The Multi-Speed Deflectometer: New technology developed for traffic-speed non-destructive structural testing of pavements.

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ABSTRACT. The Traffic Speed Deflectometer has transformed pavement structural data collection on highways, where network testing was formerly carried out with Falling Weight Deflectometer, Deflectograph or Beam. However, the Multi-Speed Deflectometer (MSD) is now also available, which can test highways but more significantly, fills a gap for an efficient device for structural testing of urban roads. In these locations, issues that are often overlooked include the frequent slowing or stopping at intersections, cornering, access, the extreme variability of structural stiffness due to pavement subservices and the collection of quality structural data over a wide range of speeds while still ensuring the unimpeded flow of traffic at all times. The Multi-Speed Deflectometer is an economical non-destructive traffic speed pavement testing device used to benchmark the structural capacity of large networks of roads. Data are collected at 1m intervals, usually in both wheelpaths and averaged to 10 or 20m intervals in each lane. MSD structural data have been collected over the last 4 years in multiple regions throughout New Zealand and Italy. When paired with traditional surface profiling from the high-speed data (HSD), reliable traffic records and maintenance history, a comprehensive understanding of the mechanisms of pavement performance can be achieved including both the surfacing and the structural layers. Examples are provided to demonstrate application. Pavements with a poor surface condition can be cross checked against the structural condition to verify whether there is an underlying structural issue. If so, these sites can then be flagged for project level testing and renewal. Sites with poor surfacing condition and no structural issues can be flagged for maintenance or re-surfacing treatment. The right solution for the right problem at the right time and over the right extents can now be economically identified, providing authorities with the capability of assessing the optimum Net Present Value expenditure for any large roading network.

Keywords. Multi-Speed Deflectometer, pavement deflections, structural evaluation, non-destructive testing

Introduction

The Traffic Speed Deflectometer (Zofka and Sudyka, 2015; Xiao et al., 2021) has transformed pavement structural data collection particularly because standard reporting at 10m intervals or less addresses the extreme variability of structural stiffness inherent in many pavements. However, its cost and the limited number of units worldwide means it is not always readily available for pavement screening. Traditionally, the Falling Weight Deflectometer (Ullidtz, 1998) has been used for both network and project level surveying in many countries worldwide. While FWD testing has proven extremely useful to confirm the distress mode and most effective type of rehabilitation design at project level, it is much less effective for network level surveying because it is slow and hence often is used with low test density (points per road area coverage). Furthermore, the FWD requires costly traffic management to minimise health and safety risks to the operators and road users. Similar limitations are associated with other traditional devices, such as the Deflectograph and Benkelman Beam.

The Multi-Speed Deflectometer (MSD) is now also available, which can test highways but also fills a gap for an efficient device for structural testing of urban roads where access, cornering, frequent reductions in speed with stopping at intersections, and the collection of quality structural data over a wide range of customary traffic speeds, are important considerations. The Multi-Speed Deflectometer is ideal for economical non-destructive traffic speed pavement structural testing in these conditions to benchmark the structural capacity of a large network of roads. Data are recorded at 1m intervals, usually in both wheel tracks (300,000 test points per day) and averaged to 10 or 20m, providing near continuous structural data useful for defining structurally homogenous sections and to indicate the location of reduced capacity within the pavement cross section i.e., which pavement layer will first develop distress and hence become critical.

Network level pavement management based solely on surface condition observations relies on identifying distress only once it manifests. Additional structural testing is required to identify the cause of distress, because assessment from surface parameters enables only short-term Forward Works Programming (1 to 2 years), hence inhibiting the planned intervention prior to the initiation of distress reaching a terminal condition. Most of the traditional surface condition parameters (rutting, roughness, cracking and visual imaging) can be collected simultaneously with the same MSD vehicle, greatly reducing the overall cost and carbon emissions for provision of comprehensive state-of-the-art network management.

