V/TI Monitor Cluster Analysis and Implementation

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Authors: Dwight Clark (Union Pacific), Thomas Toth (Union Pacific), Matthew Dick (ENSCO, Inc.), Rafael Maldonado (ENSCO, Inc.)
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ABSTRACT

The Vehicle/Track Interaction (V/TI) Monitor is an autonomous system that measures accelerations caused from interaction events between a rail vehicle and the track. Traditionally, the V/TI Monitor utilizes single event exception criteria, meaning one exception triggers one field response. In 2010 derailment analysis was performed on several track caused derailments. In the analysis, the V/TI Monitor exceptions detected leading up to the derailment were reviewed. It was discovered that many of the track caused derailments had repeated low level V/TI exceptions.

Additionally the exceptions were a mix of different types (i.e. carbody acceleration + axle impact + ten foot profile mid-chord offset). Using the data associated with the derailments, an algorithm was developed to scan the database looking for similar patterns. When the algorithm detects the pattern, it is flagged and a notification is made to field personnel. In 2011 the algorithm was put into production in Union Pacific's Northern Region. Since the implementation, an analysis was performed which found a significant decrease of track caused derailments following the implementation of the algorithm. This paper outlines the development and implementation of the V/TI Cluster algorithm to help identify derailment risk locations. Additionally the paper will discuss feedback from field personnel and lessons learned from the project.

BACKGROUND

Vehicle/Track Interaction (V/TI) Monitors are autonomous systems that provide near real-time detection of vehicle acceleration responses to identify track condition risks. The V/TI system has been utilized in the railway industry for over fifteen years and is currently in operation in USA, Canada, Mexico, and Australia. Currently, there are 309 V/TI systems operating on locomotives, passenger and freight cars in daily revenue service. Union Pacific has 64 V/TI Monitors in which 62 are installed on freight locomotives and two on coal cars. The system includes onboard measurement equipment as well as a central server data-management and reporting system.

The purpose of the V/TI Monitoring System is to continuously sample all accelerometer sensor inputs which measure vehicle response due to the interaction with the track. If it detects inputs which exceed thresholds, it will send an exception message which includes all the sensor waveforms back to a central data-management system. When the sensor waveforms are received by the data-management system, they are evaluated using an automated algorithm to eliminate false-positives. Valid exceptions are then sent to Union Pacific's internal database system to identify subdivision, milepost, and severity. Union Pacific employs three levels of severity: High, Medium, and Low. High exceptions are notified to local field personnel using an automated phone message and email notification via Union Pacific's data management system Track Maintenance Planner (TMP). Within TMP, the field personnel can record what was track issue was identified at the V/TI exception location and what remedial action was taken. Lastly a daily automated email is sent to Union Pacific Engineering Dept. management summarizing exceptions that occurred within the last 24 hours.

Figure 1 illustrates the locations of the V/TI equipment installed on a freight locomotive and a summary of the V/TI exception types can be found in Table 1.

A carbody sensor measures vertical and lateral acceleration near the left/right centerline of the locomotive cab floor. The Carbody Vertical (CBV) and Carbody Lateral (CBV) exceptions are the peak-to-peak acceleration within one second. These exception types are typically associated with track profile and alignment conditions respectively.

A truck sensor measures lateral acceleration of the truck frame. The Truck Lateral (TRL) exceptions are the root-mean squared (RMS) acceleration. TRL exceptions are generally caused by sustained oscillations caused by truck hunting.

Two axle sensors are installed on a single wheelset with each sensor installed on the left and right side bearing axle boxes. These axle sensors measure acceleration in the vertical direction. The Axle Vertical Impact (AXV1 and AXV2) exceptions calculate the wheel/rail impact force in pounds using the acceleration, static wheel load, and unsprung mass value.

The same two axle sensors are used to calculate vertical profile using a 10 foot mid-chord. This is a novel approach to utilize the same sensors for an additional purpose was first led by Union Pacific.[1] The MCO1 and MCO2 exceptions are measured in inches.

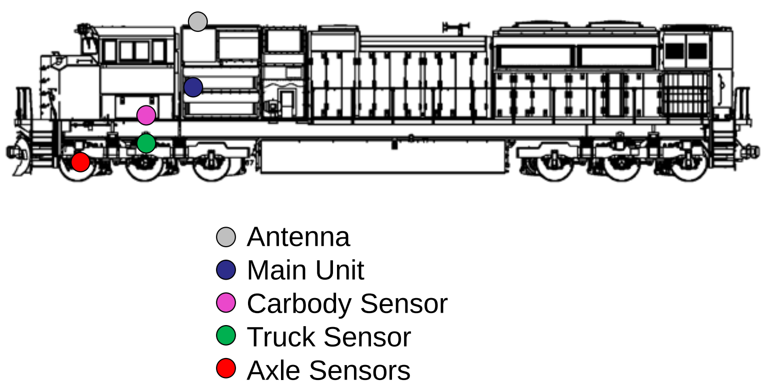
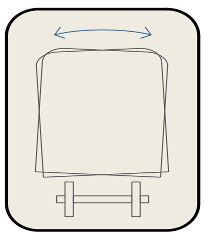
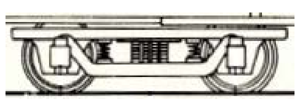
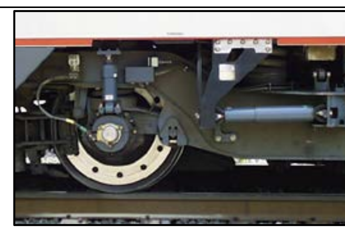
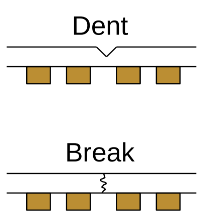
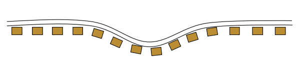


Figure 1. V/TI sensor and equipment locations on a freight locomotive.

