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Review Article

Guidelines for the use of accelerated pavement testing data in autonomous vehicle infrastructure research

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HIGHLIGHTS

- Accelerated pavement testing (APT) data are valuable in designing and evaluating pavements for autonomous vehicle use.
- Effects of traffic wander, constant speeds and short following distances can be tested.
- Future APT can focus on AV effects on pavement structures through novel use of available equipment and analysis techniques.

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ABSTRACT

There is much research conducted on the vehicle technologies required for operation of autonomous vehicles (AV) on public roads, as well as analysis of the interaction between AV and the road environment. However, limited research exists on the impact of AV on road pavement structures. The research includes issues such as the effect of more channelized traffic loading, shorter inter-vehicle following distances and potential higher traffic volumes of more uniform vehicle types and loads. This paper discusses the application of existing and generation of new, relevant accelerated pavement testing (APT) data in understanding the effects of AV on pavement infrastructure. The paper presents development of provisional guidelines for the use and application of APT data to ensure that road pavement structures cope with anticipated increase in AV use. It is concludes that the use of AV fleets on existing road pavement infrastructure may lead to different behaviors and responses than what became the norm under non-autonomous vehicle fleets; appropriate analysis of existing APT data will contribute to the improved understanding of these expected changes in behaviors and responses; appropriate planning of AV operations-focused APT is possible with existing technology to contribute to the provision of economic and durable road pavement infrastructure in future.

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1. Introduction

Experiments on self-driving cars started in the 1920s, but significant progress was made in the recent past with regular releases of smarter, more fuel-efficient and very different vehicle population compared to current vehicles. Road infrastructure is lagging far behind as it is not been designed, constructed and maintained for this new vehicle population.

Vehicles have traditionally been machines with different levels of complexity and largely controlled by humans. The driver took all final decisions regarding the act of driving, even though many modern engine management systems and vehicle control systems (e.g., Anti-lock braking systems (ABS) or cruise control systems) would assist in the process. This human-based decision system leads to inevitable variability in the way that vehicles are loaded, operated and maneuvered. Although guidance is provided to the driver (i.e., load restrictions, speed regulations and lane designations), variability in human decision-making affects the reaction and management of driving.

Over the last decade or two, an evolutionary process in vehicle development and design has led to increasing levels of automation for vehicles (Shladover, 2007). This is currently at the point where both light and heavy vehicles are programmed with origin and destination information, and the vehicle will be able to traverse autonomously in a safe and efficient way between these two points. Studies indicate that autonomous vehicles (AV) may lead to safer roads, less congestion and reduced need for parking, fewer vehicles per capita, and increased vehicle mileage traveled overall, with substantial societal benefits (Fagnant and Kockelman, 2015).

The question asked is whether these developments will have any effect on the provision of transport infrastructure in terms of design, construction, management and maintenance. On a simple level, this is similar to the difference between rail and road infrastructure. Road infrastructure traditionally had to cater for wider lanes to accommodate inherent wandering of vehicles across the width of a road. Rail infrastructure provides two strips of steel about 75 mm wide with the same function, as these two strips contain and restrict the wandering of the train.

Much research continues on the technology required for AV operation on public roads, as well as the interaction between these vehicles and the road environment. However, there is limited research regarding the effect of AV operations on road pavement structures. This includes issues such as the effect of more channelized traffic loading, shorter inter-vehicle following distances and potential higher traffic volumes of more uniform vehicle types and loads.

This paper investigates application of existing, and generation of new, applicable accelerated pavement testing (APT) data to understand effects of AV operation on pavement structures. The paper provides provisional guidelines in the preparation of road pavement structures for AV operations and design of sustainable road pavement structures with increased AV use.

2. Autonomous vehicles and road infrastructure

2.1. *Autonomous vehicles*

Autonomous vehicles (AV) are vehicles grouped into six classes (Table 1) (SAE International, 2016). These levels range from no automation (SAE level 0) through to full automation (SAE level 5). Specific effects on pavements potentially start at SAE level 2, where more channelized loading conditions can be expected due to the vehicle being able to take over steering and acceleration/deceleration capabilities in selected scenarios.

