Test Results of a Modified Turnout Designed to Increase Diverging Route Speeds Without Increasing Lead Length

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ABSTRACT

This paper presents the results of Phase II of a Federal Railroad Administration sponsored study looking at low-cost means to increase speeds through turnouts by retrofit or upgrade. To meet this objective, lead length and frog angle were considered fixed, eliminating the costs to relocate the frog or switch points.

Based on extensive research, it was determined in Phase I that the best solution was to optimize the existing AREMA geometry by reducing the switch angle, incorporating a new diverging switch rail, and reshaping both the curved stock and closure rails. Dynamic simulations showed that higher speeds could be achieved over the optimized geometry without increasing peak wheel/rail forces experienced over the traditional geometry.

In Phase II the new design was tested by retrofitting an AREMA #20 crossover on New Jersey Transit. Full testing of the crossover included comparison with a standard
AREMA #20 based on lateral and vertical wheel/rail forces and lateral car body accelerations.

From current observations and test results, the new turnout design meets the goal of providing a low-cost means to increase the speeds through existing turnouts. By establishing a superior geometry within the same dimensions as the AREMA standard, railroads will be able to make the necessary modifications at low cost and without the need of additional space. In addition, this approach, applicable to the large majority of existing turnouts, is expected to result in improved ride quality and decreased wear, leading to a longer service life and decreased maintenance costs.

**INTRODUCTION**

Turnouts are discontinuities in the track structure that are needed to move a rail vehicle from one track to another. These discontinuities can cause derailments due to abrupt or non-uniform changes in track geometry, which can produce excessive force levels. In the diverging route, these discontinuities frequently create a need for speed restrictions. The highest diverging speed permitted on turnouts of conventional design in North America is generally 45 miles per hour. To obtain a higher diverging speed, it is usually necessary to completely replace an existing turnout with a new a more costly one.

There have been many attempts at improving turnout design [1-12]. However, new designs (such as tangential geometry points or swing-nose frogs) are generally incompatible with conventional American Railway Engineering and Maintenance of Way Association (AREMA) designs. This is especially significant since many turnouts are never completely replaced. This means that, however superior a new turnout design
might be, if it is incompatible with the existing turnout population it will spread only slowly through the railroad network, and never encompass more than about one quarter of total turnouts. Further, while many new designs offer significantly better performance than conventional AREMA standard turnouts, a substantial investment of time and money is required to achieve improved performance.

For these reasons, interest has grown in finding a low-cost means of increasing permissible speeds through turnouts that are compatible with the conventional AREMA standard designs. This paper presents the results of an FRA sponsored study “Investigation of Low-Cost Techniques for Increasing Speeds Through Special Trackwork” (Contract number DTFR53-99-C-00015) that explores this need.

**PROJECT CONSTRAINT**

Due to the high cost of relocating the frog or head block ties (and switching equipment), it was determined that any proposed modification would need to maintain the location of these components. As a consequence, practical and effective low-cost design modifications were limited to the area between the switch points and the toe of frog, with no changes to the overall lead length or frog angle.

**PROPOSED DESIGN MODIFICATION (PHASE I REVIEW)**

Phase I of this FRA-funded project was to propose a low-cost design modification that would allow an increase in diverging route speeds through a conventional turnout. The work performed for Phase I is briefly reviewed here. A more in depth discussion can be found in [13].
The function of a turnout is to allow a passing train to diverge off the main track and travel along a new track and new direction. Physically, the train is turned by an angle equal to the frog angle, which as described above, is considered fixed for all possible design modifications. There are two means by which a turnout changes the direction of a train along the diverging route. The first is the switch point angle. All standard AREMA designs have some non-zero entry angle. The remainder of the turning is achieved through the diverging route curvature. When added, the entry angle and the angle of turning achieved by the curvature must equal the frog angle.

It is the lateral turning forces associated with the switch point angle and the diverging route curvature that (indirectly) establish a limiting speed. AREMA standards for allowable speed through a turnout are based on the “Vmax formula”, which was established to keep turning forces at low enough levels to ensure safety. This is the same formula used for ordinary curves, but with a modification based on switch point angle and point length. The formula is:

$$ V_{max} = \sqrt{\frac{e + 3}{0.0007 \cdot D}} $$

where:

- $V_{max}$ is the allowable speed in miles per hour
- $e$ is the superelevation in inches (zero for standard turnouts)
- “3” is the number of inches of “unbalance” allowed, and
- $D$ is the maximum degree of curvature of the turnout. For turnouts with curved switch points, $D$ is equal to the curvature of the curved closure rail. For straight switch points, $D$ is equal to the curvature of the curved closure rail or the “representative degree
of curvature” associated with the switch rail, whichever is greater (sharper). This “representative degree of curvature” for the straight switch rail is as follows:

\[ D = \frac{100 \cdot \alpha}{l} \]

where \( \alpha \) is the switch angle in degrees and \( l \) is the length of the straight switch rail in feet.

