Bi-Level Trains – Will They Fit? A Technology-Based Approach to Assessing the Feasibility of Bi-Level Trains on a Major Commuter Railroad

Authors

Finbar Holland
Geomatic Technologies
Level 6, 4 Riverside Quay Southbank
Victoria 3006 Australia
+ 61 3 9694 4244
fholland@geomatic.com.au
enquiries@geomatic.net

David Presley
Geomatic Technologies
Level 6, 4 Riverside Quay Southbank
Victoria 3006 Australia
+ 61 3 9694 4244
dpresley@geomatic.com.au
enquiries@geomatic.net

Number of Words
2806

ABSTRACT

In 2014 it was reported around the world how the French Rail utility SCNF had ordered 2,000 new rail cars that were later found to be too wide for many regional platforms. The issue was noteworthy because of the expected cost to remediate these platforms (in excess of $50 Million) and also because the capabilities already exist in North America to mitigate such risks when procuring new rolling stock.

This paper will describe a project undertaken by Geomatic Technologies and LTK Engineering which involved the application of LiDAR along with sophisticated rolling stock kinematic modelling algorithms to obtain a rapid, network wide understanding of the relationship between the proposed bi-level trains and existing infrastructure on the SEPTA network. The paper will discuss methodologies and technologies used, best practices for data collection and data processing, risks and mitigations that were implemented to underpin the project’s success, as well as lessons learnt.

INTRODUCTION

Like many commuter railroads, SEPTA is pursuing a fleet replacement program to meet a surge in passenger demand. The new fleet will be comprised of bi-level trains and with existing infrastructure supporting only a single-deck service, the engineering challenges to understand whether a new fleet of significantly different dimensions would be feasible are complex and of obvious strategic importance to maintain a program of expanding passenger services.

The implementation of a new class of rolling stock brings with it a particular set of risks that encompass track, structures and rolling stock disciplines. Validating the clearance of new rolling stock has traditionally been assessed using knowledge of existing structure gage compliance and known exceptions to compliance at particular infrastructure locations across their network.

Beyond assessing new rolling stock clearances against current compliance records, a wide range of sacrificial devices including plywood cut-outs and ‘fingers’ (to replicate the dimensions of the proposed new vehicle outline), have traditionally been employed to test the outline of the new rolling stock against the real-world state of the network. In this way any gaps in an organization’s current compliance knowledge are overcome through a thorough physical re-testing of the network.

However effective sacrificial testing might be, any “close calls” will not be evidenced and should any of the sacrificial plywood or ‘fingers’ be damaged it would logically require a re-survey of the network to validate any design adjustments made following the clearance impact. Such an iterative clearance validation process is expensive and onerous to coordinate amongst revenue services.
Global rail operators are now benefitting from efficient mobile multi-sensor survey systems that deliver purposeful engineering survey data, which combined with rolling stock kinematic modelling software allow network-wide clearance audits to be undertaken quickly and repeatedly for different rolling stock outlines. This approach is effective in replacing traditional methods for testing rolling stock and have minimal impact on train operations.

LTK Engineering and its client, SEPTA, needed to assess the clearance compliance of a fleet of proposed new bi-level passenger trains. In recognition of the age of the Philadelphia network and the potential impacts in introducing a much taller train design, LTK and SEPTA engaged GT to undertake a laser clearance survey of the network. This paper summarizes the experience from that project.

**SITUATION**

The Regional Rail network operated by SEPTA primarily services commuter passengers and is comprised of approximately 280 miles of track including both at-grade and below ground infrastructure. The network is over 100 years old and is serviced by a fleet of single deck passenger trains. Patronage on the Regional Rail network has doubled in the past 15 years and grew over two percent in 2014. Simply adding additional single-deck cars to existing passenger trains was deemed impractical as most trains already stretch the length of station infrastructure. Furthermore, adding additional services by reducing headways, while possible in some areas, would be difficult to achieve on lines shared with other operators such as AMTRAK and CSX.