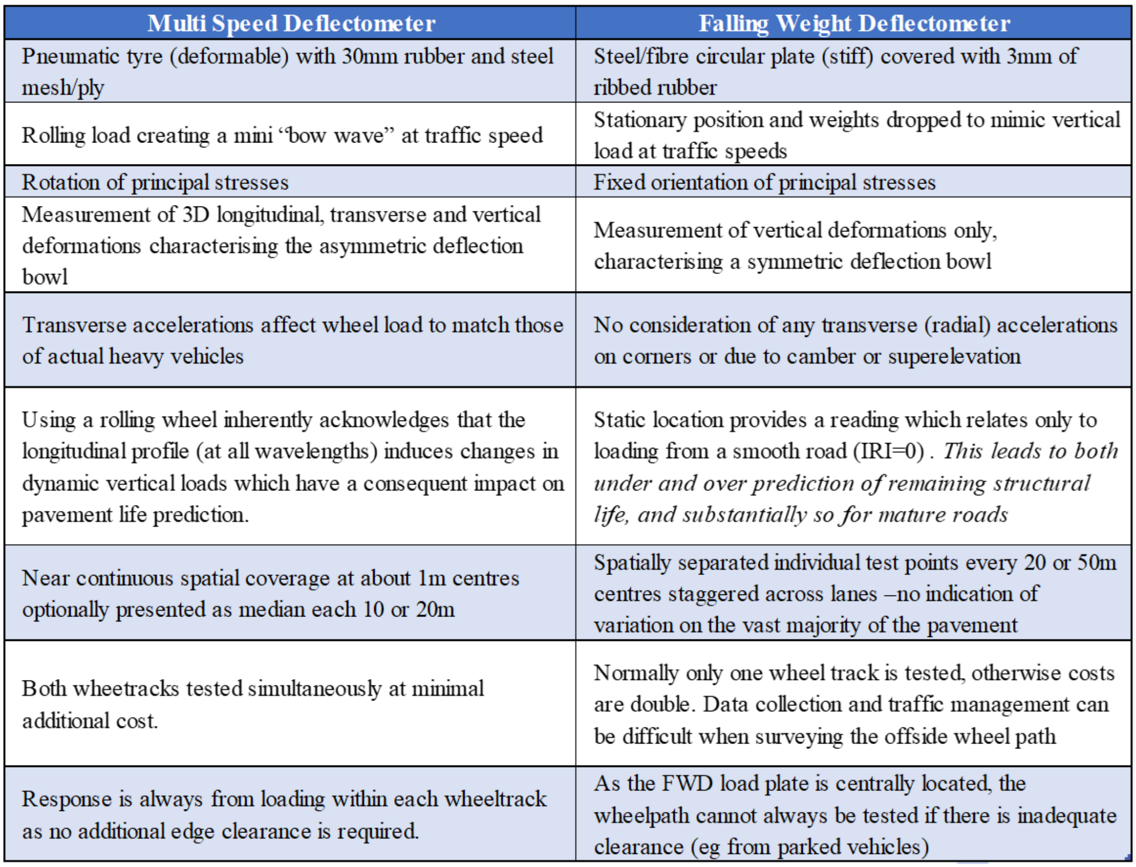
Comparison of TSD, FWD and MSD

The science underlying FWD and TSD is limited to recording of vertical velocity of the pavement surface at unloaded points near a heavy uniaxial load on a plate (FWD) or between moving wheels (TSD), whereas the science underlying the MSD involves capturing all forms of 3-dimensional deformation of the pavement surface using multiple sensors and images recording data both from beneath and around the contact patches of heavily loaded moving wheels. Differences between the FWD and MSD are compared in detail in Table 1.

The measures are fundamentally different, but it is important to note that all of the differences are such that the MSD deformations are more representative of the actual in situ deformations that occur under a heavy vehicle. Therefore, the deformations from the MSD should be more suitable for predicting pavement performance particularly where there are multiple distress modes, or where models that acknowledge only uniform layers with vertical loading are less appropriate. ASTM D5858 (2020) highlights the issues involved for calculating layer moduli from FWD test results, particularly for cracked pavements or locations without pavement layering information.

The use of lasers on the TSD limits surveys to drier conditions which in the case of New Zealand surveys and limited TSD availability has led to avoidance of testing in wet seasons when pavements are in their most susceptible condition. The MSD can survey in both wet and dry conditions and because a dedicated vehicle is not required (installation of the various devices takes only a few hours), multiple MSDs can be readily mobilised and available, including in remote locations.

Table 1. Key Differences between the MSD and FWD



Multi Speed Deflectometer	Falling Weight Deflectometer
Pneumatic tyre (deformable) with 30mm rubber and steel mesh/ply	Steel/fibre circular plate (stiff) covered with 3mm of ribbed rubber
Rolling load creating a mini "bow wave" at traffic speed	Stationary position and weights dropped to mimic vertical load at traffic speeds
Rotation of principal stresses	Fixed orientation of principal stresses
Measurement of 3D longitudinal, transverse and vertical deformations characterising the asymmetric deflection bowl	Measurement of vertical deformations only, characterising a symmetric deflection bowl
Transverse accelerations affect wheel load to match those of actual heavy vehicles	No consideration of any transverse (radial) accelerations on corners or due to camber or superelevation
Using a rolling wheel inherently acknowledges that the longitudinal profile (at all wavelengths) induces changes in dynamic vertical loads which have a consequent impact on pavement life prediction.	Static location provides a reading which relates only to loading from a smooth road (IRI=0) . *This leads to both under and over prediction of remaining structural life, and substantially so for mature roads*
Near continuous spatial coverage at about 1m centres optionally presented as median each 10 or 20m	Spatially separated individual test points every 20 or 50m centres staggered across lanes –no indication of variation on the vast majority of the pavement
Both wheetracks tested simultaneously at minimal additional cost.	Normally only one wheel track is tested, otherwise costs are double. Data collection and traffic management can be difficult when surveying the offside wheel path
Response is always from loading within each wheeltrack as no additional edge clearance is required.	As the FWD load plate is centrally located, the wheelpath cannot always be tested if there is inadequate clearance (eg from parked vehicles)

ASTM D4695-03 (2020) General Pavement Deflection Measurements also includes FWD testing intervals according to the different goals, ranging from an upper limit of 500m for network level, reducing to 10m where necessary for detailed project level. These limitations do not apply to the MSD given the continuous nature of testing.

