Aircraft Wander Effects on Unbound Aggregate Layers

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Executive Summary

Wander on airports is much wider than wander on highways due to the non-channelized nature of airport traffic as well as different gear configurations between aircraft which introduce inherent wander separate from the variation of individual aircraft movements. Full scale pavement testing of aircraft loads at the FAA's National Airport Pavement Test Facility (NAPTF) indicate that wander can negate the stiffening in unbound granular layers (the shakedown effect), and make them prone to increased deformations on subsequent aircraft passes. As part of the research activities at the FAA's Center of Excellence for Airport Technology (CEAT) established at the University of Illinois, dynamic response data from airport pavement test sections were collected due to passing of each of the 6-wheel B777 type and the 4-wheel B747 type gears for various combinations of applied load magnitudes and loading sequences (application order and stress history effects), traffic directions, gear spacings, and wander positions and sequences. The field data showed that the permanent deformation during a complete wander cycle was negated due to aircraft wander, indicating movement and rearrangement of the particles in the unbound layers of the pavement system. Analysis of multi-depth deflectometer and heavy weight deflectometer data shows that there is an increased rate of pavement deterioration due to wander indicative of a reduction of the strength and modulus properties in the unbound granular base/subbase layers. The "anti-shakedown" of unbound aggregates should be accounted for in future design procedures with a performance based criterion whereby the dilative susceptibility of the aggregate layers is minimized through aggregate selection, stabilization, and/or improved lateral confinement.

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1. Problem Statement, Background and Literature Review

The National Airport Pavement Test Facility (NAPTF) located at the William J. Hughes Technical Center on the Atlantic City International Airport was built to analyze the effects of New Generation Aircraft (NGA) on pavements. NGA will affect airfield pavements differently than older aircraft due to increased loads and changes to landing gear configurations. These differences require advanced airport pavement design procedures. The NAPTF was constructed to generate full-scale tests in support of the investigation of airport pavements subjected to such complex NGA gear loading configurations. Construction was funded by the Federal Aviation Administration (FAA) and the Boeing Company under a cooperative research and development agreement. There were three main goals for the NAPTF: provide additional traffic data for incorporation in new thickness design procedures for airfield pavements, provide full scale testing capabilities to examine response and failure information for use in airplane landing gear design and configuration studies, and provide technical data for reexamining the CBR method of design for flexible airfield pavements. All three of these objectives were established to compare the damage done by the 6-wheel Boeing 777 (B777) type dual-tridem landing gear to dual and dual-tandem gear of older aircraft (Hayhoe et.al. 2004). Individual pavement dynamic response data were collected due to passing of each gear for various combinations of applied load magnitudes, traffic directions, and wander positions.

Hayhoe et al. (2004) highlighted some of the complicated trends observed in the NAPTF pavement deformation behavior as follows:

> The net accumulated unrecovered (permanent) deformation in the pavement structure over a complete wander cycle is shown to be a small fraction of the range of the unrecovered deformations occurring during the wander cycle over individual back and forth load applications. That is, the sum of the upward and downward unrecovered displacements almost cancels, leaving the structure in approximately the same configuration at the end of a wander cycle as at the start. The unrecovered displacements are about the same magnitude as the recovered (elastic) displacements, with the relative magnitudes depending on the transverse position of the load relative to the transverse position of the measurement… One consequence of this conclusion is that typical laboratory measurements of permanent deformation in unbound pavement materials with repeated loading may not be representative of behavior under traffic.

These trends are in contradiction with current pavement design and design life predictions.

Adequate design and pavement life predictions are required to properly plan the maintenance and repair budgets of airports. If the predicted maintenance schedule is off, the potential damage to airfield pavements could be irreversible requiring complete pavement replacement instead of repair. And if replacement or proper repairs are not conducted, the potential for functional and/or structural failure of the pavement which could lead to aircraft damage greatly increases. Functional failure could be as innocuous as ruts too deep for smooth travel or as dangerous as ruts deep enough to hold water and cause hydroplaning on runways or high speed exits. Structural failure could result in foreign object damage due to the spalling or crumbling of the pavement. Therefore it is imperative that aircraft wander be investigated for its potential damaging effects to airfields.

This paper will present the methods used to separate the NAPTF multi-depth deflectometer (MDD) data and then delve into analysis of MDD and heavy weight deflectometer (HWD) readings from NAPTF full scale pavement test sections. The analysis will identify damage in the unbound aggregate layers due to applied aircraft gear loading with wander. Important conclusions will be drawn on the effects of load wander on unbound aggregates to highlight the detrimental effects of wander and eventually help improve pavement design and performance prediction.

1.1 NAPTF

The NAPTF is an indoor facility (Figure 1) designed to limit environmental effects, but it is not climate controlled. Tests are conducted using a specially designed 1.2-million-pound test vehicle which can apply loads of up to 75,000 lbs (34,020 kg) per wheel on two landing gears with up to six wheels per gear (total of 12 wheels for a load capacity of 900,000 lbs) (Figure 2). The test vehicle is supported by rails on either side which allow the load to be varied according to the testing protocols. The vehicle can be configured to handle single, dual, dual-tandem, and dual-tridem loading configurations with variable gear and wheel spacing. The maximum tire diameter is 56 inches (142 cm) and maximum tire width is

24 inches (61 cm). Vehicle control can be automatic or manual. Traffic tests were run in a fully automatic control mode at a travel speed of 5 mph (8 km/h). This speed represents aircraft taxiing from the gate to the takeoff position. It is during this maneuvering that maximum damage occurs to the pavement because the aircraft is fully loaded with fuel and payload and speed is low. Wheel loads are programmable along the travel lanes and the lateral positions of the landing gears are variable up to plus or minus 5 ft. (1524 mm) from the nominal travel lanes to simulate aircraft wander.

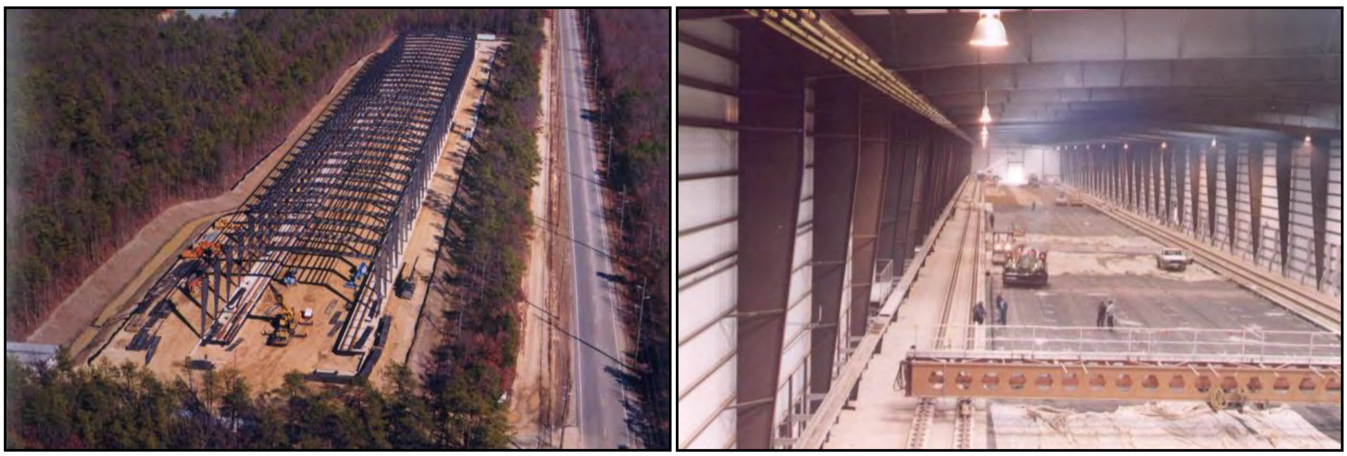

Figure 1. NAPTF Test Facility (photos courtesy of FAA NAPTF)

The first full-scale tests were designed and conducted on a pavement test strip 900 ft. (274 m) long, 60 ft. (18.3 m) wide, and 9 ft. (2.7 m) to 12 ft. (3.7 m) deep. The width of 60 ft. (18.3 m) was necessary to investigate load wander interaction effects, and the depth of up to 12 ft. (3.7 m) was necessary to minimize the influence of the finite depth of imported subgrade materials. The pavement sections were built on three subgrade materials with California Bearing Ratio (CBR) values in the range of 3 to 20 percent. This range included the subgrade strengths specified in the ICAO ACN-PCN requirements. Six asphalt and three concrete surfaced test sections were built on top of the subgrades according to standard FAA airport pavement construction and thickness design specifications.

1.2 NAPTF Instrumentation

A comprehensive instrumentation system was installed in the pavements to measure structural response to wheel loading. In all, 1,050 sensors were installed in the test pavements for measuring moisture and temperatures, and wheel/gear load related strains, deflections, and pressures. A computer controlled data acquisition system was used to automatically collect and store the pavement response and performance data from the sensors as the vehicle traveled along the test pavement.

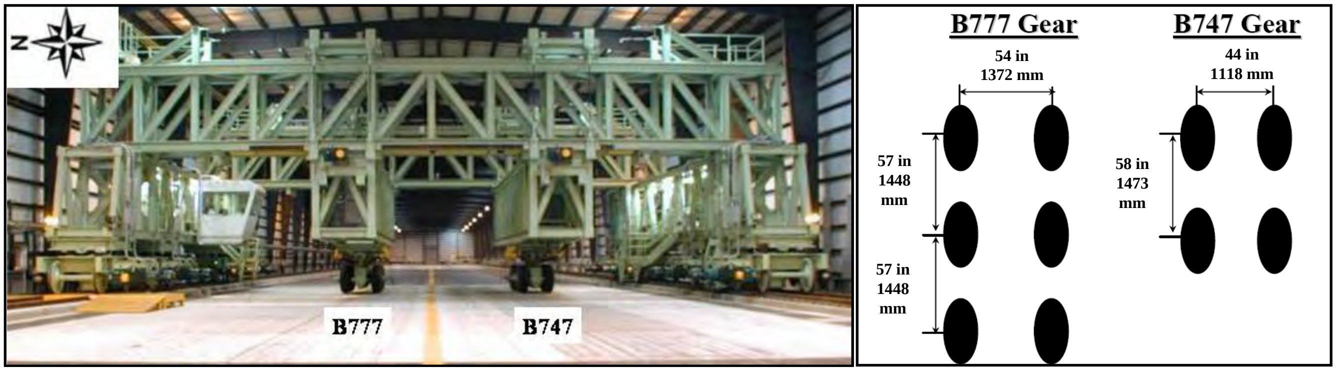

Figure 2. NAPTF Test Machine and Landing Gear (photo courtesy of FAA NAPTF)

The flexible pavement test sections were instrumented with Multi-Depth Deflectometers (MDDs), Pressure Cells (PCs), and Asphalt Strain Gauges (ASGs) to measure the response of the pavement system to trafficking loads. These instruments record at 20 samples per second. Static moisture and temperature readings were recorded every 15 minutes. Rutting was monitored manually throughout the test program using a transverse surface profile (TSP) device, a rolling inclinometer, and straightedge rut depth measurements. Individual layer rut data was also collected automatically using MDDs.

The MDDs were installed in the test sections at various depths to record the important deformation trends in individual layers to wheel/gear loads. It is possible to divide the MDD data into the recoverable response (also called the elastic or rebound deformation) and the unrecoverable response (also called the inelastic, plastic, or residual deformation) by subtracting out the residual response from the overall MDD data. Figure 3 shows the relative locations of the MDD sensors in the B777 North traffic lane. MDD sensors in the B747 traffic lane are in similar critical locations. Each seven sensor MDD stack had one anchor sensor and the other MDD sensors within the pavement layers recorded movement in relation to this anchor. All sensors but the anchor require processing to determine their actual absolute movement. Section 2.4.1 details this processing.

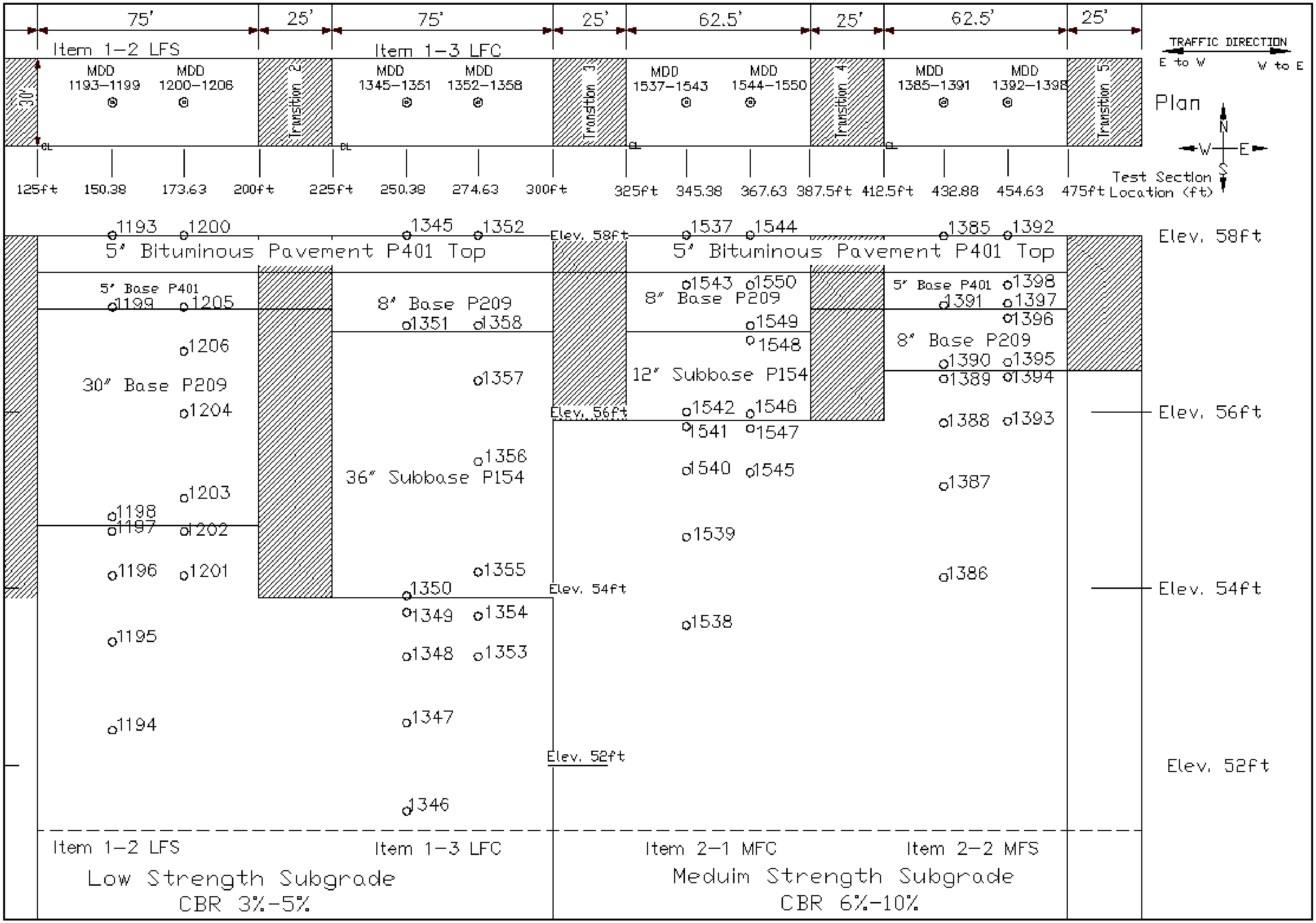

Figure 3. MDD Sensor Locations in the North B777 Trafficking Lane

1.3 Test Series

The first series of tests conducted are referred to as Construction Cycle 1 (CC1) tests and the first NGA aircraft to be analyzed was the Boeing 777 (B777). The B777 landing gear tested in the north testing lane was a six wheel dual-tridem configuration. Loads from the Boeing 747 (B747) type gear in a dual-tandem configuration were tested at the same time in the south testing lane so that comparisons in the pavement responses from each aircraft could be made. The dimensions of the two landing gears are shown in Figure 2 while Figure 5 shows the locations of the gear and wheel centerlines with respect to the MDD locations. The wheel loads were set to 45,000 lbs (200.2 kN) and the tire pressure was 189 psi (1,303 kPa). Trafficking speed was applied at 5 mph (8 km/h).

Pavement cross section details are show in Figure 4. The letter designations indicate the subgrade strength (L – Low, M – Medium), the type of pavement (F – Flexible) and the type of base course (C – Conventional unbound aggregate, S – Stabilized [P401 asphalt]).