Much research deals with AV technology, including technical aspects, legal aspects and social aspects. From an infrastructure viewpoint, much focus is on the road furniture (signage, etc.). Zhang (2013) discussed a selection of aspects of adaptation required on infrastructure for automated driving. These include issues such as dynamic speed limit systems, safety messages, additional reflective lane markings, and dynamic parking inventories. No mention is made of changes required to the road pavement structure. Various other authors also mentioned the visibility and consistency of road markings and signage (De la Escalera et al., 2003; Fleyeh, 2004; Sebanja and Megherbi, 2010).

Table 1 – Levels of automation for autonomous vehicles (SAE International, 2016).

SAE level	SAE name	Narrative definition
0	Non-automated	No autonomous vehicle controls; driving can be enhanced by warning or intervention systems; human driver does all driving
1	Assisted	Human drivers control critical driving tasks; may get minor technological assistance (e.g., system assistance with operating steering, acceleration/deceleration control, stability control, cruise control, lane correction technology)
2	Partial automation	Vehicle takes over steering and acceleration/deceleration capabilities in selected scenarios; human driver still in control of vehicle at all times
3	Conditional automation	Vehicle safely controls all aspects of driving in mapped environment; human driver need to be on-board monitoring and managing changes in road environments or unforeseen scenarios
4	High automation	No human driver interaction needed; can stop if systems fail; handle driving from point A to point B in most cases; vehicle include functional driving apparatus, like wheels, brakes and gas pedals
5	Full automation	Completely autonomous; no human driver involvement or intervention

Although many AV developments focus on passenger vehicles, there are similar developments for trucks and buses (Franke et al., 1995; Ginsburg and Uygur, 2017; Petty, 2017). The major difference between passenger vehicles, trucks and buses from a road pavement viewpoint, is the higher loading that trucks and buses exerts onto the road pavement. While a typical passenger car exerts a load of around 750 kg per tire onto the road surface, a standard truck may exert a load in the region of 2250 kg per tire. Tire-pavement contact stresses also differ, with cars exerting between 220 and 600 kPa and trucks between 620 and 1320 kPa (De Beer et al., 1997; Steyn and Ilse, 2015).

The primary effect that increased use of AV may have on transport infrastructure is the lower variability in a number of parameters. These include loading levels (improved logistics systems and increased optimization in freight use), operating speeds, following distances, wander across the road width, etc. Further, the inherent safety systems should enable more frequent use of road network at night and at more productive levels (platooning of vehicles with shorter following distances). These expected lower variability of parameters, enables pavement engineers to come up with a more optimum design, construction and maintenance plans.

2.2. *Road pavement design*

Road pavement design defines the combination of material layers that make up the road structure on which traffic travels. Design, construction and maintenance of pavement structures depend on the expected traffic loading and prescribed level of service (SAPEM, 2014).

The combination of layers for a road pavement structure typically includes, from the in situ ground layer, the subgrade layers, followed by stabilized subbase layers, a combination of stabilized and/or bituminous base layers and, finally, surfacing layers. The introduction of AV into the vehicle fleet will affect the surfacing and base layers mostly, as these layers support the bulk of the stresses applied onto the pavement structure.

Although not the focus of this paper, it is interesting to evaluate some of the potential influences on the design of road pavement structure due to the application of AV. A study on the effect of channelized traffic in an accelerated pavement test as reported by Harvey et al. (2000), showed between 25% and 45% greater rutting in channelized sections as compared to sections in which the APT device moved laterally with a normal distribution. A focused strip road option can address the higher incidence of channelized load application, where materials design and construction of the wheelpaths are to a higher standard than in-between and outside of the wheelpaths. Changes to laboratory evaluation of bituminous surfacing materials can result in mix designs that cater for resultant changes in load application frequencies.

