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# INVESTIGATION AND MITIGATION OF DIFFERENTIAL MOVEMENT AT RAILWAY TRANSITIONS FOR US HIGH SPEED PASSENGER RAIL AND JOINT PASSENGER/FREIGHT CORRIDORS

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## ABSTRACT

*As with most highway bridges, railway transitions experience differential movements due to differences in track system stiffness, track damping characteristics, foundation type, ballast settlement from fouling and/or degradation, as well as fill and subgrade settlement. This differential movement is especially problematic for high speed rail infrastructure as the "bump" at the transition is accentuated at high speeds. Identification of different factors contributing towards this differential movement, as well as development of design and maintenance strategies to mitigate the problem is imperative for the safe and economical operation of both freight and passenger rail networks. This paper presents the research framework and preliminary findings from a recently initiated research effort at the University of Illinois at Urbana-Champaign. Aimed at developing design and repair techniques to mitigate differential movement at railway transitions, this research project involves instrumentation, performance monitoring and numerical modeling of new and existing track transitions.*

## INTRODUCTION

Track geometry problems at railway transitions are well recognized in the United States as well as Europe. The Association of American Railroads (AAR) reported an annual expenditure of approximately \$200 million to maintain track transitions [1, 2], whereas more than \$110 million was spent annually on transition zones in Europe by 1999 [2, 3]. Although tunnels, special track work, and highway/rail at-grade crossings are all examples of railway track transitions, the most common transition problems are often encountered at bridge approaches. Due to drastic differences in substructure and loading conditions, the tracks on a bridge deck undergo significantly lower deformations under loading compared to the approach tracks. This sudden change in track deformation behavior at the transition point results in extreme dynamic loading conditions and ultimately leads to rapid deterioration of the track and bridge structural components. These structural damages often manifest themselves as track geometry defects.

Differential movement at bridge approaches often results in the development of a "bump" usually within 50 ft. from the bridge end [4]. A survey of railroads in North America, Australia and Europe conducted in 2006 [5] indicated that approximately 50 percent of bridge approaches developed a low approach, usually 1/4 to 4 inch (6.4 to 102 mm) in depth and 4 to 50 feet (1.2 to 15.2 m) in length, that adversely affected ride quality. Development of sudden dips adjacent to the bridge deck increases the dynamic impact loads significantly. Koch [6] reported vertical dynamic loads above twice the static wheel load level for coal gondolas at track transitions. Read and Li [7] concluded that the bump problem at track transitions was more significant as a train moves from a high-stiffness track to a low-stiffness track. There-

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fore, the problem of differential settlement is more critical at the exit end of a bridge, whereas the sudden track stiffness increase at the bridge entrance leads to rail surface fatigue, tie deterioration and rail seat pad deterioration.

To address the need to minimize differential movement at railway transitions for joint high speed passenger and freight routes in the US, a new research study sponsored by the Federal Railroad Administration (FRA) has been undertaken at the University of Illinois at Urbana-Champaign in collaboration with several industry research partners. This project will monitor and numerically model new and existing track transitions to develop cost-effective design and mitigation solutions to minimize the differential movements. This paper presents first a summary of previous research studies investigating track transition problems followed by a list of individual research tasks planned under the scope of the current study. Several new and in-service track transitions selected for instrumentation and performance monitoring are listed, and the primary objectives behind each instrumentation effort are emphasized. Instrumentation plans developed for the selected transitions following a systematic approach are outlined, and different sensors to be installed for performance monitoring are introduced. Finally, future research tasks involving field investigation and numerical modeling of the instrumented transitions with an overall objective to develop new design and rehabilitation techniques for improving track transition performance are outlined.

## PREVIOUS RESEARCH ON DIFFERENTIAL MOVEMENT AT TRACK TRANSITIONS

Although the problem of "bump" development at highway bridge approaches has been extensively studied [8–11], only limited research studies have focused on mitigating the differential movement at railway track transitions. These few studies investigating track transition problems have primarily focussed on pre-selected mitigation techniques and presented test section and parametric analyses results on the effectiveness of these remedial measures [1, 7, 12]. Important findings from some of these past research studies are summarized below along with an emphasis on the effectiveness of different remedial measures adopted.

### Factors Contributing to Differential Movement at Track Transitions

The relative importance assigned by researchers to different mechanisms contributing to differential movement at track transitions varies from one study to another. For example, from the investigation of four bridge approaches with concrete ballast-deck bridges and concrete ties, Li and Davis [13] reported inadequate ballast and subballast layer performance to be the primary cause of track geometry degradation. Using settlement rods installed in the test sections, they observed no significant subgrade movements, but instead they reported significant track geometry deterioration for a site with cement-stabilized backfill. On the other hand, Selig and Li [14] identified subgrade stiffness to be the most influential parameter affecting the moduli of ballasted tracks. As track transition problems are often related to the stiffness of the approach track bed, this would indicate that the subgrade layer plays the most significant role in governing the differential movement at track transitions.