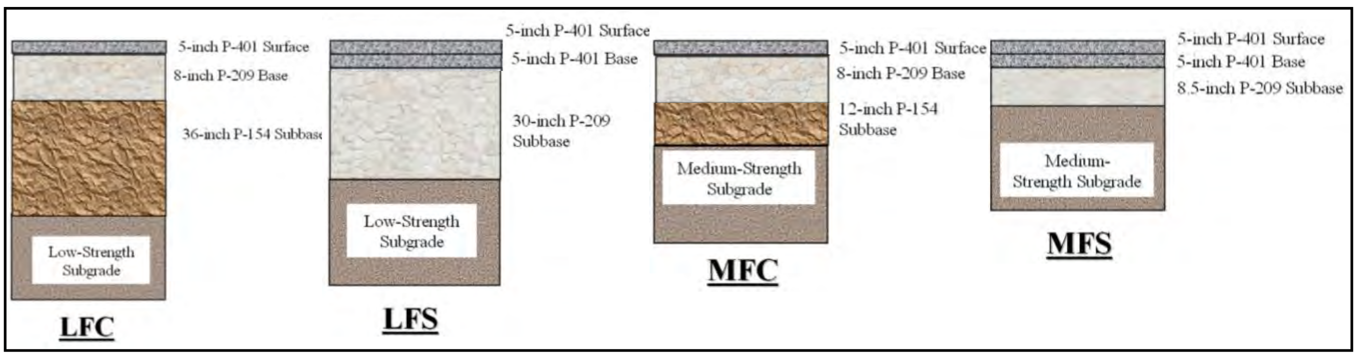

Figure 4. Test Section Cross Section Details.

1.4 Induced Aircraft Wander

To account for aircraft wander, the test passes or load applications were divided into nine wander positions spaced at intervals of 9.843 in. (250 mm) for a total center to center wander width of 78.75in (2m). Each position was traveled a different number of times based on a normal distribution with a standard deviation that is typical of multiple gear passes in airport taxiways, 30.5 in. (775 mm). The nine positions of the wander pattern covered 87% of all traffic (approximately 1.5 standard deviations). One complete wander pattern consisted of 66 vehicle passes (33 East and 33 West). Figure 5 shows the location details of the applied trafficking wander positions. The “0” wander position is the center wander position. Table 1 summarizes the distance from the gear wheel centerlines to the MDD locations. Note that the tire contact areas are to scale in Figure 5 indicating there are no gaps between tire imprints for the complete wander pattern.

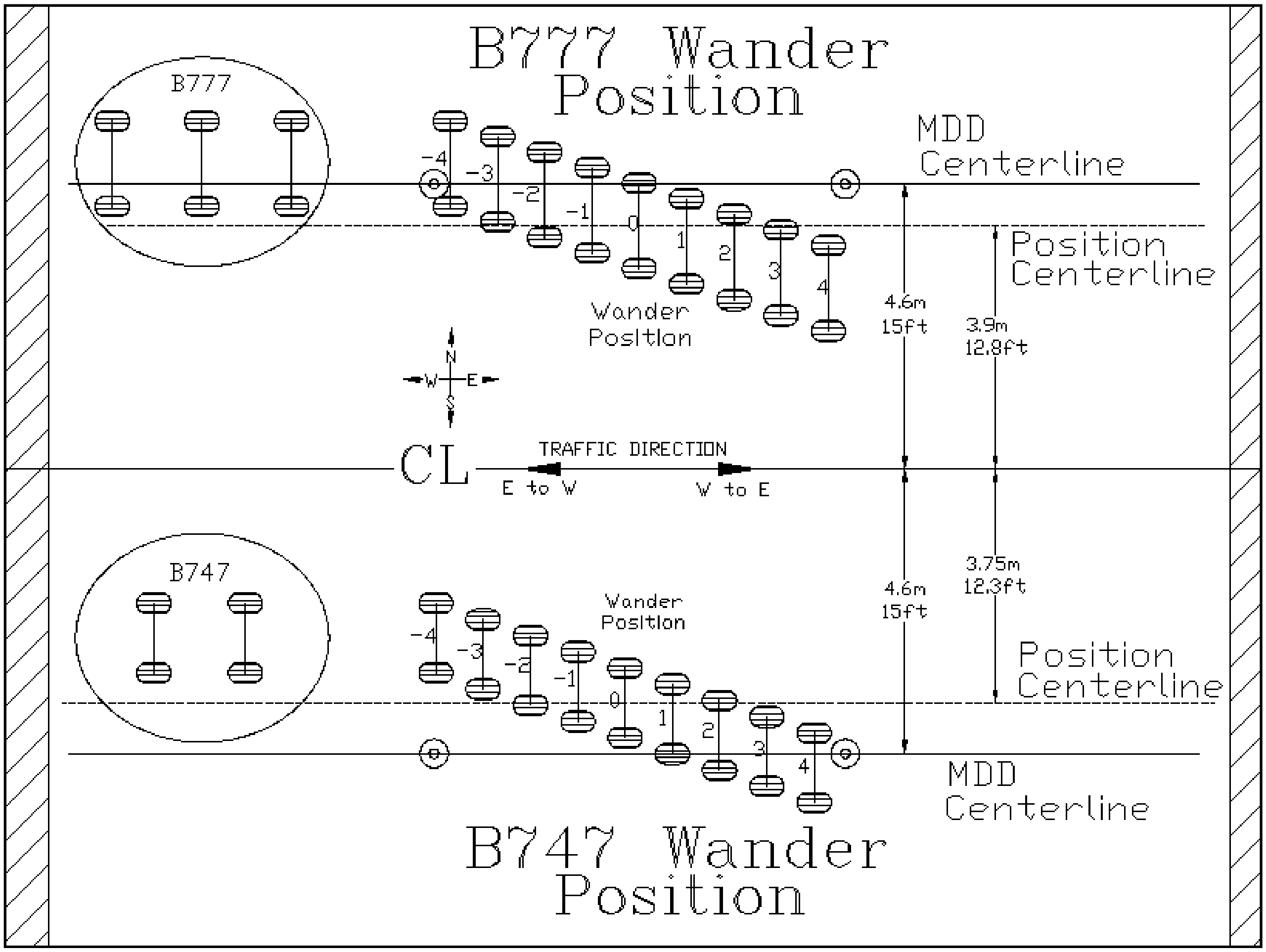

Figure 5. Gear Wander Position and Wheel Centerlines

Table 1. Passes per Lane and Wheel Centerline Locations in Relation to the MDD (inches)

Wander Position #	**-4**	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**
% of passes	6.1%	9.1%	12.1%	15.2%	15.2%	15.2%	12.1%	9.1%	6.1%
777 North Wheel location	-39.87	-30.03	-20.19	-10.34	-0.50	9.34	19.19	29.03	38.87
777 South Wheel Location	14.13	23.97	33.81	43.66	53.50	63.34	73.19	83.03	92.87
747 North Wheel Location	-93.37	-83.53	-73.69	-63.84	-54.00	-44.16	-34.31	-24.47	-14.63
747 South Wheel Location	-49.37	-39.53	-29.69	-19.84	-10.00	-0.16	9.69	19.53	29.37
*** North MDD offset -26.4in from 777 "0" Pattern**									
*** South MDD offset 32in from 747 "0" Pattern**									
*** Wander Positions are offset by 9.843"**									

To minimize the interaction of gear loads at the subgrade level, the six-wheel B777 and the four-wheel B747 type gears moved in phase, with both gears moving left and right together rather than towards and away from each other. Each pass started out going from West to East and then traveled back along the same path East to West. The gear was then moved to the next wander start position. Figure 6 shows the correlation of wander position, pass number, and wander sequence.

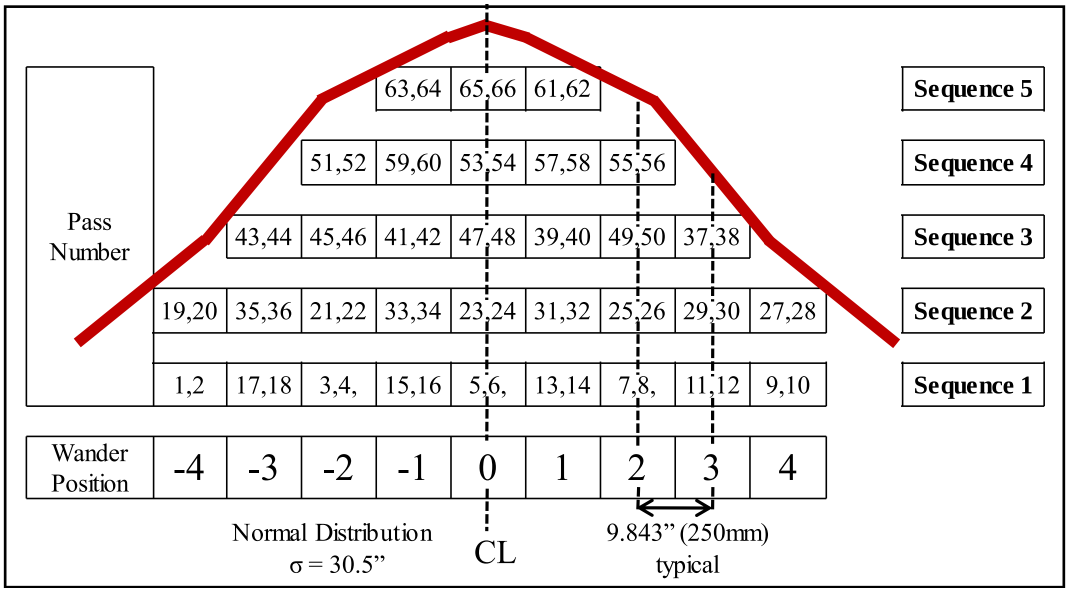

Figure 6. Correlation of Wander Position, Pass Number, and Sequence

2. Problem Solving Approach and Technical aspects of the Design Challenge

2.1 Wander

Individual aircraft wander patterns create traffic lanes that are wide, unchannelized, and normally distributed. Data collected in the 1970’s indicate wander widths of 70in (1778mm) for taxiways and 140in (3556mm) for runways. The standard deviation for a taxiway was found as 30.5in (775 mm) and for a runway 60in (1524 mm) (Ho Sang, 1975). The wander width is defined by the zone containing 75% of the aircraft centerlines (1.15 standard deviations on either side of the mean value with a normal distribution). However, it is not only individual aircraft wander that affects pavement performance. Each aircraft has a unique gear configuration and different combinations of aircraft will induce additional “wander” that is not associated with lateral deviation of individual aircraft. Figure 7 shows the transverse gear wheel locations for various large aircraft. Of note is how many of the aircraft gear wheels bisect the gear locations of other aircraft. For example the A380 has gear wheels traveling almost directly between the B747, B777, and L1011 gear wheels.

Additional information on wander and previous studies on multiple gear wheel effects can be found in Ahlvin et.al. (1971), Gomez-Ramirez and Thompson (2001), and Ledbetter (1977).

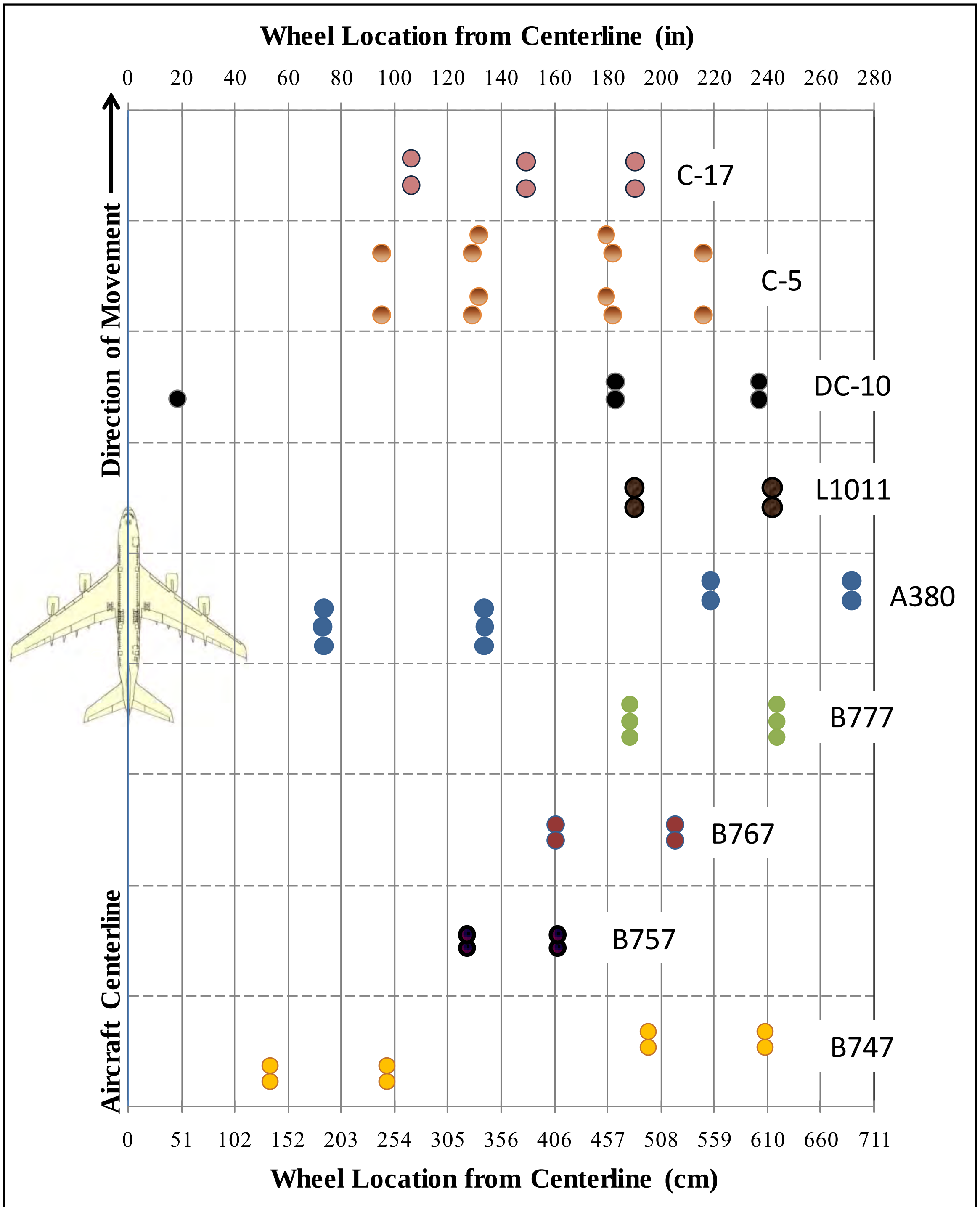

Figure 7: Aircraft Landing Gear Wheel Centerline Positions

2.2 Shakedown

Unbound granular layers are said to "shakedown" when application of additional loads cause the unbound layers to consolidate, gain strength with time, and stabilize with little additional residual deformation. This process is seen in the field as well as with repeated load triaxial testing. The use of the shakedown concept in pavement design was first introduced in 1983 and the first attempt at using the shakedown concept indicated there were four categories of shakedown response; purely elastic, elastic shakedown, plastic shakedown, and ratcheting. Analyses of repeated load triaxial tests on unbound aggregates indicate that there is no purely elastic range for unbound aggregate response and therefore only three zones of shakedown should be identified; A – plastic shakedown, B – plastic creep, and C – incremental collapse (Werkmeister et. al. 2002).

In range A (plastic shakedown) the residual strain rate decreases quickly and eventually the layer shows no further residual deformation with additional load repetitions. Range B (plastic creep) initially shows a decreasing residual strain rate but as the number of load cycles increase the residual strain rate resumes an upward climb, eventually leading to incremental collapse. This behavior has been attributed to grain abrasion caused by the large resilient deformations seen in this stress range. The grain abrasion is thought to decrease the angle of internal friction by polishing the grain contact points thus lowering the coefficient of friction between grains and leading to more residual deformation with additional load cycles without increasing the applied stress.

In range C (incremental collapse) it is probable that due to the high stress range both grain abrasion and particle crushing combine to quickly destroy an unbound aggregate layer. This region is characterized by a slower reduction in the residual strain rate than range A or B and a quick resurgence of the strain rate after a very limited number of load cycles. It is also likely that for all shakedown ranges, any particle movement or rearrangement that occurs will relieve some small amount of the residual compressive stress in an unbound layer that was induced by compaction and preloading of the layer; which in turn will cause additional rutting.

2.3 Observed Anti-Shakedown Response

Data from testing at the NAPTF using new generation aircraft loads on asphalt pavement indicate that a sequential wander pattern causes residual deformation to be recovered. What has been seen is that the downward residual deformation (rutting) caused by a pass of heavily loaded landing gear is canceled by the upward residual deformation (heave) resulting from the pass of the same gear offset by wander (Hayhoe and Garg 2002). Initially this may seem to be beneficial to the pavement system as the rutting is reduced; however, the particle rearrangement caused by this upheaval has the potential to reduce or even negate the stabilizing shakedown effect. The particle rearrangement reduces the strength of the unbound layer causing more residual deformation with future load applications, the “anti-shakedown” effect. It is thought that the strength reduction is due to three factors; 1) reduction in any residual compressive stress in the layer 2) a less dense particle matrix and 3) grain abrasion which reduces the coefficient of friction between particle contact points (as seen in range B shakedown behavior).

2.4 Sensor processing

2.4.1 MDD Response Values

The initial MDD data provided by the FAA from the CC1 NAPTF testing was in a comma separated value format and each sensor as described above was related to the anchor sensor and therefore required extensive processing to transform the provided values into actual sensor location movements. The files contained all of the sensors in a MDD group for a limited number of events. For example, file #1 contained the data from the sensors in the first MDD group in the 777 path in the MFC section for events 2796 to 2940. File #2 contained the same sensors but events 2941 to 3400. The first step in the data processing involved dividing all of the sensor files into individual sensors and combining all events for each sensor in that file. This resulted in seven files for each MDD group because there were seven individual sensors in each MDD group. Each sensor was at a different location in the testing cross section. Figure 3 is a plan and cross sectional view of the MFS and MFC MDD locations. Each MDD group has a slightly different location for the sensors, but the critical response locations have sensors.