The lower wander patterns may also result in more focus on rut resistant surfacing and base material designs. The current design approaches need adaptation for these different and more concentrated types of stress application onto these layers. This will have to be in conjunction with focus on the development of potential longitudinal fatigue cracks along the channelized wheelpaths. A research work by Monismith et al. (2000) reported accelerated fatigue cracking failures by a factor of three or more due to channelized traffic on WesTrack.

Another aspect that requires investigation is the elastic deflection bowl under truck tires that are following at close distances (due to platooning). De Beer (1992) demonstrated how axle loads applied at short intervals (closely spaced axles or at higher speeds) can cause the pavement to remain in a slightly deflected condition before the next axle causes another deflection bowl. The subsequent deflection is typically higher for the subsequent loads, causing higher elastic deflections than when applications of these loads are at such frequencies that allow the pavement to rebound completely after each load application. In APT this phenomenon will depend on the spacing between following axles on the APT device and the speed at which the axle loads are applied (further discussed in Section 3.2).

An interesting phenomenon that may find application in a future world of increased AV usage is the strip road concept. This concept requires two narrow, parallel strips of constructed pavement (i.e., asphalt, concrete or improved soil) for the two wheel-tracks of vehicles using the road. The concept has been used for many years in mostly farm and rural roads (Mlambo, 1994; Wolhuter, 2015; Zhang et al., 2013). With controlled wandering possible in AV applications, an option of strip road development could save significant costs on road pavement construction and maintenance. Research would be required into the modern construction and maintenance of such roads on a high volume, as well as aspects such as the material selection and pavement design in-between the wheel-track strips. APT would be an ideal option for evaluation of such strip road options.

2.3. *Vehicle-pavement interaction*

Vehicle-pavement interaction (V-PI) describes the interaction between the applied vehicular loads and the supporting road pavement structure. Some of the effects of the operation of AV on road networks that directly affect the V-PI include:

i) Ability of the AV fleet to operate in a more channelized manner (less wander over the width of the road pavement surface);
ii) Ability of these vehicles to have much smaller following distances (platooning);
iii) More consistent operational conditions such as constant speed and less stop/start actions at intersections due to better traffic volume – intersection control management.

The summary of effects of lower and/or managed variability in mainly operational aspects of AV on road pavements is as follows.

- Wander – more focused load application and therefore increased expected permanent deformation (rut) and longitudinal cracking. This can, to an extent, be circumvented through the application of a wander pattern in the AV operations to spread vehicle loads over a wider width of the road;

- Operating speeds – vehicle operating speed affects the contact time between the load and the bituminous surfacing materials of the road. More consistency in these speeds means that the design of bituminous surfacings can be optimized to specific load frequencies sensitivity;
- Acceleration/deceleration – more consistent acceleration and deceleration as managed through the AV potential leads to lowering of longitudinal surface stresses applied to the bituminous surfacing;
- Less stop/start actions at intersections – improved control of AV flow through urban areas, combined with improved traffic light control to lower the incidence of vehicles stopping at managed intersections. This causes lower longitudinal stresses on the bituminous surfacing materials resulting in lower permanent deformation;
- Increased driving by AV at night - temperature of bituminous surfacing materials is lower during the night, resulting in higher stiffness for these materials, increased bearing capacity and expected longer pavement life.

There is potential increase and successful use of AV through increased implementation of Intelligent Transportation Systems (ITS) on road networks due to proliferation of advanced wireless communications such as the fifth generation of cellular mobile communications (5G).

