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**Design Philosophy and Requirements of Granular Wear Surface Thickness
for Bridges Subjected to Extreme Truck Load**

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ABSTRACT

With the increasing demand to build bridge systems to transport extremely heavy trucks in the mining industry, advancements in the current bridge design provisions are needed to account for the extraordinary weight and configuration of the mining trucks. There are no design provisions specifically developed to determine the granular wear surface thickness for haul road bridges. This research study proposed a design philosophy for bridge gravel wear surface design and developed a set of provisions for possible inclusion in international bridge and pavement codes. Three design requirements were developed, among which are two compulsory requirements and one optional requirement. The two compulsory design requirements include: Maintain gravel cohesion, and prevent concrete deck cracking during the passage of the design vehicle. The optional design requirement is: Minimize concrete deck cracking during the rare event of truck braking. Design recommendations and design-aids pertaining to each design requirement based on detailed analytical modeling.

Keywords: Design Aids, Finite Element, Gravel, Mechanistic Design, Mines, Haul Truck, Wear Surface

30 Introduction

31 The growing demand to increase production while reducing cost in the mining industry
32 promotes the need to design and construct bridges that convey extremely heavy mine haul
33 trucks from the ore to the processing facility via the shortest route. In addition to designing
34 for extreme static and impact loads induced by these heavy trucks, determining the thickness
35 of the gravel wear coarse layer presents a major design challenge (Oudah et al. 2016; Oudah
36 and Norlander 2016). Maintenance of the gravel surfaced haul roads supporting haul trucks
37 requires frequent grading to sustain the original surface sections and profiles. This operation
38 would be somewhat dysfunctional should the gravel surface become discontinuous when
39 approaching the concrete deck of a bridge. In addition, a required depth of gravel over a
40 bridge deck is beneficial in limiting the concentration of wheel loading and thus reducing the
41 punching shear imposed on the concrete decks under the tires.

42 AMEC Foster Wheeler (AMEC FW) Oil and Gas Calgary Office has been involved in the
43 design of a bridge system subjected to extraordinary vehicle load at one of Alberta's Oil
44 Sands mines. The bridge transports the world's heaviest mining truck CAT 797 (> 600 ton).
45 Aside from the complex design of the 135 m three-span bridge, the design of the gravel wear
46 surface was a challenging task. Extensive literature review and consultation with bridge
47 experts were conducted to examine the principle design parameters of the bridge wear
48 surface. The collected information with this regard revealed the following:

- 49 • Research regarding the response of bridges subjected to extreme load is scarce.
- 50 • North American design codes do not include guidelines regarding the design of gravel
51 wear surface subjected to extreme load.
- 52 • Surveying haul road bridges in North America suggested that the current practice of
53 wear surface thickness design is based on subjective judgement.

54 Structural analysis of the bridge designed by AMEC FW indicated a significant contribution
55 of the total maximum bridge moment and shear was attributed to the wear surface self-
56 weight. For example, the contribution of the moment induced by the gravel weight varied
57 from 13% to 40% of the total design moment for a 250 mm and 1250 mm thick gravel layer,
58 respectively, when placed on a representative composite steel girder bridge configuration. It
59 was, therefore, decided to conduct a rational design procedure to suggest a wear surface
60 thickness that can provide a robust performance while imposing the smallest impact to the
61 overall moments and shears. The Special Structures group at AMEC FW Calgary Office
62 conducted a pioneering investigation to articulate the design philosophy for a bridge gravel
63 wear surface. Design aids were developed for bridge systems conveying extremely heavy
64 mining trucks for use in design and for possible inclusion in the North American Design
65 Codes (CSA-S6, AASHTO LRFD, and AASHTO). The design aids provide simple, yet
66 rational tools for design engineers in the mining industry.