Once the sensor data was separated into individual sensor files, the actual sensor movement had to be calculated. The first step in processing the data was to normalize all readings so that the sensors showed 0 mils of deflection before the event began. Figure 8 shows a typical sensor reading before being normalized and after being normalized. If the sensor readings are not normalized peak responses cannot be obtained because the peak response has to be relative to zero mils of deflection; Figure 8 demonstrates this discrepancy where before normalization the peak value would be recorded as 15mils when the actual peak response is 20 mils.

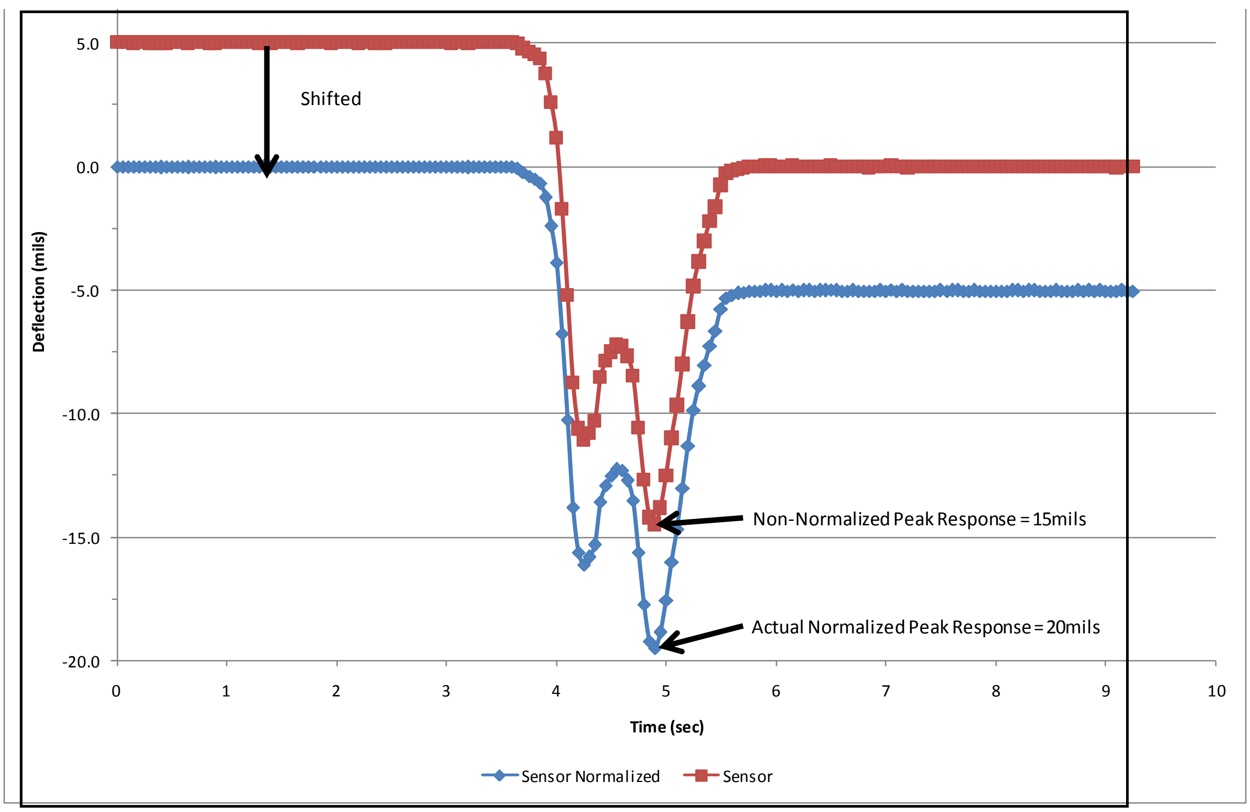

Figure 8: Normalization of Sensor Readings

Once the sensor readings are normalized they must be processed to show the absolute movement of each sensor. For each MDD group, only the "anchor" sensor data was the actual movement of the sensor because the anchor data recorded the movement of the surface relative to the anchor block some distance below the surface. The LFC and LFS MDD groups had their anchors approximately 120in (3m) below the surface, while the MFC and MFS MDD group anchors were 100in (2.5m) below the surface. The anchor sensor reading was the actual movement of the surface. All other sensor readings were relative to the surface position because the other sensors were linked to the surface position with connecting rods. In order to know the actual movement of the other sensors, the sensor reading must be subtracted from the anchor reading. Figure 9 shows an anchor reading, a sensor reading, and the processed actual sensor movement. An example of the calculation is provided: at time equal to 4.25 seconds the anchor reading is -99 mils, the sensor reading is -60 mils, and the actual movement of the sensor is the anchor reading minus the sensor reading [(-99)-(-60)=-39mils].

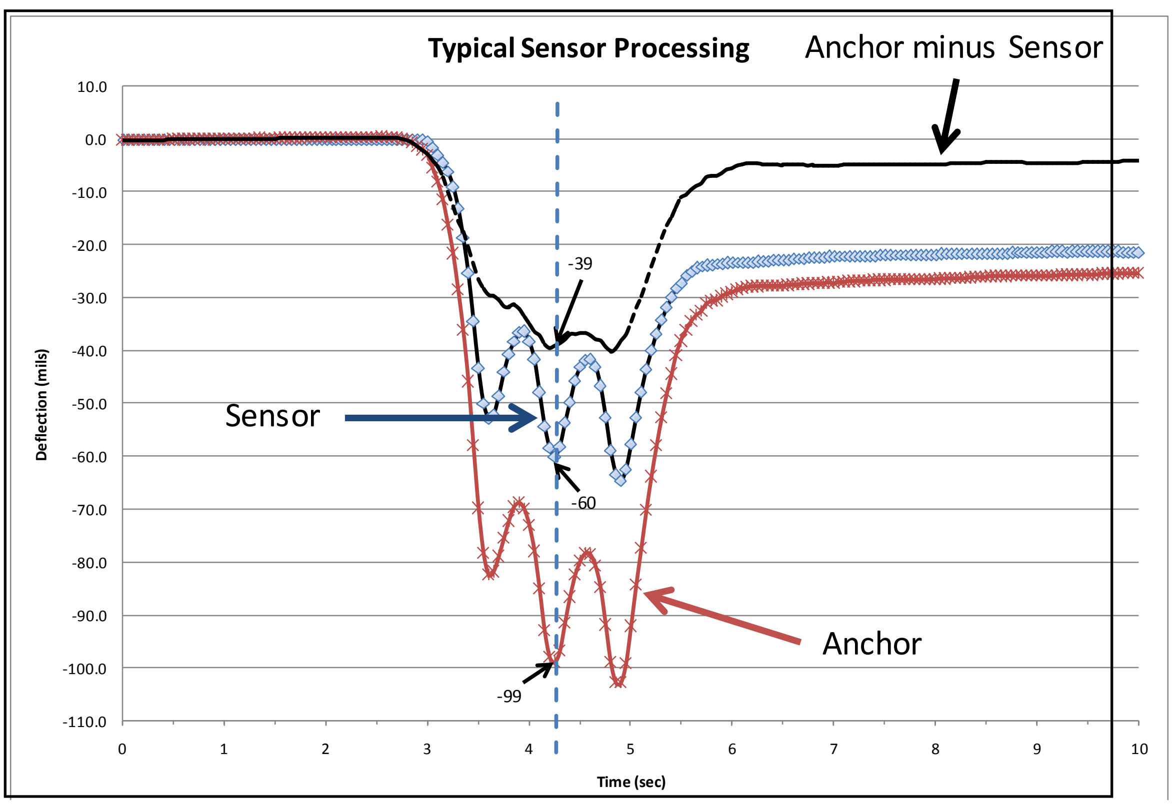

Figure 9: Anchor Data, Sensor Data, and Actual Sensor Movement

One issue with the above calculation is that it can only be done if the two sensors readings are at the exact same time. Most of the sensors and anchors were not triggered to start collecting data at the exact same moment and thus could not immediately be processed for the actual sensor movement. Figure 10 shows this dilemma; the sensor started recording data after the anchor. If the sensor is subtracted from the anchor without aligning their timelines the resulting sensor reading is incorrect (also shown in Figure 10). In order to obtain the actual sensor movement each sensor reading was time aligned manually in Microsoft Excel so that the timeline of each sensor reading matched the anchor. Figure 11 shows the same data as Figure 10 but with the readings aligned and the correct absolute movement of the sensor shown.

Once aligned, critical response values can be obtained. The peak response is the easiest value to obtain from the data. It is the maximum displacement reading recorded by the sensor and can either be contractive (negative) or dilative (positive). The residual response of each event can be calculated using Microsoft Excel and the time-deflection histories of each event. Residual response is the final value of the sensor reading minus the original sensor reading.

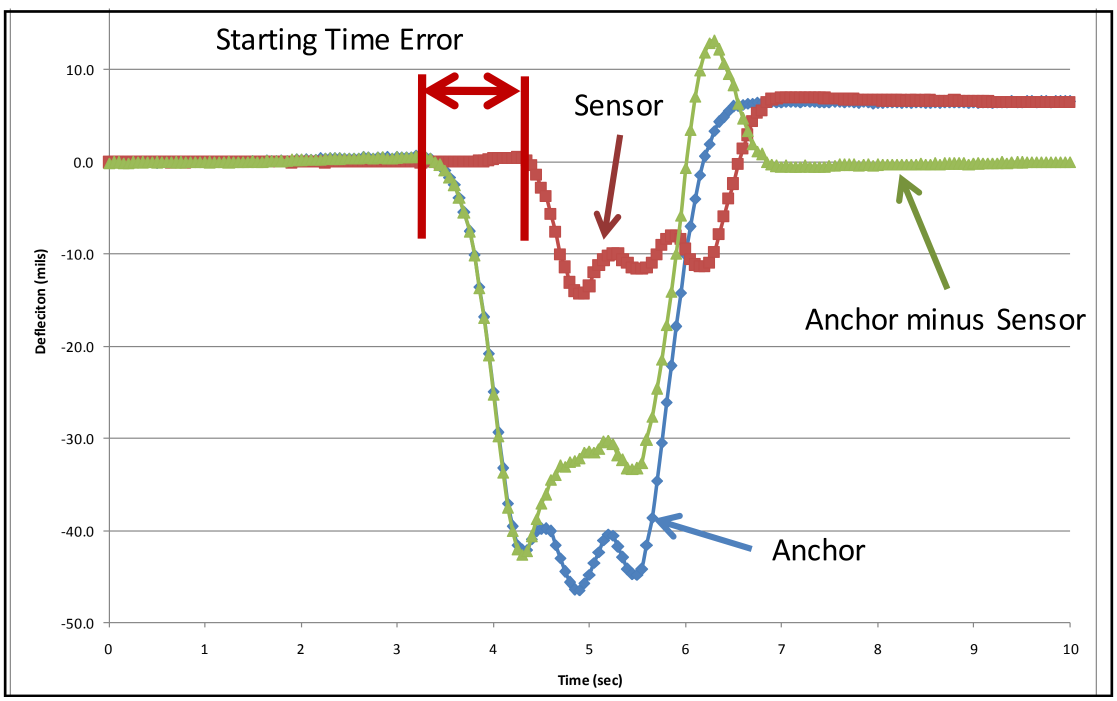

Figure 10: Sensor and Anchor Readings Offset due to Triggering Time Differences

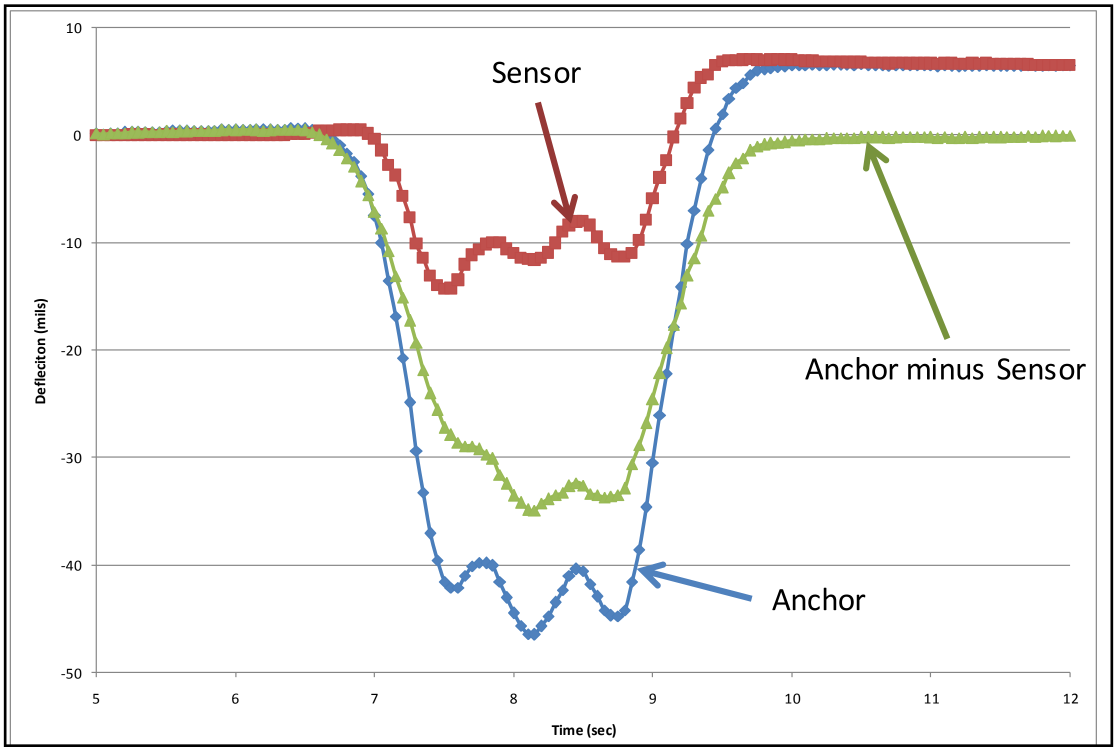

Figure 11: Time Aligned Sensor and Anchor Readings for Proper Analysis

The CC1 data was provided with two values intended to assist in this residual response calculation. “Offset left” and “offset right” values were provided with each sensor and each event. The offset left values are the displacement reading of each sensor before the landing gear carriage came within the influence zone of the sensor. The offset right values were the displacement readings of each sensor after the landing gear had passed; again with the landing gear outside the influence zone of the MDD group. Initially, all sensor data was processed using these values to provide residual displacements for each event. However, it was observed that the offset values were relative to the anchor, so to use the offset values one would need to subtract the offset values of the anchor from each reading. Instead of using the offset values, the average displacement of the first 1.5sec of data was subtracted from the average displacement of the last 1.5secs of data (see Figures 12 and 13). To check this method the residual response of the anchor calculated using the offset right and left values was compared with the residual response of the anchor calculated using the 1.5sec average values and the results showed a very close match with any discrepancies attributed to minor fluctuations in the sensor readings during the 1.5sec intervals. The residual response can be either contractive (negative), dilative (positive), or zero.

