked with medium highlighting.

The bottom section of Table 6 shows forces on a 6-car train stopped under the conditions shown. This assumes the entire train acts as a single ‘solid’ unit and ignores compression in the draft gear. The dark highlighting shows forces that exceed the crush load of the draft sill and would result in significant damage of the lead car. The medium highlighting shows forces that exceed the FRA required buff strength of conventional equipment and may result in damage to the car.

The middle section shows forces on a single cab car stopped under the same conditions with the same highlighting. In an actual impact, the loading would be somewhere between the single-car load and the ‘solid’ train loading and is a function of the draft-gear stiffness and the longitudinal stiffness of the carbody. One study [2] found that doubling the length of a passenger train (a push-pull consist operating in the push direction) from four to eight cars only increased the severity of the crash by 24% whereas the ‘solid’ train model shows an increase of approximately 85%. For purposes of conservatism, bumpers will be designed assuming a solid train but impact with a single car will also be checked to so that reasonable deceleration rates are maintained.

5.2 Acceptable Deceleration Rates

Research into safe longitudinal accelerations for passengers in railcars was reviewed. For reference, 0.15 g is equivalent to 4.9 ft/s^2, 3.3 miles per hour per second (mphps) and 1.5 m/s^2.

Tests performed in the 1930s as part of a program to develop the PCC trolley car [3] determined the average deceleration rate at which standing people can retain their balance without taking a step or grabbing a hand rail. For forward facing unsupported standees this was 0.13 g, for all standees (forward, rearward and side facing) this was 0.165 g, for standees holding an overhead strap this was 0.23 g and for those holding a vertical grab rail this was 0.27 g. Other studies have been performed since the PCC work and are summarized in Reserach Report 40: A survey of longitudinal acceleration comfort studies in ground transportation," Council for Advanced Transportation Studies, 1976 [4] and Passenger Stability Within Moving Railway Vehicles: Limits," *Urban Rail*

Transit, vol. 1, no. 2, pp. 95-103, 2015 [5]. No studies have proposed a definitive upper limit for safe longitudinal deceleration rates, although 0.11 to 0.15 g has been suggested.

The PCC work was completed for the development of a trolley car and is often cited in design criteria for light rail equipment. A common performance requirement for modern LRT equipment is 3 mphps (0.14 g) as the maximum acceleration rate and the maximum service braking rate [6]. Emergency braking rates of 4.5 to 6 mphps (0.21 to 0.27 g) are also common on LRT. One source recommends 0.30 g as a design deceleration rate for LRT [6].

Unlike transit systems where higher acceleration and braking rates are common during normal operations, commuter rail typical operates with lower levels of acceleration. For example, the emergency braking rate for NJ TRANSIT's Multi-Level railcars is listed as 0.11 g (2.42 mphps). For trains operating at slow speed into a terminal, it is assumed that passengers are beginning to stand and move toward the doors, and may not be grasping handholds on the train. Impact with a bumper that decelerates the train at a much higher rate than passengers are accustomed to may result in passenger injuries.

5.3 Other Agency Criteria

Bumping block standards from three overseas railroads were reviewed. Each consider a range of equipment weights and a tiered criteria for maximum deceleration rates.

UK Rail Safety Standards Board, Railway Group Standard, Terminal Tracks – Requirements for Buffer Stops, Arresting Devices and End Impact Walls: For new installation, this standard requires consideration of a range of equipment weights that would be expected on a given track. For that range of equipment weights, the desirable average deceleration rate should not exceed 0.15 g with an absolute maximum for the lightest train of 0.25 g where space constraints require.

Israel Railways Technical Specification for Buffer-Stops, Fixed Buffer Stops and Braking Wheel Stop Set: This specification covers standard sliding friction bumpers for use with a variety of train types. The specification requires bumpers to "arrest the full range of trains between the heaviest and lightest using a track without risk of serious injury to people on the train." It includes a range of train weight for each of 6 standard bumpers ranging from 180 kips to 7,000 kips and impact speeds from 6 to 9 mph (10 to 15 km/hr). Maximum average deceleration rates are specified; the preferred is 0.15 g but when site constraints limit the slide length, the average acceleration for 'lightweight trains' must not be more than 0.25 g (2.5 m/s^2).