To meet demand for passenger services SEPTA decided to investigate bi-level trains as a way to transport more commuters per train. The preferred bi-level train design was that currently operated by New Jersey Transit (NJT). This design now had to be tested on the SEPTA network to understand the locations and magnitude of potential modifications to the network to accommodate the new trains.

**SOLUTION APPROACH**

Both SEPTA and LTK were aware of tight locations on the network from current clearance records, however, specific clearances through tunnels and overpasses were less well understood. To obtain accurate information on all tight locations, both known and unknown, and to minimize any disruption to train operations, the decision was made to pursue a mobile LiDAR survey of the Regional Rail Lines.

Technical Considerations

Assessing a new train design along an entire track network and not only at ‘tight-spots’ requires a linear clearance response that accurately identifies clearance conflicts regardless of GPS signal quality. Such an assessment should also support the re-use of data where iterative vehicle clearance modelling is required for either vehicle or track modifications.

**Accuracy Requirements**

Key to the success of a network wide clearance audit is the selection of a survey system that corresponds to the needs and requirements of the network in question. Commonly, engineering survey requirements are expressed in terms of positional accuracy.

A survey with highest order accuracy is both costly and time consuming. However the advantage of multi-sensor data collected at speed is that the broad coverage and higher speed/lower accuracy surveys can identify any corridor locations requiring a higher accuracy survey.

In addition to identifying accuracy requirements for the project, it is also necessary to understand if the local rail environment will impact or constrain survey system accuracy.

**Sensors**

Survey data point accuracy in multi-sensor surveys is largely dependent on the accuracy specifications of each sensor data point.

Each sensor has its own accuracy and precision characteristics, for example: the accuracy of laser sensor data points can vary with distance from the sensor; inertial sensor accuracy generally remains constant so long as acceptable temperature or electrical interference ranges are maintained; whilst
the GPS location accuracy will vary with environmental conditions such as overhead structures or vegetation that can obstruct the signal path. (1)(2)

Network Access
Multi sensor survey systems will most likely be mounted on dedicated track inspection vehicle or on a hyrail vehicle. In choosing a vehicle or platform it is important that the needs of the survey are considered. For example, some vehicle dimensions can constrain where laser sensors are mounted, resulting in a suboptimal field of view. It is also important that sufficient power is available to run computing equipment and data storage systems. Hyrails have the benefit of being relatively easy to fit sensor equipment to, but track inspection vehicles have the advantage of having existing train paths that the survey can leverage. Finally, vehicle travel velocity must understood because it can impact on survey quality and the data density obtained.

Project Execution
Mobilization
To complete the SEPTA network-wide clearance, an existing in-service SEPTA track inspection vehicle was utilized. The SEPTA track inspection vehicle was mobilized with high speed laser equipment allowing rich point cloud laser data to be collected during a regular train path.

Sensor Equipment
The equipment mounted on the SEPTA track inspection vehicle (Figure 1) were comprised of two lasers manufactured by SICK in Germany. Each included a ‘sweep’ of 190 degrees thus ensuring that when mounted back-to-back, a full 360 degree profile of rail easement measurements were taken. The lasers were configured to record data at an angular resolution of 0.617 degrees and to a range of 80 metres. These properties resulted in 220,000 measurement points per second when the system was set to recording mode.

FIGURE 1- 2x LMS 511 Laser Hardware & IMU Installed On the SEPTA Track Inspection Vehicle

GPS and an Inertial Measurement Unit (IMU) were also mobilized to record positioning information which could then be later processed to generate an actual track alignment file. Although the actual vehicle outline has known measurements, kinematic effects such as end-throw and center-throw are influenced by track curvature. Therefore, track alignment information in a consistent, digital format is required that software that analyzes LiDAR data can realistically model the train’s behavior as it moves through the network.