In spite of different factors being identified as most critical affecting the differential movement at track transitions, a general consensus exists regarding the list of plausible mechanisms. Sasaoka and Davis [15] attributed track transition problems to three primary factors: (1) differential settlement, (2) differences in stiffness characteristics, and (3) discrepancies in track damping properties between adjacent sections. Similarly, Li and Davis list (1) track stiffness change, (2) ballast settlement, and (3) geotechnical issues as the major causes of bridge approach problems [13]. From an extensive review of published literature, Nicks [12] listed the following ten factors identified by researchers as contributing to the "bump" development at railway bridge approaches: (1) differential track modulus, (2) quality of approach fill, (3) impact loads, (4) ballast material, (5) drainage, (6) damping, (7) abutment type, (8) bridge joint, (9) traffic considerations, and (10) quality of construction.

Note that although most researchers list "track stiffness difference" as an important factor influencing the differential movement and other track deterioration problems at transitions, Plotkin and Davis [4] used five different analysis methods to conclude that stiffness differences did not play an important role as far as track behavior and ride quality at track transitions was concerned.

### Remedial Measures

Several different remedial measures have been suggested by researchers to mitigate differential movement problems at track transitions. Nicks [12] divided the remedial measures aimed at mitigating bump development at railway bridges into the following inter-related categories: (1) reduce approach settlement, (2) decrease modulus on bridge deck, (3) increase modulus on approach track, (4) reduce ballast wear and movement, and (5) increase damping on the bridge deck. Kerr and Moroney [16] concluded that most problems at track transitions arise from rapid changes in the vertical acceleration of wheels and cars in the transition zone. Accordingly, all remedial measures should aim to reduce the train vertical acceleration at the transition zones, and can be divided into the following three categories [16]:

1. Smoothing the stiffness (k) distribution on the "soft" side of the transition

2. Smoothing the transition by increasing the bending stiffness of the rail-tie structure on the "soft" side, in close vicinity of the transition point, and
3. Reducing the vertical stiffness on the "hard" side of the transition

Remedial measures under category 1 include: use of oversized ties, reduced tie spacing, ballast reinforcement using geogrids, Hot-Mix-Asphalt (HMA) underlayment, and use of approach slabs. On the other hand, the most commonly known method under category 2 was developed by the German Federal Railways (DB) and involves attaching four extra rails (two inside and two outside the running rails) to the cross ties [17]. Finally, the primary approach in category 3 involves the installation of tie pads and/or ballast mats to reduce the track stiffness on the "hard" side of a transition point (e.g., on the bridge deck). Using analytical procedures, Kerr and Moroney [16] engineered pad stiffness to "match" the track running over the bridge to the approach track. Accordingly, a later study [17] installed these "matched pads" on three different open-deck bridges near Chester (PA), Catlett (VA), and Philadelphia (PA). Field test results subsequent to the installations indicated significant improvements in track geometry near the bridge abutments.

Sasaoka and Davis [15] tried different methods to alter the track stiffness and damping characteristics on bridge approaches. Installing ties made of different materials, they reported that plastic ties on a concrete span ballasted-deck bridge effectively reduced the stiffness difference at track transitions. Moreover, using rubber pads underneath concrete ties on the bridge deck, they were able to achieve lower track stiffness on the bridge compared to the approach. Through parametric analyses using Geotrack$^{TM}$, they concluded that subgrade improvement in the approach and altering tie pad properties on the bridge deck were the most effective methods to minimize track stiffness differences at bridge approaches. Similarly, from dynamic analyses using NUCARS$^{TM}$, they concluded that providing extra dampers on the bridge deck could improve the impact attenuation at the transition by up to 30 percent. Li and Davis [13] concluded that remedies intended to strengthen the subgrade were not effective for sites where ballast/subballast layers were primarily responsible for the differential movement. In such cases, mitigation techniques such as rubber pads under the concrete ties, or rubber mats on the concrete bridge deck should be used to reduce the track stiffness and enhance the damping characteristics.

Rose and Anderson [18] presented asphalt underlayment trackbeds as an effective method for improving the performance of track transitions at tunnels, bridge approaches, special trackwork like crossing diamonds, crossovers and turnouts, as well as at rail/highway at-grade crossings. Placement of a thicker HMA underlayment adjacent to the bridge and a thinner section close to the existing all-granular trackbed reportedly improved performances of both open-deck and ballast-deck bridges. For example, CSX Corporation has been using such asphalt underlayment trackbed extensively for the construction and routine maintenance of track transitions. Their routine maintenance involves removal of a 40-ft. (12.2-m) long track panel and excavation of the old trackbed to about 30 in. (0.76 m) below the top of rail. A 6-in. (15.2-cm) thick HMA layer is placed on top of the subgrade, and subsequently topped by a 10-in. (25.4-cm) thick compacted ballast layer. Rose and Anderson [18] report 4 bridge approaches that were rehabilitated using this technique along a Kentucky mainline with over 50 MGT annual tonnage and a line speed of 50-60 mph (80-96 kmph). Over five years since the renewal of these approaches, no resurfacing was needed to correct track geometry.