MSD Design Objectives

The MSD has been developed by installing and exploring the recordings of all types of high performance sensors and continually upgrading their configuration as available specifications for these are progressively enhanced. The prime objective is to extend beyond the traditional limitation (recording only vertical deformation) to more realistically characterise the "myriad ways" (Dawson, 2002) in which pavements respond when experiencing different modes of distress. Effectively recording their multi-dimensional dynamic behaviour provides the basis of a more mechanistic approach for performance prediction.

MSD vehicles can be supplemented with other sensors (such as GPR & TDR), but these substantially increase the cost/km, yet the consequential effects of their parameters are already incorporated in the primary deformations beneath and around the tyre contact patch as recorded by standard MSD.

MSD Data Collection and Rationale for Interpretation

State-of-the-art pavement condition data collection and its structural evaluation requires:

- Collection of data to be non-destructive at traffic speed (no impediment to road users).
- Coverage of both the surface of existing roads and where practical, each layer of any road under construction, recording all data, near-continuously from both wheel paths of all appropriate lanes.
- Processing that determines all parameters relevant to pavement performance in a manner that also enables mechanistic characterisation.
- Identification of all modes of distress in all layers.
- Characterisation of spatial and temporal maintenance or renewal needs (extents, depths, and optimum timing) for each test point.
- Sub-sectioning all test points into homogenous Structural Treatment Lengths (STL), with ongoing re-sectioning (dynamic incremental-recursive model).
- Design of the most economic form of maintenance and timing for sub-intervals within each STL, and categorise each for local maintenance versus full length renewal
- Prediction of Remaining Structural Life, with a usefully reliable “Hit Rate” for each STL
- Determination of the optimum Forward Work Programmes for both Maintenance and Renewals (with due recognition of their interdependence) and determination of their respective costs.

Historically, such evaluations with FWD have been slow, costly and of variable reliability (Arnold et al, 2009). Speed has been greatly increased with the advent of the Traffic Speed Deflectometer, although the length of the TSD makes it impractical on many local authority roads. Now with the Multi-Speed Deflectometer as well, all roads (under construction or completed, surfaced or unsurfaced, dry or wet in any condition) can be tested at traffic speed. MSD provides the additional advantages of measurements where the rubber meets the road (beneath the contact patch not just in the unloaded gap between dual wheels) as well as providing mechanistic insight into 3-dimensional deformations, testing continuously in both wheelpaths. The instrumentation is readily transportable to remote sites and can be installed or adapted to fit most heavy vehicles (including trailers or forklifts). Calibration is carried out using FWD, TSD, (or even Deflectograph or Beam if necessary), initially for seamless transition by their practitioners but ultimately for the more comprehensive characterisation of pavement properties and performance obtainable from the new technology.

Since the introduction of non-destructive testing of pavements by A C Benkelman in 1952 (Highway Research Board, 1955) until now, the focus has been almost exclusively on one parameter: vertical deflection.

The science underlying FWD or TSD is somewhat limited in view of the above. Both devices record only vertical velocity of the pavement surface at unloaded points near a heavy uniaxial load on a plate (FWD) or between moving wheels (TSD). Widely recognised analytical models are then used for quantification of moduli, stresses and strains for known as-built layering.

The science underlying the MSD is somewhat different in that it focuses on capturing all forms of 3-dimensional deformation of the pavement surface. The relevant stress/strain tensor field throughout the deflection bowl (with each point having 9 components), and its observed asymmetry beneath a moving wheel precludes using just a simplistic measure (vertical deformation) if pavement life for a network is to be predicted with any reliability (particularly where there is minimal as-built information). Technology now provides a practical option with the capability for much more relevant, more comprehensive and more extensive data collection at traffic speed and at much lesser cost. MSD uses multiple sensors and images recording data both from beneath and around the contact patches of heavily loaded moving wheels then applying primarily machine learning to correlate the large volumes of data with equivalent simple data from an FWD or TSD recording of the same interval of road. Machine learning is then extended to associate other forms of 3-dimensional deformation recorded, using calibrations to sites that have known precedent performance in that region, including those observed to be experiencing specific distress modes or are in a terminal condition. This approach is taken because often there is little or no as-built information and so far, there appears to be no existing analytical model that will:

(1) interrogate all of the recorded 3-dimensional dynamic characteristics of the deformations induced by a moving wheel and
(2) output relevant parameters for an asymmetric layered visco-elastic model in a practical timeframe for network structural analysis and
(3) evaluate them using any existing recognised criteria (fatigue limits).