Specific positioning equipment used on the project included

- Dual frequency GPS receiver compliant with Philadelphia base station network
- Inertial Measurement Unit capable of heave/pitch/roll measurements at a frequency of 100 times per second
- Wheel encoder to provide linear distance measurements critical through tunnel sections without GPS signal reception
Data Collection
Prior to data collection it was necessary to agree some conventions with SEPTA and LTK. These included the unit system to be used for the project (decimalized feet) and the adoption of the datum as mid-gauge top-of-rail.

The SEPTA EM80 was driven through a section of the depot that had been established as a calibration range to ensure that the laser, positioning and camera systems were all working together and that raw laser measurements recorded to nearby trackside assets were accurate.

The data collection program was based on the SEPTA quarterly track recording schedule that is generally undertaken through the night over a 2 week period to avoid disruption to passenger services. Data collection was undertaken at normal EM80 travel speeds with most data recorded at 40 miles per hour resulting. In total, approximately 50 Gb of data was recorded.

On a daily basis the GT project team in Philadelphia were responsible for downloading GPS dual frequency base station data and for completing preliminary data QA from the previous night's recording.

Vehicle / Load Design Documentation
A new bi-level train model was developed with client input for exposure to the network laser point cloud. Both the bi-level car and the locomotive required a maximum kinematic envelope to be generated.

A static model for the car and locomotive were derived using section drawings of the proposed vehicle provided in arrangement drawings and transposed into CAD (Table 1). The individual sections were combined into a single, maximum static outline of the vehicle that could then be ‘expanded’ to accommodate various kinematic parameters that were once again issued by the client.

All bi level car kinematic parameters (Table 2) were applied from a New Jersey Transit Multi Level Clearance Diagram utilizing the worst case configuration for lateral and vertical displacements. The locomotive kinematic outline (Figure 2) was generated from an AMTRAK drawing with worst case kinematic parameters applied.

### TABLE 1 - SEPTA Bi Level Car Dimensions

<table>
<thead>
<tr>
<th>TITLE</th>
<th>TITLE PLS</th>
<th>TITLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Height</td>
<td>175.16” +/- 0.5”</td>
<td>14.596’</td>
</tr>
<tr>
<td>Vehicle Width</td>
<td>119.75” +/- 0.5”</td>
<td>9.98’</td>
</tr>
<tr>
<td>Vehicle Length</td>
<td>1020”</td>
<td>85’</td>
</tr>
<tr>
<td>Front Bogie Position</td>
<td>867”</td>
<td>72.25’</td>
</tr>
<tr>
<td>Rear Bogie Position</td>
<td>153”</td>
<td>12.75’</td>
</tr>
<tr>
<td>Roll Centre</td>
<td>80.052”</td>
<td>6.671’</td>
</tr>
</tbody>
</table>

### TABLE 2 - SEPTA Bi Level Car Parameters

<table>
<thead>
<tr>
<th>Bi Level Car Parameters</th>
<th>Physical Tolerance for Wheels</th>
<th>Lateral: Wheel Rail Gap including wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Tolerance for Wheels</td>
<td>2.95”</td>
<td>0.246’</td>
</tr>
<tr>
<td>Lateral: Wheel Rail Gap including wear</td>
<td>2.3”</td>
<td>0.192’</td>
</tr>
<tr>
<td></td>
<td>0.64”</td>
<td>0.125’</td>
</tr>
</tbody>
</table>
Bearing House Play
Car body at CG height 1.535"

Vertical:
Wheel Wear
Car body at CG Height 1" 0.083'

Dynamic Car body Roll 0.936 deg.
Additional Lateral 4"
Additional Vertical 18"

FIGURE 2 - Bi Level Static and Kinematic Vehicle Outline

The track itself is subject to design and compliance tolerances. Laser processing algorithms also need to assess vehicle clearances while considering the maximum track tolerance and not simply the track as it was at the time of the survey. SEPTA provided track tolerances to GT (Table 3) and these were based on the track standard Class 3 track.