Rail Corporation New South Wales Engineering Standard – Buffer Stops: RailCorp is the government agency that holds the rolling stock and railroad infrastructure in and around

Sydney Australia (a separate entity operates passenger service). Their standard also requires consideration of a range of equipment weights which varies from 180 kips to 3,000 kips. For the range of equipment weights expected on a given track, the maximum desirable deceleration rate is 0.15 g with an absolute maximum for the lightest train of 0.25 g where space constraints require.

5.4 Existing Energy-absorbing Bumping Posts

Existing energy absorbing bumping posts on commuter and inter-city passenger terminals were surveyed. In many cases, incomplete information was found.

Rawie hydraulic and sliding friction bumpers are installed at MBTA's North Station in Boston. They are designed to stop a 1,159,000 pound train from 10 mph with a maximum deceleration rate of 0.15 g. See Figure 3.

Terminal tracks in Denver use hydraulic Western-Cullen-Hayes bumpers (see Photo 3) with a rated capacity of 1,000,000 foot-pounds over 30 inches of travel. Chicago Union Station has a hydraulic bumper on some tracks (see Photo 4) with approximately three feet of travel. Although the design speed is not known, both bumpers would be limited to below 5 mph given the short stopping distances provided by the hydraulic element.

RAWIE

Friction Element Bumping Post

Type 20 EB (insulated) with Jarret BCLR 600V3 Shock Absorber

M. B. T. A. Boston, Mass.

Design Criteria:

Train weight: 1,158,940 LB (525.7 Tonnes)

AT 3 M.P.H. (4.8 K.P.H.)
The shock absorber arrests the train without the sled moving.

AT 10 M.P.H. (16.09 K.P.H.)
The combined shock absorber and sled will safely arrest the train when the sled has moved 22' 8'' with a maximum deceleration of 0.15 G.

Figure 3 MBTA Bumper

Photo 3 WCH Hydraulic Bumper Denver

Photo 4 - Chicago Union Station Hydraulic Bumper

Photo 5 NJ TRANSIT Atlantic City Terminal Bumper

Table 6: Deceleration rates and forces at various stopping distances and from various initial speeds

