Automated Inspection Technologies: a new paradigm for preventive maintenance programs

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Automatic Vehicle Inspection System

A breakthrough

In August 2013, the Bombardier site team at the Midrand depot in South Africa, together with experts from MRX technologies and IBM, commissioned an Automatic Vehicle Inspection System (AVIS), completing three years of cutting edge technology development, to deliver a revolutionary integrated solution that could become a game changer in the rolling stock maintenance industry. The commissioning was achieved without major problems, all functionalities were tested with conclusive results, and the team was so enthusiastic about the preliminary results that plans were already being devised for the next generation.

The system’s benefits are such that a second similar system is currently being installed at Bombardier’s Central Rivers depot in Midlands, UK, and several other projects are currently being planned or developed in the UK, Australia and North America. AVIS is a significant addition to Bombardier’s World Class Operations & Maintenance approach and paves the way for exciting new developments in the industry.

Figure 1: The AVIS Station at Midrand Depot

An integrated tool

The AVIS system as proposed by Bombardier is a complete system that measures, analyzes, monitors, establishes trends and automatically generates work orders for the maintenance crew. It also generates alarms and permits data trending for long-term engineering investigations.
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As the system only calls for the train to run through it at reduced speed (5 mi/hour) and does not require the intervention of a maintenance technician at any moment, this automatic inspection can be performed when entering/exiting revenue service every day. Data is gathered, sorted, stored, analyzed and work orders are generated automatically.

The system:
- Performs measurements on the train using lasers, thermal and optical imaging technologies;
- Processes the raw data to determine equipment condition;
- Automatically records key train components condition;
- Reports on remaining life;
- Automatically raises a work order to enable rectification on condition.

This enables:
- A progressive move towards true Condition-Based Maintenance (CBM);
- A dramatic improvement in Total Cost of Ownership (TCO);
- Reduction of component usage and wear rate;
- Fewer but more focused maintenance interventions for better overall results at a lesser cost;
- Feedback on product performance to further develop products;
- Increased equipment and depot tracks availability, resulting in operating flexibility.

System Description

The system is composed of:
- The Vehicle Equipment Measuring System (VEMS), which is the measuring apparatus where sensors, lasers and cameras collect live train data. It is housed in a dedicated structure and/or buried in and around the tracks.

![Figure 3: The VEMS Equipment at Midrand Depot](image-url)

The Bombardier ORBIFLO Software which applies decision support software algorithms on the VEMS event data to raise applicable maintenance alerts for system maintenance; it performs state detection, health status assessment, prognostic assessment, and raises alerts.
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- The Maximo® Asset Management Software that automatically generates work orders to the maintenance crew while feeding environment data (such as mileage and configuration) to the VEMS.

- A Dynamic Planning System which provides a general visual overlay for all work planned on a vehicle, and permits resource and material optimized allocation.

*Figure 4: ORBIFLO Monitoring Screen*

*Figure 5: Maximo® Work Order*

**The Vehicle Equipment Measuring System (VEMS)**

The VEMS is a modular system and is configured depending on the train design and operational needs. It can contain the following modules:

- An axle end temperature monitoring system
  This system measures every axle end temperature, issuing alerts when there is a variance from the side average.

- A brake pad monitoring system
  This system will issue an alert if a brake pad is missing, and will measure every brake pad thickness, calculate brake pad wear rate and predict when replacement is due.

- A brake disc monitoring system
  This system will measure brake disk thickness, disk profile and maximum wear depth, providing alerts if something is out of parameters.

- A wheel profile monitoring system
  This system will measure the wheel profile and assess condition in comparison to several key markers (flange height, thread hollow, etc.).

*Figure 6: Fleet Status Overview*
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Figure 7: Wheel Profile Monitoring

- A pantograph wear monitoring system
  This will assess the carbon strip profile, the maximum wear depth and localized chip size. A similar measuring system can be implemented for collector shoes.
- A wheel damage monitoring system
  This will measure flat spots on wheels and report the damage condition of a wheel by a system of thresholds, to determine when it must be sent for wheel re-profiling.