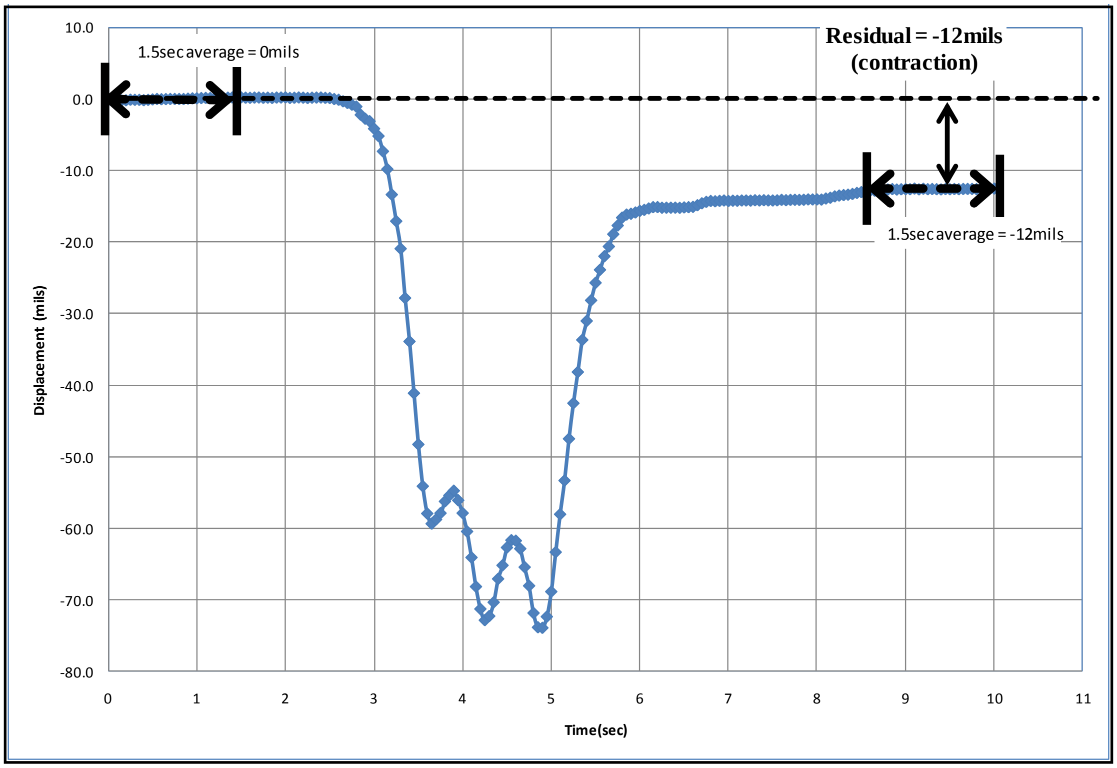

Figure 12: Residual Calculation (Contractive)

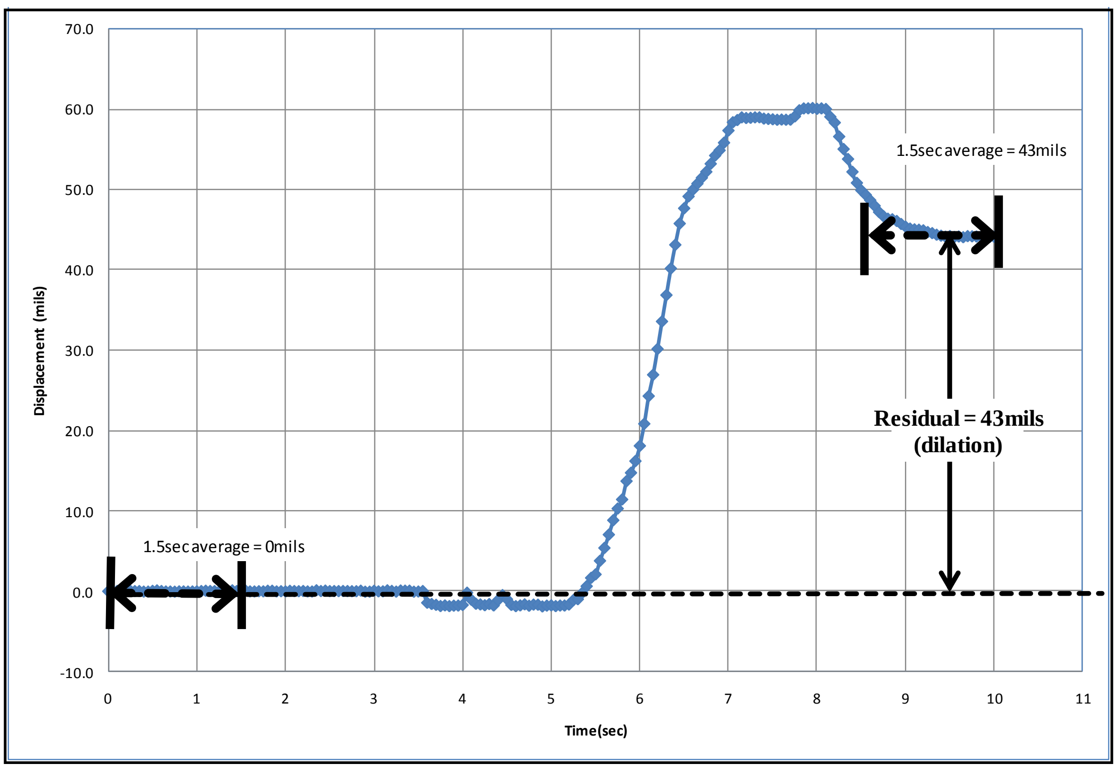

Figure 13: Residual Calculation (Dilative)

The most difficult data point to find is the rebound response value of each event. The wander pattern used in the CC1 testing resulted in time-displacement graphs that varied widely. Each different time history requires a slightly different method to calculate the rebound response. Figure 14 shows the values that can readily be obtained using Microsoft Excel (Figure 14 is an idealized graph). Excel can find the maximum and minimum values of a series without additional equations. The initial and final values of each time-displacement graph where an average of the beginning and ending 1.5 seconds of data respectively as shown in Figures 12 and 13. The maximum and minimum values can coincide with the beginning average or ending average.

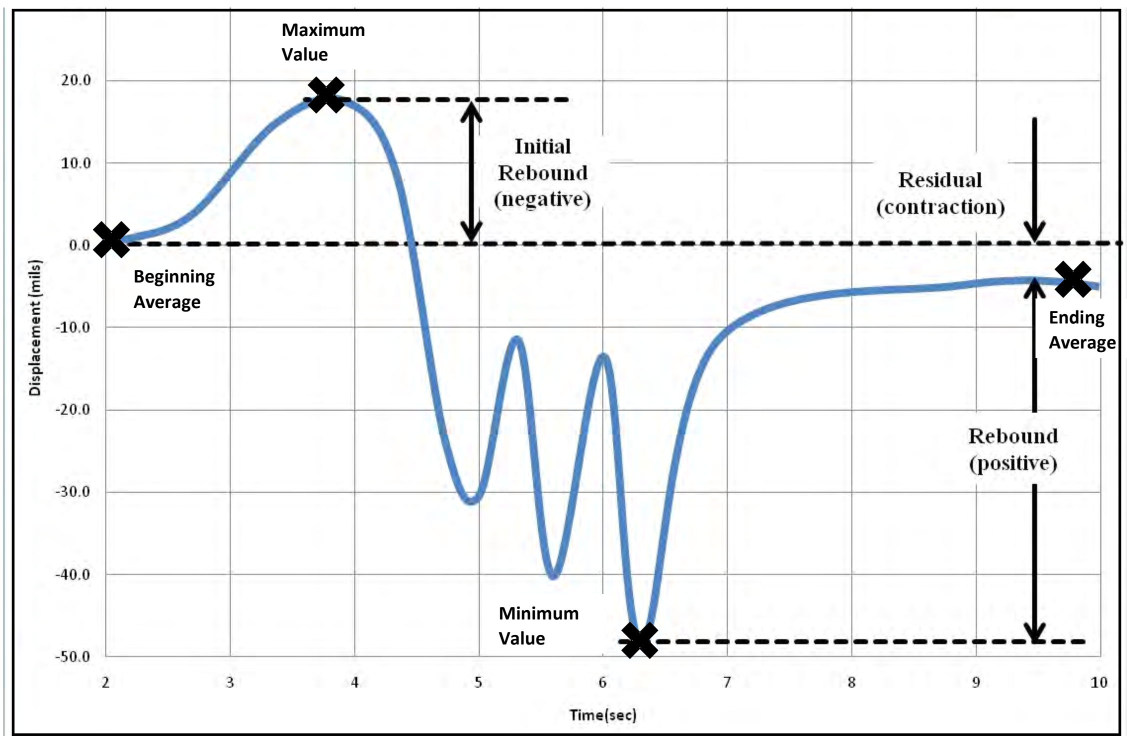

Figure 14: Microsoft Excel Obtainable Values

Traditionally, rebound response has been the amount of contractive deflection that is recovered after the pass of a wheel load; Figure 15 shows this situation. The wheel load causes contraction of the soil element to a peak displacement value and as the wheel moves past the point some of the peak displacement is recovered. The rebound response value of Figure 15 is simply the ending average value minus the minimum peak response value [(-12mils) – (-75mils) = 63mils]. Positive rebound indicates that some of the contraction of the soil element has been recovered. Conversely, if the soil element dilates as the wheel load moves past, a negative rebound value indicates that some of the dilation of the soil element is recovered (Figure 16). Dilative rebound is a logical result of dilation if there is any confinement of the soil element, however it has not been recognized or used for pavement analysis; but it is interesting to note that the MDD sensors recorded the phenomenon.

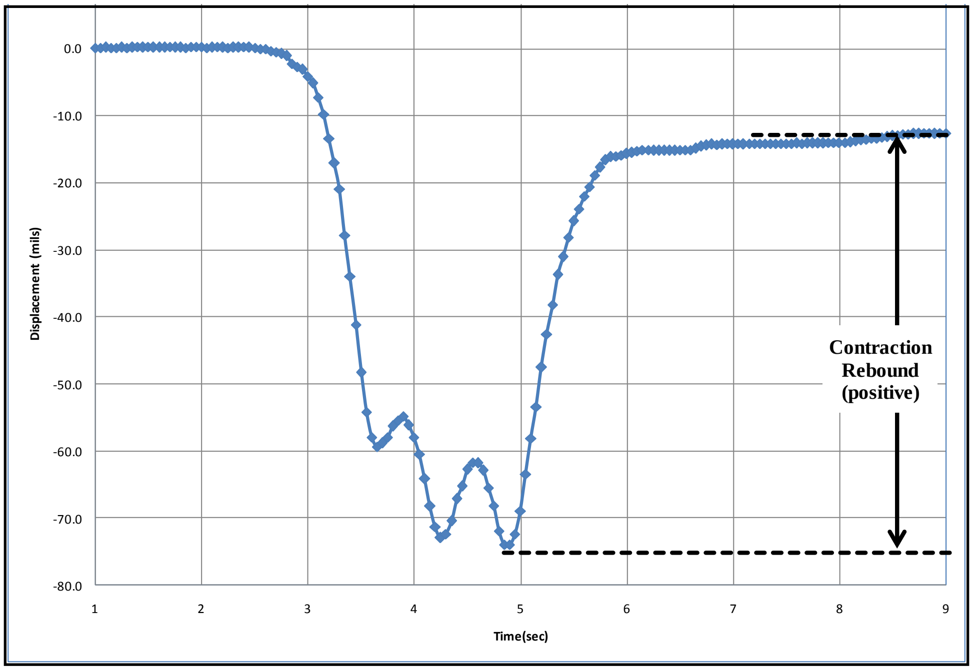

Figure 15: Contractive Rebound Response

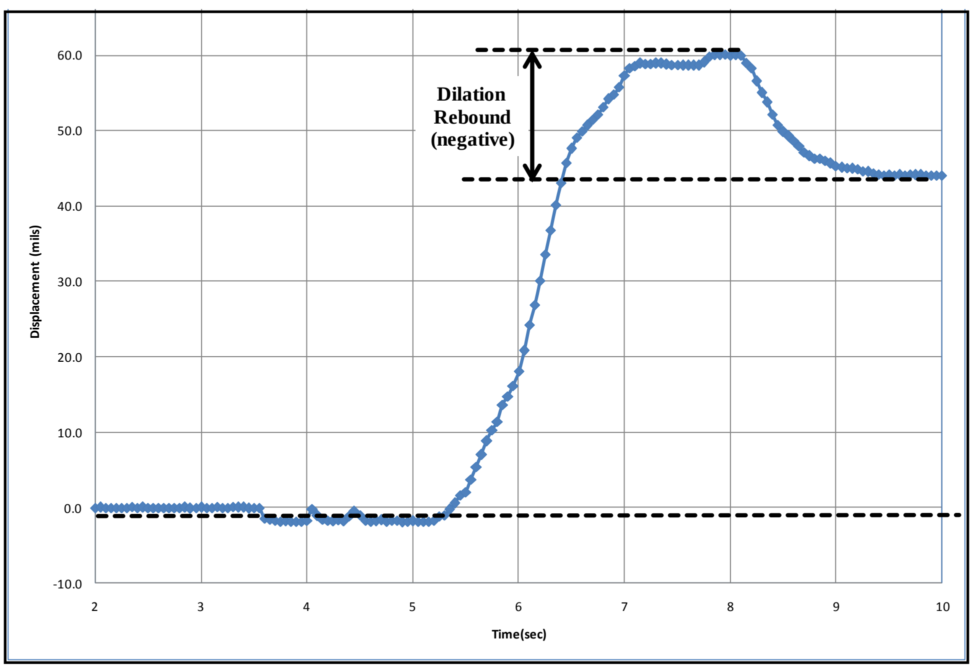

Figure 16: Dilative Rebound Response

2.4.2 Layer Response Values

Once the absolute sensor readings are known the individual layer response values can found by subtracting the lower sensor reading from the upper sensor reading. The response of the P154 layer in the 777 lane of the MFC section is shown in Figures 17 and 18 and is the response of the of the top of the layer minus the response of the bottom of the layer. Figure 17 is a typical contractive response under wander position 0 and Figure 18 is a dilative response under wander position 4

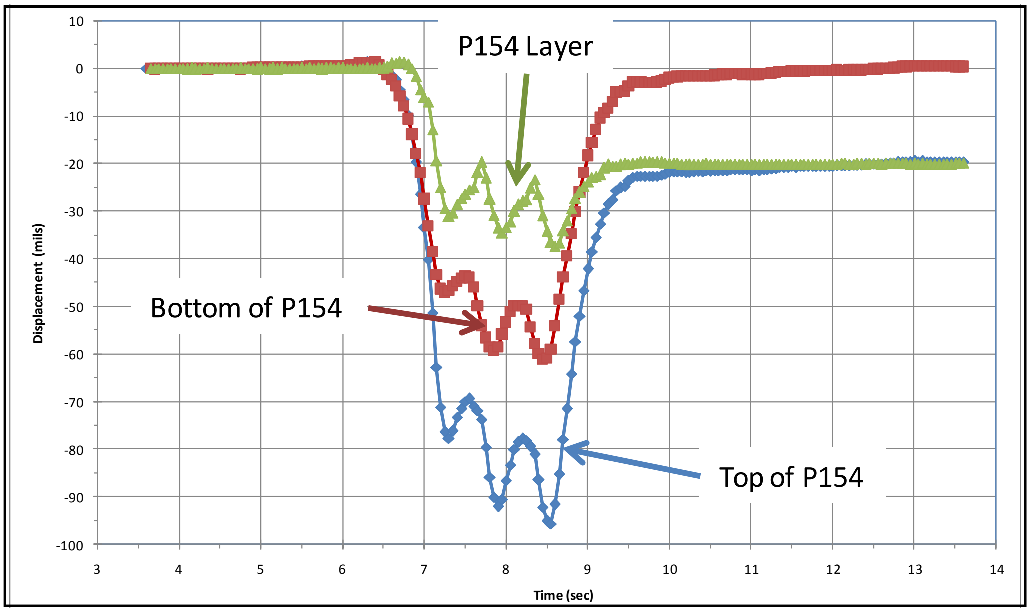

Figure 17: P154 Layer Response in MFC, 777 Lane, Wander Position 0, W-E Direction, Pass 166

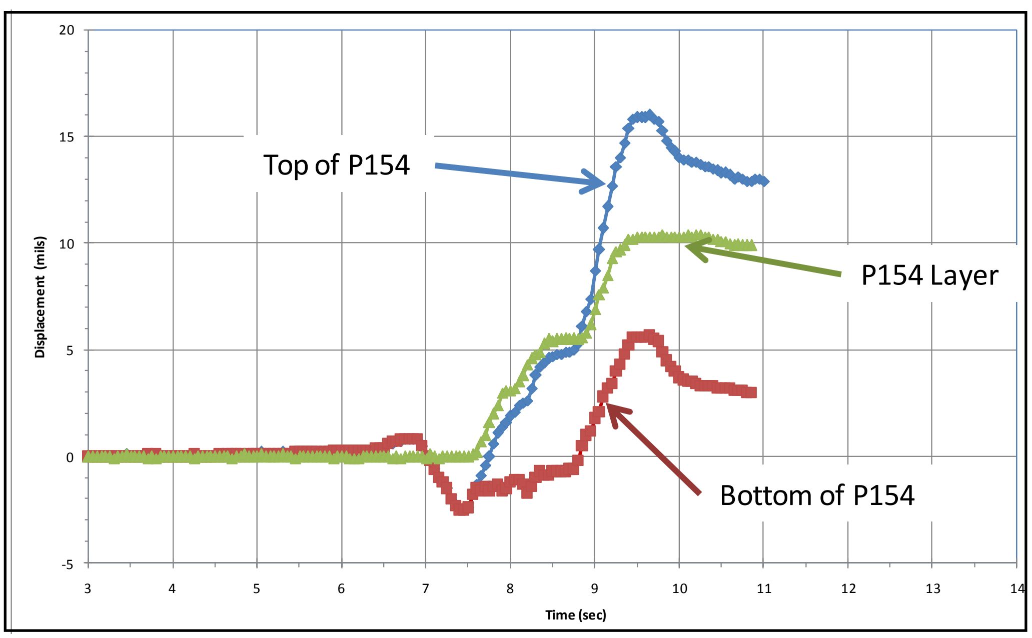

Figure 18: P154 Layer Response in MFC, 777 Lane, Wander Position 4, W-E Direction, Pass 188

2.4.3 Separation of MDD Response Values by Wander Direction, Position, and Sequence

When analyzing the response values from a specific MDD sensor in total, the data seems erratic and random; Figure 19 shows the residual response data from the P209 layer in the MFC section. It does seem that there are linear patterns within the data but analyzing the data as a complete set does not elicit what those patterns are. Only when the data is separated by wander position, travel direction, and wander sequence, do distinct patterns emerge that show some rationale for the linear patterns.