Table 1. V/TI Monitor Exception Types Summary

Exception Type	Look For:		Examples
CBV Carbody Vertical		• Look for repeated vertical profile dips in track • Look for mud and pumping conditions	
CBL Carbody Lateral		• Look for lateral alignment irregularity in track	
CBR Carbody Roll		• Look for staggered joints or repeated crosslevel irregularities • Only associated with coal car V/TI Monitors	
TRL Truck Lateral		• Indicates truck hunting. • Look for worn wheel profiles, degraded dampers, worn gibs	
AXV1 and AXV2 Axle Vertical Impact		• Look for broken rail, broken joint, broken frog, battered joint, engine burn, crushed rail head, loose/missing bolts.	
MCO1 and MCO2 10-Foot Mid-Chord Offset Vertical Profile		• Look for mud and pumping conditions. • Look for pumping joints	

V/TI CLUSTER BACKGROUND

Historically the V/TI Monitor had taken the same philosophy as track geometry cars, which was each detected exception created a single notification to field personnel. This approach works well; however, it can be low value to investigate the numerous lower severity exceptions. Generally there are a few High severity exceptions, a few more Medium severity exceptions, and numerous Low severity exceptions. Obviously too many notifications cause “data overload” and become counterproductive.

In 2010, Union Pacific and ENSCO pursued a data analytics investigation in which the goal was to utilize all the V/TI Monitor data including the low severity exceptions to determine if there was more value to be gained from the data. The approach started with reviewing known track caused derailments and looking up all V/TI Monitor data that was measured up to six months prior to each derailment. Approximately 30 derailments from 2007 to 2010 were reviewed. Additionally as the analysis proceeded, new derailments into 2011 were evaluated. Table 2 lists a short list of ten derailments that were found to have a significant amount of low level V/TI Monitor data at the point of derailment (POD) location prior to the derailment occurring. The V/TI data for these derailments were deeply evaluated during the study. It is important to note that “T220 Transverse/Compound Fissure” derailments did not have V/TI data detected. It is also important to note that a “T109 Track alignment irregular (buckled/sunkink)” derailment was investigated, but it was found that these derailments are dictated primary by conditions that the V/TI Monitor does not measure and therefore wasn’t considered in future work.

Table 2. Short list of investigated derailments having V/TI data present.

Derailment #	State	Year	Cause Code
1	California	2007	T215 Joint bar broken (noninsulated)
2	Nebraska	2009	T204 Broken weld (field)
3	Kansas	2009	T204 Broken weld (field)
4	Iowa	2009	T399 Other frog, switch and track appliance defects
5	Texas	2009	T109 Track alignment irregular (buckled/sunkink)
6	Nebraska	2009	T201 Bolt hole crack or break
7	Kansas	2010	T001 Roadbed Settled or Soft
8	Wyoming	2010	T316 Turnout Frog (Rigid) Worn, Or Broken
9	Nebraska	2011	T299 Other Rail and Joint Bar Defects
10	Wyoming	2011	T001 Roadbed Settled Or Soft

Data from these derailments were first evaluated in geospatial programs, ArcGIS and Google Earth. When viewing the data in this manner it quickly illustrated that V/TI data was “clustering” at the POD locations of the derailments. Figure 2 is an example Google Earth plot of V/TI data cluster at a derailment location. The data was manually evaluated empirically and the following common traits were observed:

- The V/TI exceptions “clustered” near the derailment location.
- Nearly all of the exceptions were Low severity. It was rare to observe Medium exceptions and no High severity exceptions were observed.
- The clusters nearly always had a combination of multiple exception types including CBV, AXV, and MCO. This led the team to call the clusters “Combo Clusters”.