- A visual image capture system
  This powerful system, through laser scanning and optical imaging, will capture many data points of the train exterior, permitting verification of any deviation from the vehicle profile or previous vehicle condition. Specific measurements can also be taken to determine car height, coupler height, detection of missing or displaced elements, open equipment boxes, foreign bodies, etc. It will assess and detect damper leakage condition and vehicle contamination (oil leakage, impact damage, graffiti, etc.).

Figure 8: Visual Image Capture System

These systems are housed in a dedicated enclosure, strategically located when possible on a track entering the depot. In this manner, complete sets of measurements can be taken several times per week – if not every day -, providing precise trends and, for the components it measures, a fleet monitoring capability significantly more accurate, more frequent and more consistent than any inspection system depending on depot staff.

Furthermore, all data is captured, recorded and logged without human intervention, which permits the creation of a highly dependable historical database on each vehicle.

Figure 9: Captured Visual Image
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Finally, as the criteria is clearly defined and uniformly applied, all subjectivity is removed from the process.

In summary, this system automatically performs many activities that would normally require a train to be brought inside a workshop, over a pit so that technicians can perform their inspection work.

Now, considering a system where . . .

(1) ORBIFLO captures and instantly reports failures or problems developing on on-board systems (doors, HVACs, non-communicating equipment, etc.) connected on the train monitoring system;

(2) AVIS provides to ORBIFLO a frequent and accurate assessment of the condition of the undercar, exterior and roof components; the condition of all components subject to wear (brake shoes, discs, pads, collector shoes, pantographs); measurements such as coupler height, floor height, wheel profile and more generally any known abnormal condition such as displaced or missing equipment;

. . . It becomes obvious that many of the tasks performed during traditional daily and scheduled inspections are now becoming redundant. It is thus time to re-examine the goals and rationale of the maintenance plans as we know them to see how the introduction of this new technology can make them better, faster and leaner while enhancing their effectiveness.

A modified paradigm

The AVIS system, which collates detailed on-board equipment statuses, challenges long-lasting established preventive maintenance programs, as many of the time consuming activities and verifications can now be automated and implemented in a more accurate and more frequent manner than ever before.

These applications permit introduction of condition-based maintenance as a standard operating mode relying on technology to detect and warn maintenance crews of developing conditions or failures before they actually occur.

These technologies reduce the total cost of ownership by permitting a more efficient maintenance approach; simply adding them on top of a standard established maintenance program would improve it but miss out on the significant economies that can be generated: it would be an expensive and redundant maintenance program.

The main benefits of such a system lie in its capacity to reduce the maintenance burden by:

- Reducing the standard inspection time;
- Extending maintenance periodicities;
- Reducing train movements in and out of the maintenance facilities.

All these enhancements contribute in increasing trains’ availability, increasing shop availability and keeping trains in revenue service, where they belong.

For many authorities who are running at capacity and for which fleet or facility expansions are challenging, the introduction of such technological solution represents an elegant alternative as it creates affordable extra availability.

A new approach

In order to take full advantage of the new capabilities offered by the technology, a complete re-assessment of the current maintenance must occur. Bombardier proposes two phases:

Phase 1: Create a leaner scheduled inspection plan by eliminating redundancies and extending periodicities. This will immediately improve equipment availability

Phase 2: Eliminate scheduled maintenance as it is performed today and replace it with modularized maintenance interventions to be planned and performed on an opportunity basis.

Phase 1: A leaner and better inspection regime

Inspection time reduction

As the AVIS equipment conducts an inspection each time the rolling stock asset travels over the system, with a high level of repeatability and accuracy, all similar activities should be phased out from the ongoing maintenance program. As a measure of precaution, it is customary to let both
types of inspection run in parallel for a period of time after the introduction of the new system, mainly to ensure that there are no conditions that are not covered by the automatic inspection.