Machine learning provides pavement engineers using MSD with a particularly effective tool to advance this new discipline mechanistically, beyond the limitations of the traditional scientific method, paraphrasing Anderson (2003):

> “This is a world where massive amounts of data can, to a large degree at least, replace every other tool or test that might be brought to bear. Numbers give us not only immediate lessons from relevant history (regional precedent performance), but also unlimited potential for ongoing improvement.
>
> Who knows the full theory of why roads perform the way they do? The point is they do, and for every region’s permutation of terrain, sources, practices, loadings and climate, machine learning can now track and quantify their precedent performance with unprecedented fidelity.
>
> With enough data, the numbers speak for themselves.”

Pavements are highly variable structures that are not often amenable to simplistic analysis yet many of the traditional models are uni-variate (sometimes bi-variate). Experience with MSD data from large networks has demonstrated that multi-variate models that give due recognition to the myriad ways in which pavements become distressed, provide more reliable solutions. Many pavement models are based on results from laboratory testing or Accelerated Pavement Test facilities located at great distance from the relevant region. Few practitioners use relevant calibrated models that take into account all of the local conditions; subgrades, aggregate sources, construction methods, maintenance practices, environment etc. Until recently there was little choice. Such regionally-specific, calibrated mechanistic models based on historic observations of all relevant distress modes and precedent performance were often too costly or time-consuming to establish. However, high-speed collection of both structural and surface condition data together with the recent advances in big-data machine learning technology has effectively transformed the industry and provided a choice. Informed pavement management, more reliable performance prediction and optimised planning of forward work have become practical and economic realities for both categories of pavement networks, (highways and local roads).

Software has been developed, e.g., Regional Precedent Performance (RPP) which uses multi-variate analysis to analyse these huge data sets providing informed understanding of pavement deterioration and modelling of future performance. The cost is typically orders less than the cost of one kilometre of pavement rehabilitation, and benefits continue for many years.

Traditional methodology with visual inspections provides some information on pavement life predictions for up to 1-2 years ahead at best. The MSD provides the potential for a significant step forward that addresses Transport Agency focus on improving longer term predictions i.e. from 30 months out to 30 years. While reliability has been very low to at least until 2010, the potential for better reliability on highways with FWD supplemented by TSD data was indicated more recently by Stevens & Schmitz (2018), and with appropriate MSD output as well this is now being successfully extended to wider networks, including for the first time, local authority roads. Regional Precedent Performance longer term prediction of pavement life (RPP 30-30) is now being targeted with the latest MSD upgrades in hardware, firmware and software.

Outputs are now able to be delivered in close to real time, (the same day if necessary) enabling much more cost-effective and timely decision making for construction projects.

MSD Outputs

MSD data output comes in three forms with varying detail in their characterisation: Basic, Empirical or Developmental.

Basic MSD Outputs

Basic output is generated simply by correlation to the widely recognised FWD parameters, i.e. central deflection and curvature, standardised to 40kN load by default (50kN if required). Curvature for thick structural surfacings is commonly required as Surface Curvature Index, although where thin surfacings predominate, Curvature Function may be preferred.

Empirical MSD Outputs

Empirical outputs include the HDM IV parameter, Adjusted Structural Number (SNP). In addition, more pertinent indices are available, similar to those promoted in Italy by ANAS (2021) since 2009 and in South Africa by Horak (2008), that focus on which layer is of interest and are determined from vertical deflection bowl offsets (at unloaded locations). Horak uses indices (with units of distance) and suffix of I for Index. To distinguish from these, MSD uses the prefix SN as the range of values is tied to SNP range for the network (normally 0 to 8). The corresponding MSD layer parameters are generated at or near loaded locations and are:

- Structural Number for Rutting (SNR) reflecting the stiffness of the whole pavement. It is similar to structural number (SNP) and relates inversely to central deflection. SNR relates to the resistance to rutting from the combination of movement in all layers resulting from both vertical and longitudinal deformations, scaled to the same range as SNP. The Structural Number for Vertical deformation (SNV) is also generated, relating to the vertical component of rutting deformation only.

- Structural Number for Base (SNB) a measure of the strength of the main structural layer and relates inversely to surface curvature index.

The above are the principal indices that may be provided for those familiar with FWD, TSD, Deflectograph or Beam, and calibration may be to whichever form of data is most readily available for any individual network.