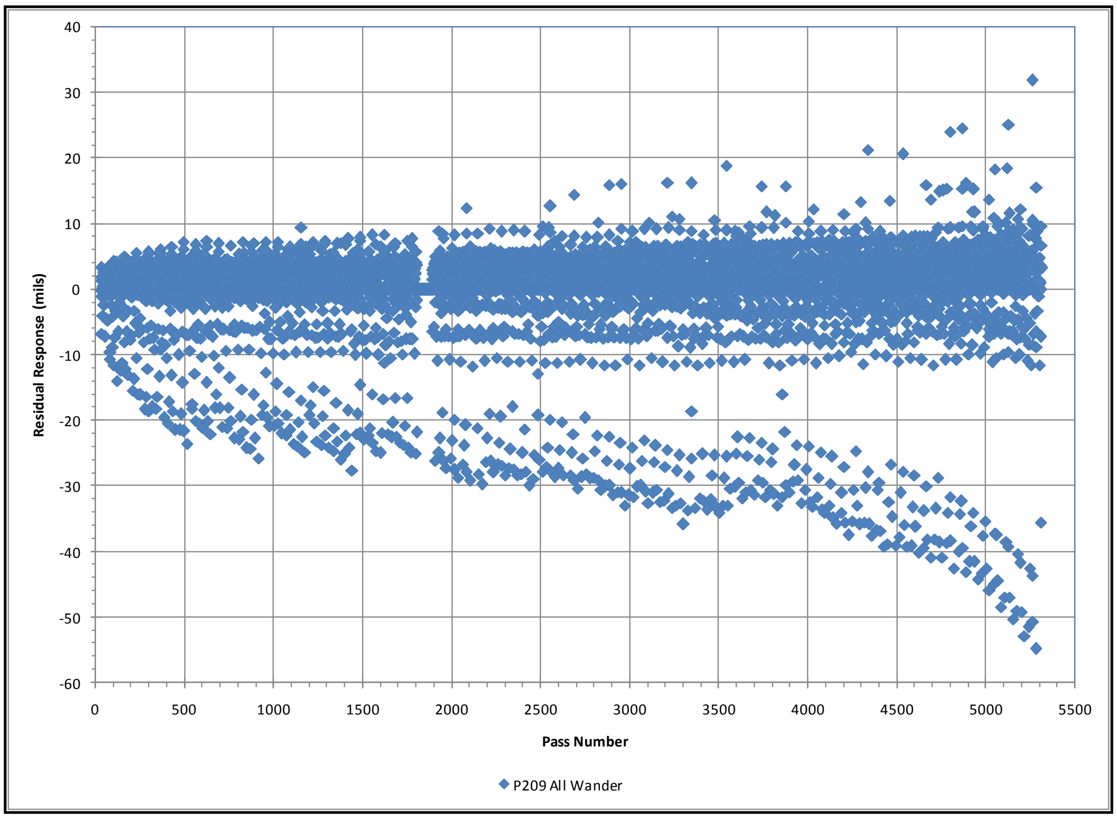

Figure 19. Residual response P209 layer all wander positions (1mil = 0.001in = 0.0254mm)

Figure 20 shows the isolated residual response data for wander position 0 in the P209 layer and Figure 21 shows the wander position 0 data in the P154 layer. It is only through the separation of the data that analysis of the layer response to individual wander positions and sequences can be accomplished. The P154 layer is thicker and of lower quality than the P209 layer and thus one would expect more residual deformation in this layer as shown in Figure 21. Something else that is only visible when the data is separated is that the first pass on each wander position in the west to east direction causes the most response and the return pass along the same wander position shows significantly less residual deflection. This provides an indication that shakedown does occur in the unbound aggregate layer but because the wander position shifts every other pass, the layer does not fully stabilize and the residual response continues to increase.

It is interesting to see in Figure 21 that if the wander pattern is kept narrow enough, shakedown occurs. As the 66 pass wander pattern goes from sequence 4 to sequence 5 (as defined by Figure 6) the residual deflection caused by the west to east pass on wander position 0 decreases 50% yet the other sequences all have similar responses under wander position 0. This is because the gear loading of sequence 5 is in a narrow path only 19.686in (500mm) wide. The effect is visible in Figure 20 also, but it is not as pronounced possibly because of the higher quality and thinner P209 layer which is not as susceptible to the dilative effects of wander.

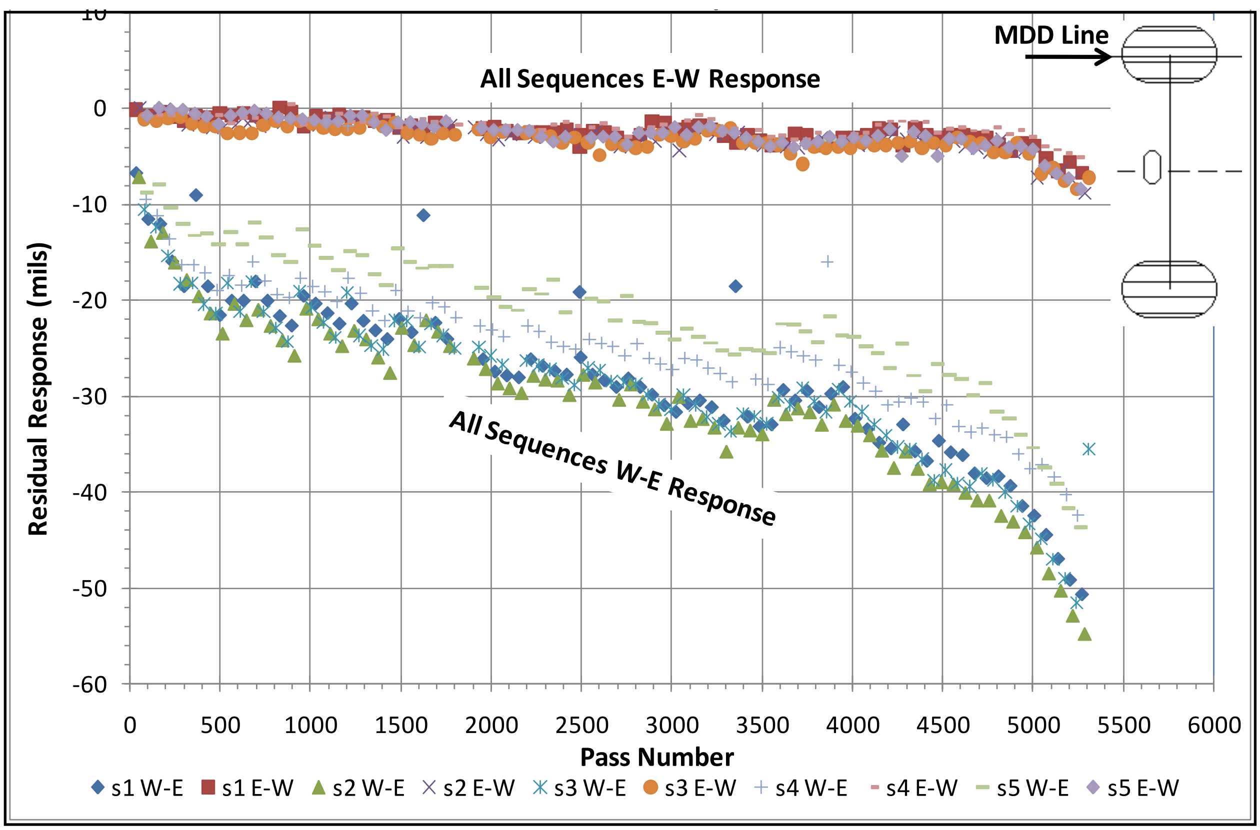

Figure 20. Residual response P209 layer wander position 0 (1mil = 0.001in = 0.0254mm)

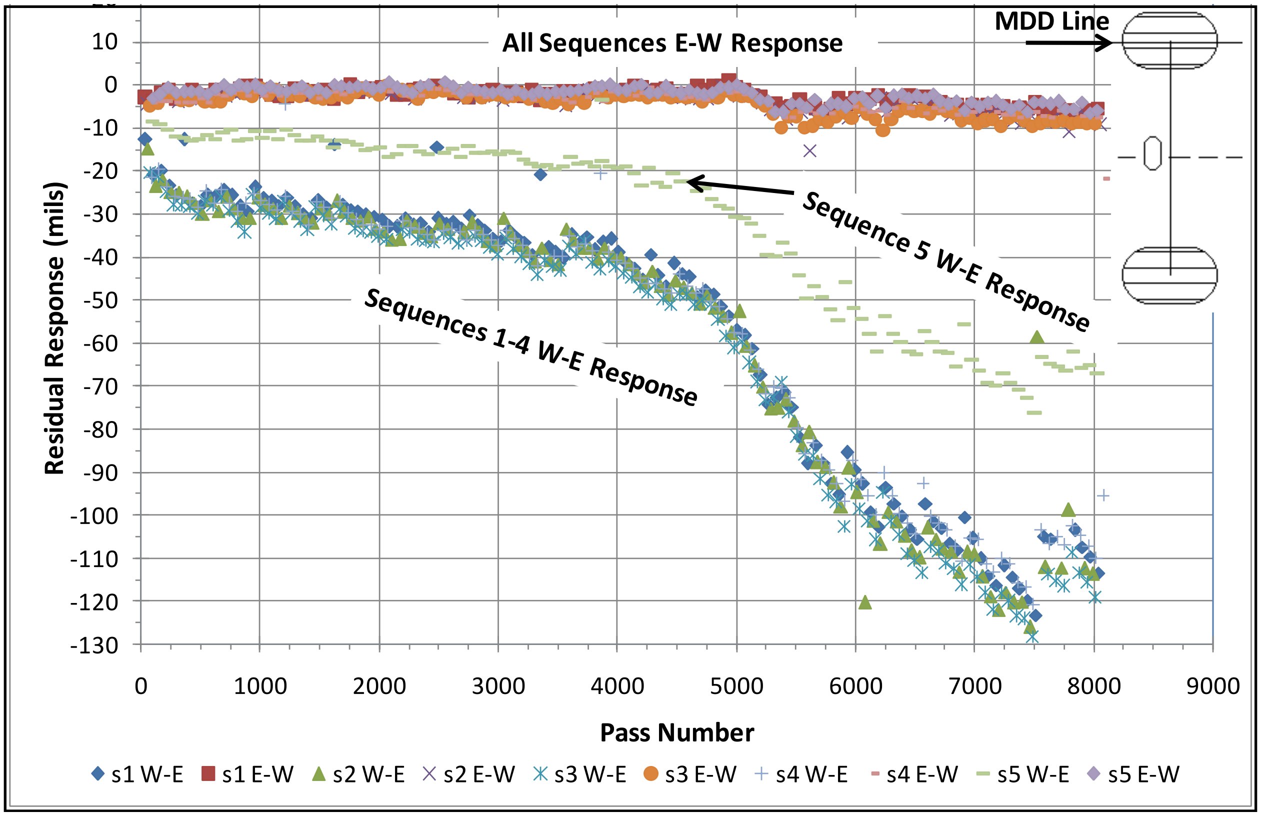

Figure 21. Residual response P154 layer wander position 0 (1mil = 0.001in = 0.0254mm)

2.4.4 Residual Response of P209 and P154 Layers

In order to fully understand the influence wander sequence and wander position have on the residual response it is necessary to combine the data into 66 pass wander patterns. Figure 22 shows 66 pass wander patterns for the P209 layer and Figure 23 the P154 Layer.

Both figures indicate that traffic in the west to east direction on wander position 0 produces the maximum downward residual deformation; which correlates with the maximum load position of the wheel centerline, located a mere 0.6in (1.5cm) from the MDD centerline. Wander position 1 is the only other wander pattern to produce a consistent downward residual deformation of both the P154 and P209 layers and is the second closest wheel load. All of the other wander positions contribute various amounts of contraction or dilation. Wander position 2 seems to provide the most dilation (heave) for both layers, but due to limited data points cannot be conclusively regarded as the wander position causing the most dilative effect.

Even though the detail is limited due to graph size restrictions, Figures 22 and 23 do show that in general as the number of passes increase both the contractive and dilative residual deformation values increase. This is in contrast to stable shakedown behavior where residual deformation per pass decreases with increasing repetitions.

When compared to the residual deformations in the subgrade (section 2.4.5), the maximum contractive response in the P209 layer is double the subgrade response while the P154 layer shows triple the response. The P209 layer shows less dilative response than P154 layer and a similar dilative response with the subgrade. The P154 layer on the other hand shows approximately 50% more dilative response than the subgrade. It is the combination of the upward and downward residual deformation that proves the unbound aggregate layers are being rearranged and anti-shakedown is occurring.

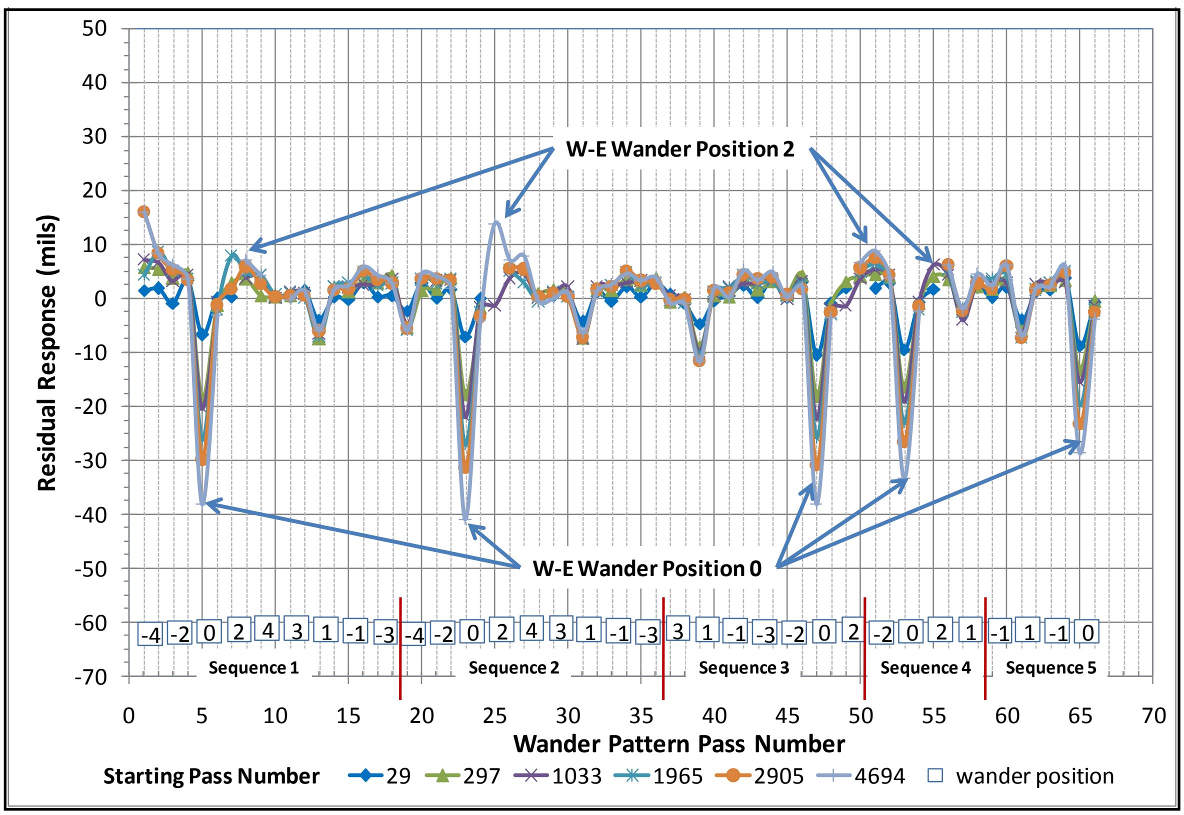

Figure 22. P209 residual response - 66 pass wander pattern and wander sequence, MFC section, B777 lane (1mil = 0.001in = 0.0254mm)