Based on the mathematics of Equation 1, there are only four general avenues of exploration for increasing speeds. One is to add superelevation to a turnout. However, research and simulations have shown that this may only be practical for longer turnouts (#26 or higher). A second possibility is to increase the allowable unbalance above 3 inches. Although this is permitted for some vehicle types, it is not typically allowed based on track design. A third possibility is the reduction of limiting degree of curvature, \( D \). A fourth avenue is to provide conclusive and convincing evidence that the design modifications made warrant a higher speed limit than given by the “Vmax formula”. This could conceivably be done by demonstrating that the safety limits on lateral force and L/V ratio for the modified design are reached only at a considerably higher speed than that predicted by the “Vmax formula”.

Pursuit of a reduction in limiting curvature leads to the pursuit of optimized geometry. If the curvature (or effective curvature due to the switch point angle) is made uniform throughout the length of the turnout, then the limiting value cannot be further reduced. Once uniform, any reduction in one location would result in an increase in another. Attaining uniform curvature is analogous to minimizing peak turning forces throughout the turnout. If the turning force required to turn the train is uniform, then there will be no single location of peak value. Controlling or eliminating these peak values is, after all, the purpose of imposing the speed restrictions in the first place.
Simulations using NUCARS [14], a dynamic simulation model for rail vehicles, were performed to study the behavior of a rail vehicle traversing the diverging route of a turnout. Due to its prevalence in the industry and a focus on high speed track, a #20 turnout was chosen for the simulations. Several designs and speeds were evaluated by simulation including the following: 1) AREMA #20 with straight points, 2) AREMA #20 with curved points, 3) a tangential #20 geometry that is 20 feet longer than AREMA standards (and hence not a suitable low-cost solution), and 4) a #20 Willow-point turnout (also longer than AREMA standard). By studying all of these designs, the vehicle response predictions could be assessed not only against safety limits (e.g. L/V ratio, lateral accelerations, etc.), but also against behavior currently permissible in the industry.

These simulations showed that, by far, the highest lateral forces and L/V ratios were due to the switch point angle of the AREMA designs. Even for the curved point AREMA design, the switch point angle produced significantly high forces, accelerations, and L/V ratios. However, for the AREMA curved point design, switch point angle is not considered by the “Vmax formula”. Instead, limiting speed is based only on closure rail curvature. As suggested above, this finding raised questions of the use of the “Vmax formula” for turnouts.

Based on these findings, the proposed design modifications considered in Phase I focused on the reduction of the entry angle at the switch points without any lengthening of the turnout lead. In order to reduce the switch point angle and maintain the same lead length and frog angle, it is necessary to sharpen the curvature of the closure rail. Although an increase in curvature seems counter productive, especially considering the
“Vmax formula”, simulations consistently showed vast improvements in safety and performance when reducing the switch point angle and sharpening the curve.

Figure 1 shows the single wheel L/V ratio for the left wheel of axle 1 predicted by NUCARS. The plot shows the results for the AREMA straight switch point design at its limiting speed of 36 mph, the AREMA curved point design at the speed limit of 51 mph, and the tangential geometry design (which, again, is 20 feet longer than allowed) at 60 mph. In addition, simulation results from a proposed low-entry angle design are shown at three different speeds: the Vmax limit of 42 mph, 51 mph, and 60 mph.

These and all other simulation results showed that this low-entry angle design provides significant improvement over both the AREMA straight and curved switch point designs. Furthermore, the 60-mph run on the low entry angle design produced results nearly as good as from the tangential geometry design, while still adhering to allowable lead length.

Given these results, FRA authorized Phase II of this project with the purpose of fabricating, installing, and testing the new optimized turnout geometry. Test procedures and results from both before and after testing are discussed in detail in the remainder of this paper.

**Testing Procedures**

For Phase II of the project, an agreement was reached with New Jersey Transit to find a site, conduct “before testing”, modify the turnout to the new design specifications, and conduct the “after testing” in an effort to prove or disprove the Phase I simulation findings. The location chosen by New Jersey Transit was a crossover in northern New Jersey. The crossover consisted of two standard AREMA #20 turnouts each with curved
switch points. Cleveland Track Materials, Inc. joined the project to fabricate the necessary components needed to implement the modified diverging route geometry.