Developmental MSD Outputs

The MSD processing also outputs “Developmental” indices which relate to more specific characteristics which are at present recorded only by the MSD or are newly developed or under development (because they can be collected at minimal additional cost with the same vehicle). MSD research began in 2015 and the “signatures” of the multi-dimensional tensor field deformations present an enigma of which about 10% has been able to be deciphered each year, using principally, machine learning calibrations to observed performance. Many of the recorded features are not yet fully understood in relation to the progression of specific distress modes. Note not all of the following developmental indices have yet been advanced to the stage they can be used for production, but are documented here so that longer term goals can be indicated, and others may elect to use them for research (eg by applying them on sites where the reasons for premature distress are unknown but can then be explored by observing whether the extents of distress severity correspond consistently with extreme values). Feedback of this type of information and re-analysis greatly accelerates understanding of the relevant distress mechanisms, and ongoing feedback loops become successively more useful each year especially on heavily trafficked roads, as the significance of the MSD deformations becomes more evident from distress progression on each network. Re-processing to incorporate any changes in distress severity that are observed is fully automated. On most local roads where the traffic loading is reasonably well known or recorded, the structural testing should remain current and not need to be re-tested for several years.

Some of the developmental indices can be utilised in lieu of traditional HSD parameters. If HSD data are already available or become available in due course, they should be used in preference, otherwise the interim MSD equivalents may be adopted for network evaluation to refine or guide remaining life algorithms using MSD deformations.

- Structural Number for the Surface (SNS) a measure of the resistance to near surface instability along the wheelpath. It is significant only occasionally and is relevant to distress in unbound aggregates or thin surfacings.
- Modular Ratio Index (MRI) is a measure of the ratio of the moduli of successive layers above the subgrade, calibrated to the Normalised Modular Ratio parameter for FWD. A value of 1.0 indicates compaction is likely to be satisfactory and conforming with the Austroads modular ratios expected from good quality unbound granular aggregates. Values less than 1.0 may indicate under-compaction. Significantly higher values indicate bound layers may be present.
- Structural Number for Transverse Shear. (SNT) is a measure of the resistance to transverse shear. Low values are expected to be relatively rare in full width pavements but occasionally experienced in narrow (rural) thin surfaced unbound granular pavements on low strength shallow subgrade where the outer wheelpath is too close to a soft shoulder, and as a result may be accompanied by deep-seated shear or possibly edge break. There is no closely equivalent parameter in traditional tests using vertical

deflection. Interim calibration uses the ratio of the FWD shear strain at the top of the subgrade to the equivalent thickness (as far as the transition only with truncation of values). Beyond the transition, an interim mirror calibration could be attempted, to see what can be learnt. Very low values will suggest subgrade deformation is likely. The intermediate values around the transition are all expected to indicate soundly compacted unbound granular pavements or thick bound layers, that may also relate to high modular ratios. Further trials to find suitable correlations are needed.

- Bound Cracking Index (BCI) is a new parameter that quantifies the potential for cracking of a near surface bound layer because it is underlain by a significantly more flexible layer. It is correlated to FWD data using pavements that have known construction (usually those with thick AC or cement stabilised basecourses) and known current condition.
- Apparent Cracking Index (ACI) is generated by MSD as a simplistic measure of cracking from JPeg images, 300mm square, taken in the wheeltrack at 1 m intervals. Machine learning is used to quantify in real time, just the number of cracks which are essentially continuous ie pass fully from one side to another, returning numbers of 0, 1, 2, 3, or 4 with counting truncated at 4. Shorter cracks are ignored.
- Estimated International Roughness Index (eIRI) and Estimated Mean Texture Depth (eMTD). The estimated descriptions are used to distinguish the parameters from those collected using traditional equipment, as the MSD uses laser imagery to provide localised measures that approximate the traditional International Roughness Index and Mean Texture Depth, both correlated to existing data typically measured by HSD in roading databases such as RAMM (New Zealand).
- Apparent Rolling Resistance (ARR) is the ratio of the dynamic shear resistance (acting longitudinally on the pavement surface at the tyre contact patch) that is generated against the direction of motion of a free rolling wheel, to the normal force on the pavement, expressed as a percentage. The shear force is the resultant of the forces contributed by tyre deformation (including contact patch hysteresis losses around the patch perimeter as well as internally from texture indentation) and pavement layer deformations (that impose energy losses as the wheel continually attempts to "climb out" of the deflection bowl). The bowl becomes progressively more asymmetric with speed. Because Rolling Resistance has been found to be strongly speed dependent (Cenek, 1996), it is standardised to a reference speed (currently 50 km/hr) as well as other aspects, particularly tyre temperature and pressure. It has associated parameters that allow correction to other vehicle speeds, tyre types and pressures where required. In recent years, Rolling Resistance has been a feature of detailed research in Europe (for identification of pavement types which result in reduction of carbon emissions) using more costly traditional test procedures. However, it was recently discovered that the same parameter was generated incidentally (an unexpected "by product" of the machine learning technology) in the MSD interpretation. For that reason, it may also be outputted when required by interested researchers.

The advantage of this extended form of data collection available via MSD is that users may elect either to use simply one or two parameters such as SNP or central deflection, along with traditional HSD data collected separately, or they may elect to encompass the dozen or so supplementary parameters that can now be readily generated in a single MSD pass. In either case, basic interpretation can be limited to dTIMS or Austroads, or extended to include the more versatile tools of a Regional Precedent Performance evaluation and hence Remaining Structural

Life and a Forward Work Programme, generated from calibrations to terminal sites in the network – the ultimate reality checks.