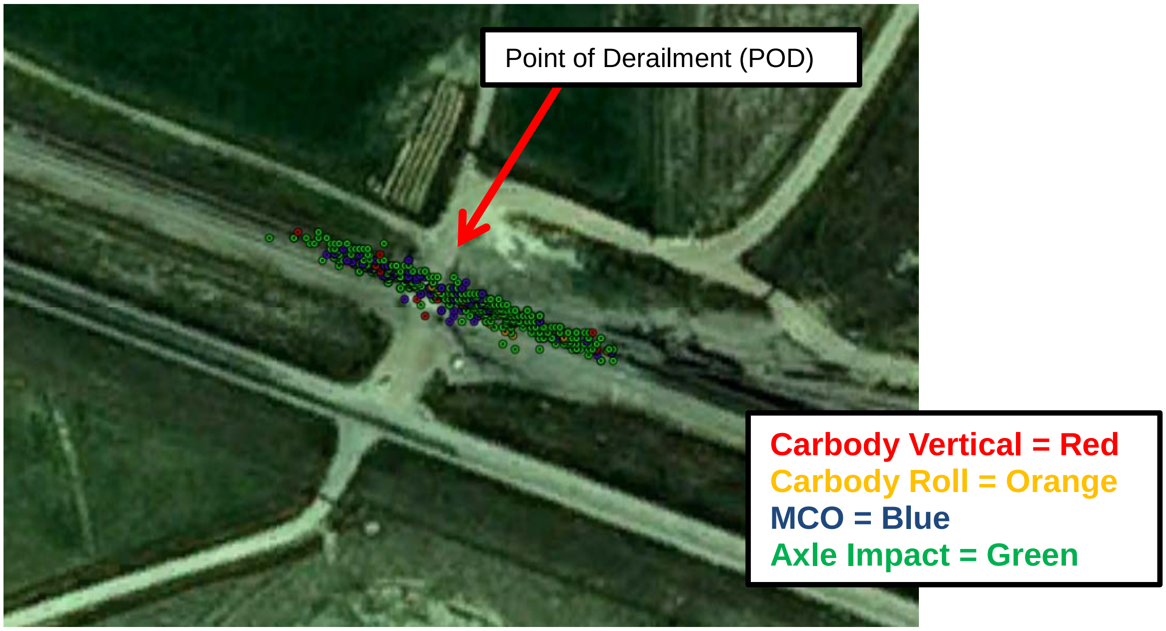


Figure 2. Investigated derailment #10 V/TI data.

ENSCO manually developed an "empirical" algorithm and fine-tuned by trial and error using the investigated derailments and known non-derailment data. This approach was utilized as compared to statistical correlation or regression data analytics mainly because there were a limited amount of training events (i.e. derailments) and the project team wanted to utilize the collective derailment subject matter expertise when evaluating the data and creating the algorithm. Using Microsoft Excel and Matlab, the algorithm was evaluated and adjusted to improve detection of the known derailments. The resulting algorithm took the following architecture:

1. Each subdivision was evaluated individually. First all the V/TI data within a given subdivision was "linearized" to the track. Meaning, the gps latitude and longitude values were converted to high fidelity milepost values. Through trial and error it was found that looking at three months of data performed the best.
2. Next a "hot spot" algorithm was built to identify cluster locations. This process looked at the density of exceptions to identify the center position of each cluster. The minimum cluster size is two exception types with two exceptions each (4 exceptions total).
3. A geo-fence query of all exception data around each cluster center is then performed. During the evaluation, it was found that a geo-fence radius of 60 feet performed the best.
4. The V/TI data deemed to be within the cluster was then evaluated by type, quantity, and locomotive speed at the time of the exception detection. This evaluation resulted in a "strength" value to be calculated for each cluster. An important aspect of the strength calculation is that older data was intentionally made "weaker" in the calculation as compared to more recent data. This was done to give greater strength to recently measured data.
5. Within a given subdivision, the strength values of all the identified clusters were ranked and normalized. This resulted in a final cluster value, which is a "normalized strength value". Figure 3 depicts example normalized strength values of clusters within a subdivision. Interestingly, a pattern was observed from this analysis, which often times there were would be a "knee" in the data with only a few high strength locations. These cluster locations that "poked their head above the crowd", were matched to the clusters observed in the investigated derailments. These clusters were identified as High severity when they exceeded a 0.1 normalized strength value threshold.

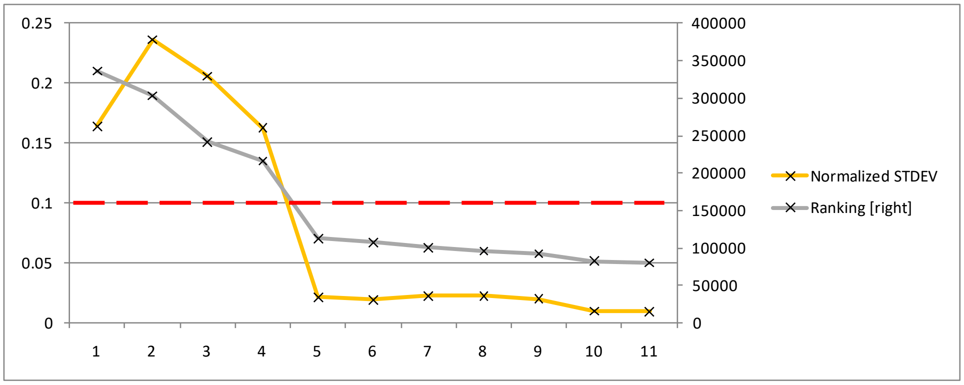


Figure 3. Example normalized strength values for clusters within a subdivision.

V/TI CLUSTER IMPLEMENTATION

After identifying and tuning the cluster algorithm in Microsoft Excel & Matlab, ENSCO then recreated the algorithm in JAVA server-side production code. The JAVA application was setup to run once a week and identify the cluster exceptions. A pilot program was started in April 2011 on the Union Pacific "Red-X" territory, which includes Nebraska, Wyoming, Kansas, Iowa, Missouri, and Illinois. In the pilot program, cluster data was calculated but not acted upon by field personnel. The data was simply produced to evaluate the quantity of cluster exceptions and viability for production use.

In July 2011 a derailment occurred within the Red-X which was found to be a T214 Joint Bar Broken (Insulated). Because the cluster pilot was producing data, the team evaluated what cluster data was found prior to the derailment. It was discovered that multiple High combo cluster exceptions were identified at the derailment location (insulated joint near switch) in the weeks leading up to the derailment as shown in Figure 4.