Apart from the above listed remedial measures, researchers have also suggested converting open-deck bridges to ballast-deck [2], and stoneblowing [19, 20] as alternatives to mitigate track transition problems. Hyslip et al. [2] proposed chemical grouting as a conceptual solution for bridge transition improvement. Note that most of the research efforts listed above, primarily focused on the implementation of pre-selected remedial measures and no study was found focusing on field instrumentation and performance monitoring of track transitions to measure settlements of individual track substructure layers. Accordingly, the current FRA-sponsored research study was undertaken to quantify the contributions of individual substructure layers to the differential movement problem, and subsequently to develop design and repair techniques for mitigating the same.

## PROJECT SCOPE AND RESEARCH FRAMEWORK

The current research study will evaluate different factors contributing to the differential movement at track transitions through field instrumentation and performance monitoring, as well as numerical modeling. Field-recorded data from new and existing track transitions will be used to calibrate numerical models developed to evaluate the effectiveness of different remedial measures on improving track transition performance. The following research tasks will be completed towards accomplishment of the overall project objectives. Outlines of the research work to be conducted under each task are presented in subsequent sections of this paper.

1. Identification of new and existing track transitions experiencing or likely to experience differential movement problems;
2. Instrumentation and performance monitoring of selected track transitions;

3. Field investigation of instrumented transitions to collect individual layer properties as inputs for numerical models;
4. Numerical modeling of instrumented transitions to evaluate the effectiveness of different remedial measures; and
5. Identification of most effective design and rehabilitation techniques for long-term mitigation of differential movement problems.

## IDENTIFICATION OF NEW AND EXISTING TRACK TRANSITIONS UNDERGOING DIFFERENTIAL MOVEMENT

The primary objective of this task is to identify existing or new track transitions that experience, or are likely to experience differential movement problems. Field monitoring will be conducted at the selected sites to better understand the material(s) and factor(s) that contribute to differential movement and the effectiveness of current design and rehabilitation techniques. The objective will be to monitor the performance of track transitions under different loading environments, namely: heavy haul freight traffic, high-speed passenger traffic, and high speed operation of heavy haul traffic on shared corridors. As reported in literature, the differential movement may be a result of the combined action of one or more of the following mechanisms: (1) excessive deformation of ballast layer, (2) fill settlement, and (3) subgrade settlement. Care was taken during the selection of candidate transitions to include sites where different mechanisms are likely to contribute towards the differential movement problem.

Four different track transitions have been identified for instrumentation and performance monitoring based on inputs from railroad research partners. Coincidentally all four identified transitions were at bridge approaches. However, each selected transition will be unique with respect to the design and rehabilitation technique adopted for mitigating the differential movement problem. Data collected from these transitions will clearly identify the location of differential movement, e.g., ballast settlement or degradation, fill settlement, or subgrade movement. Two of the selected bridge approaches experienced recurring differential movement problems due to excessive ballast deformations, whereas subgrade and/or fill movement is likely to be the primary mechanism causing differential movement at the other two approaches. Brief descriptions of the selected transitions are presented below.

### Transitions with Excessive Ballast Movement

A problematic portion of Amtrak's Northeast Corridor (NEC), South of Philadelphia near Chester, Pennsylvania, has 8 to 10 bridges with recurrent differential movement problems and rough ride qualities. The NEC is an existing joint-use, high-speed line with maximum speeds up to 150 mph. Two of these