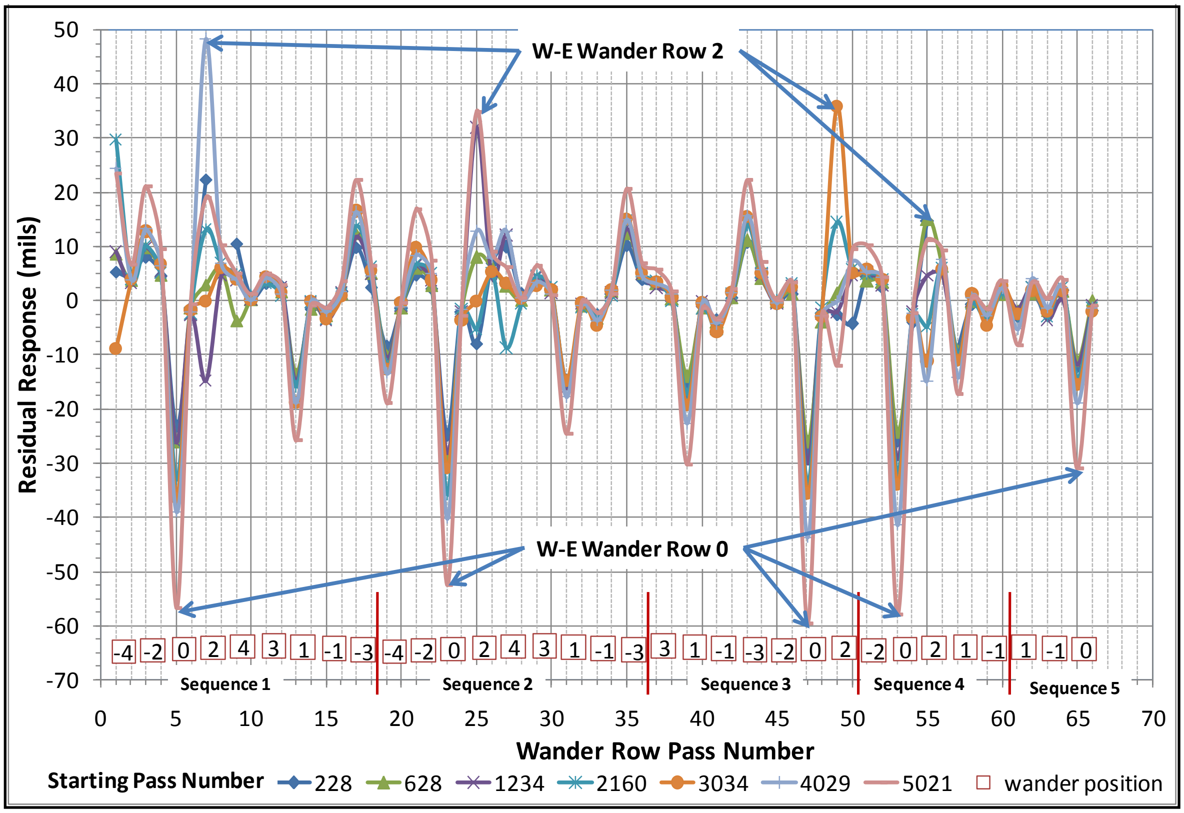

Figure 23. P154 residual response - 66 pass wander pattern and wander sequence, MFC section, B777 lane (1mil = 0.001in = 0.0254mm)

2.4.5 Response of the Subgrade Layer

The subgrade showed equal amounts of contractive and dilative residual deformation (Figure 24). The residual response values rarely exceeded ±20mils which are significantly less than the residual responses in the unbound aggregate layers. As seen in Figure 24, the maximum contractive as well as dilative residual responses are caused by multiple wander positions indicating that the gear wheel interaction is higher for the subgrade layer (as expected). What is unexpected is that the subgrade residual response is so much less than the unbound aggregate response. Most of the total residual response is recorded in the unbound aggregate layers, which is in contrast with normal FAA pavement design where the base and subbase courses are assumed to have little to no rutting.

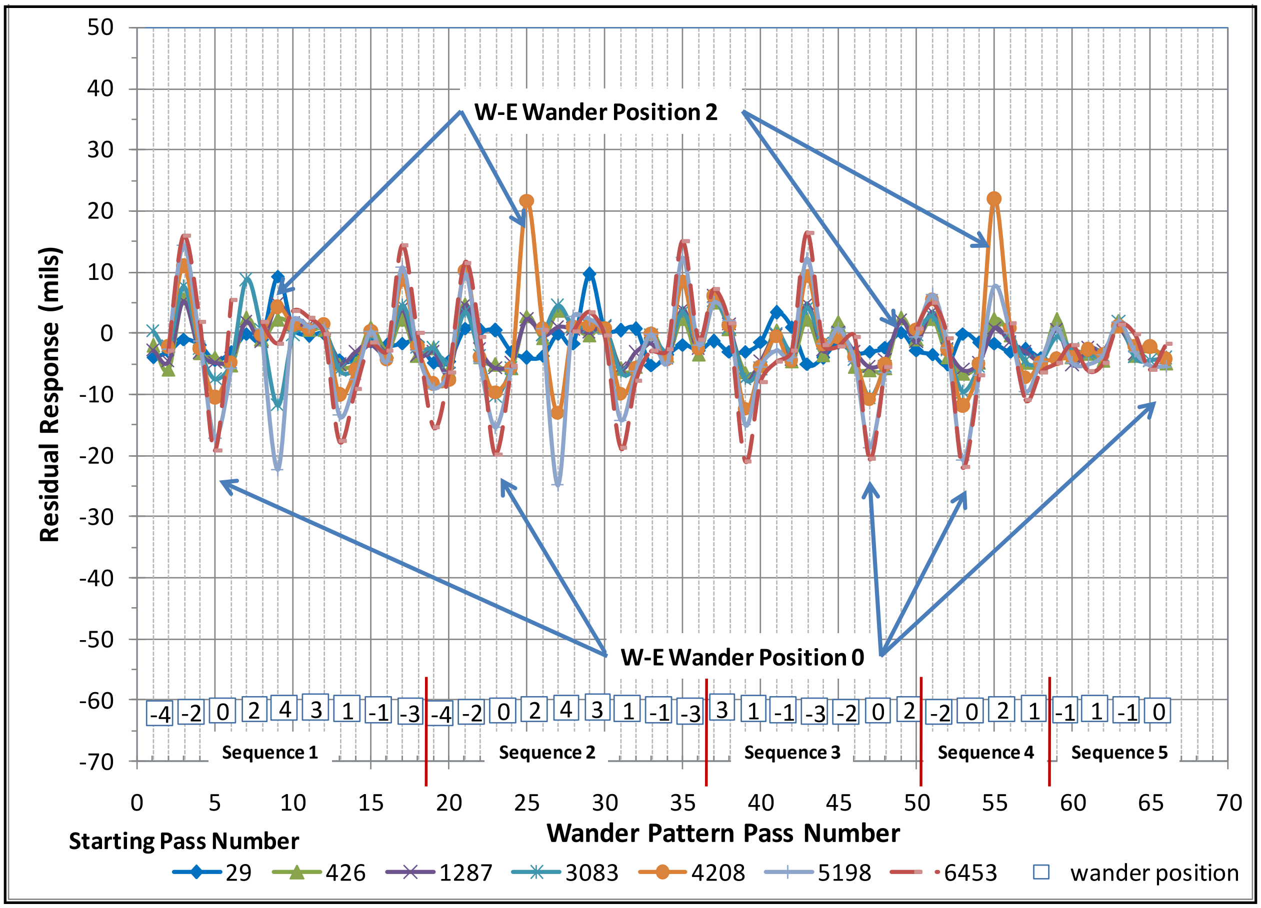

Figure 24. Subgrade residual response - 66 pass wander pattern and wander sequence, MFC section, B777 lane (1mil = 0.001in = 0.0254mm)

2.4.6 Comparison with Surface Rutting

Surface rutting was monitored manually throughout the traffic test program using a transverse surface profile (TSP) device, a rolling inclinometer, and straightedge rut depth measurements. The profile data was not measured after a specific wander position or wander sequence. Figure 25 shows the rut depth at the MDD location at various passes. As expected, the rut depth does generally increase with the number of passes; however in contrast to expected behavior, there are numerous measurements where the rut depth decreased. It is the induced aircraft wander that causes this anomaly; however, there is no way to adequately compare the affect of wander position on the manual rut depth measurements because the manual measurements do not cover a complete 66 pass wander pattern. In future tests, every 10th wander pattern should be manually measured after each of the 66 passes to properly define the influence of wander on the surface rut depth.

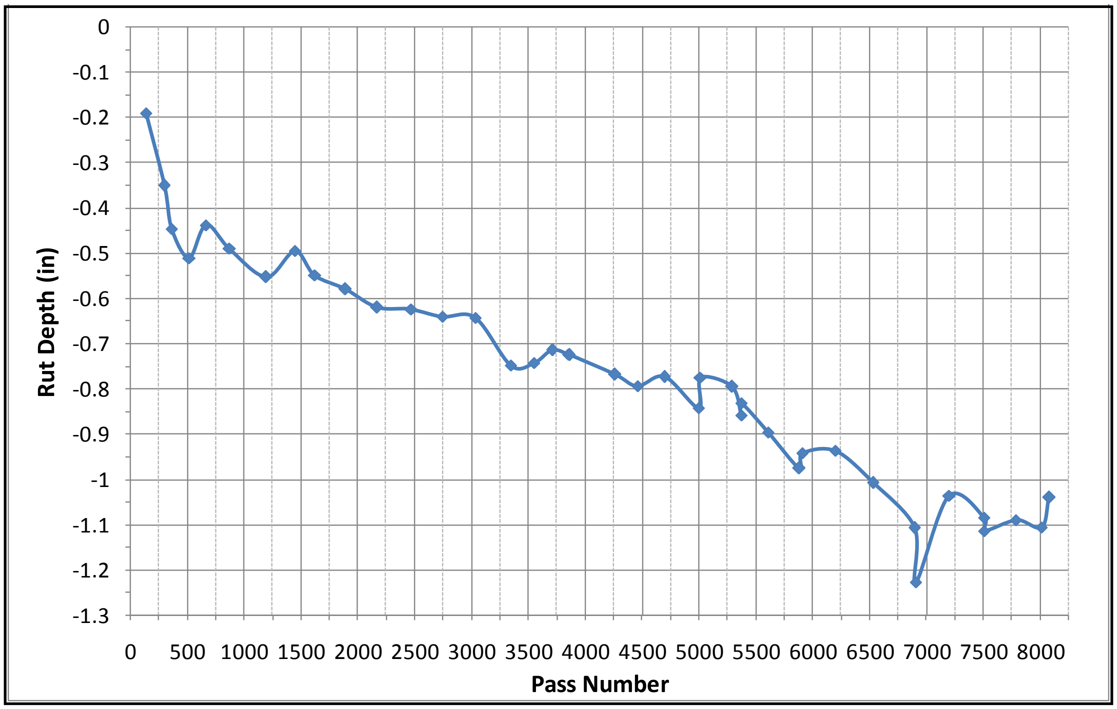

Figure 25. Rut depth measurements at the MFC 777, Lane, MDD location (1in = 25.4mm)

2.4.7 Heavy weight Deflectometer Testing

The heavy weight deflectometer (HWD) is a machine similar to a falling weight deflectometer with the only difference being a larger loading capacity for the HWD machine. The principle behind falling weight tests is the same as for any weight/deflection measurement test; deflection can be used as an indicator of the condition and strength of a pavement system. Higher deflections point to a degraded or weaker pavement system. The falling weight deflectometer uses instantaneous loads (20-60msec) to induce deflections. Deflection can be induced by static loads, but the falling weight is indicative of the transient nature of actual traffic and the impact load can be changed by varying the drop height. HWD tests can be conducted regularly during testing to help determine the degradation of the pavement system.

The FAA used a KUAD Model 240 HWD in their CC1 testing and has a standard procedure for routine HWD tests. They use a 12in (30.5cm) segmented loading plate, a pulse width of 27-30msec, and four drop heights consisting of a 36kip (160kN) seating drop followed by impact loads of 12, 24, and 36kips (53.4kN, 106.8kN, and 160kN) (Garg and Marsey 2004). The deflection basin is recorded for each drop with seismometers placed radially from the center of the load at 0in (D0), 12in (D1), 24in (D2), 36in (D3), 48in (D4), and 60in (D5), (0, 30, 60, 90, 120, and 150cm). As the distance of the sensor increases from the center of the load, the depth to the effective layer properties increases. For example the deflection of sensor D2 may indicate the combined properties of the layers deeper than 6in (15cm) while deflection of sensor D4 could correlate to layer properties deeper than 12in (30cm). The deflection at the center of the loading plate, D0, is a function of the loading plate diameter, the applied load, and the pavement structure as a whole. While deflection at the outermost sensor, D5, is predominately controlled by the subgrade properties (Garg and Marsey 2002). Depending on the thickness of the pavement system layers, sensors D1 to D4 may provide insight into base and subbase layer properties.

2.5 Analysis

2.5.1 MDD

The MDD data from the MFC sections indicates that the base and subbase layers do not consolidate and shakedown during testing. Figure 26 is the residual response by layer for the MFC section, B777 lane, wander position 0, west to east direction, for wander sequences 1-4 and Figure 27 is the percentage of the residual response by layer. Wander position 0 has one gear wheel directly over the MDD location (Figure 5). If shakedown does occur in the unbound aggregates one would expect that the percent of residual response by layer would decrease for the P209 and P154 layers and increase for the subgrade, however as shown in Figure 27, this does not happen. The percent of the residual response remains relatively constant for each layer as the testing progresses, 8% P401, 36% P209, 46% P154, and 10% subgrade. The exception can be seen in the P401 and P209 layers. Shakedown occurs in the P401 layer as evidenced by the decrease in the percent of residual response by the P401 layer during the initial 1000 passes. This shakedown in the P401 layer is counteracted by an increase in the percent of residual response by the P209 layer for the same 1000 passes. In general the percent of residual response by the P154 layer is decreasing while the percent of residual response by the subgrade is increasing, and this correlates with the subgrade failure of the MFC section at around 12,000 passes. The P209 and P401 layers show consistent percent of residual response after the first 1000 passes.

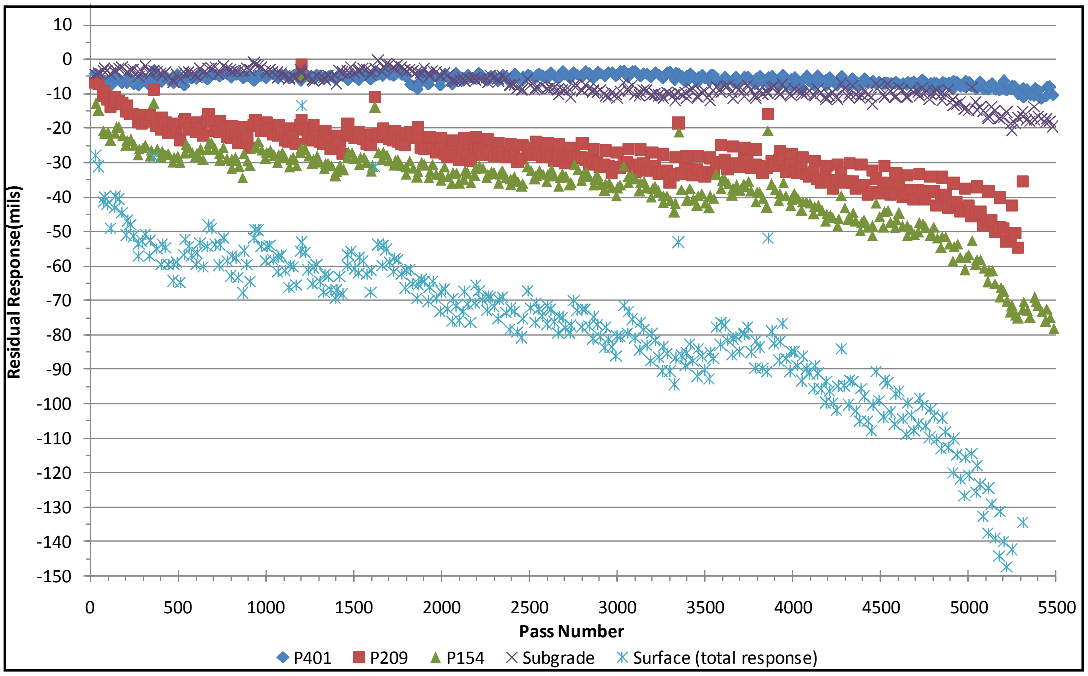

Figure 26: Residual response by layer for MFC, B777 lane, wander position 0, west to east direction, wander sequences 1-4

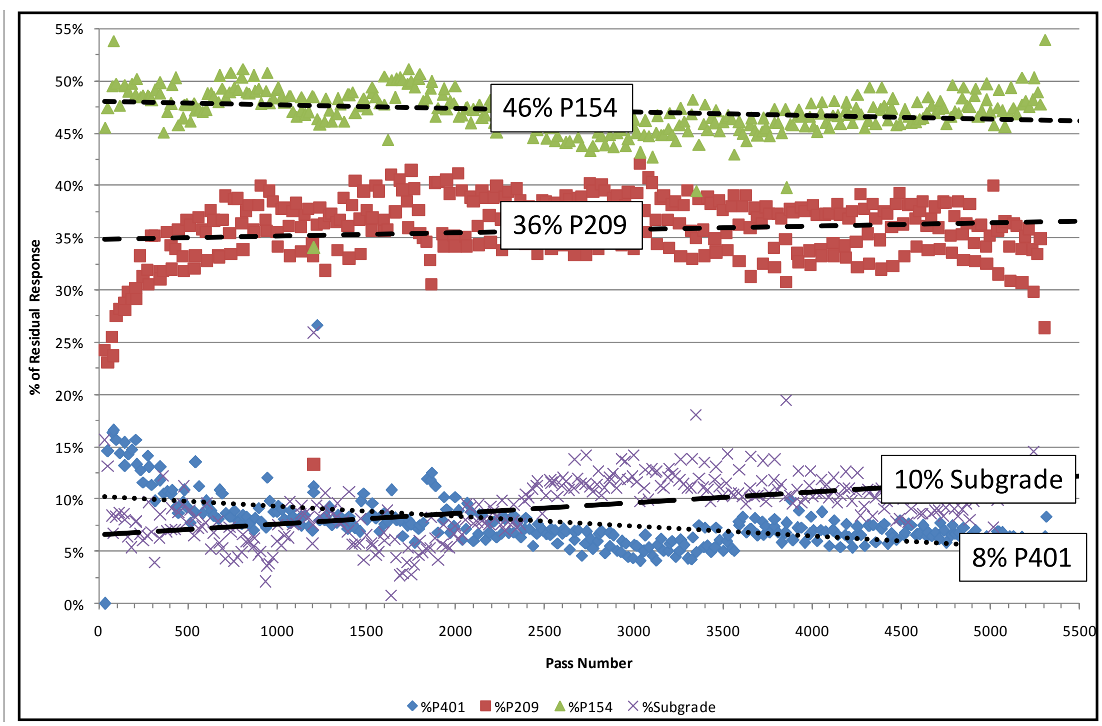

Figure 27: Percent of residual response by layer for MFC, B777 lane, wander position 0, west to east direction, wander sequences 1-4

The MFC section B777 lane was declared failed after 12,000 passes due to 4-6in (10-15cm) ruts with upheaval outside the traffic lane and asphalt surface cracking within the traffic lane (Hayhoe and Garg 2003). Because of the excessive movements of the layers and displacement of the surface sensor box, the MDD data is only reliable up to 5500 passes; however Figures 26 and 27 show that for those 5500 passes shakedown does not occur. And because the pavement was considered failed after only 12,000 passes failure is likely the result of shakedown range B behavior. Again range B shakedown is characterized by an initial phase where residual deflections taper off, but then a dramatic increase in residual deflections after a limited number of cycles caused by the gradual reduction in the stress capacity of the unbound materials from constant particle rearrangement. Post traffic trench studies found that the subgrade had penetrated into the P154 subbase layer due to lateral movement of the P154 unbound aggregate particles after the tensile stress caused by loading exceeded the residual compressive stress in the layer (Hayhoe and Garg 2003). From the shakedown range comparison this can be thought of as the final range B behavior. Though this failure may seem to be range C, incremental collapse, the number of passes was too high to correlate with the sudden dramatic failure seen in range C.