Figure 10: VEMS Status Board

The result is a reduction of the number of man hours per standard inspection. Clearly, the exterior and undercar visual only represent a fraction of the total time devoted to standard inspection. It changes depending on car type and configuration, but early estimates show that perhaps 8 to 10% of the total inspection time is devoted to exterior visual inspections. The system does not open equipment boxes, does not perform a visual inspection of the car interior, does not grease, wipe or clean equipment, or take oil samples. But it sees and measures consistently every visible feature of the car exterior – including undercar, with precision.

The ultimate goal of inspection time reduction is to permit shorter inspection windows, which permit inspections to be carried out only during off-peak hours. This increases the fleet availability during peak hours, as no train is withheld for inspection.

Bombardier has applied time studies and Yamazumi techniques to . . .

- Reduce inspection times and
- Break inspections into small executable modules

. . . to permit a high level of flexibility with inspection scheduling and performance around peak periods.

It requires enhanced work scheduling and tracking capabilities, but with the use of the Bombardier Maximo© platform, it is easily achievable. The inspection activities removed by AVIS further decrease the inspection time.

Figure 11: Inspection Time Optimization

Furthermore, reducing the time spent performing the exterior visual inspection not only enhances car equipment availability, it also increases precious workshop space availability.

**Increasing periodicities**

The capacity to increase inspection periodicities as a result of the AVIS introduction generates savings to the maintenance organization.

Since:

1. many of the critical, obvious consumable items such as brake pads, pantograph carbon strips, collector shoes, etc., are being measured several times a week, and
2. the train is already undergoing a daily mandatory safety tour and test,

extended scheduled inspection periodicities can be considered and implemented, following a thorough review process.

In order to determine how much the periodicities can be extended, one must return to basics and understand why the periodicities have been established where they are.

Train Daily inspections serve two main purposes:
1. Safety: ensure that trains meet basic safety requirements for passenger travel: operating brakes, headlights, marker lights; operational doors, fire extinguishers, horns, wipers, radios
2. Readiness for passenger service: proper interior lighting, cleanliness, passenger announcements, serviced toilets, full sanders...

Therefore, the periodically scheduled maintenances go one step further: they service the car and its various sub-systems and permit a detailed inspection. But what is the determining factor behind the periodicities used?

**Rationale behind established periodicities**

As a well-established car builder and operator that works closely with many Original Equipment Manufacturers (OEM)’s and operating authorities, Bombardier has had the opportunity to witness differences in practice across the industry. Based on observations, it appears that periodicities are determined by one or more of the following:

- **Equipment design characteristics and supplier recommendation**, which are generally provided by the OEM’s of the various sub-systems on board the train.
- **Specific operating conditions**
  - For example, if a train’s collector shoes typically last four months, one must ensure that the inspection intervals will be such that they can be inspected before condemning limits are reached. The operating conditions also include seasonal variance; for instance, more frequent wheel inspections during the fall season when fallen leaves on the track create slip-slide conditions.
- **Specific known safety or equipment operability conditions**, such as when specific equipment has a known bad track record in some weather patterns (for example, electrical arcing when the weather is hot and humid) or when equipment is susceptible to specific failures.
- **Legacy practices** based on a wealth of specific system experience and historical trial and error. Legacy practices can be the most decisive criteria to determine periodicities, as they can be the most elusive ones. The most decisive as it will capture ad hoc solutions to issues that are specific to a particular system or configuration and that have demonstrated their effectiveness at mitigating the problem. The most elusive criteria when some practices are carried forward as solutions to legacy problems without being revisited when the legacy problem no longer exists.

- **Operational and logistical constraints**
  - For example, if a maintenance facility has 380 cars and has the space and resources to process 10 cars per week day, it can hardly consider less than an eight week inspection cycle.