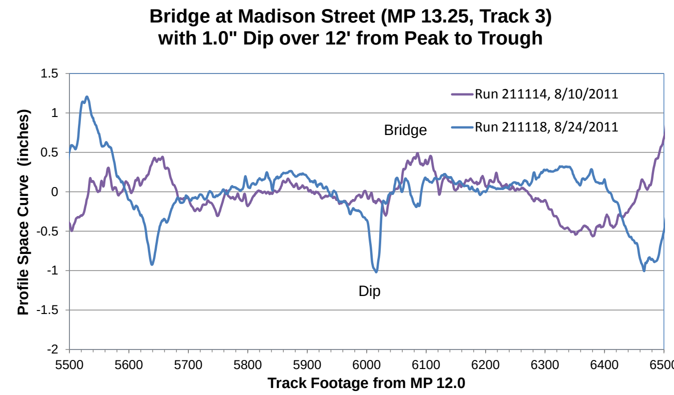


**FIGURE 1**. TRACK GEOMETRY DATA FOR BRIDGE OVER MADISON STREET NEAR CHESTER, PENNSYLVANIA (1 in. = 25.4 mm).

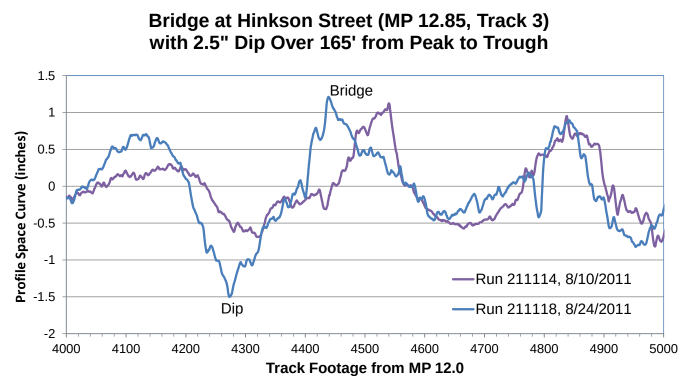


**FIGURE 2**. TRACK GEOMETRY DATA FOR BRIDGE OVER HINKSON STREET NEAR CHESTER, PENNSYLVANIA (1 in. = 25.4 mm).

bridges will be instrumented, and monitored after the implementation of different rehabilitation techniques. Figures 1 and 2 present example track geometry car data for these two selected bridge approaches (bridges over Madison and Hinkson streets) collected on the 10th and 24th of August 2011 after both were resurfaced in July 2011.

Track geometry undulation is apparent at both the bridge locations. The bridge over Madison street (see Fig. 1) has been surfaced seven times since 2009, and rapidly develops an abrupt 1 in. (≈25 mm) dip off the North end shortly after the resurfacing. Similarly, the bridge over Hinkson street (see Fig. 2) has been surfaced four times since 2009, and the original dipped profile returns after 2-3 weeks following the resurfacing. The recurring "dip" formations at these two bridge approaches are believed to primarily result from excessive ballast deformations. Therefore, the rehabilitation techniques investigated at these locations will primarily involve ballast improvement. Some rehabilitation alternatives currently under consideration include: (1) replacing existing ballast with a different ballast gradation or compactive effort, (2) use of stone blowing to add a thin layer of clean stone to the undisturbed ballast underneath, (3) replacing existing ballast with ballast containing one or two layers of geogrid reinforcement, and (4) application of elastomer polyurethane coating on the ballast to reduce aggregate breakage and increase lateral confinement. Instrumentation of these two bridge approaches is scheduled for the spring of 2012.

### Transitions with Potential for Excessive Fill and/or Subgrade Movement

Union-Pacific (UP) Railroad is currently reconstructing its tracks from Dwight, Illinois to St. Louis, Missouri as part of the ARRA HSIPR Track 2A Project. This reconstruction involves a major high speed track upgrade that includes improving grade crossings and constructing approximately 23.7 miles (38.1 km) of new track with nearly 60 bridges. Heavy-haul freight trains along with future high speed passenger traffic on these tracks are likely to induce excessive fill and subgrade settlement in the newly constructed bridge embankments. Two bridge approaches have been identified along this route for instrumentation and performance monitoring to quantify the sources of differential movement. Figure 3 shows a map of the area with relative locations of the two bridges located approximately 7 miles (11 km) apart. The bridge at milepost MP238.47 is located approximately 2.2 miles (3.5 km) South of Shipman, Illinois, whereas the one at MP231.52 is located 3.8 miles (6.1 km) North of Plainview, Illinois.

The bridge at MP231.52 will serve as the “control” bridge for this study. In other words, the performance of this bridge will be monitored in its original state with no remedial measures implemented. The bridge approach at MP238.47, however, will be reconstructed using one or more subgrade and/or fill improvement techniques. With new fills approximately 5 to 6-ft. (1.5 to 1.6-m) thick, this double-track approach will be subjected to equal distribution of traffic on either track. Both the main track and the siding (through Shipman, IL) will be instrumented to measure any movements of the fill and/or subgrade under the heavy-haul traffic. Different remedial measures currently under consideration include: (1) flowable fill, (2) rammed aggregate piers (Geopier™), (3) select fill material, and (4) asphalt underlayment. Construction at this bridge site is scheduled to start in the summer of 2013. Instrumentation of the bridge at MP231.52 is scheduled for the summer of 2012.