**Before Testing**

Testing of the crossover prior to its modification included collection of both strain gauge and ride quality data. Specifically, the lead turnout (denoted as 5A) was instrumented with strain gauges so that vertical and lateral forces of passing revenue trains could be recorded along the diverging route. Two locations in turnout 5A were instrumented. The first was 50 feet from the switch points, while the second was 80 feet from the points. Using the attached gauges, lateral and vertical wheel/rail forces were measured and recorded for a number of passenger trains that traveled through the crossover.

A ride quality meter was used to capture the accelerations of passenger train car bodies as they traveled through the crossover. The ride quality meter was placed on the floor of a passenger train just over the bolster of the lead truck. Numerous trains were ridden while using the meter to collect accelerations in lateral, vertical, and longitudinal directions. Of primary significance were the lateral accelerations as the design modification is only with in the horizontal plane of the turnout.

**After Testing**

After completion of the “before testing”, the crossover was modified to match the newly designed diverging route geometry. This modification required the installation of modified switch points (and other miscellaneous components) built by Cleveland Track Materials, Inc. Once these modifications were made by New Jersey Transit, the crossover was ready for the after tests. Three sets of testing were performed: 1) strain gauge testing of the modified turnout 5A, 2) ride quality testing on passenger trains, 3) use of the strain
gauges and ride quality meter during incremental speed testing by New Jersey Transit’s new Track Geometry Vehicle.

The strain gauge testing of the modified turnout was similar to the “before testing”, described above. The gauges were used to capture the lateral and vertical wheel/rail forces of passing revenue trains traveling across turnout 5A of the modified crossover. As before, two sites were instrumented, but in this case, the first site was 80 feet from the points, while the second was 110 feet from the points. These locations, which were further from the points than the locations for the “before testing” were deemed equivalent to the sites of the before testing due to the reduced entry angle of the modified design. Wheel forces from numerous passenger trains were measured and recorded during this test.

Ride quality testing was again conducted aboard numerous passenger trains that traveled through the modified crossover. As before, the ride quality meter was placed on the floor of the car bodies just above the bolster of the lead truck. Lateral, vertical, and longitudinal accelerations were recorded. In an effort to generate more data to compare with the results over the modified design, ride quality testing was also conducted on passenger trains traveling through a nearby crossover (denoted herein as Crossover #1), which contained two AREMA #20 turnouts each with curved switch points (the same design that originally existed in the newly modified crossover). Given the proximity and identical design, this ride quality testing of the #1 crossover effectively provided additional “before data” to be compared with the results from the modified crossover (#5).
The final testing involved the use of New Jersey Transit’s new Track Geometry Vehicle (TGV) traveling at specified speeds through the modified crossover and another nearby conventional AREMA #20 (curved point) crossover. The TGV was operated through the modified crossover at speeds from 25 miles per hour (mph) to 55 mph in five mph increments. The crossover was traversed in each direction (eastbound and westbound) at each of the test speeds. During these passes, the strain gauges installed on turnout 5A were used to record lateral and vertical wheel/rail forces from the TGV. Computed L/V ratios were used to assess safety during this test to ensure that the next highest speed in the test could be taken. In addition, the ride quality meter was used on-board the TGV during these passes through the modified crossover. The meter was placed over the bolster of the truck at the observation end of the vehicle. This was the lead truck in all eastbound passes and the trailing truck in all westbound passes. Similar ride quality tests were also conducted through a nearby crossover (denoted as Crossover #3). In these tests, the TGV traveled at speeds from 25 mph to 45 mph (top permissible speed for the conventional curved point AREMA design), again in five mph increments. As before, the crossover was traversed in each direction for each speed.

**TEST RESULTS**

This section will present the results of the testing described above. Specifically, comparisons of before and after data will be presented for both ride quality and strain gauge data.
Passenger Train Wheel Force Data

Table 1 summarizes the strain gauge test results for both the before test and after test. This table gives the maximums and averages found for vertical wheel force, lateral wheel force, and L/V ratio. This data demonstrates that the design modification results in a reduction in all of these force measurements. To show that the tests were comparable, the table also shows the minimum, maximum, and average speed of the trains tested. The average train speed over the modified design was actually 2.5 miles per hour faster than the trains over the conventional design prior to modification. Despite the slightly higher train speeds, maximum L/V ratios were reduced from 0.4 to 0.28 and average L/V ratios were reduced from 0.15 to 0.07.