MSD Case Histories

Auckland Transport, Auckland, New Zealand

Over two months in May and June 2021, 4,460 lane km in both left (outer) and right (inner) wheelpaths were collected using MSD data technology on behalf of Auckland Transport. Readings were typically collected at 1 to 3m intervals and reported as the median value of the readings within each 10m road segment. Left and right wheelpath data were staggered. Roads tested comprised mainly arterials and primary collectors. The scale of the data collected over the entire network is best appreciated geospatially as shown in Figure 1.

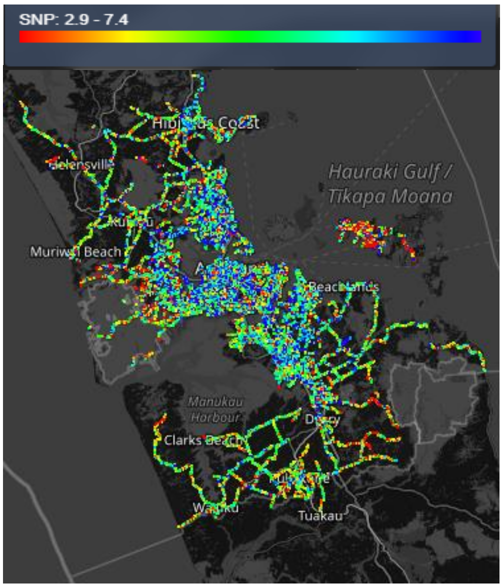


Figure 1. MSD Test coverage for Auckland Transport

The final outputs are as per the MSD outputs outlined earlier in the report. Structural Treatment Lengths (section lines in lieu of points) have yet to be determined and reported at time of writing this paper, however their characterisation can at present be readily inferred on inspection as shown in **Error! Reference source not found.** for Meola Rd and will in due course be computed algorithmically.

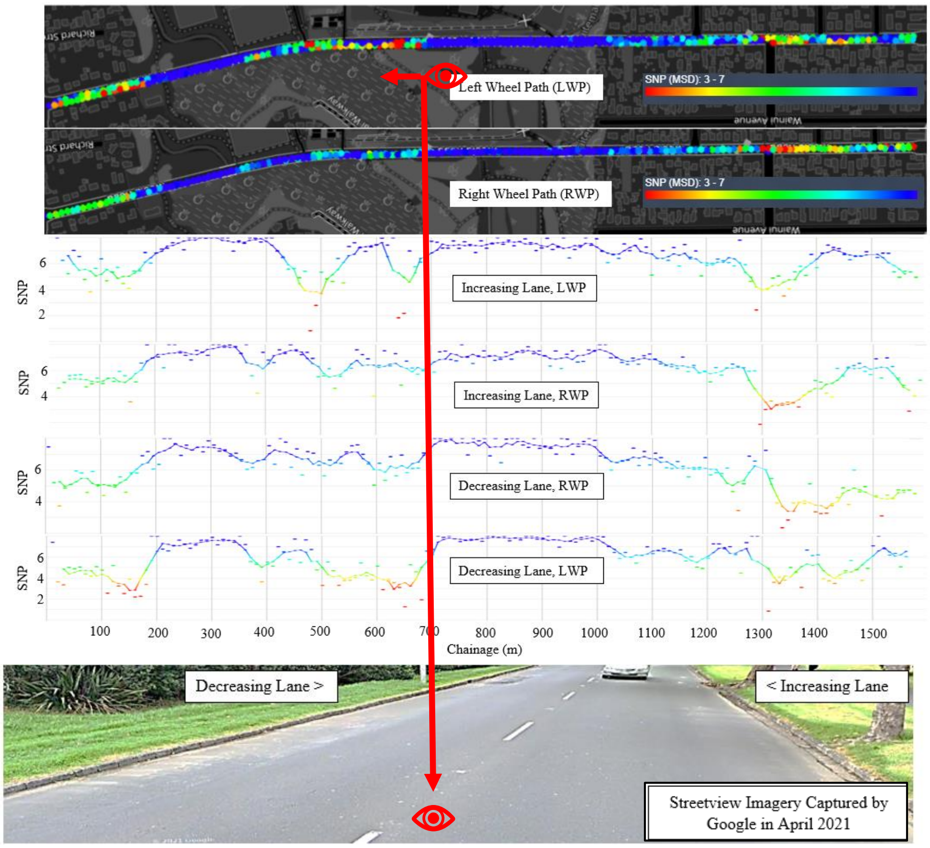


Figure 2. Meola Rd, Auckland example of MSD data in all lanes and wheelpaths, well supported by visual reality checks