DECELERATION RATES AND FORCES AT VARIOUS STOPPING DISTANCES AND FROM VARIOUS INITIAL SPEEDS												
Stopping Distance, ft		0.21	0.375	1	1.5	2	2.5	5	10	15	20	25	30
Stopping Distance, in		2.50	4.50										
	Initial Speed	Deceleration rates at various initial speeds and stopping distances, g's						Shading indicates rate above 0.15 g's					
	MPH							Shadding indicates rate above 0.3 g's					
	2.5	1.002	0.557	0.209	0.139	0.104	0.084	0.042	0.021	0.014	0.010	0.008	0.007
	5.0	4.008	2.227	0.835	0.557	0.418	0.334	0.167	0.084	0.056	0.042	0.033	0.028
	7.5	9.019	5.010	1.879	1.253	0.939	0.752	0.376	0.188	0.125	0.094	0.075	0.063
	10.0	16.033	8.907	3.340	2.227	1.670	1.336	0.668	0.334	0.223	0.167	0.134	0.111
	12.5	25.052	13.918	5.219	3.479	2.610	2.088	1.044	0.522	0.348	0.261	0.209	0.174
	15.0	36.075	20.041	7.516	5.010	3.758	3.006	1.503	0.752	0.501	0.376	0.301	0.251
	17.5	49.101	27.279	10.229	6.820	5.115	4.092	2.046	1.023	0.682	0.511	0.409	0.341
	20.0	64.133	35.629	13.361	8.907	6.680	5.344	2.672	1.336	0.891	0.668	0.534	0.445
	22.5	81.168	45.093	16.910	11.273	8.455	6.764	3.382	1.691	1.127	0.845	0.676	0.564
	25.0	100.207	55.671	20.876	13.918	10.438	8.351	4.175	2.088	1.392	1.044	0.835	0.696
	Initial Speed	Average Force to Stop Cab Car, lbs											
	MPH							Shading indicates force above 800 kip buff strength					
	Vehicle Mass, slugs		5,893					Shading indicates force above 1,700 kip assumed crush strength					
	2.5	191,000	106,000	40,000	27,000	20,000	16,000	8,000	4,000	3,000	2,000	2,000	2,000
	5.0	761,000	423,000	159,000	106,000	80,000	64,000	32,000	16,000	11,000	8,000	7,000	6,000
	7.5	1,712,000	951,000	357,000	238,000	179,000	143,000	72,000	36,000	24,000	18,000	15,000	12,000
	10.0	3,043,000	1,691,000	634,000	423,000	317,000	254,000	127,000	64,000	43,000	32,000	26,000	22,000
	12.5	4,754,000	2,641,000	991,000	661,000	496,000	397,000	199,000	100,000	67,000	50,000	40,000	34,000
	15.0	6,845,000	3,803,000	1,426,000	951,000	713,000	571,000	286,000	143,000	96,000	72,000	58,000	48,000
	17.5	9,317,000	5,176,000	1,941,000	1,294,000	971,000	777,000	389,000	195,000	130,000	98,000	78,000	65,000
	20.0	12,169,000	6,761,000	2,536,000	1,691,000	1,268,000	1,015,000	508,000	254,000	170,000	127,000	102,000	85,000
	22.5	15,401,000	8,556,000	3,209,000	2,139,000	1,605,000	1,284,000	642,000	321,000	214,000	161,000	129,000	107,000
	25.0	19,014,000	10,563,000	3,962,000	2,641,000	1,981,000	1,585,000	793,000	397,000	265,000	199,000	159,000	133,000
	Initial Speed	Average Force to 8-Car Train, lbs											
	MPH							Shading indicates force above 800 kip buff strength					
	Train mass, slugs		55,494					Shading indicates force above 1,700 kip assumed crush strength					
	2.5	1,791,000	995,000	374,000	249,000	187,000	150,000	75,000	38,000	25,000	19,000	15,000	13,000
	5.0	7,163,000	3,980,000	1,493,000	995,000	747,000	597,000	299,000	150,000	100,000	75,000	60,000	50,000
	7.5	16,116,000	8,954,000	3,358,000	2,239,000	1,679,000	1,343,000	672,000	336,000	224,000	168,000	135,000	112,000
	10.0	28,650,000	15,917,000	5,969,000	3,980,000	2,985,000	2,388,000	1,194,000	597,000	398,000	299,000	239,000	199,000
	12.5	44,766,000	24,870,000	9,327,000	6,218,000	4,664,000	3,731,000	1,866,000	933,000	622,000	467,000	374,000	311,000
	15.0	64,462,000	35,813,000	13,430,000	8,954,000	6,715,000	5,372,000	2,686,000	1,343,000	896,000	672,000	538,000	448,000
	17.5	87,740,000	48,745,000	18,280,000	12,187,000	9,140,000	7,312,000	3,656,000	1,828,000	1,219,000	914,000	732,000	610,000
	20.0	114,600,000	63,667,000	23,875,000	15,917,000	11,938,000	9,550,000	4,775,000	2,388,000	1,592,000	1,194,000	955,000	796,000
	22.5	145,040,000	80,578,000	30,217,000	20,145,000	15,109,000	12,087,000	6,044,000	3,022,000	2,015,000	1,511,000	1,209,000	1,008,000
	25.0	179,061,000	99,479,000	37,305,000	24,870,000	18,653,000	14,922,000	7,461,000	3,731,000	2,487,000	1,866,000	1,493,000	1,244,000

5.5 Deceleration Rates and Forces at Various Stopping Distances

The first two stopping distances listed in Table 6, 2.5 and 4.5 inches, represent impacts with a fixed bumper. The 2.5 inch stopping distance represents impact with a highly rigid fixed bumper and uses only the compression of the draft gear of the lead car to stop the train. An impact of above 5 mph exceeds the structural strength of the draft sill for a single car. The 4.5 inch stopping distance assumes an impact with a strong but flexible fixed bumping post and assumes additional stopping distance is provided by elastic compression of the lead car. For both conditions, deceleration rates in the lead car exceed the 0.15 or 0.3 g even at 2.5 mph.

Increasing the stopping distance to one or two feet reduces the forces to acceptable levels but the deceleration rates in the lead car are still an order of magnitude higher than 0.3 g. For speeds above 10 mph and deceleration rates below 0.15 g, a stopping distance of 30 or more feet is required.

A third factor illustrated is that the mass of the train affects the force required to stop it. For a 6-car train at 10 mph to be stopped in 15 feet, a bumper force of 315,000 pounds is required. If a single coach strikes a bumper with the same resisting force, the coach would stop in just over two feet and at a deceleration rate of almost 1.6 g. For this reason, energy absorbing bumpers are often designed with an incremental braking force that limits the resistance for lower-speed or lighter-weight trains but eventually builds to a higher force.