TABLE 3 – SEPTA Class 3 Track Tolerances

<table>
<thead>
<tr>
<th>Track Parameters</th>
<th>Track Gauge</th>
<th>56.5&quot;</th>
<th>4.708'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral Rail Wear</td>
<td>0.88&quot;</td>
<td>0.073'</td>
<td></td>
</tr>
<tr>
<td>Horizontal Alignment</td>
<td>1.75&quot;</td>
<td>0.146'</td>
<td></td>
</tr>
<tr>
<td>Vertical Alignment</td>
<td>2.25&quot;</td>
<td>0.188'</td>
<td></td>
</tr>
<tr>
<td>Super Elevation</td>
<td>2&quot;</td>
<td>0.167'</td>
<td></td>
</tr>
</tbody>
</table>

Data Processing and Analysis
While the recorded laser data can be thought of as a 3 dimensional point cloud (Figure 3), clearance processing is most efficiently undertaken using individual laser profiles as it is far easier to automate a large number of successive point-in-polygon queries whereby the vehicle outline (polygon) is tested against a single 360-degree laser profile made of laser point reflections, than to assess the vehicle outline for obstructions within the context of a 3 dimensional point cloud.
The widely used and generic laser data format for point cloud information is .LAS and within an .LAS dataset each point is assigned an accurate XYZ coordinate that can also be expressed as Latitude, Longitude and Height. .LAS files however do not carry embedded milepost or linear referencing information that is needed by railroad clients to describe features and clearance encroachments in a location language understood within the organization. Similarly, other import characteristics such as track curvature needed for clearance modelling are also missing from the .LAS data convention.

To complete the SEPTA bi-level clearance investigations a laser profile data format was used and is referred to as the .LS standard. Laser profiles in the .LS standard do carry mileage information and track alignment properties including curvature.

Within an .LS file, the individual profiles are organized with a user configurable spacing interval and for the SEPTA project the average distance between successive laser profiles was 3 inches.

Once the .LS files were available, user-configurable kinematic parameters were then input into a clearance analysis software based on dynamic tolerances provided by the client (Tables 1, 2 and 3).

Clearance assessments were completed on a Line by Line basis and digital imagery recorded with the laser system was used to complete a detailed description of all encroachments and identified tight spots.

FIGURE 3– Laser Point Cloud at SEPTA Regional Rail Station

Deliverables

The SEPTA project had a coordinate origin of mid-gauge /top of rail and all laser processing was required to report clearance conflicts relative to that datum.

All 280 track miles of recorded data were analyzed for both the bi-level vehicle and locomotive outlines. Reports were produced providing mileage, easting & northing, magnitude of encroachment and type of encroachment (Figure 4), i.e. Overhead catenary, Platform, Vegetation.
GT supplied these reports in a standard .xls format graphing the magnitude of encroachments through each corridor to LTK and SEPTA so that additional investigations could be carried out and re-engineering plans could be considered.

**FIGURE 4 – Clearance Report Indicating Magnitude of Overhead Wire Encroachments (Orange) and Platform Encroachments (Blue) In Decimalized Feet Against Mileage**

Additional reports provided were AutoCAD .dwg files (plus a .pdf version) presenting composites (Figure 5) of all the laser data in specific sections of rail corridor against the bi-level static and kinematic envelopes. The coordinate system within these composites were referenced to mid-gauge & top-of-rail, with the z value providing a real-world mileage.

190 of these composite profiles were produced for LTK & SEPTA.
CONCLUSIONS / RECOMMENDATIONS

GT was provided detailed reports of the previously known tight locations as identified by LTK & SEPTA prior to the project commencement. It became apparent through the survey that the overhead catenary proximity to the kinematic envelope could prove problematic as the bi-level vehicle did not have a pantograph or any other insulated surface on the roof.

Additional tight locations were identified that were unknown to LTK & SEPTA, proving the value in the approach taken to survey the network. The tightest spot on the network was through the underground downtown section, the overhead catenary came within 5 inches of the static vehicle outline which was previously unknown.