Rome Municipality, Rome, Italy

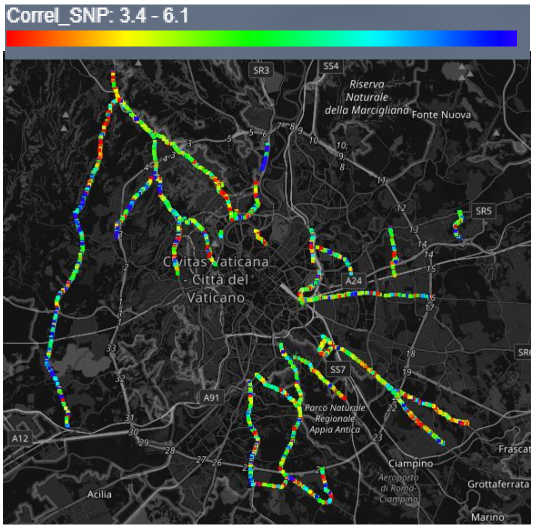


Figure 3. MSD Test coverage for Rome

Over three days in April 2021, 300 lane km in the right (outer) wheel path were collected using MSD technology. Roads tested mainly comprised arterials and primary collectors of the municipality network as shown in Figure 3.

Via Prenestina in the vicinity of Villa Gordiani was selected for closer inspection as shown in Figure 4. Sub-sections of sustained low and high SNP were reality checked with Google Street View Imagery captured in January 2022, just a few months after MSD testing. Review of historical imagery indicates that the pavement had been resurfaced or rehabilitated circa 2015. Within 2-3 years distress manifested at the surface in the form of fine alligator cracks and pumping. Distress is more severe in the left rather than right wheelpath highlighting the potential benefit of dual wheelpath MSD surveys particularly for mature roading networks such as Rome.

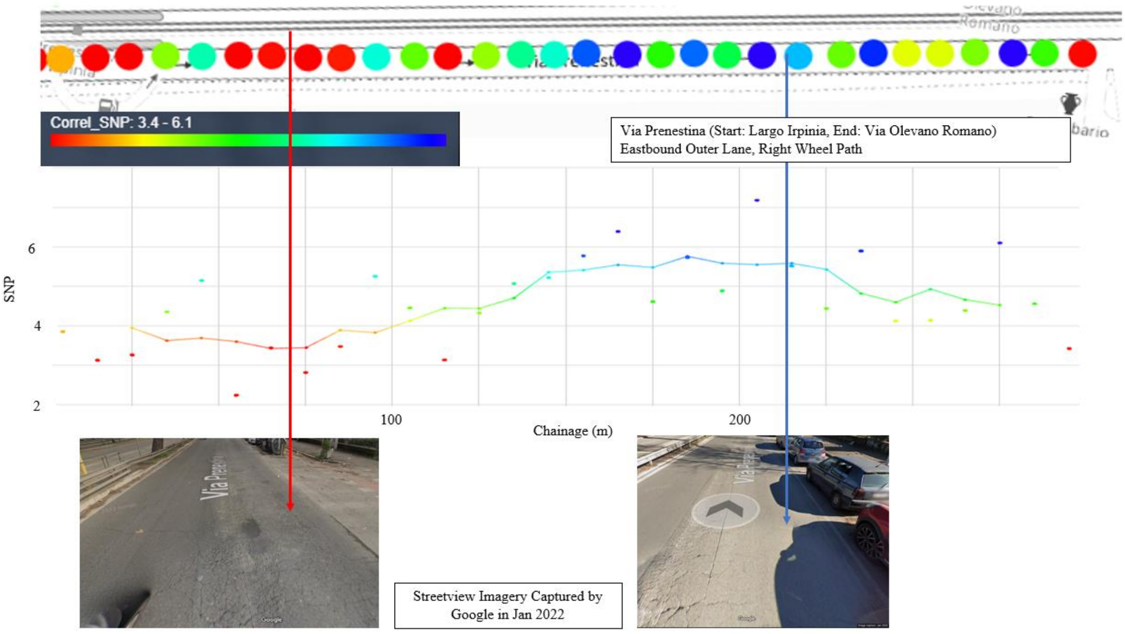


Figure 4. Reality checks on sub-sectioning of Via Prenestina.

Florence Municipality, Florence, Italy

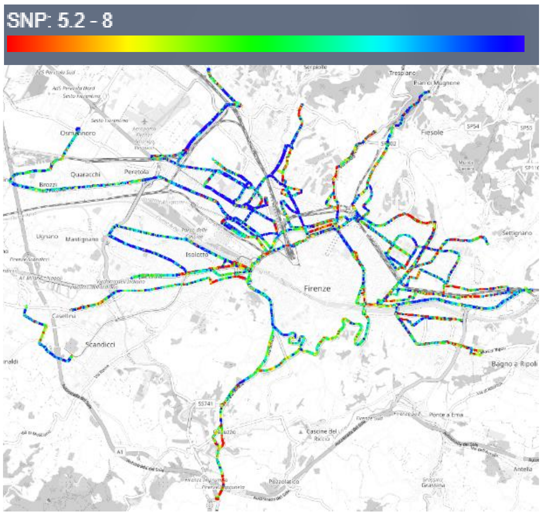


Figure 5. MSD Test coverage for Florence

Over three days in December 2021, 185 lane km in the right (outer) wheelpath were collected using MSD technology. Roads tested comprised arterials and primary collectors. The scale of the data collected over the entire network is best appreciated geospatially as shown in Figure 5.