6.0 Existing Bumper Evaluation

6.1 Steel and Concrete Bumpers

The analysis is based on the work-energy principal. Work is done on and by the train when it impacts the bumper block. The primary forms considered are elastic strain in the lead carbody and its draft gear and elastic and plastic deformation of the bumper block. The sum of the work done during the collision is equal to the pre-collision kinetic energy of the train. A corresponding impact speed is calculated based on the mass of the train using the following equations.

$$\sum Collision\ Work = Precollision\ kinetic\ engergy = \frac{1}{2}mv^2$$

$$Bumper\ Capacity = v = \sqrt{\frac{2 \times Collision\ Work}{m}}$$

Over time, the steel and concrete bumper blocks have been modified from their original design (see inspection section of this report).

A reduction of operating speed from 10 miles per hour to 5 miles per hour reduces the magnitude of energy to be absorbed by a factor of four, and is appropriate.

Herein, an approximate evaluation of the bumpers in their current condition was made for this reduced impact speed. A complete collision analysis involves a detailed assessment of the equipment and structure response and cannot be comprehensively performed without detailed simulations that are often supplemented with crash test data. While a significant number of tests have been conducted by Volpe National Transportation Systems Center, these tests were conducted at much higher impact speeds and are therefore not directly applicable. However, low-impact behavior was estimated with insights gained from these higher impact crash tests and simulations. A key assumption in the evaluation is that a typical consist may be approximately represented by the behavior of a single lead car. Therefore, two primary sources of energy dissipation associated with the first car only were accounted for, those being draft gear compression and car body elastic strain. In addition, the analysis considers steel bumping post elastic strain and bumping post foundation energy capacity.

Draft Gear Compression

The coupler, which is connected to the carbody through the draft gear, is the first element of the train to impact the bumper. Appendix B - Attachment 1 shows the energy absorption capacity of a typical passenger car draft gear of 40,000 ft-lbs at 650,000 pounds of load. Note that this is conservative as 800,000 lbs of impact force is assumed. In a multi-car impact, multiple draft gears absorb energy, but the distribution of forces between cars cannot be determined without a time-dependent dynamic analysis.

The 40,000 ft-lbs of energy associated with a 650,000 pound load for the first car only is assumed to be the energy dissipated through draft gear compression.

Carbody Elastic Strain

Additional energy is absorbed through the compression of the car structure. From tests conducted for the FRA, a load-deflection curve for a typical passenger car is shown in Figure 14 of Appendix B - Attachment 2. This shows a nearly linear load-deflection curve with two inches of deflection at 800,000 pounds. This equates to an energy capacity of 66,667 ft-lbs.

Steel Bumping Post Elastic Strain

A finite element model of the steel portion of the bumping post was loaded in line with a train collision. The steel assembly was found to be extremely stiff, deflecting about 0.12 inches under 1,576,000 pounds of load. Above this load the bumper starts to yield. Because the bumper is very stiff, very little energy is absorbed, however it is included in the analysis. At the 800,000 pound buff force, 2,030 ft-lbs of energy is absorbed. A detailed evaluation of the bumper block to arrive at this stiffness is included in Appendix C.

Bumping Post Foundation Energy Capacity

The elastic energy dissipation capacity for the upper portion of the bumper block is small. However significant energy dissipation is achieved through sliding, soil compression and bumper rigid rotation. These three components result in energy dissipation of approximately 70,000 ft-lbs for the steel bumper blocks and a similar magnitude for the concrete bumper blocks.

The energy dissipation methods and vehicle impact loading assumptions noted above result in a permissible bumper block impact speed of 5 mph.

6.2 Sliding Friction Bumper

The sliding friction bumper on Track 15, as installed, requires a slide distance of 19.14 feet to successfully stop a 985 kip train with an impact speed of 10 mph. At some point after the original installation of the bumper, a portion of the track was removed which reduced the amount of slide distance to 15’-2”. This reduction in slide distance and an increase in the weight of the design train correlates to reduction of acceptable impact speed from 10 mph to 7 mph.

6.3 Rail-Mounted Fixed Bumper

The Nolan Company rail-mounted fixed bumping post (model# HDBP) has a published yield point of 804,000 lbs new. This equates to an approximate maximum impact speed of 2.5mph for a 6 car train mass. The field investigation revealed multiple deformed tension and compression elements meriting a reduction in capacity. A two (2) mph maximum impact speed is appropriate (504,000 lbs average force).