These types of communications are termed Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V) or Vehicle-to-Everything (V2X), depending on the linkages used in the communication (Harding et al., 2014). It describes the communications that can occur between intelligent vehicles and the range of possible other objects that are part of the intelligent infrastructure landscape. Through such communication, one vehicle may warn other vehicles of specific issues encountered (such as heavy braking) (V2V), or, information may be communicated from road infrastructure (e.g. traffic signals) to vehicles (V2I). Increased use of sensors inside the road pavement infrastructure will enable more feedback from infrastructure to the AV. This allows for efficient operations of AV and optimum maintenance and management of the transport infrastructure. Further, guiding AV to avoid infrastructure that is in stress and/or duress before doing any maintenance, will lower potential short-term traffic induced damage on that infrastructure.

There are examples where V2X communication based on vehicle response to infrastructure condition already allow vehicles to detect road condition dynamically (Wessels and Steyn, 2015). Incorporating this information into a dynamic database will enable infrastructure to communicate to vehicles, and vehicles to road managers, regarding their instantaneous condition.

Automated route selection will lead to optimum selection and use of alternative routes. Improved logistics in loading frequency for specific vehicles, improved dynamic road condition information on V2X systems, and provision of constant traffic conditions, will lead to better selection of alternative routes. This will enable transportation of goods on more vehicle and freight friendly routes, with less potential damage caused to transported cargo (Pretorius and Steyn, 2016). However, optimum route selection will also result in more stress on these roads leading to potentially premature deterioration.

3. Accelerated pavement testing

3.1. *Background*

Accelerated pavement testing (APT) is the controlled application of a wheel loading, at or above the appropriate legal load limit, to a pavement system to determine pavement response in a compressed time. The acceleration of damage is achieved by means of increased repetitions, modified loading conditions, imposed climatic conditions (e.g., temperature and/or moisture), use of thinner pavements with a decreased structural capacity, and thus shorter design lives or a combination of these factors (Steyn, 2012).

Traditionally, APT evaluates the response of road pavements to a selection of axle loads and environmental conditions (Aguiar-Moya et al., 2016). The application of APT focuses, mostly, on the evaluation of road pavement structure. The design of the APT test plan must be in such a way that very specific research questions are addressed (Steyn and Kleyn, 2017). For example, if the permanent deformation performance of a pavement structure needs to be evaluated, the test will typically be designed to be conducted under elevated temperatures and slower moving loads, on a pavement structure with relatively fresh bituminous layers (unaged). These conditions are typically critical for permanent deformation development. However, when bituminous layer fatigue is the focus of the evaluation, the test conditions will be on colder temperatures and more aged bituminous materials. Analysis of the data obviously takes the test conditions in consideration when developing inferences from the results.

Classification of APT machines includes static and mobile, linear and circular, and uni- or bi-directional devices. The classification refers to their mode of load application to the road pavement section. The load levels, varying from around 20 to 200 kN are applied on one half of an equivalent truck axle, using either dual or single tires. The load speed ranges from creep speed to around 32 km/h (for linear systems). Loads are, typically, applied at a range of speeds up to the maximum, depending on a specific type of device. Current developments focus on the manufacturing of APT devices that can apply loads at higher speeds, as this improves the productivity of the test (more load applications in a shorter period). It also allows for more accurate elastic pavement response data, as the load speed (and pavement materials) affects the elastic pavement response (Barksdale, 1971; De Beer, 1992). There are a small selection of APT devices that can apply loads with more than one bogey to the road pavement section, allowing inter-axle distances (and therefore load frequency) to be adapted for a specific test (Steyn, 2012).

3.2. *Selected APT issues of AV*

In terms of addressing specific AV issues using APT, the focus is in those aspects identified in Section 2.3.