Viale Francesco Talenti was selected for closer inspection as shown in Figure 6Figure 5. Sub-sections of sustained low and high SNP were reality checked with Google Street View Imagery captured in January 2022, just a few weeks after MSD testing. Once again the MSD appears to have correlated well with identified sections of weak and strong pavements.

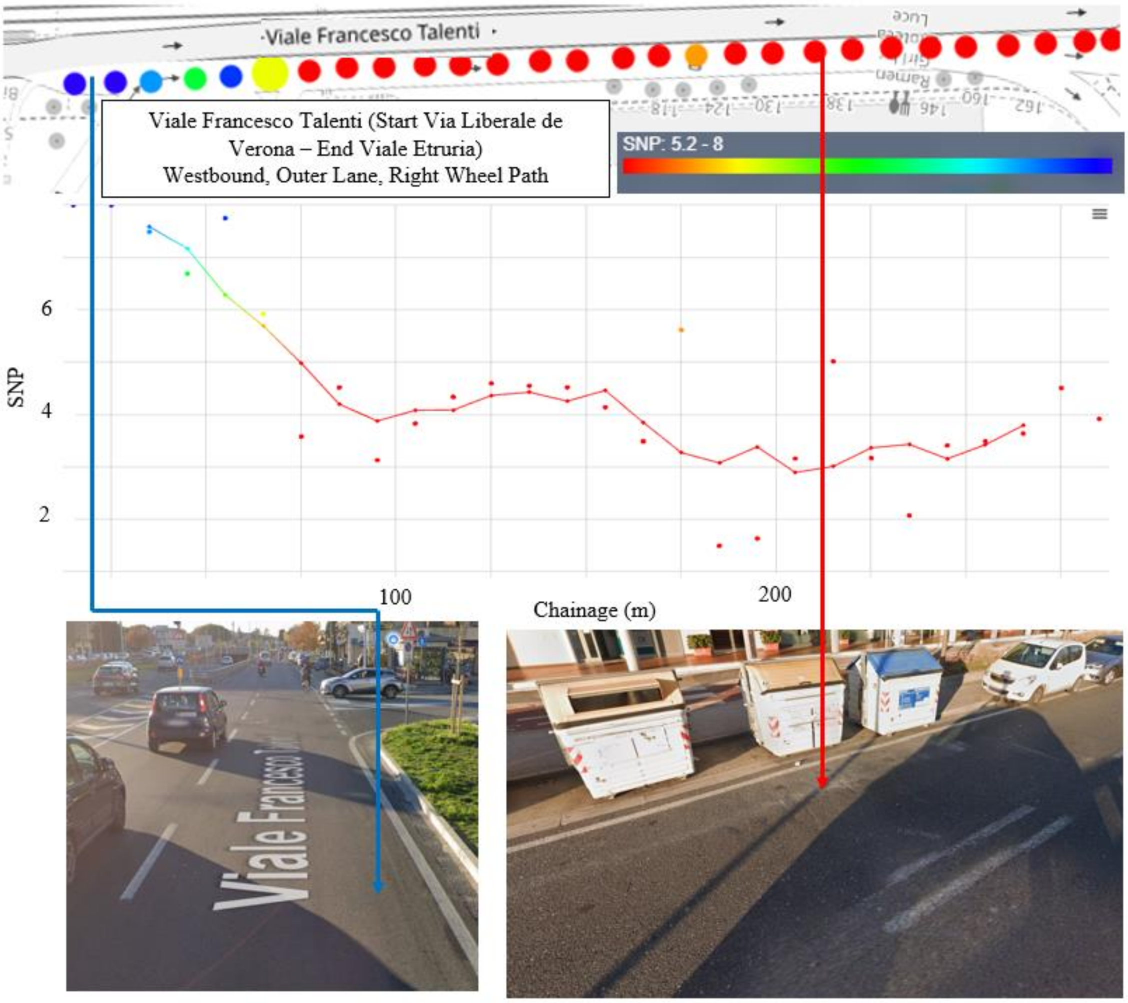


Figure 6. Viale Francesco Talenti Reality Checks

Conclusions

The Multi-Speed Deflectometer, fills a gap for an efficient device for rapid low-cost testing and structural evaluation of a large network of urban roads. The above recent case histories demonstrate its effectiveness using Google Streetview. Management of pavement deterioration can now be expedited by development of an optimised Forward Works Programme which can be readily validated with traditional methods (visual inspection, destructive tests or minimal Falling Weight Deflectometer testing).

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