6.4 Existing Bumper Ratings & Recommended Actions

Considering the engineering analysis of the bumping blocks/posts and accounting for their current configurations and conditions, the recommended permissible bumper block impact speed rating is 5 mph at Tracks 1 to 4, Tracks 6 to 14, and Tracks 16 to 18.

Rehabilitation of the seventeen bumpers to meet the minimum impact speed criteria is not recommended. HNTB recommends replacement of bumping blocks on Tracks 1 to 4, Tracks 6 to 14, and Tracks 16 to 18. Relocation of the sliding friction bumper on Track 15, as shown in Table 10, is recommended to provide the appropriate amount of slide distance to meet the minimum 10 mph criteria. Track 19 appears to not be a revenue track and bumper replacement to obtain a minimum 10 mph impact criteria is not necessary. While an energy absorbing bumper block is not required to protect revenue service trains, a more robust fixed bumper could be considered to protect the site beyond the end of track.

7.0 Recommended Design Speed and Deceleration Rate

The normal timetable speed for trains in the terminal is 10 mph. Impact at speeds above 10 mph is possible, but designing a bumper for greater than 10 mph will either reduce the usable length of the track or require a deceleration rate above 0.15 g. Use of a bumper with a lower design speed would not protect against trains operating at the normal timetable speed of 10 mph.

Tables 7 and 8 show the resulting stopping length and track capacity at initial impact speeds between 2.5 mph and 25 mph. Table 7 shows the stopping distance, bumper length, stopping tolerance and signal preview assumptions for each speed increment. Table 8 shows the track capacity and contingency track length for each track and each speed increment. The term contingency length indicates that the track length that exceeds the requirements for design stopping distance, signal preview, stopping tolerance, consist length and bumper post length.

Maintaining the 0.15 g deceleration rate, increasing the speed to 15 mph reduces the capacity on 11 of the 18 tracks. To maintain the existing track capacity and to avoid excessively high deceleration rates, HNTB recommends a 10 mph design speed for all tracks.

Table 7: Stopping Distance at Various Initial Speeds

Deceleration Rate = 0.15 g

Initial Speed MPH	**Stopping distance ft**	**Bumper Length ft**	**Stopping Tolerance ft**	**Signal Preview ft**
2.5	1	10	15	30
5.0	6	10	15	30
7.5	13	10	15	30
10.0	24	10	15	30
12.5	35	10	15	30
15.0	50	10	15	30
17.5	68	10	15	30
20.0	89	10	15	30
22.5	113	10	15	30
25.0	139	10	15	30

Table 8: Track Capacity at Various Initial Speeds

Track	**1**		**2**		**3**		**4**		**5**		**6**		**7**		**8**		**9**		**10**		**11**		**12**		**13**		**14**		**15**		**16**		**17**		**18**	
Length	344		607		605		666		667		844		843		1096		845		840		834		607		599		805		793		856		856		936	
Initial Speed MPH	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
2.5	2	47	5	55	5	53	6	29	6	30	8	37	8	36	11	34	8	38	8	33	8	27	5	55	5	47	7	83	7	71	8	49	8	49	9	44
5.0	2	43	5	51	5	49	6	25	6	26	8	33	8	32	11	30	8	34	8	29	8	23	5	51	5	43	7	79	7	67	8	45	8	45	9	40
7.5	2	36	5	44	5	42	6	18	6	19	8	26	8	25	11	23	8	27	8	22	8	16	5	44	5	36	7	72	7	60	8	38	8	38	9	33
10	2	25	5	33	5	31	6	7	6	8	8	15	8	14	11	12	8	16	8	11	8	5	5	33	5	25	7	61	7	49	8	27	8	27	9	22
12.5	2	14	5	22	5	20	5	81	5	82	8	4	8	3	11	1	8	5	8	0	7	79	5	22	5	14	7	50	7	38	8	16	8	16	9	11
15.0	1	84	5	7	5	5	5	66	5	67	7	74	7	73	10	71	7	75	7	70	7	64	5	7	4	84	7	35	7	23	8	1	8	1	8	81
17.5	1	65	4	73	4	71	5	47	5	48	7	55	7	54	10	52	7	56	7	51	7	45	4	73	4	65	7	16	7	4	7	67	7	67	8	62
20.0	1	45	4	53	4	51	5	27	5	28	7	35	7	34	10	32	7	36	7	31	7	25	4	53	4	45	6	81	6	69	7	47	7	47	8	42
22.5	1	21	4	29	4	27	5	3	5	4	7	11	7	10	10	8	7	12	7	7	7	1	4	29	4	21	6	57	6	45	7	23	7	23	8	18
25.0	-	-	4	2	4	0	4	61	4	62	6	69	6	68	9	66	6	70	6	65	6	59	4	2	3	79	6	30	6	18	6	81	6	81	7	76

Table Notes:

Column A shows the maximum number of coaches based on one locomotive, bumper stopping distance, bumper length, stopping tolerance and signal preview. Values are based on a constant deceleration rate of 0.15g and will vary from design values based on number of friction shoes selected.