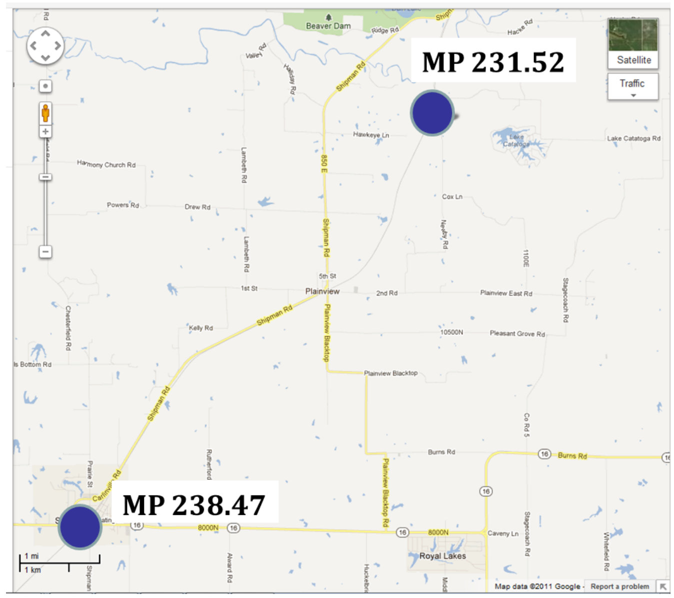


**FIGURE 3**. RELATIVE LOCATION OF BRIDGE APPROACHES SELECTED FOR INSTRUMENTATION ALONG UNION-PACIFIC TRACK.

## DEVELOPMENT OF INSTRUMENTATION PLANS

After identification of the track transitions for instrumentation, the next task involved the development of detailed instrumentation plans for each transition. As a major component of the current study involves instrumentation and performance monitoring of new and existing track transitions, collection of quality and reliable field data is imperative to ensure successful accomplishment of the study objectives. Accordingly, the task of planning a field monitoring program needs to be treated as a logical and comprehensive engineering process beginning with definition of the objectives, and ending with implementation of the data collected [21]. Detailed instrumentation plans for each selected track transition site were developed following the “systematic approach” recommended by Dunnicliff [21]. For identification and quantification of different factors contributing to the differential movement, the primary response parameters of interest in this study are: (1) deformations (both elastic and plastic) of individual track substructure layers, and (2) train-imposed stress levels in the track substructure at different depths. Moreover, measurement of vertical wheel loads is also desired for analyzing the effects of axle load levels and operating speeds on transition performance.

A list of candidate remedial measures to be implemented at the selected bridge approach sites was prepared along with the sensors to be installed at each location. As mentioned, the two bridge approaches along the NEC of Amtrak will be used to evaluate the effectiveness of "near-surface" or ballast improvement techniques. This decision was based on the recurring track performance trends observed for the two selected bridge approaches. The two Amtrak bridge approaches selected for instrumentation have been in service for more than 100 years, and have experienced recurrent differential movement problems, with the "dips" appearing within weeks after track resurfacing activities. Discussion with track maintenance personnel indicated that these two approaches have not been subjected to any significant subgrade and/or fill replacement activities. Recurrent differential movement problems noticed after the resurfacing activities are therefore most likely due to excessive particle rearrangement within the ballast layer. Trying different "near-surface" remedial actions and monitoring the approach performance through instrumentation will evaluate the effectiveness of the selected remediation techniques.

On the other hand, bridge MP237.48 along the UP-operated line between Dwight, IL to St. Louis, MO will be characterized by newly constructed track over fill sections. The subgrade and embankment fill in these approaches are likely to undergo consolidation under the heavy freight loading. Any differential movement observed at these approaches is likely to have significant contributions from subgrade and/or fill settlements. Subgrade and/or fill improvement techniques should be implemented at these newly constructed bridge approaches to potentially limit the differential movement problem. It is important to emphasize at this point that if instrumentation of the newly constructed bridge approaches indicates significant movement within ballast and subballast layers, different "near-surface" rehabilitation techniques may also be implemented at these locations. As rehabilitation and modification of the subgrade and fill layers require significant time and financial commitments, it is important to limit the contribution of deeper layers to the differential movement problem by implementing different remedial measures during the construction phase, before the track is subjected to loading. Finally, instrumentation of the control bridge approach (MP 231.52) in the summer of 2012 will identify different factors contributing to the differential movement problems. These field monitoring results will greatly facilitate the selection of appropriate remedial actions for implementing at the bridge at MP238.47 in the summer of 2013.

Ideally, selection of different remedial measures to mitigate the differential movement problem at track transitions should be carried out after careful analyses of the instrumented track response. The rehabilitated track transitions should subsequently be instrumented and monitored to evaluate the effectiveness of the remedial measures. However following such an approach would require two stages of instrumentation for each selected transition, and will require significant commitments as far as track availability and instrumentation budget are concerned. To

**TABLE 1**. SELECTED TRANSITION LOCATION AND CANDIDATE REMEDIAL MEASURES.

| Site | Instruments | Remedial Measures |
|---|---|---|
| Amtrak-Madison | MDD, SG | Geogrid |
| Amtrak-Hinkson | MDD, SG | Glue |
| UP-231.52 | MDD, SG, EPC | None |
| UP-238.47 | MDD, SG, EPC | Flowable Fill |
| | | Geopier® |