Figures 28 and 29 show the same data for the MFC, B747 lane. Only wander sequences 1-3 are shown for clarity in Figure 28 as wander sequences 4 and 5 show reduced residual deformation due to the narrower band of wander positions in sequences 4 and 5 (this sequence induced shakedown is negated once the wander pattern restarts on pass 67). For the 747 path, wander position 1 has one gear wheel directly over the MDD. Once again the percent of residual response by layer remains relatively constant indicating shakedown is not occurring. The only difference is that for the 747 lane, the P154 layer dominates with 53% of the contractive residual response while 20% is from the subgrade, 18% from the P209 layer, and 13% from the P401 layer. The P401 layer seems to be consolidating and exhibiting stable shakedown behavior (negative slope of P401 trend in Figure 29) at the expense of the destabilization and degradation of the P209 layer (positive slope of P209 trend in Figure 29). This is likely the result of shakedown range B behavior where the P209 layer is gradually losing strength.

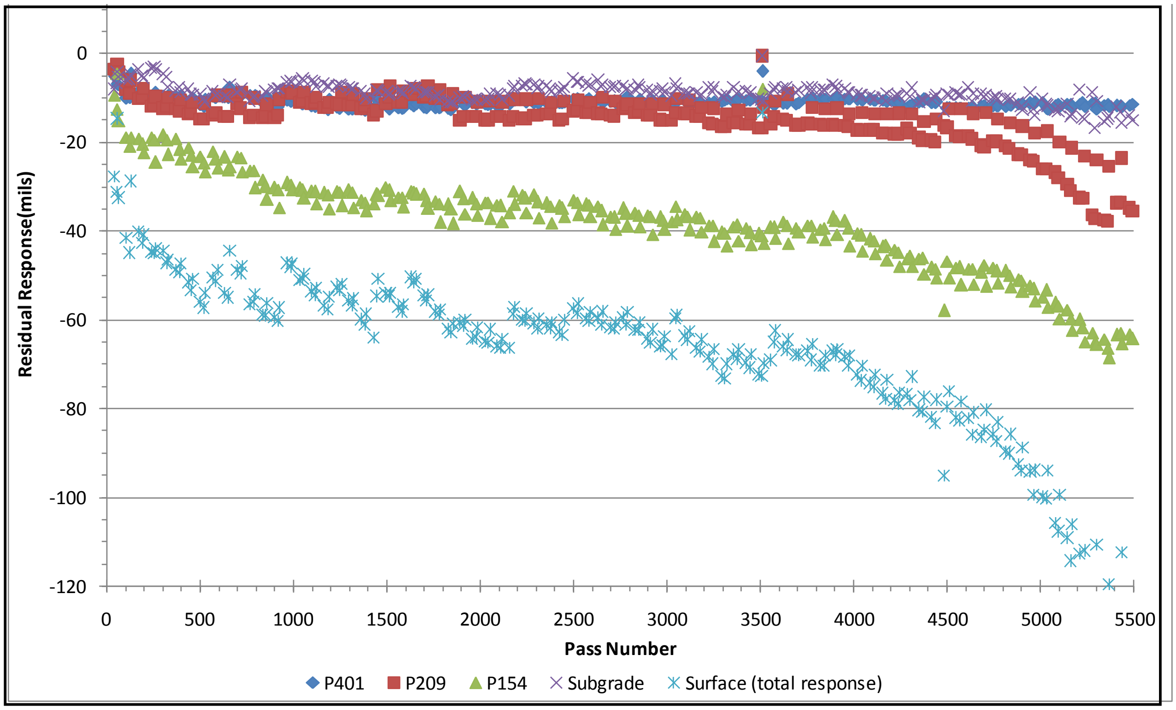

Figure 28: Residual response by layer for MFC, B747 lane, wander position 1, west to east direction, wander sequences 1-3.

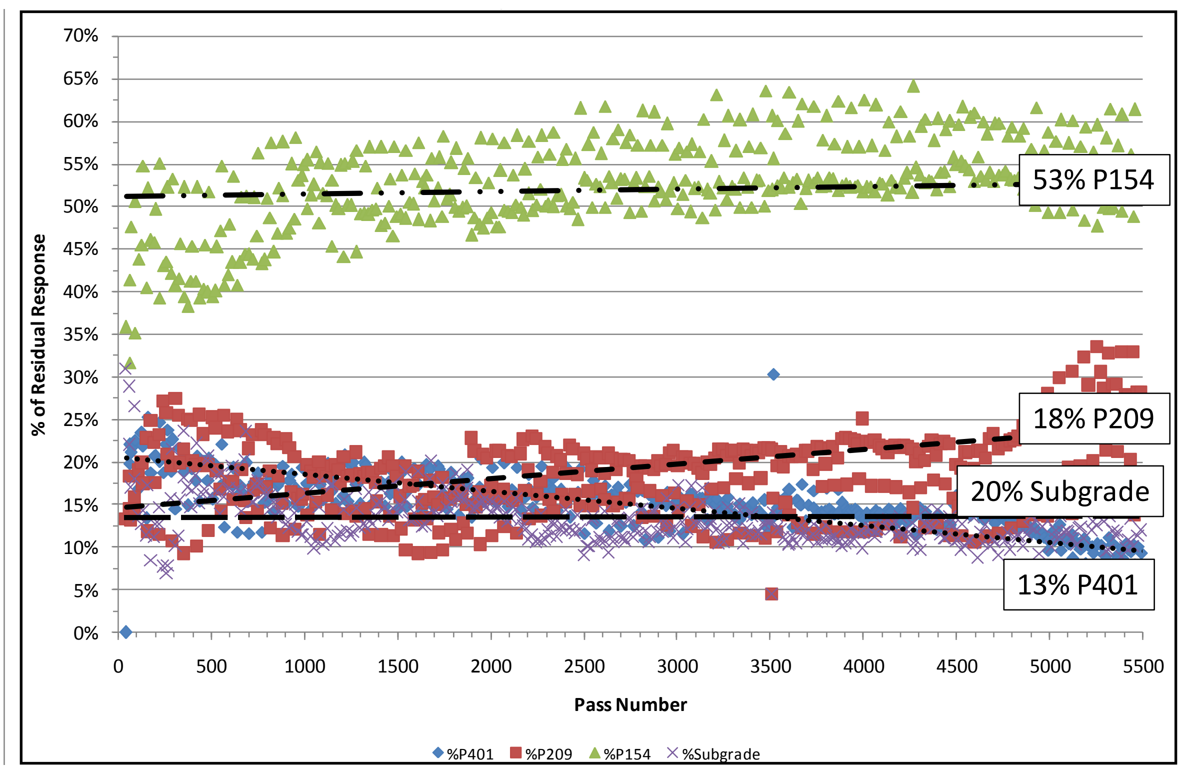

Figure 29: Percent of residual response by layer for MFC, B747 lane, wander position 1, west to east direction, wander sequences 1-5

2.5.2 Heavy Weight Deflectometer

HWD data and the associated deflection basin parameters can be used to determine the degradation of the layers in a pavement system (Gopalakrishnan and Thompson 2004). The HWD data will be used to calculate the Base Damage Index (BDI) and the Base Curvature Index (BCI) to investigate the relative damage to the base courses and the subgrade. The BDI is related to the modulus of the base course (unbound aggregates) and the BCI is related to the modulus of the subgrade; the higher the BDI or BCI values the weaker the layer. Gopalakrishnan and Thompson (2004) investigated conventional Base Damage Index (BDI, D1–D2) and Base Curvature Index (BCI, D2–D3) values for the NAPTF tests and found that the BDI was 10-20% higher than the BCI. However the conventional calculations do not account for the thicker pavement layers and higher loads in the NAPTF tests where D2 and D3 may not indicate the base and subgrade behavior. As an example, Figure 30 shows HWD deflection readings from the MFC section indicating that D3 grows as the testing progresses; which means that D3 is not indicative of stable subgrade behavior. However, D5 is clearly a consistent value and can be used in the BCI calculation.

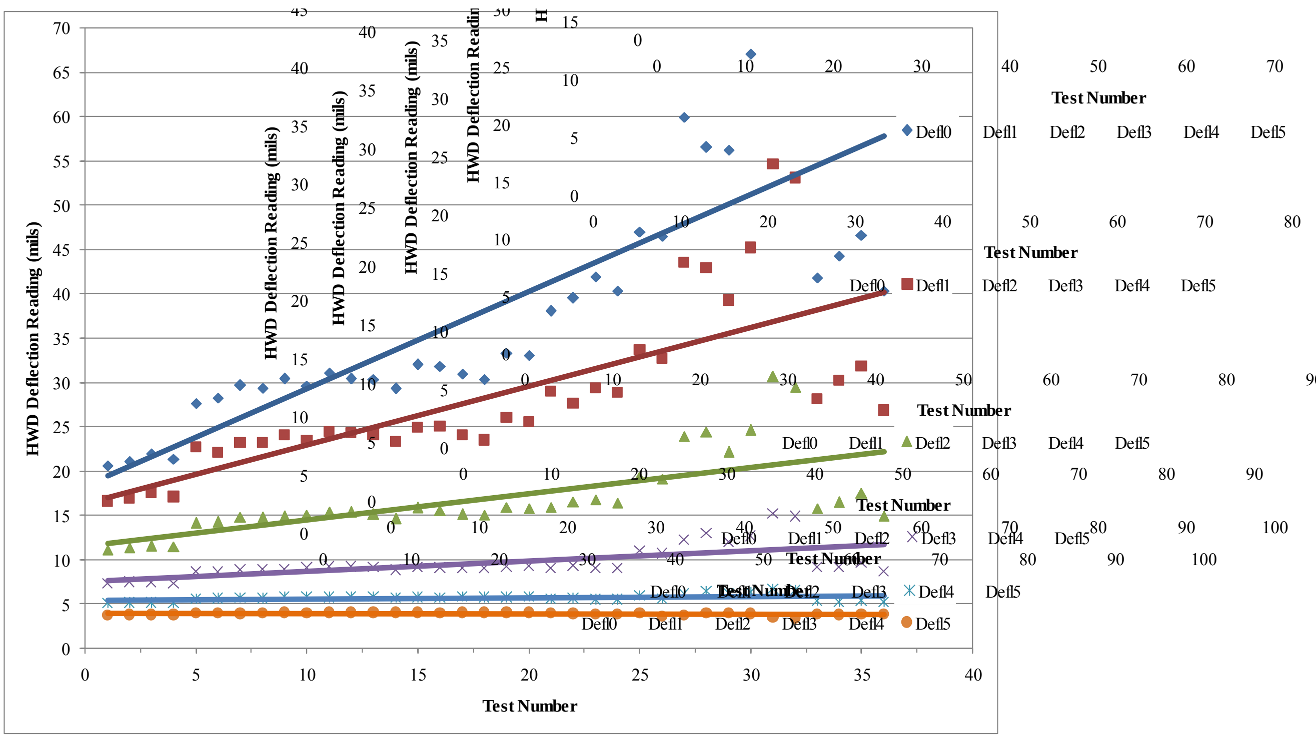

Figure 30: General HWD Deflection Response for MFC Section

To account for the thicker layers and loads, a modified BDI will be used to identify the degradation in the unbound aggregate layers and a modified BCI for the subgrade to more clearly see the distinction between base and subgrade damage. The BDI is normally calculated as D1 – D2 [deflection at D1, 12in (30.5cm), minus D2 the deflection recorded at 24in (60cm)]; however due to the thickness of the layers in the NAPTF tests, the BDI is calculated as D1 – D3 [D3 is the deflection at 36in (90cm)]. Because non-traffic lane HWD tests were conducted at the same time and pavement temperature as the traffic lane tests, the BDI value from the traffic lane should be higher than the BDI from the non-traffic lane. Dividing the traffic lane BDI by the non-traffic lane BDI will normalize the calculation for both temperature and damage increase. The BDI will then be compared to the BCI which is modified to be D3 – D5 (instead of D2 – D3) and is also divided by the non-traffic lane BCI to normalize for damage and temperature. The BDI and BCI are normalized with respect to the impact load by dividing the respective traffic lane or non-traffic lane value by their respective D0 deflection measurement.

The BDI damage ratio should be larger than the BCI damage ratio if the base is sustaining the most damage. If the damage in both layers is equivalent, then the ratio between the damage normalized BDI and BCI should be 100%, but if the damage in the unbound aggregate layers is higher, then the ratio should be greater than 100%. And looking at Figure 31 one can clearly see that more damage is occurring in the unbound aggregates than in the subgrade. The MFC 747 lane sustains up to 75% more damage in the unbound aggregate than in the subgrade while the 777 tops out at 20% more damage.

Figure 31 also demonstrates the shakedown range B behavior of the pavement system. The unbound aggregates initially sustained the most damage (high BDI/BCI ratio), but after 5000 passes, the stresses increase in the subgrade due to the decreased stiffness and load bearing capacity of the unbound aggregates caused by the aggregate particle movement and rearrangement (lower BDI/BCI ratio). So at the beginning of trafficking the unbound aggregates are supporting the load and sustaining the most residual deformation, but after 5000 passes the damage caused by the repetitive loads becomes too great and higher stresses are transferred to the subgrade resulting an increase in the subgrade residual deformation.

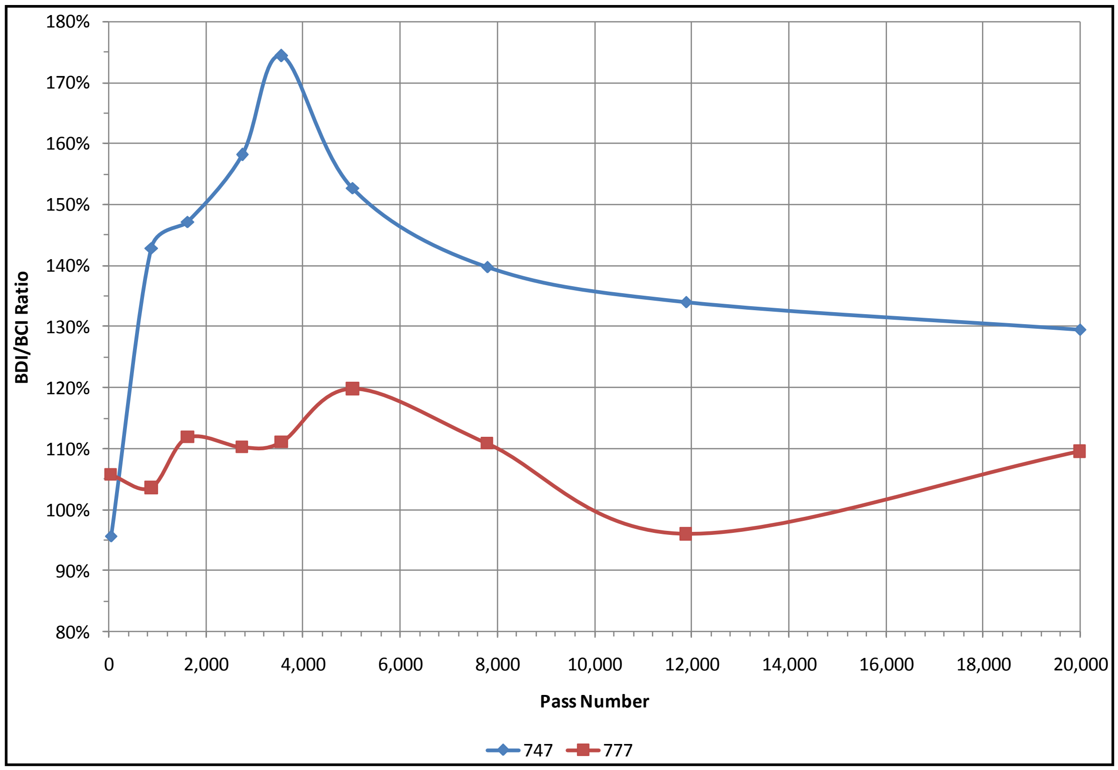

Figure 31: Ratio of Base Damage to Subgrade Damage in MFC Section (BDI/BCI)

2.6 Conclusions from Analysis

Wander has a dramatic effect on the stability and strength of the unbound aggregate layers because it causes constant particle rearrangement. Stresses that would normally result in stable range A shakedown behavior actually cause range B behavior with eventual collapse of the system at a greatly reduced number of load cycles. Multi-depth deflectometer and Heavy Weight Deflectometer data indicate that shakedown does not occur in the unbound aggregate layers of the NAPTF MFC section. The MDD data shows that the percent of residual response by each layer of the pavement system is relatively constant which is in contradiction to the shakedown theory where the unbound aggregate layers should consolidate and thus reduce their contribution to permanent deformation. HWD data indicates that the unbound aggregate layers degrade much more quickly than the subgrade which results in a cascading degradation of the pavement system with the unbound aggregate layers degrading first followed in quick succession by the subgrade.