Column B shows the contingency length.

8.0 Recommended Bumper

HNTB recommends that a sliding friction bumper be installed on all 18 revenue tracks. Each existing bumper should be removed and the track should be extended to the concourse to maximize stopping distance. A portion of the under-grade structure of the existing bumper should be removed to allow for construction of tangent level track.

The final design of the bumper will be by the manufacturer. HNTB has provided design criteria to Rawie and has received a preliminary bumper design. Rawie has proposed a sliding friction bumper with between 10 and 28 friction elements. See Table 1 for the bumper recommendation for each track.

The bumper head will be similar to that on Track 15, shown in Appendix A, which accommodates both the knuckle coupler on NJ TRANSIT push-pull cab cars and locomotives and the transit coupler on EMUs.

For lighter trains, the stopping distance and deceleration rates are shown in Table 9. Although on some tracks, the deceleration rate exceeds 0.15 g, the deceleration rate does not exceed 0.30 g.

The bumper should be installed as shown in Table 10. This will provide the signal preview and stopping tolerance numbers stated above. IJs should be relocated to at least 20 feet in advance of the bumper face. This will reduce the stress on the IJs during an impact.

Additional work that will be required to install the bumper includes:

1. Relocation of insulated joints and impedance bonds to a point 20 feet from the proposed face of bumper.
2. Relocation of the end-of-track signal to the bumper face.
3. Removal of existing bumper and foundation.
4. Extension of track to the concourse.
5. Welding of rail within slide distance, if required. Also, all welds must be ground smooth in accordance with bumper manufacture's specifications.
6. The end of the track should be surfaced and aligned to a horizontal and vertical tangent to a point at least one car length west of the proposed bumper installation location.

An order of magnitude cost is shown below for a bumper manufactured in Germany:

Item	*Quantity*	*Unit Price*	*Unit*	*Cost*
Track Installation	25	***$650***	***LF***	***$16,250***
Sliding Friction Bumper	1	***$44,000***	***EA***	***$44,000***
New Insulated Joints	2	***$4,000***	***EA***	***$8,000***
Relocate Impedance Bonds and Signals	1	***$8,500***	***EA***	***$8,500***
			Subtotal	***$76,750***
			Contingency (30%)	***$23,025***
			Grand Total	***$99,775***
			Say	***$100,000***

For a Buy America compliant bumper, the cost increases as shown:

Item	*Quantity*	*Unit Price*	*Unit*	*Cost*
Track Installation	25	***$650***	***LF***	***$16,250***
Sliding Friction Bumper	1	***$57,000***	***EA***	***$57,000***
New Insulated Joints	2	***$4,000***	***EA***	***$8,000***
Relocate Impedance Bonds and Signals	1	***$8,500***	***EA***	***$8,500***
			Subtotal	***$89,750***
			Contingency (30%)	***$26,925***
			Grand Total	***$116,675***
			Say	***$120,000***

Table 9 Stopping Distance and Deceleration Rate for 3-Car Train

TRACK	10 MPH STOPPING DISTANCE	DECEL. RATE
1	-	-
2	32	0.11
3	32	0.11
4	16	0.21
5	16	0.21
6	16	0.21
7	16	0.21
8	11	0.30
9	16	0.21
10	11	0.30
11	11	0.30
12	32	0.11
13	26	0.13
14	16	0.21
15	16	0.21
16	16	0.21
17	16	0.21
18	16	0.21

Notes:

1. Based on bumpers sized to stop design train.
2. Three-car stopping distances exceeds Track 1 length.

Table 10 Face of Bumper Installation Location

TRACK	FACE OF BUMPER TO CONCOURSE	FACE OF BUMPER TO DEPARTURE IJ
1	59	285
2	67	540
3	65	540
4	41	625
5	42	625
6	49	795
7	48	795
8	46	1,050
9	50	795
10	45	795
11	39	795
12	67	540
13	59	540
14	95	710
15	83	710
16	61	795
17	61	795
18	56	880

9.0 References

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