Figures 2 and 3 show all of the L/V measurements obtained for both the before and after data, respectively. These graphs again convey the significant reduction in L/V ratio achieved by the modified turnout geometry. This is evident by the narrow band of scatter for the modified turnout.

Another way to view this data is as a histogram. Figure 4 shows the percentage of samples as a function of L/V = 0.25 “buckets”. As can be seen, the modified turnout results shift to the left indicating a lower incidence of higher L/V ratios.

Passenger Train Ride Quality Data

Using the ride quality meter measurements of car body accelerations when traversing the different turnouts were obtained. Most important of these were the measurements of lateral car body acceleration. The meter was used on passenger trains traversing the following crossovers on New Jersey Transit: 1) Crossover #5 before modification (i.e.
AREMA Standard #20 with curved switch points), Crossover #1 (another AREMA Standard #20 with curved switch points), and the modified Crossover #5 (new geometry).

The key parameter in the raw lateral acceleration data obtained is the maximum value experienced (maximum absolute value, i.e. positive or negative maximum). Another important way to examine the lateral acceleration behavior is to calculate the peak to peak accelerations. This is the difference between the maximum and minimum values observed over a one second interval. Maximum values of the peak to peak lateral acceleration were found for each pass through a crossover.

Table 2 summarizes the findings obtained with the ride quality meter on board passenger trains. The table gives the average of each run’s maximum lateral acceleration. As shown, the average maximum over the modified geometry was 0.166 g’s (gravity units = 32.174 feet per second per second). The average maximum over all runs on the AREMA standard design was 0.285 g’s. This results in a reduction of 41.8 percent. For peak to peak accelerations, the average maximum from all runs on the modified design was 0.240 g’s, while for the AREMA standard design it was 0.422. Here the reduction is 43.1 percent.

This ride quality data for the passenger trains shows that the modified diverging route geometry greatly reduces peak lateral accelerations experienced in the car body. There is also a significant reduction in maximum peak to peak lateral accelerations. These acceleration reductions demonstrate a substantially smoother ride by passenger trains over the modified design over the range of speeds currently allowed by the AREMA standards.
Track Geometry Car Ride Quality Data

The New Jersey Transit Track Geometry Vehicle traversed the modified crossover at speeds from 25 to 55 mph in five mile per hour increments. One pass was made in each direction (eastbound and westbound) for each of these speeds. The ride quality meter was used on the geometry vehicle for each of these runs and the strain gauges were used to monitor wheel forces to ensure that the next highest speed could be attained safely. The geometry vehicle was also used at speeds from 25 to 45 mph in five mph increments over a nearby AREMA standard #20 crossover, again using the ride quality meter for accelerations measurements in the car body.

Figure 5 shows the lateral acceleration and peak to peak lateral acceleration of the track geometry vehicle when traversing an AREMA standard #20 at 45 miles per hour in the eastbound direction. As the graph shows, the maximum lateral acceleration was 0.39 g’s, while the maximum peak to peak acceleration was 0.71 g’s. Figure 6 shows the same accelerations for the track geometry vehicle traveling at 45 miles per hour over the modified crossover in the eastbound direction. Here the maximum lateral acceleration was 0.33 g’s while the maximum peak to peak acceleration was 0.44 g’s. Finally, Figure 7 shows the results over the modified turnout at 55 miles per hour in the eastbound direction. The maximum lateral acceleration was 0.36 g’s and the maximum peak to peak lateral acceleration was 0.57 g’s. These results show that the lateral accelerations experienced over the modified design are significantly reduced compared to those from the AREMA standard design when traveling each at the same speed (45 mph). Furthermore, the accelerations at 55 mph over the modified design are, in general, equivalent to the accelerations at 45 miles per hour over the standard design. In fact, the
peak to peak accelerations at 55 mph on the modified are still significantly lower than the peak to peak accelerations at 45 miles per hour on the standard crossover.

Figure 8 shows a graph of all of the lateral acceleration data obtained from the track geometry vehicle over both the modified and standard turnouts (all speeds, both directions). Linear trend lines are included to summarize the behavior over each turnout design and to extend the results from the AREMA standard design to speeds that were not possible due to limiting speed restrictions. As shown, in the range from 25 to 45 miles per hour, the modified design always resulted in lower lateral accelerations when compared to the AREMA standard design at similar speeds. As before, the accelerations found at 55 mph on the modified design were roughly equivalent to those at 45 miles per hour on the AREMA standard design.