- **Wander** – most APT devices has the ability to set the transverse wander pattern used for application of the tire loads. The maximum width for the load applications

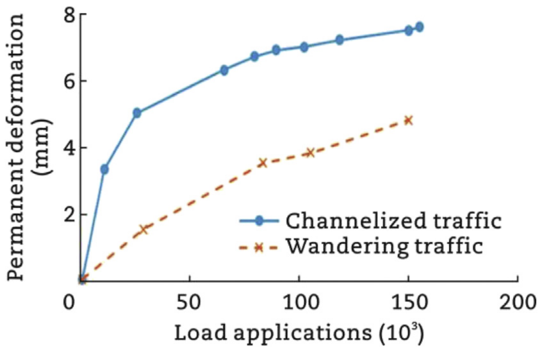

Fig. 1 – Channelized versus wandering permanent deformation response for a standard hot mix asphalt surfaced road pavement (Steyn and Fisher, 2008; Steyn, 2009).

defines the wander pattern, and a transverse step size of around 50 mm is used. Some devices can program more complicated wander patterns. With the introduction of AV vehicle fleets, it would be possible to determine the wander pattern used by the AV fleet and replicate this pattern in the APT test. This may lead to wheelpaths that are more concentrated with a channelized APT test as the result. Selection of the option for channelized or wander test patterns has been used for many years in APT evaluations (Hugo and Epps Martin, 2004; Steyn, 2012). Some of the studies indicate that

- Lateral wander caused the asphalt surfacing to move laterally during trafficking. Evidence indicate that the material could be shoved upwards when the mix was shear susceptible at high temperatures (Epps, 2001; Hugo, 1999);
- Comparison between typical wheel path permanent deformation profiles on selected highways (normal traffic wander) with wheel path profiles generated by the Texas MLS (less wander), indicated that an adjustment factor, based on the respective wheel path widths is required to match these permanent deformation development (Chen et al., 1999; Chen and Lin, 1999);
- Reductions of between 30% and 40% in permanent deformation depth was observed when lateral wander was distributed over a width of 250 mm instead of channelized (no wander) trafficking (White et al., 1999);
- Lateral wander most likely decreases the stability of unbound and weakly bound granular base materials (Chen and Abu-Farsakh, 2010);
- If loads are applied channelized (no wander) significantly faster rutting development was observed in uni-directional than in bi-directional loading mode (Tia et al., 2003);
- Finite element (FE) simulations of an APT test under both wandering and channelized traffic agreed well with typical APT observations, and indicated up to 56% decrease in permanent deformation due to application of wandering, rather than channelized traffic (Wu and Harvey, 2008).

An example of the effects of wandering versus channelized traffic on the same test section is shown in Fig. 1 (Steyn and Fisher, 2008; Steyn, 2009). The tests were conducted using a linear APT device on typical Hot Mix Asphalt (HMA) sections (same design). Results indicated that the permanent deformation caused by the channelized trafficking is around 60% higher than the permanent deformation for the same conditions (speed and temperature), but with a wandering loading pattern (Steyn and Fisher, 2008; Steyn, 2009). This phenomenon indicates that a move to more channelized load application under AV conditions can affect pavement deterioration, and that APT can, effectively, be used to quantify such effects.

Operating speeds – APT tests are normally conducted at a standard speed, which is typically selected to be the maximum speed of the device for productivity reasons. Although the speed range of most APT devices are limited (typical operating range between 8 and 32 km/h), some APT tests have been conducted at a range of speeds. Fig. 2 indicates the potential difference in deflections when applying test loads at different load speeds on an APT section (the graph is to be seen as generic as it depends heavily on the type of road pavement structure) (Steyn, 2016). Use of APT speeds close to the actual AV fleet speeds is thus essential in APT planning. Circular systems can typically operate at speeds of up to 60 km/h (Steyn, 2012). As their availability is, however, limited and the majority of APT systems are linear, the discussion in this paper focuses on linear APT systems.

The data in Fig. 2 are for a single axle, as is typically the case for APT tests. Combined with the phenomenon discussed by De Beer (1992) (Section 2.2 - pavement remaining in a slightly deflected condition before the next load application) this means that higher loading speeds will cause lower elastic deflection for individual axles if they are distributed far enough from each other not to influence previous axles' elastic deflection bowls. However, if the axles are following closely due to either shorter spacing between axles and/or higher load application speed, the combined effect would be a potentially higher total elastic deflection than the combination of single following axles. Basic pavement engineering analysis will show this phenomenon and allow the researcher to distinguish between the two clear situations of a single or a repetitive elastic surface deflection bowl.