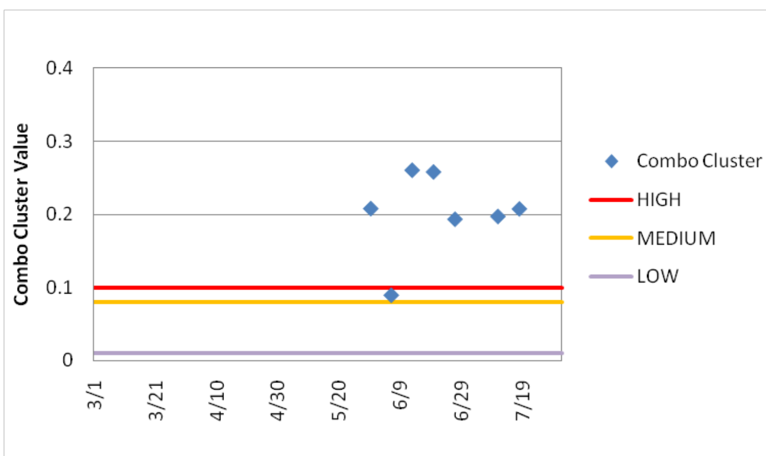


Figure 4. Combo Cluster exceptions prior to derailment.

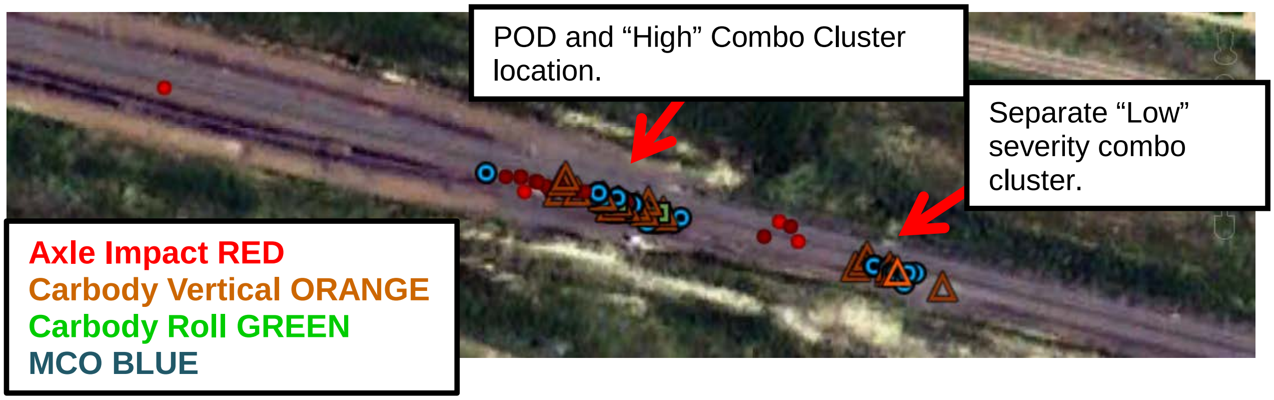


Figure 5. Individual V/TI exceptions in the Combo Cluster exception prior to derailment.

Following the derailment, the team asked the question if the algorithm is just identifying every switch and it just simply got lucky predicting this particular derailment. To investigate this question, the previous four months of data was processed for cluster exceptions in the subdivision that had the derailment. The following are the findings of the study:

- In the 4-months prior to the derailment there were 7 switches that have had High Combo Cluster Exceptions. (5.9% of all switches in the subdivision).
- 84.9% of the switches in the subdivision did not have a Combo Cluster in the 4-month period.
- The derailment site had most pronounced combo cluster activity than all other locations in the subdivision. The second most severe location was recommended to be inspected immediately.

After the derailment and analysis the Combo Cluster algorithm was put into production for the Northern Region (which includes the Red-X). Having the algorithm in production meant that field personnel would respond to the identified cluster exceptions. For the first few months an automated PDF report was emailed to division management. Eventually the Combo Cluster exceptions were sent to Union Pacific's TMP database the same way as regular individual V/TI exceptions, which of course would disseminate the notifications to field personnel the same as regular V/TI notifications. The Combo Clusters were given the mnemonic "CCL". Also following the derailment the Combo Cluster normalized strength value threshold was re-evaluated and changed to 0.18. Additionally the weekly processing and notification was adjusted to occur on Monday mornings.

V/TI COMBO CLUSTER EVAULATION

In the years following the production deployment of the Combo Cluster algorithm, Union Pacific recorded field personnel inspection findings and remedial actions of the High severity Combo Cluster locations. Table 3 summarizes the inspection findings and remedial actions and Figure 6 depicts two example Combo Cluster locations and field personnel comments. A comparison of Combo Clusters and track geometry car data was performed. Figure 7 depicts a Combo Cluster and the corresponding track geometry data, which indicates a profile irregularity. Overall the findings indicate combinations of impacts caused by joints, welds, etc.. and surface conditions. A common comment from field personnel is that they appreciate that the Combo Cluster exceptions are a management amount of data for them to follow up on. On average there is one High Combo Cluster exception per major subdivision per week. It's also important to note that field personnel accepted and adopted the Combo Cluster exceptions even though they were abstract.

Table 3. Summary of findings and remedial actions.