Meeting with clients as early as possible before data collection is important to set project objectives and understand the technical aspects of the network, the rolling stock to be analyzed, the mode of recording and the quality of existing documentation such as track alignment files, if available. This ensures that the correct sensor equipment is chosen, that the recording campaign can proceed without problem, and that the analysis work produces the right outcomes for the client.

Providing a quick turnaround from data recording to reporting for the client was vital to allow SEPTA & LTK opportunity to consult and design through the tight locations of the network.

ACKNOWLEDGEMENTS

The assistance of Michael Johnson and John Janiszewski from LTK engineering is acknowledged with many thanks.
REFERENCES


A Technology-based Approach to Assessing the Feasibility of Bi-level Trains

Finbar Holland
**SEPTA Network - Situation**
- Track length 280 miles
- 13 branch lines
- 150 stations
- Fleet GE Silverliner IV (230), Rotem Silverliner V (120)
- 36M passengers (Regional Rail)
- Growth – 3% per annum

**Bi Level Trains Rationale**
- Adding new cars to the Silverliner fleet not an option
- Reducing headways is possible but complex
- Going upwards would deliver 20%-30% more seating capacity.

**SEPTA Regional Rail Network**

**How To Test for Bi-Level Trains?**
- Do it the old way
- Run an actual bi-level train
- Use LiDAR to simulate a bi-level train

**Train Selection**

**LiDAR Collection**
Mobilization

**EM 80 Geometry Car**

Laser installation

**LiDAR Video**

Model Dynamic Envelope

**Vehicle Outline**

**Vehicle Dynamic Parameters**

**Track Parameters**

Derive Static Outline

**SEPTA supplied vehicle drawings**

Derive scale measurements from SEPTA drawings

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Derive Dynamic Parameters

NOTES:

1. NEW DRAWING REPRESENTS THE PASS ENGER CAR UNDER
   THE FOLLOWING CONDITIONS:
   - Slight Influence of Acceleration
   - 1.5% Grade
   - Longitudinal Torsion
   - LEVELING VALVES
   - Cylindrical Torsion
   - 3.5% Torsion
   - Wheel Height
   - Wheel Height
   - Wheel Height

2. CROSS SECTION DRAWN AT 1:M AND FURTH FROM CAR CENTER.
   THE INFRACTURE TOLERANCES ARE TAKEN INTO ACCOUNT.

3. LATERAL DEVIATION
   "SEGMENT"
   "SEGMENT"

4. VERTICAL DEVIATION
   "SEGMENT"
   "SEGMENT"

5. CROSS SECTION DRAWN AT 1:M AND FROM CAR CENTER.
   THE INFRACTURE TOLERANCES ARE TAKEN INTO ACCOUNT.

6. DEVIATIONS OBTAINED FROM VARIOUS DYNAMIC SIMULATIONS WITH
   MODEL "SEGMENT"

7. PRIMARY VERTICAL DEFLECTION OF "SEGMENT" AT 1:M IS INCLUDED IN THE
   LOCATION OF THE ICE AND IS OMISSION.

8. WATERWAY AND SURFACE AREA EIGHT

Derive Track Parameters

<table>
<thead>
<tr>
<th>Rail Wear</th>
<th>Rail Wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>15mm</td>
<td>15mm</td>
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</tbody>
</table>

Profile Analysis (Analyzer)

- Integration of Field Sensor Data
- Milepost information
- Curve Fitting Algorithms

Analysis Outcomes
Deliverables

- Reports on all encroachments (type, mileage, magnitude, etc)
- Clearance Graphs
- CAD Drawings (190 composites)

Risks and Challenges

- Having essentially two clients
- Vehicle choice
- Track access arrangements
- Timeliness of processing and reporting

Mitigations and Lessons Learned

- Early engagement with clients on deliverables
- Early site visit to vehicle and network
- Using proven methods for data collection and processing
Acknowledgements

- SEPTA management and field staff
- LTK Engineering – Michael Johnson and John Janiszewski