MDD: Multidepth Deflectometer; SG: Strain Gauge; EPC: Earth Pressure Cell

accommodate the constraints imposed by limited track availability, limited funds for instrumentation, as well as project duration, the current research study adopts a "parallel approach" to identify the factors contributing to the differential movement problem, as well as to evaluate the effectiveness of different remedial measures. Accordingly, remedial actions for the few identified transitions have been selected based on discussion with the railroad industry partners, and the effectiveness of each remedial measure will be measured through field instrumentation and monitoring. Response analyses of the instrumented track transitions as well as numerical modeling of different alternatives will facilitate the comparison of different alternatives for future applications. Moreover, instrumentation of the "control" approaches will indicate the extent to which different substructure layers contribute towards the differential movement at track transitions. Table 1 lists the different remedial measures likely to be investigated at each location, along with the instrumentation to be installed. Note that the remedial measures listed in Table 1 were selected after discussion with the railroad industry partners, and are primarily targeted towards "stabilizing" the near-surface layers for the bridge approaches along the Amtrak NEC corridor, and the subgrade and/or fill movement for the approaches along the UP-operated tracks. The following sections present the objectives and primary features of different sensors selected for use in the current research study.

### Measurement of Individual Layer Deformations using Multidepth Deflectometers (MDDs)

Multidepth deflectometers (MDDs) will be used in the current study to monitor the elastic and plastic deformations in track substructure layers. The use of MDDs to measure layer deformations in highway pavements was first started in South Africa in the early 1980's [22]. Comprising up to six linear voltage differential transducers (LVDTs) installed vertically at preselected depths in a small-diameter hole, an MDD system measures the

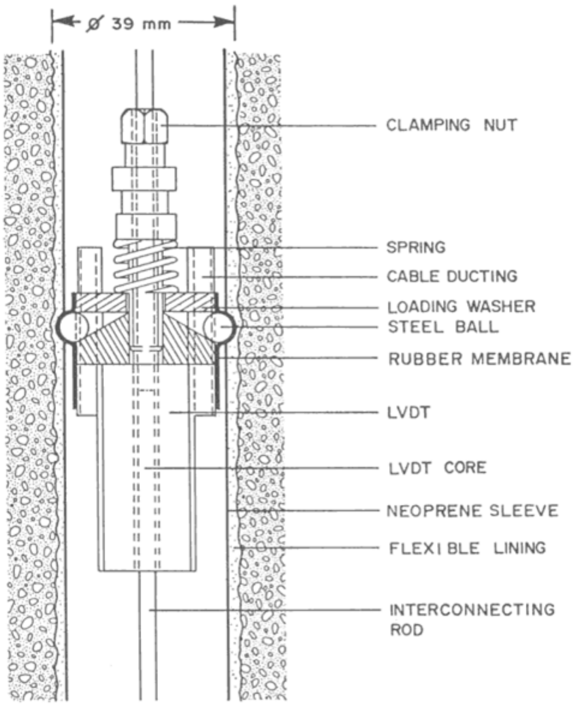


**FIGURE 4**. SCHEMATIC OF A MULTIDEPTH DEFLECTOMETER (MDD) MODULE [23]

deformation of individual pavement/track layers with respect to a fixed anchor buried deep in the ground [23]. Figure 4 shows the schematic of an MDD module [23]. The clamping nut (see Fig. 4) is tightened to displace the steel balls radially, and "clamp" against the inside wall of the borehole at a pre-determined depth. As the layer deforms under loading, these modules register corresponding displacements with respect to the fixed anchor point.

Although several studies in the US have involved the use MDDs to measure layer deformations in highway and airfield pavements, only two research studies have involved the installation of MDDs to monitor railway track performance [24, 25]. Unlike most other sensors used to monitor individual layer performance, MDDs can be installed on an existing pavement and track infrastructure to monitor performance under loading.

Figure 5 shows the schematic of two MDDs with five modules each installed on either end of a cross-tie. The numbers 1-5 shown in the figure correspond to individual LVDT positions and the five LVDTs are placed at different depths inside the borehole to measure the deflections at the (1) bottom of tie, (2) top of ballast layer, (3) top of subballast layer, (4) top of fill, and (5) top of subgrade respectively. Note that the subgrade layer is conceptually divided into two separate segments: "deformable" and "non-deformable", respectively. The MDD anchor (A) is fixed in the "non-deformable" portion of the subgrade, and movements of individual modules (1 through 5) are measured with respect to this fixed-anchor position. Individual layer deformations can be determined by subtracting the displacements registered by adjacent sensors. Accordingly, settlement of the ballast layer can be determined by subtracting the displacements from sensors 2 and 3, whereas settlement of the fill can be determined by subtracting the displacements of sensors 4 and 5. Note that the primary assumption associated with an MDD is that the anchor point (A) remains stationary and does not move under loading. It is therefore critical to ensure that the anchor point is sufficiently deep below the surface and will not be affected by the stresses imposed by train loading. The MDDs in this research study will be anchored in the subgrade at a depth of approximately 10 ft (3.1 m) below the top of the tie.