What is being found:
Non-supported joints
Striped IJ's
Broken concrete ties
Transitions from wood to concrete at turnouts, bridges, crossings etc.
Crushed heads and rail conditions with signs of pumping

Corrective Actions:
Hand and production tamping
Undercutting
Replaced ties
Bent rail, cut out and welded
Wheel burns, cut out and welded
Replaced broken IJ's and standard joints

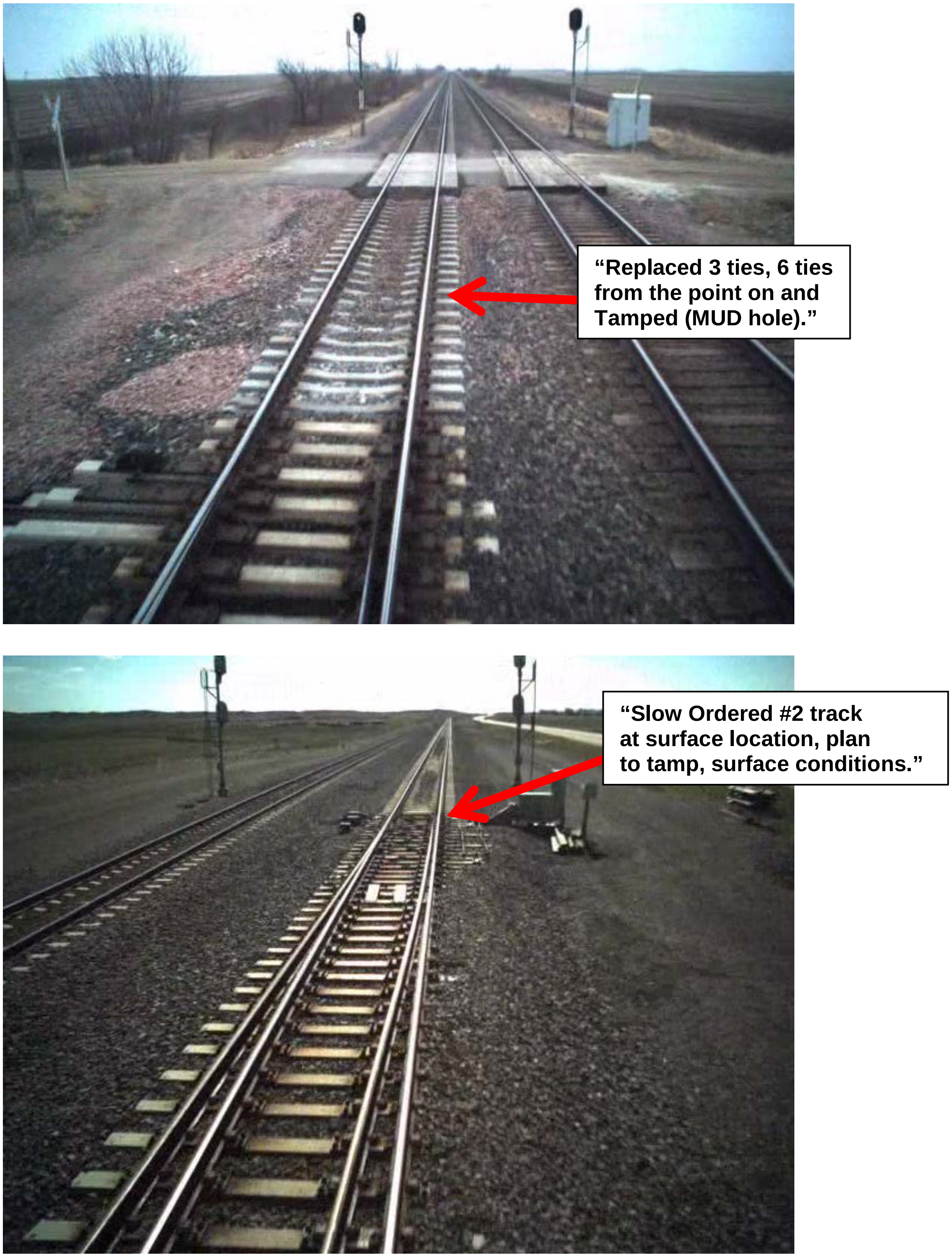


Figure 6. Example combo cluster inspection findings and remedial actions. Photographs from Union Pacific Evaluation Car (EC) Right of Way Video. Comments from field personnel.