Following distances – shorter following distances of AV fleets due to platooning can only be replicated using APT

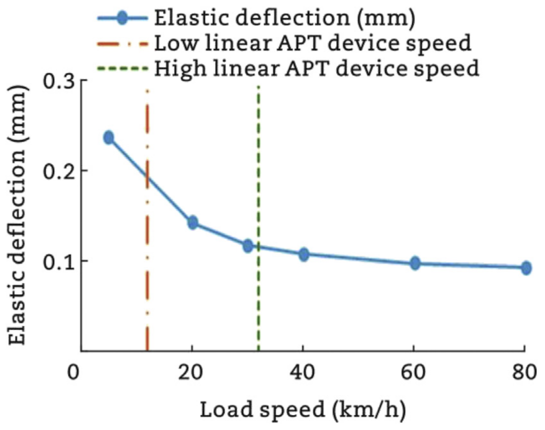

Fig. 2 – Typical (generic) elastic deflection behavior affected by speed of APT load application (Steyn, 2016).

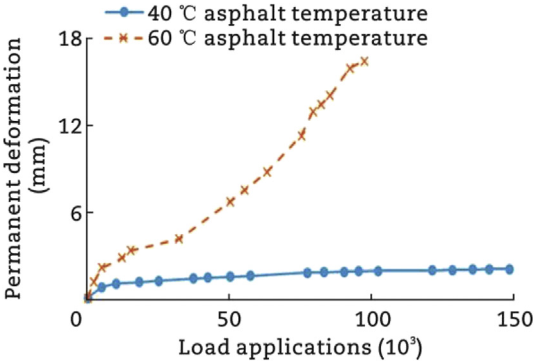

Fig. 3 – High (daytime) versus low (night-time) temperature effects on typical HMA permanent deformation under similar APT loading (Steyn and Denneman, 2008).

devices that have the ability to apply loads with a combination of loading bogeys. No changes are possible to the simulated following distances for APT devices with single loading bogeys. There is, currently, only one standard APT device that can apply this type of multi-bogey load application. For this type of APT device, the APT testing requires selection of the distance between bogeys and the operating speed to replicate the short axle intervals expected from platooning vehicles. For single bogey APT devices, the closest resemblance to platooning effects will be to relate the time between any two applications of a load repetition on any location of the test section to the expected time interval between platooning truck axles. A load speed that shortens this interval to be as close as possible to the platooning interval should then be applied.

Acceleration/deceleration and stop/start actions at intersections – APT devices typically operate at constant loading speeds and cannot simulate acceleration/deceleration loading on the short testing sections, except for the end portions of the test sections.

Increased driving by AV vehicles at night – Possible increased operation of AV fleets during the night due to safer operations through the management of the driving conditions, has a direct effect on the stiffness of the bituminous materials in the pavement structure. Typically, the surfacing and base will have higher stiffnesses, which increase the bearing capacity of the road pavement structure. This, however, can also lead to a move from more permanent deformation type failures, to fatigue type failures in the road pavement surfacings. In the APT context, the basis of temperature control of the road pavement section during testing (Steyn and Denneman, 2008) is on typical diurnal temperature distributions in bituminous layers (Denneman, 2007; McGennis et al., 1995; Viljoen, 2001). APT planning include a selection of a range of typical temperatures with pavement responses under different road conditions, to develop a more general pavement response model under expected field conditions.

Fig. 3 (Steyn and Denneman, 2008) indicates the effect of road pavement temperature (i.e., day versus night driving) on the permanent deformation of a typical HMA road pavement structure (same design). It shows around 790% higher permanent deformation under the higher temperature than the lower temperature (both channelized APT loading). These data are obviously dependent on the type of bituminous binder used in the HMA. The figure is included in this paper as illustration of the typical effects of temperature on pavement response. Similar studies evaluating increase in fatigue cracking due to loading during periods of low temperature have been reported extensively in the APT literature (Steyn, 2012).