Note that the depths of individual substructure layers shown in Figure 5 will be determined during installation of the MDDs. Drilling of the MDD holes will be carried out in small increments to ensure that the holes are perfectly vertical, and the drill bit does not get stuck in track substructure. The drill bit will be extracted from the ground after every 3-4 inch (75-100 mm) increments to remove accumulated soil from the bits, and to clean drilled hole using compressed air. Drilling in such small increments will ensure that the substructure layer boundaries can be identified up to a resolution of about 1 inch (25 mm). Layer boundaries will be marked upon noticing significant differences in the material type being removed from the drilled hole.

### Stress Measurements in Track Substructure using Earth Pressure Cells

Earth pressure cells will be installed to measure the stress levels in the track substructure due to train loading. This is particularly important for the bridge approaches where subgrade and/or fill settlement is likely to be the primary mechanism contributing to differential movement. A reduction in the stress-levels experienced by the fill and subgrade layers will help mitigate the differential movement at such locations. Accurate measurement of substructure stress levels will help evaluate the effectiveness of different subgrade improvement techniques like flowable fill. It is anticipated that earth pressure cells manufactured by Geokon™ will be used in the current study. Previous experience of the researchers on the installation and use of these pressure cells in pavement and other geotechnical applications will ensure successful completion of this task. Note that the depth of installation for individual earth pressure cells will be selected to evaluate the effectiveness of different subgrade and/or fill improvement techniques, and will be based on the final construction drawings for the instrumented bridge approaches. Accordingly,

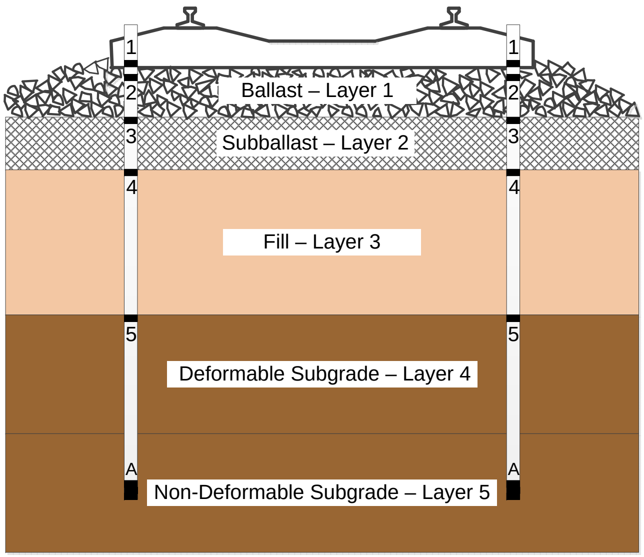


**FIGURE 5**. SCHEMATIC SHOWING LOCATION OF THE MDD SENSORS AT LAYER INTERFACES (NOT TO SCALE).

earth pressure cells will be installed in the transition zones only to quantify the stress levels imposed on the subgrade and fill layers.

### Measurement of Vertical Wheel Loads using Strain Gauges

Strain gauges will be installed on the rail and the rail-seat to measure the vertical wheel load. A total of sixteen (16) strain gauges will be installed per instrumented track transition. Figure 6 shows the picture of a rail section instrumented with “weldable” strain gauges for measuring vertical wheel loads.

### Settlement Plates and Top of Rail Survey

Apart from the MDDs, earth pressure cells and strain gauges, several other measurements will also be taken to monitor the transition performance with time. For example, periodic top of rail (TOR) surveys will be conducted to collect reference measurements for verifying the deflections recorded by the top-most MDD (sensor 1 in Fig. 5). Similarly, on transitions where MDDs cannot be installed due to time and budget constraints, settlement plates may be installed to quantify the permanent deformation of different layers through digital surveying. Decisions regarding the number and location of such installations will be taken after discussion with the railroad research partners Amtrak and UP.

### Tentative Layout of Sensors

Based on the preliminary instrumentation plans, Fig. 7 shows the relative locations of MDDs and strain gauges to be

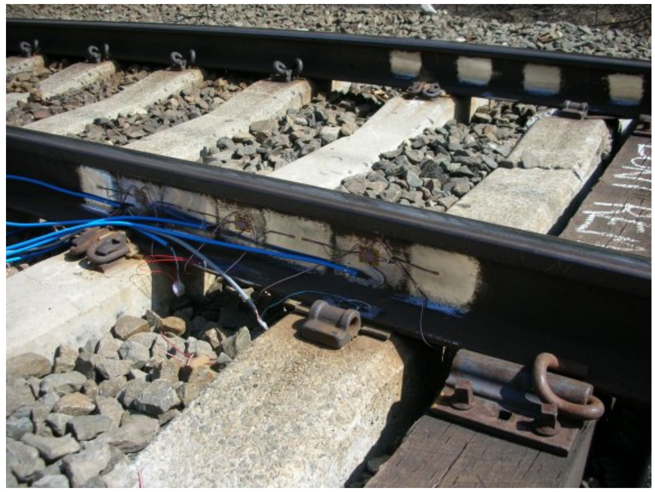

**FIGURE 6**. RAIL INSTRUMENTED WITH STRAIN GAUGES FOR VERTICAL WHEEL LOAD MEASUREMENT (PICTURE COURTESY: MIKE TOMAS, AMTRAK).

installed at individual bridge approaches. Note that two MDDs will be installed at either end of a cross-tie for each instrumented bridge approach to ensure data redundancy and confirm repeatability. Figure 7 also shows the relative locations of the strain gauges to be installed on the rail and the rail-seats. Positions of the earth pressure cells are not shown in Fig. 7 as they will be decided after development of the final design and construction plans for the transitions to be instrumented.