**Criteria to develop new periodicities**

The scheduled inspections are generally composed of:

- **Routine maintenance**, which consists of servicing the mechanical systems of the train (e.g. greasing, replacing filters, topping off liquids and consumables). These tasks are generally conducted at deterministic intervals based on measurable consumption rate and if not performed will eventually lead to costly equipment failure. They can accept some variation in timing, but there are direct consequences of not performing that are tangible.

- **Preventive maintenance**, which consists of preventing failures by assessing the general condition of the train: inspecting torque seals, detecting frayed or loose wires, inspecting freedom of movement of moving parts, thickness of sacrificial parts, etc. These are inspection activities rather than actions on the train and are intended to capture possible failures before they occur, through inspection and monitoring. There is a randomness aspect to the timing of these activities in relation to the occurrence of the events that are to be prevented: the more frequent they are, the better the overall health of the train. However these inspection activities could also be completely omitted at one interval without any direct consequence. Their effect is comparable to insurance against possible
conditions; it does not completely mitigate the risk but does reduce it.

The understanding of the distinction between these two types of maintenance activities is essential in the extension of periodicities, as:

- weak points will appear when the periodicities attempt to extend beyond the routine maintenance requirements and
- specific hazards will appear where the inspection frequency is an important aspect of the mitigation.

In both cases, specific action plans (such as targeted actions or inspections) must be devised to tackle these specific items.

Greasing as a routine maintenance activity is less important in determining periodicities than it once was, with the reduction of metal to metal friction in the various car systems. Thanks to new materials, except on very demanding mechanical systems such as diesel engines in locomotives or diesel multiple units, the need for greasing regularly has reduced considerably in the last decades.

Similarly, with the advances in monitoring of subsystem performance which reports immediately to the operator the condition of subsystems (such as a poorly operating door or a hot car), and the improvements in sub-system reliability, there is a general move in the industry to enlarge equipment inspection periodicities.

As the cycle extends, two types of limitations are appearing:

1- To forecast what a collector shoe or brake pad’s wear will be 90 days from today in order to determine if it must be changed or not requires the introduction of a generous safety factor or the risk of costly equipment repair if the forecast is wrong.

2- Wariness about the condition of the equipment and if a developing problem could be caught before it becomes a safety hazard.

With AVIS providing:

- Trends in sacrificial parts rate of wear, permitting a precise determination of when they will need replacement;

Figure 12: Brake pad wear trend analysis

- Surveillance of critical fasteners condition, suspension elements, and wheel condition;

Figure 13: Fastener Surveillance

- Monitoring of the performance of individual subsystems; and
- Monitoring of the VEMS output data, detecting early signs of failure;

a lot of the obstacles for longer inspection cycles are disappearing.

In order to establish what could be a new periodicity for equipment inspection, it is thus recommended to list all the activities performed during a standard inspection, and for each of them, determine:

1- What preventive inspection is not already covered by AVIS and ORBIFLO; then what hazards could develop through long inspection intervals that would not be detected by monitoring;

2- What routine maintenance actions are being performed that alter the subsystem (such as greasing, wiping, filling) and what is the sensitivity of the system to not receive the
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treatment, or to see the interval extended by 30, 60 or 90 days.

Thus one will be able to determine the activities that can be either eliminated or deferred.

Figure 14: Preventive Activities Analysis

Such a discussion can involve the OEM or the car builder. In some cases it will be determined that some inspections cannot be deferred. These exceptions should then become the focus of OEM development of new and better product designs, oriented towards automatic monitoring and detection of anomalies.

Preserving and increasing safety

The main concern when reworking a maintenance plan is to overlook, discard or compromise essential inspection elements, exposing the authority and its riding public to hazards otherwise mitigated by the previous inspection plan.

For this reason, we recommend that before abandoning activities in an ongoing inspection plan or increasing periodicities, the following takes place in order to ensure that the new plan is at least as efficient, if not better, at detecting developing issues than the old plan.