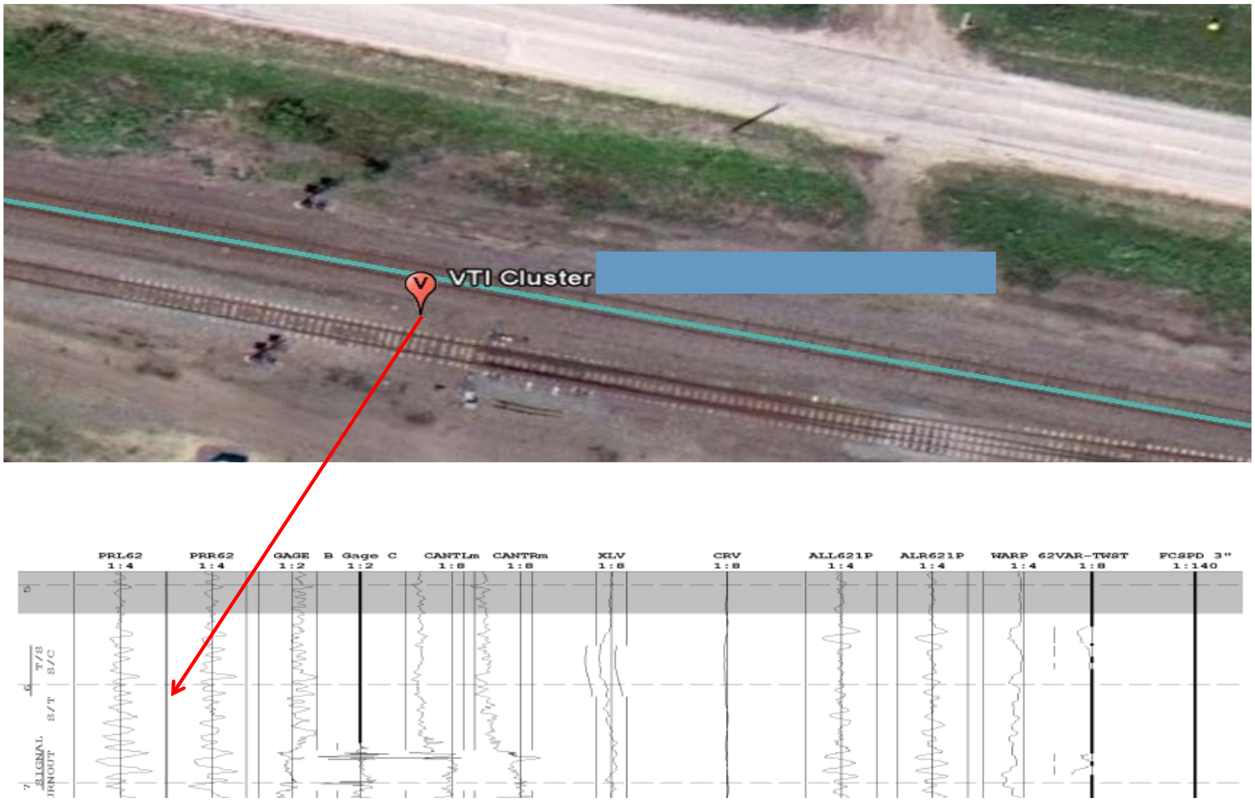


Figure 7. Comparison of V/TI Cluster site to EC track geometry profile measurement.

Derailment statistics were evaluated for the heaviest tonnage routes of the Red-X territory (Wyoming & Nebraska) before and after the V/TI Combo Cluster algorithm was put into production. Plots of the derailment damage costs and number of derailment incidents is shown in Figure 8. The list of derailment cause codes included in the analysis is shown in Table 4.

The findings look promising, but it is important to keep a skeptical and investigative mindset when looking at the data. The following are a few key items with the data:

- A large program maintenance program occurred on the Red-X coal route prior to the V/TI Combo Cluster algorithm being put into production. However, this program maintenance was also conducted prior to the July 2011 derailment. So it would seem that the algorithm identified unique conditions that had slipped through. This may indicate that the combination of program maintenance and the algorithm are collectively improving derailment performance.
- Coal traffic is currently reduced as compared to the 2000's. However, in a cursory review of another Class 1 railroad's coal route Table 4 derailment types, it appears that coal traffic reduction did not have an effect and derailment damage and quantity remained the same. This may hint that the V/TI Combo Cluster algorithm which was employed on Union Pacific, but not the other Class 1 railroad is a contribution to the improved derailment conditions for Union Pacific.