Figure 9 shows a graph of the peak to peak lateral accelerations for all runs of the geometry vehicle over both crossover designs. Again linear trend lines are included. Here, the data shows that peak to peak accelerations are slightly increased by the modified design at speeds of 25 to 30 miles per hour. However, as speed increases, the modified design greatly reduces peak to peak accelerations. In fact, the results at 55 miles per hour on the modified design are significantly lower than the results from the AREMA standard design at 45 mph.

Figure 10 shows just the four trend lines from the previous two figures. This graph demonstrates that for the modified design, the lateral acceleration and peak to peak lateral acceleration grow at the same rate as speed increases (the lines have roughly the same slope and stay roughly the same distance apart). For the AREMA standard design,
however, the peak to peak lateral acceleration grows much more quickly with speed than
does the lateral acceleration. This indicates that as speed increases on the standard
design, the car body responds with increasing side to side oscillation and impacts as well
as increased acceleration due to centrifugal forces in the curve. For the modified design,
the ride is much smoother and the increase in peak to peak acceleration is only due to the
increase in lateral acceleration that results from higher centrifugal forces in the curve.

CONCLUSIONS

A modified turnout geometry intended to provide a low-cost means to increase diverging
route speeds through a turnout was installed and tested as part of an FRA-funded project.
The modified geometry was designed to reduce the switch point angle which simulations
have shown is typically the cause for the highest lateral wheel/rail forces, L/V ratios, and
lateral accelerations in a conventional AREMA turnout. As such, reduction of the switch
point angle so that forces used to turn the passing train remain uniform were predicted to
result in a smoother, safer ride and allow higher speeds to be attained.

Before and after tests were used to quantify the effect of the geometry
modification. Specifically, strain gauges were used to determine lateral and vertical
forces of passing trains though an AREMA standard #20 turnout (with curved switch
points) and through the modified #20 turnout. A ride quality meter was also used to
capture lateral accelerations through both the standard and modified turnouts. Strain
gauge testing and ride quality data collection was performed for numerous revenue trains
as well as for a series of controlled speed passes with a track geometry vehicle.
Strain gauge results showed a significant reduction in lateral forces and in L/V ratios for revenue trains on the modified geometry when compared to the AREMA standard geometry. For example, the peak L/V ratio observed was reduced from 0.4 to 0.28. The average L/V ratio observed was reduced from 0.15 to 0.07. Similar reductions were also found for maximum and average lateral forces.

Ride quality data from the passenger trains also showed a significant reduction in lateral acceleration and peak to peak lateral acceleration for the modified geometry. The maximum lateral and peak to peak lateral accelerations were found for each passenger train tested. Those maximums were then averaged over all tests of each design. The modified geometry resulted in a reduction from 0.285 g’s to 0.166 g’s for lateral acceleration and from 0.422 g’s to 0.240 g’s for peak to peak lateral acceleration. These results from strain gauging and ride quality show the significant reductions in lateral forces, lateral accelerations, and L/V ratios that are attainable with the modified turnout geometry.

Tests using the track geometry vehicle at speeds from 25 to 55 miles per hour on the modified #20 and from 25 to 45 miles per hour on the standard AREMA #20 also showed the reduction in lateral and peak to peak lateral accelerations. In fact, lateral accelerations experienced at 55 mph on the modified design were roughly equivalent to those at 45 miles per hour on the standard design. Furthermore, peak to peak lateral accelerations at 55 mph on the modified design were significantly lower than peak to peak lateral accelerations at 45 miles per hour on the conventional AREMA design.
This series of tests has shown that by implementing a low-cost reshaping of the diverging route geometry to minimize the switch point angle while still maintaining original lead length, higher speeds can be safely achieved without any increase in lateral wheel forces, L/V ratios, or lateral accelerations. Incorporation of a superior geometry within the same dimensions as the AREMA standard will allow railroads to achieve higher diverging route speeds safely, at low-cost, and without the need of additional space. Finally, this approach, which is applicable to the majority of existing turnouts, is expected to result in enhanced ride quality, reduced wear, thus leading to longer service life and reduced maintenance costs.

ACKNOWLEDGEMENTS:

The authors would like to thank Robert McCown and Don Plotkin of the FRA, New Jersey Transit, and Cleveland Track Materials, Inc. for their support and assistance.

REFERENCES:


### TABLE 1: Summary of Passenger Train Wheel Force Measurements

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### TABLE 2: Summary of Passenger Train Car Body Accelerations

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FIGURE 2: L/V Ratios for Passenger Trains Over AREMA Standard #20 Turnout
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