## FIELD INVESTIGATION OF INSTRUMENTED TRACK TRANSITIONS

Field investigations will be conducted at the instrumented track transitions to obtain necessary data to model the railway transition and better understand the factor(s) that contribute to the observed differential movement. The field investigations will measure the height of fill, type of fill, degree of compaction and water content with depth, type of foundation, type of bridge structure, embankment soil type and compaction specifications, and drainage conditions. Soil samples will be collected during installation of the MDDs, and will be transported to the laboratory for detailed classification and characterization. Similarly, ballast samples will be collected from the instrumented transitions and will be tested in the laboratory for providing inputs to the track substructure numerical models. Finally, the bridge approaches will be surveyed to quantify the current magnitude of differential movement.

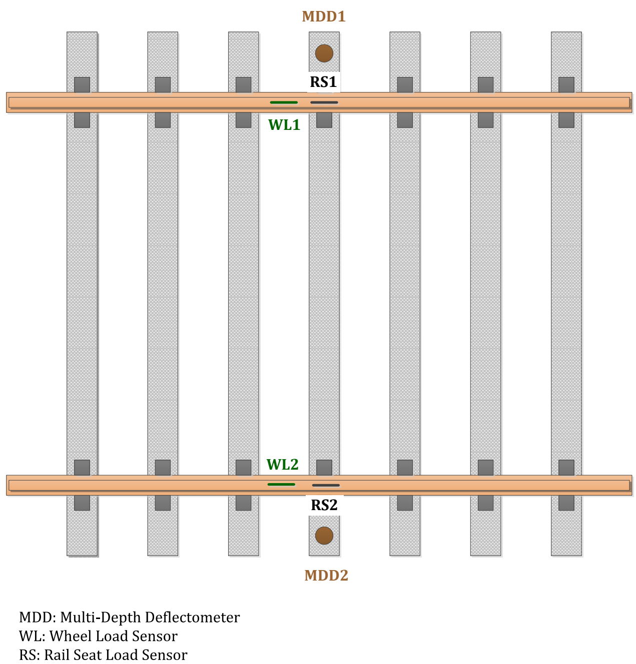


**FIGURE 7**. RELATIVE LOCATION OF SENSORS AT IDENTIFIED TRACK TRANSITIONS (MODIFIED FROM [24]).

## NUMERICAL MODELING OF INSTRUMENTED TRACK TRANSITIONS

The final phase of this study will focus on developing calibrated numerical models of the monitored track transitions to predict the performances of different design and/or rehabilitation techniques. This would allow the contributions of the ballast, fill, and subgrade to the total differential movement to be studied in various configurations.

The numerical analyses will utilize the finite difference program FLAC™ and the finite element program PLAXIS™ (http://www.plaxis.nl/) to simulate the behavior of structures built of soil, rock, or other materials that undergo deformation when their yield limit is exceeded. FLAC™ (Fast Lagrangian Analysis of Continua) is a two-dimensional and three-dimensional explicit finite difference code that simulates the behavior of structures built of soil, rock, or other materials that undergo plastic flow when their yield limit is reached. PLAXIS™ is a two-dimensional and three-dimensional finite element code that will be used to verify and/or augment the FLAC analyses. In addition, this research project will also utilize BLOKS3D DEM program which has been under development at the University of Illinois to generate a model for the mass of typical railroad ballast. The BLOKS3D program uses rigid but random shaped 3-dimensional (3D) "polyhedrons or blocks" as the basic elements to realistically simulate interactions, such as interlock/contact, of actual aggregate particles.

Through modeling different design and rehabilitation techniques implemented at the instrumented track transitions, and using the field data to check the accuracy of the models, this research study will recommend the most efficient alternatives for mitigating differential movement problems at track transitions.

## SUMMARY

This paper presented the research framework and preliminary findings from a recent FRA-sponsored research study aimed at investigating and mitigating the problem of differential movement at railway track transitions. The project objectives were listed along with the scope of each individual research task currently being undertaken. Candidate track transitions identified for instrumentation and performance monitoring were highlighted along with the primary factors of interest at each location. A preliminary instrumentation plan was developed for performance monitoring of the selected sites. Finally, future project tasks involving field investigation and numerical modeling of the instrumented track transitions were outlined. Through combination of field instrumentation and numerical modeling of new and existing track transitions, this research project aims to develop design methods to mitigate the differential movement problem at such locations.

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