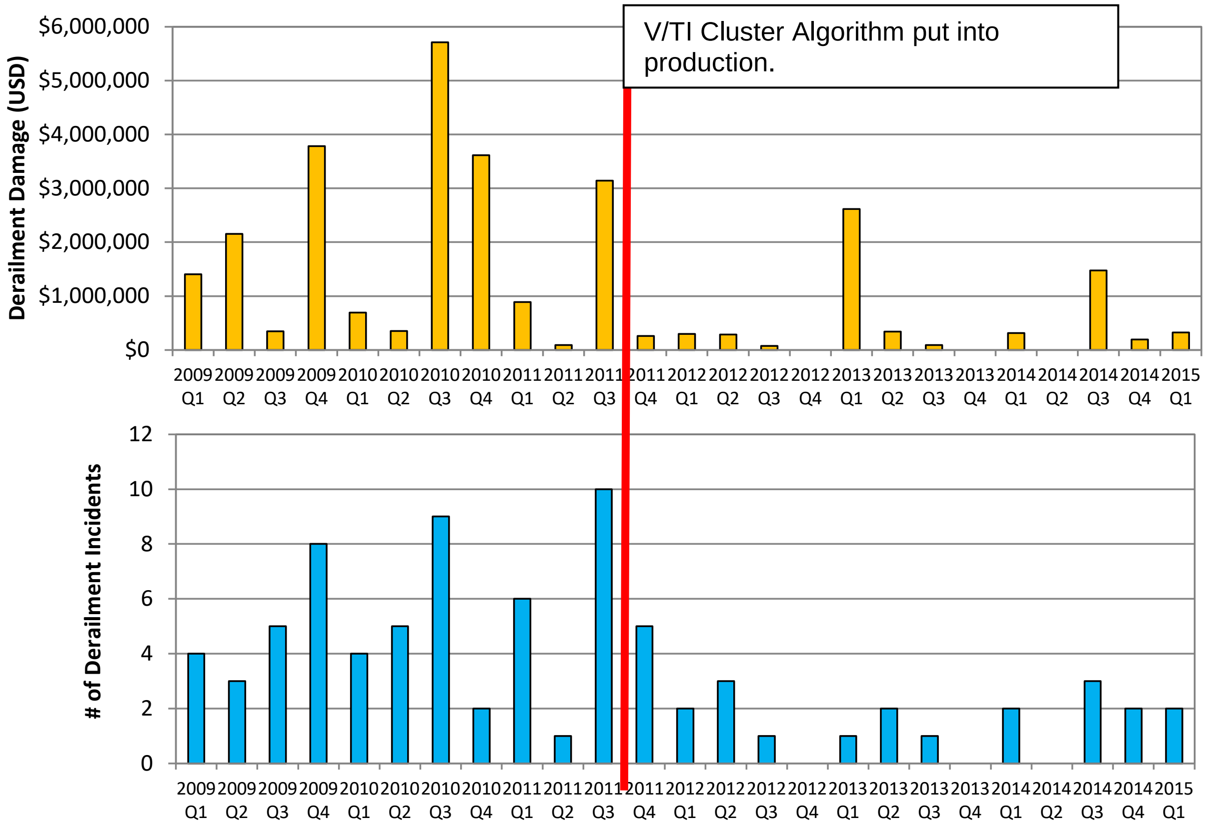


Figure 8. Evaluation of derailment statistics before and after V/TI Combo Cluster implementation.

Table 4. List of derailment cause codes used in Figure 8.

T001 ROADBED SETTLED OR SOFT
T099 OTHER ROADBED DEFECTS
T101 CROSS LEVEL OF TRACK IRREGULAR (AT JOINTS)
T102 CROSS LEVEL OF TRACK IRREGULAR (NOT AT JOINTS)
T110 WIDE GAGE (DEFECTIVE OR MISSING CROSSTIES)
T111 WIDE GAGE (DEFECTIVE OR MISSING SPIKES OR OTHER RAIL FASTENERS)
T199 OTHER TRACK GEOMETRY DEFECTS
T201 BROKEN RAIL - BOLT HOLE CRACK OR BREAK
T202 BROKEN RAIL - BASE
T204 BROKEN RAIL - WELD (FIELD)
T205 DEFECTIVE OR MISSING CROSSTIES
T206 DEFECTIVE SPIKES OR MISSING SPIKES OR OTHER RAIL FASTENERS
T207 BROKEN RAIL - DETAIL FRACTURE FROM SHELLING OR HEAD CHECK
T214 JOINT BAR BROKEN (INSULATED)
T220 BROKEN RAIL - TRANSVERSE/COMPOUND FISSURE
T221 BROKEN RAIL - VERTICAL SPLIT HEAD
T222 WORN RAIL
T299 OTHER RAIL AND JOINT BAR DEFECTS
T311 SWITCH DAMAGED OR OUT OF ADJUSTMENT
T314 SWITCH POINT WORN OR BROKEN

T316 TURNOUT FROG (RIGID) WORN, OR BROKEN

V/TI CLUSTER ALGORITHM ADJUSTMENT

Over the years following the cluster algorithm deployment, adjustments were made to improve performance. First, it was quickly found out that since the algorithm runs weekly and looks at the last three months of data, that a track condition can be recently fixed, but would still have a strong normalized strength value due to all the data prior to the repair. To combat this issue, additional code was added by ENSCO to review V/TI data to see if "clean passes" were detected by V/TI Monitors that would indicate that the track condition was in fact corrected. Next it was found that often times the exact same cluster exception would repeat. In order to cut down on redundant data, ENSCO modified to the code to only send the exception once to Union Pacific's TMP database. Once the exception is within TMP, it is tracked to inspection and resolution. Lastly, it was discovered that the methodology to normalize over a subdivision worked well for most subdivisions, but struggled with small branch subdivisions. ENSCO then "group" small and similar branch subdivisions together when the normalization process occurred.

FUTURE WORK

An interesting aspect of the V/TI Combo Clusters is that they appear to be identifying unique combinations of track conditions that can result in derailment. However, the specific mechanism of this combination is not well understood. At this time, the algorithm is simply "empirically" recognizing the patterns in the data, but we do not yet understand the underlying physics which is causing the increased risk. A current theory is detailed in Figure 9, which surmises that it is the combination of "Low" severity long wavelength profile, short wavelength profile, and wheel/rail impact that cumulate to produce rail stresses high enough for fatigue and component failure. If any of the three conditions were on their own they would be insignificant and would not be cause for concern. But because the three are overlaid and collaborating, they are producing the risk. In order to discover the underlying condition further data analysis, testing, and modeling would likely need to be conducted.