1. A re-assessment of RAMS plans be performed in regards to the new technology:
   a. Activities review: a thorough review of the current maintenance activities must be conducted in light of the Reliability, Availability, Maintainability and Safety (RAMS) constraints they address. Follows a determination of how these constraints will be covered once the new technology is operational; with the introduction of alternate measures if and where gaps are observed.

b. System hazards review: for every known system hazard where the mitigation relies on inspection, one must assess if the need is still covered by the new technologies and associated inspection plan. If not, some specific action must be sought to ensure that the system is safer, not less, after the installation of the new plan.

2. The two systems run in parallel for a while to ensure the repeatability and accuracy of the automated data collection.

For hazards mitigation, U.S Military Standard MIL-STD-882 suggests the following hierarchy of mitigations:

1- Eliminate hazards through design selection
2- Reduce risk through design alteration
3- Incorporate engineered features of devices
4- Provide warning devices
5- Incorporate signage, procedures, training and PPE.

If the introduction of the AVIS system is correctly implemented, the hazards that were previously mitigated through inspection (the fifth and less desirable level of hazard mitigation as it relies on human intervention) can now be mitigated by warnings generated by the automatic inspection, effectively improving the general safety of the system.

Phase 2: Modular maintenance driven by opportunity

Maintenance modularization

The introduction of a powerful asset management software such as Maximo® in maintenance practice provides opportunities that were not foreseen when scheduled maintenance was originally planned.

Today, in many shops in North America, the basic principle remains: every train will pass through the workshop on fixed intervals (optimized through experience). When the train is inside, a complete, thorough, well sequenced and well organized inspection is performed. This guarantees consistency in process, tooling, and materials supply. Some authorities also equalize the extra load created by less
frequent inspections, such as annual inspection among the more frequent ones in order to have equalized effort and manpower demand.

This periodic inspection is typically performed during day time on Service and Inspection tracks, and therefore blocks a train inside the shop to receive this service.

![Figure 15: Modularization at Work](image)

Modularized maintenance recognizes that maintenance demand fluctuates, and some days will be much busier than others due to variation in equipment reliability, extraordinary activities, weather conditions, and personnel attendance. For this reason, instead of blocking a full day with a full crew of a train over a pit, if all the activities to be performed in the inspection are parcelled into small blocks of 1 or 2 man-hours per piece, maintenance ‘blocks’ can be scheduled with much more flexibility. This mode of operation suits well a system with AVIS, ORBIFLO and Maximo© because: AVIS will already have significantly reduced the need to perform an undercar inspection; ORBIFLO will report specific performance problems with sufficient warning prior to failure, creating maintenance activities to be performed on the train; and Maximo© will track all the maintenance activities (modules) outstanding on any given train.

In practice, this means that if at 10:00PM the shift supervisor is advised by ORBIFLO through Maximo© that Car 1101 needs to be brought in because higher than normal current has been detected on one of the door actuators, the Supervisor can query Maximo© to see if any regular maintenance task is also pending on that train, and time and resource permitting, have them closed at the same time. Similarly, if a car is due to have its brake shoes replaced, it might as well be combined with several other regular maintenance activities.

In this process, Maximo© is used as a watchdog to ensure that all maintenance is still performed within prescribed intervals, but offers the flexibility to do it at a convenient time, and optimize workforce and train movements by permitting the combination of preventive maintenance with corrective.

The ultimate goal is to increase flexibility and availability by executing the remaining preventive maintenance activities at convenience during non-peak and shutdown hours, therefore replacing the rigid regime provided by fixed and firm scheduled inspections with a more manageable one.