3.3. *Data science options for APT data analysis*

In terms of the data analysis from APT for developments in AV-ready pavements, it is important to realize the options that data science techniques offer. The field of data science has grown significantly in the recent past, and techniques such as machine learning, big data analysis and deep learning are typically used to evaluate large and complex data sets to identify trends and relationships. In the general pavement engineering field, these techniques has given rise to efforts such as predicting the non-linear layer moduli of asphalt road pavement structures (Gopalakrishnan et al., 2013), modeling pavement serviceability indices (Terzi, 2006) and backcalculating pavement moduli using data mining (Mehmet et al., 2011) and asphalt mix performance prediction (Maalouf et al., 2008).

In this regard it is important to head the warning that not all patterns that are identified are necessarily valid, and that sound engineering judgment is always important to evaluate the outcomes of such approaches (Allen, 2019). Trained and experienced APT engineers are thus required to plan, conduct and interpret such data science results from the analysis of APT data.

Application of data science analysis techniques may the option to also interrogate existing databases from the various international APT programmes to harvest these completed data for new implications into application of the APT results in an AV-pavement environment. Through such a process new insights may develop based on test data that were not necessarily planned for AV-pavement analysis, but where specific aspects such as wandering and rut development have been addressed.

4. Accelerated pavement testing guidelines

Based on the literature and discussions regarding APT and the potential effects of the use of AV on the behavior and performance of road pavement structures, there are clear guidelines possible for the planning of new APT programs, and the use of data from existing APT datasets.

The possible APT test controls are the wander pattern, load magnitude, speed and test section temperature. The following guidelines are therefore applicable.

- Wander
  - Determine the wander pattern programmed for the AV fleet and replicate that on the APT test section;
  - Compare the results from existing APT data sets where both channelized and wandering tests were conducted under similar load magnitudes and environmental conditions (such as Fig. 1), to determine possible changes in road pavement responses under AV loading.

- Load magnitude
  - Load magnitude for AV fleets is expected to be higher than traditional load level limits. Limited use can thus be made of existing data sets where a range of load levels were used to determine the damage exponent for a specific road pavement structure (Kekwick, 1985);
  - Load magnitudes for new tests should be similar to the allowable AV fleet load levels – including tire type and inflation pressures.
- Load speed
  - Load speed selected at the closest to the AV fleet. If the maximum APT device speed is significantly different than the AV fleet speed, the speed-deflection response of the pavement type should be determined using real vehicles before the APT analysis is conducted;
  - Use existing data sets collected at significantly lower loading speeds with caution, if no relationships with actual vehicle speed is available. If these relationships are not incorporated, the inferences from the datasets may be quite conservative.
- Test section temperature
  - Existing APT data collected at a range of bituminous material temperatures (such as Fig. 3) can be used to evaluate the sensitivity of the local bituminous materials to temperature changes, if AV operations at night are expected;
  - Appropriate temperature regimes should be selected to ensure that new APT data reflect not only typical daytime bituminous layer response, but also expected night-time responses.
- Existing APT databases - consult datasets that resemble AV fleet conditions extensively, to enable the novel application of these datasets for improved understanding of expected AV fleet effects on existing road pavement structures.

5. Conclusions

The following conclusions are drawn from the information discussed in this paper.

- The use of AV fleets on existing road pavement infrastructure may lead to different behaviors and responses than what became the norm under non-autonomous vehicle fleets. This is mainly due to reduced wander, increased speeds and controlled loading magnitudes for AV;
- Appropriate analysis of existing APT data will contribute to the improved understanding of the expected changes in behaviors and responses of road pavement structures;
- Appropriate planning of AV operations-focused new APT is possible with existing technology to contribute to the provision of economic and durable road pavement infrastructure in future.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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