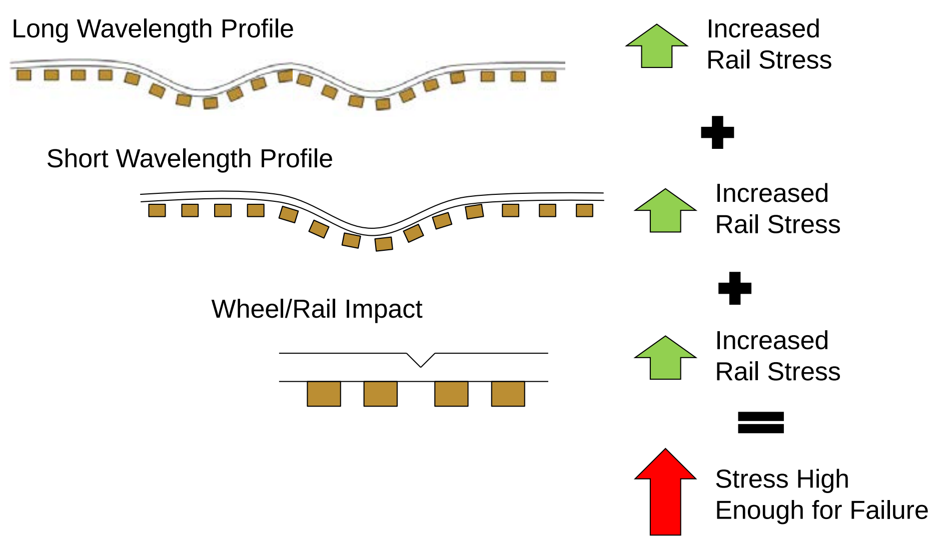


Figure 9. Theory to the underlying track conditions that the combo cluster algorithm is identifying.

Another area of future work is to better understand the effect of V/TI coverage on the algorithm. Currently the algorithm is operating the best on the Red-X, particularly in Nebraska and Wyoming. Figure 10 depicts the annual V/TI Monitor coverage on Union Pacific. As shown, the Nebraska and Wyoming Red-X territory has the best coverage of the network. An interesting finding of the project was that it seems that the more data collected, the better the cluster algorithm operates. Additionally it doesn't produce more exceptions with more data, rather more accurate identification of risk locations. Further work is needed to understand what is the optimum coverage needed for optimum cluster algorithm performance.

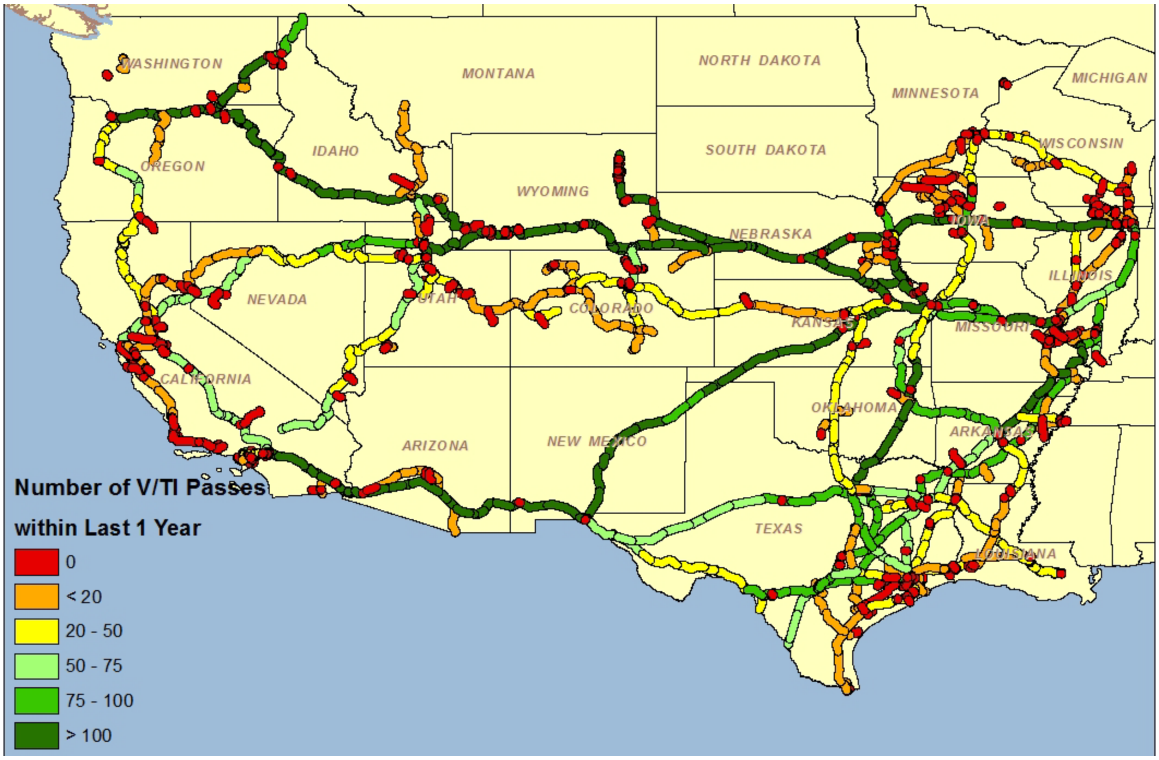


Figure 10. Union Pacific annual V/TI Monitor coverage map.

CONCLUSIONS

In summary, the V/TI Monitor Combo Cluster algorithm has been successfully implemented on Union Pacific and results indicate that it has contributed to a reduction of derailments. This algorithm marks a unique milestone in the rail industry as being the first time that a wide spread network of multiple track inspection systems have collectively identified at-risk track conditions in an automated manner.

REFERENCES

[1] D. Clark, T. Toth, "Vehicle Track Interaction ", *Proceedings of the 2006 AREMA Annual Conference*, 2006

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For additional information on ENSCO Inc.'s V/TI Monitoring and V/TI Combo Cluster algorithm please contact Bob Coakley at +1 203-417-3940 or Coakley.robert@ENSCO.com