The maintenance program still needs to be formally documented with signed scheduled inspection reports, which will at least contain:

- Positive affirmation that automated inspection has been undertaken on all required tasks
- All core data measurements
- Equipment status summary
- Confirmation that all statutory inspections have been performed within the prescribed time frame
- Artisan & Supervisory signature (electronic or paper)

This ensures that at scheduled inspection periodicity, records are maintained regarding all (manual and automated) inspections, and that automation does not lead to a potentially dangerous ‘assumption’ that all is fine unless the system raises an alert.

**Culture Change**

Technologies, computers, software and sensors are powerful tools that bring exciting new capabilities to the organizations they serve. The introduction of these new technologies, to be successful, requires a change in maintenance culture at all levels of the organization, from shop floor to senior management. If the changes that are presented herein are only implemented partially, or if some departments of the shop or organization embrace the new technology while others stay away, there is potential
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for gaps and mishaps that could lead to the whole idea and project to be shelved, or at least prevent the full return on investment from materializing. It is thus important to prepare the various sides of the organization with a solid training program, so that everyone understands the benefits of the new technology and how it will impact its day to day activities.

Return on Investment

Although these new technologies are surprisingly affordable, the set-up cost still represents a capital investment which must be met with a decent return on investment.

The return on investment depends on:

1- The initial set-up cost --- The number of lasers and cameras and level of software development for data interrogation in the VEMS will depend on the equipment layout, line of sight and angles. Bombardier is currently developing rolling stock design guidelines to better benefit from the new technology.
2- The fleet size and utilization --- The larger the fleet (and the harder it works), the bigger the savings.
3- The location of the equipment, and how often each train will be circulating through the sensors
4- The nature of the work performed during maintenance and how many activities will be cut/deferred
5- The extent to which periodicities extensions and work modularization can effectively result in lesser labor costs considering the work set-up, permanence and shift coverage requirements, etc.
6- The value to the authority of the capacity to put more trains in service during peak hours
7- The logistics involved in bringing cars in and out of the workshops.

Following are some of the economies brought forward:

- Equipment availability --- permits to generate higher revenues by providing better service in peak hours
- Preventive material costs --- Optimizes usage of collector shoes, pantograph strips, brake pads, brake shoes, brake discs, and wheels;
- Preventive inspection hours --- Cuts inspection time, and reduces the train movements in and out of the workshop;
- Corrective hours and material cost --- Prevents failures from occurring through close monitoring of equipment and fixing issues before they degenerate into failures;
- Overhaul cost --- Re-examines overhaul periodicities through close monitoring of equipment performance and data trends;
- Energy and logistics --- Allows fewer train movements in and out of the shop; better, more focused interventions; and higher equipment reliability.

Bombardier estimates that, in most cases of medium to large fleets, this technology should pay for itself within the first few years. But the final assessment rests with each specific site, and situations must be examined on a case by case basis.

Data like never before

A significant benefit from this system that is yet to be evaluated precisely comes from the massive amounts of data being collected and made available for further analysis. With the quality and the quantity of data collected, and the new data processing capability offered by data analytics software, the capacities of the new systems to precisely and quickly evaluate trends in behavior resulting from design or environmental changes provides the system owner with statistical capability unparalleled in railroad maintenance history.

Conclusion

After ensuring that the hazards are mitigated in an equivalent or better way by the new plan as compared to the old, and ensuring that basic economics are covered through the enhancements and savings provided in labor and materials, the system is in place and operational. It is
time to contemplate the exciting opportunities provided by frequent automatic monitoring of critical components. It opens a whole new world of inspection capability that was out of reach before. It is a potential that is yet to be tapped into, which we are just starting to explore.

The rail car maintenance industry is contemplating a change in paradigm comparable to what the auto industry experienced in the early 1980s with the introduction of welding robots on car assembly lines. Although there were hesitations and setbacks in the process, in the end the consistency of the equipment won the case and today welding robots are the norm.

For the passenger train maintenance industry, the systematic gathering of high quality data is key to measuring and optimizing the maintenance approach. The introduction of an Automated Vehicle Inspection System provides that capability – at an affordable cost.