3.0 Safety Risk Assessment

While pavement condition does not readily present itself as a safety problem for airfield operations, ignoring it can quickly result in hazardous situations. Without accounting for aircraft wander pavements could fail prematurely and at a point in time where maintenance budgets do not allow for repair or replacement. Obviously, serious pavement degradation will either be addressed by repair or in severe cases the pavement in question may be deemed off limits for aircraft use. Either way the operation of the airport will be restricted.

Potential safety problems could be from the functional failure of the pavement where the roughness is too high for large aircraft to navigate or it could be a structural failure where the crumbling of the pavement could present a FOD hazard. However unlikely these situations are, they must be addressed before an accident occurs. And to address them involves proper design consideration of wander as well as proper analysis of existing pavements for wander.

4.0 Description of Interactions with Airport Operators and Industry Experts

This project was completed under the direction and cooperation of the National Airport Pavement Test Facility. Future research will expand upon these initial findings and will likely result in modifications to FAA design and analysis of unbound aggregate layers.

This paper was prepared from a study conducted in the Center of Excellence for Airport Technology. Funding for the Center of Excellence is provided in part by the Federal Aviation Administration. The Center of Excellence is maintained at the University of Illinois at Urbana-Champaign in partnership with Northwestern University and the Federal Aviation Administration. Ms. Patricia Watts is the FAA Program Manager for Air Transportation Centers of Excellence and Dr. Satish Agrawal is the FAA Airport Technology Branch Manager.

The contents of this paper reflect the views of the author who is responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the Federal Aviation Administration. This paper does not constitute a standard, specification, or regulation.

5.0 Description of the Projected Impacts

The most important knowledge gained from this proposal is that knowing how wander influences unbound aggregates within an airfield pavement will allow future design and analysis to incorporate the seemingly random travel paths of aircraft into calculating the critical pavement stresses and strains for use in the mechanistic-empirical design procedure. Being able to predict the transverse effect of an aircraft load on unbound aggregates will allow calculation of the response and changes in layer properties transversely across a pavement. These new layer properties can then be used with the location and load of the next aircraft pass to calculate the expected response. In this "incremental-recursive" approach the last pass is used to predict the response of the next pass and this calculation can be iteratively applied to future aircraft passes in an attempt to predict the lifetime response of the pavement.

With this knowledge pavement design procedures for airfield should be modified to include analysis of horizontal stresses and strains within the unbound aggregate layers. This will indicate the possibility of dilation and strength reduction in the unbound aggregate layers.

Testing procedures for unbound aggregates should be changed to include the susceptibility of the aggregate to dilation due to horizontal or shear stresses. If the aggregate is susceptible to excessive dilation it should not be used in regions of the pavement system where dilation may occur.

If wander is predicted to cause unbound aggregate problems there are mechanical and chemical stabilization procedures to solve the problem. Simply adding more aggregate will not solve the dilation problem because the additional aggregate does nothing to reduce the shear or horizontal stresses that cause dilation and strength reduction of the layers (as evidenced by the degradation of the thick P154 layers in the NAPTF testing). The most logical and easiest way to prevent wander problems with the unbound aggregates is to increase the thickness of the asphalt layers. This will reduce the stresses applied to the aggregate while at the same time provide more confinement, both of which can negate the dilative effect of wander. Of course this could also be the most expensive option.

Chemical stabilization can take many forms from using cement to using lime to provide some tensile capacity to the unbound layers. Regardless of the method used, the chemical stabilization should be analyzed for its improvement of the tensile capacity of the unbound aggregate layers because it is the improved tensile capacity that will reduce the horizontal particle movement and thus the dilative effect. Mechanical stabilization can involve geotextiles, geogrids, or geocells to provide confinement and/or an increase in the tensile capacity of the unbound aggregate layers.

Costs for these improvement techniques vary widely and without the exact specifics of the required remedy it is impossible to accurately assess the additional cost of treating an unbound aggregate layer to prevent dilation. However, if the layer is not adequately designed or analyzed for wander effects, the potential costs of repair or replacement are extremely high. As with most construction projects it is cheaper to prevent a problem than to fix it and therefore aircraft wander should be incorporated in the design and analysis of future airfield pavements. Implementing unbound aggregate improvements during the construction cycle will be much less expensive than repairing or treating the problem after operations have degraded the pavement.

6.0 Summary

The NAPTF data illustrates that wheel loads cause a dilative effect in unbound aggregate elements some distance away from the load centerline. Many factors combine to establish the dilative effect; the combination of wheel load, tire pressure, dual wheel spacing, axle spacing, trafficking speed, trafficking direction, and pavement system characteristics dictate where the dilative element or elements are. They also dictate the magnitude of the dilation. A strong stabilized layer may have little dilation while an unbound aggregate layer will dilate much more readily.

If the stresses within an unbound aggregate are kept low enough stable shakedown can occur and the residual deformation per pass should decrease with increasing repetitions, but this is not the case when wander is introduced. If there were no wander, the elements dilated by the loading would not change and the transverse area of weakness would not change, thus shakedown could take place with range A stress levels. When the location of the elements that dilate varies because of wander (based on an individual aircraft or due to varying gear configurations), the transverse area that experiences dilation and particle rearrangement expands. More rutting occurs because the loads are being applied to areas weakened by dilation and particle rearrangement. And stresses normally associated with stable range A shakedown cause range B behavior.

The particles in an unbound aggregate layer are designed to interlock to support loads. The dilative effect of wander negates this interlock and reduces the load capacity of the layer. Analysis of multi-depth deflectometer and heavy weight deflectometer data shows that there is an increased rate of pavement deterioration due to wander indicative of a reduction of the strength and modulus properties in the unbound granular base/subbase layers. The “anti-shakedown” of unbound aggregates should be accounted for in future design procedures with a performance based criterion whereby the dilative susceptibility of the aggregate layers is minimized through aggregate selection, stabilization, and/or improved lateral confinement.

Appendix A. Contact Information

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Appendix B. University of Illinois at Urbana-Champaign

Since its founding in 1867, the University of Illinois at Urbana-Champaign has earned a reputation as a world-class leader in research, teaching, and public engagement.

A talented and highly respected faculty is the University's most significant resource. Many are recognized for exceptional scholarship with memberships in such organizations as the American Academy of Arts and Sciences, the National Academy of Sciences, and the National Academy of Engineering.

Our faculty have been awarded Nobel Prizes, Pulitzer Prizes, and the Fields Medal in Mathematics. The success of our faculty is matched by that of our alumni: 11 are Nobel laureates and another 18 have won Pulitzer Prizes.

Academic resources on campus are among the finest in the world. The University Library is one of the largest public university collections in the world with 10,500,000 volumes in its 37 unit libraries. Annually, 53,000,000 people visit its online catalog. Students have access to thousands of computer terminals in classrooms, residence halls, and campus libraries for use in classroom instruction, study, and research.

Students and scholars find the University an ideal place to conduct research. The Beckman Institute for Advanced Science and Technology is a model for interdisciplinary research, where eighteen research groups from sixteen University departments work within and across three broadly defined themes: biological intelligence, human-computer intelligent interaction, and molecular and electronic nanostructures. The University is also home to the National Center for Supercomputing Applications (NCSA).

The University has a fundamental commitment to undergraduate education. Nearly 28,000 undergraduate students are enrolled in nine undergraduate divisions, which together offer some 4,000 courses in more than 150 fields of study.

Undergraduate admission is highly selective. In the 2001 freshman class, students in the middle 50% had ACT scores between 25 and 30 and ranked between the 83rd and 96th percentiles of their high school graduating classes.

The University enrolls over 9,000 graduate and professional students in more than 100 disciplines. It is among the top five universities in number of earned doctorates awarded annually in the United States.

Also integral to the University's mission is a commitment to public engagement. Each year about 65,000 Illinois residents participate in scores of conferences, institutes, courses, and workshops presented statewide. Research and class projects take students and professors off campus to share expertise and technical support with Illinois farmers, manufacturing firms, and businesses. In a typical year, student volunteers log more than 60,000 volunteer hours.

A major center for the arts, the campus attracts dozens of nationally and internationally renowned artists each year to its widely acclaimed Krannert Center for the Performing Arts. University also supports two major museums: the Krannert Art Museum and Kinkead Pavilion; and the Spurlock Museum, a museum of world history and culture.

Other major facilities include the multipurpose Assembly Hall (16,500 seats); Memorial Stadium (70,000 seats), site of Big Ten Conference football games; and the Intramural-Physical Education Building, one of the largest recreational facilities of its kind on a university campus.

Appendix C. Non-University Partners

The Federal Aviation Administration through the National Airport Pavement Test Facility collected the data used for this project. They also provided background knowledge about the Multi-depth deflectometers and the database of collected response values.

Appendix E. Evaluation of the educational experience provided by the project. Evaluation questions for both student and faculty are provided on the Competition website.

1. Did the FAA Airport Design Competition provide a meaningful learning experience for you? Why or why not?

This competition reinforced the importance of my dissertation work, so yes it was a meaningful learning experience. Working with the FAA and the National Airport Pavement Testing Facility opened my eyes to the enormity of the pavement challenges faced by airport design and rehabilitation personnel. The simple task of putting all of the aircraft gear wheel locations on one graph for comparison was extremely enlightening to the difficulty of figuring out where the critical pavement design parameters should be calculated. Adding individual aircraft wander into this effort increases the complexity even further.

2. What challenges did you and/or your team encounter in undertaking the Competition? How did you overcome them?

The amount of data in the FAA database for the CC1 tests is enormous. Attempting to analyze gigabytes of data is difficult enough, but on top of that the information required processing before meaningful results were available. Initially it was impossible to handle the data in Microsoft Excel due to program limitations, it was only after upgrading to Excel 2007 that the data limits were overcome. And even then the file and processing was so intricate that files routinely exceeded 100 MB for one sensor. As explained in the paper, the data also had to be extensively processed to provide the absolute movement values of each sensor. The only way to overcome these issues was with patience, fortitude, and an intern working all summer on data processing.

Separation of the data by wander direction and wander position was relatively easy and resulted in some dramatic finds; however the data still seemed to have patterns that were not attributable to wander position or direction. The solution was to separate the data by wander sequence and then the true patterns from a complete wander cycle visible (this only took a month or so to figure out).

HWD data while excellent, required normalization for load level, temperature, and separation of seating loads before proper comparisons and trends could be observed. Looking at the deflection readings of the HWD data, it was apparent that the D1 to D3 values did not capture the full response of the pavement and subgrade layers. Therefore the basin parameters also had to be modified for the thicker pavement layers and higher loads which has not been done before.

3. Describe the process you or your team used for developing your hypothesis.

This project was the result of the ongoing effort by the FAA and the Center of Excellence for Airport Technology at the University of Illinois to fully comprehend the degrading effects of aircraft wander and moving wheel loads on unbound aggregates.

The requirement to investigate the CC1 test results in detail came from work by Professor Tutumluer and his previous PhD candidates. Once the data was in a format that could be analyzed by Excel it was just a matter of investigating the individual factors like wander position, travel direction, pavement temperature, load, and wander sequence for their effect on the MDD response.

HWD data was investigated using routine parameters for the deflection basin, but as a result of the thicker pavements the basin parameters were modified so that subgrade properties were related to D5, not D3 because D3 was higher than D4 which was slightly higher than D5 and if D3 described the subgrade then D3, D4, and D5 should have been similar.

4. Was participation by industry in the project appropriate, meaningful and useful? Why or why not?

Participation by the FAA was absolutely crucial to the success of this project. Their knowledge and experience kept the research focused and provided invaluable information in the effort to understand the data provided.

5. What did you learn? Did this project help you with skills and knowledge you need to be successful for entry in the workforce or to pursue further study? Why or why not?

The most important fact that I learned during this experience is that the variation of aircraft wander and gear configurations can have an extremely significant impact on the stresses in an unbound aggregate layer. Once that fact was realized I was able to learn that dilation of unbound aggregates caused by wander can actually hurt the pavement system by reducing the frictional capacity of unbound aggregate particles.

As an Air Force officer, having the chance to study airfield pavements for my PhD is thoroughly appreciated. Most Air Force civil engineers rarely have the chance to further their education and if they do it is generally in a non-CE related field; so studying airfield pavements is a unique and challenging opportunity that will not be wasted. The knowledge that this competition and project have given me will be used for years to come for my work with airfield pavements as well as a professor at the Air Force Academy preparing the next generation of Air Force civil engineers.

For faculty members:

l. Describe the value of the educational experience for your student(s)s participating in this Competition submission.

As an Air Force Major attending the University of Illinois at Urbana-Champaign, Phil's PhD research focus, which is essentially the topic of this competition paper, is by all means very meaningful since it is utilizing the FAA's National Airport Pavement Test Facility NAPTF trafficking dynamic response database for a detailed analysis and better understanding of the pavement deformation behavior; both recovered and unrecovered deformations due to aircraft gear/wheel passes on runways and taxiways. The National Airport Pavement Test Facility (NAPTF) was constructed to generate full-scale testing/trafficking data to support the investigation of the performance of airport pavements subjected to complex gear loading configurations of new generation aircraft. Therefore, Phil's research project addresses a current national priority for building more durable and longer lasting airport pavement infrastructure such as runways and taxiways.

Phil Donovan's participating in the FAA Airport Design Competition has been primarily with his own initiative. I have no doubt that the detailed technical content Phil compiled and is presenting in this paper will soon find its way into scholarly publications in technical journals and FAA sponsored conferences.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

Phil Donovan has successfully completed all the required PhD level courses in his related field of advanced airport pavement engineering. In addition, Phil's writing this Competition paper is now helping him greatly with drafting of his research findings for his upcoming PhD Preliminary Examination. The research findings presented in this Competition paper is therefore the end result of his hard work for nearly the past one and a half years. What is more fascinating is that much of the technical approach/content in this paper is not only new and cutting edge but at the same time very educational for the airport engineering profession. Literally, no significant work in the past was done on the damaging effects of aircraft gear patterns since there was not a way to control and record systematically the mixed aircraft traffic patterns and their impacts on runways/taxiways. With the analysis results presented in Phil's paper, some of the pavement design and traffic control issues will need to be revisited to minimize the damage on pavements due to known aircraft gear wander patterns and pavement application locations.

3. What challenges did the students face and overcome?

Phil had the major issue of dealing with a huge NAPTF full scale pavement test section database to first of all obtain meaningful data for his analyses. Even, Microsoft Excel 2003 was not powerful enough to deal with such data until the 2007 version came out. In addition, throughout his relentless efforts on sorting and deciphering the dynamic response data, Phil was immensely challenged by the complexity of the data sets the way they were stored in the database. Defining the methodology and and types of deformations was the next major long but successful step. Still, separating the dynamic wheel load data according to gear wander sequences was another unknown. All of these tasks Phil successfully accomplished to overcome major difficulties throughout his work. To give an example, Phil was so thorough in his data interpretations that he was able to even identify mislabeled data sensors from the field. These efforts were certainly appreciated and acknowledged as great help by the FAA'a NAPTF research and implementation team.

4. Would you use this Competition as an educational vehicle in the future? Why or why not?

As Phil's PhD advisor, I am extremely pleased with the educational experience Phil has gained from this Competition paper. This has especially been valuable for him to summarize his main research tasks and the results from these tasks in a concise paper that has also helped him with writing his PhD proposal and future scholarly publications for technical journals and FAA sponsored conferences.

I definitely intend to have my other students working on airport projects to compile and submit papers to this FAA Airport Design Competition.

5. Are there changes to the Competition that you would suggest for future years?

Possibly better advertisement of this competition among many of the FAA Centers of Excellence.

Appendix F: References

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