67 **Literature Review**

68 **Haul Road Surface Construction Material**

69 Most mines do not use imported materials for haul road construction to minimize the
70 construction cost. Survey results also show that 82% of mines use crushed run of mine
71 (waste) for road surface, 36% use crushed pit run gravel, while the remainder of mines use
72 shale, plant coarse reject, crushed sandstone or other material (Tannant and Regensburg
73 2001).

74 The key parameters in selecting the road surface material are the road adhesion and rolling
75 resistance factors (Thompson and Visser 2000). The former factor refers to the resistance
76 acting between the road and tire, while the latter refers to the amount of drawbar pull or
77 tractive effort required to overcome the retarding effect between the haul truck tires and the

ground. Tractive effort is typically expressed in terms of percent road grade or in terms of resistance force as a percentage of the Gross Vehicle Operating Weight (GVOW). A great number of surface mining operations in North America are utilizing gravel since it offers a stable roadway, when constructed and maintained properly, that resists deformation and provides a relatively high coefficient of road adhesion, 0.55 to 0.85 (Kaufman and Ault 1977), and low rolling resistance, 2.0 to 2.7% of road grade (Tannant and Regensburg 2001). Frequent road maintenance is required after a haul road surface is constructed. Most of the maintenance consists of periodic grading to remove small ruts and potholes that are inevitably created by passing traffic (Collins et al. 1987; Thompson and Visser 2006).

Mining Trucks

The size and capacity of haul trucks used in surface mines has grown significantly over the last decade from trucks capable of moving 20 tons of material to vehicles that transport as much as 400 tons. Truck payload capacity follows the rapid advancement in tire technology for larger trucks. A variety of haul trucks for ore and waste transportation are used by different mines. The Oil Sand mines use the largest trucks, namely; CAT 777 (100 ton), CAT 793 (240 ton), Komat'su 830E (240 ton), Komat'su 930E (320 ton or 340 ton), and CAT 797 (623 ton). Coal mines typically use trucks with smaller capacities, approximately 220 ton, while smaller mining operations use trucks with payload capacities under 110 ton (Tannant and Regensburg 2001).

Large haul trucks typically have two axles with four tires on the rear axle to provide better manoeuvrability and a tighter steering radius. The design of tires is the limiting factor in the design of larger haul trucks, as larger gross weights imply higher load per tire (reaching up to 100 ton per tire).

101 **Construction Practices versus Design Methods**

102 The design of haul roads has not advanced at the same rate as the rapid development in the
103 haul truck payload. Road-building technology from the early 70s is still being practiced today
104 (Kaufman and Ault 1977). Haul road designs were entirely empirical until the early 1980s
105 when the California Bearing Ratio (CBR) cover thickness design technique emerged. Despite
106 the empirical nature of the technique, a mathematical approach to the calculation of the wear
107 surface thickness was derived. This conventional design approach characterizes the bearing
108 capacity of a given soil layer as a percentage of the bearing capacity of a standard-crushed
109 aggregate (Thompson and Visser 1996; Thompson 1996). The bearing capacity of each layer
110 is determined in accordance with ASTM D1883. The soil thickness is calculated based on the
111 wheel load and the soil CBR ratio. The CBR approach is simple, but it encounters numerous
112 disadvantages. The method assumes a constant elastic modulus for the layers of different
113 materials, although each material has its own engineering properties. It is based
114 fundamentally on empirical results applied to public roads subjected to a maximum axle load
115 of 80 kN.

116 Developments over recent decades have offered an opportunity for more rational-based and
117 rigorous haul road design procedures. The Mechanistic Design approach was developed
118 based on the theories of mechanics and relates the road structural behavior and performance
119 to traffic loading and environmental influences (Thompson and Visser 1997a; Thompson and
120 Visser 1997b). This method is a hybrid, for practicality purposes, in the sense that empirical
121 models are used to fill in the gaps that exist between the theory of mechanics and the
122 performance of the road. Finite Element (FE) layered elastic models are used to examine the
123 distribution of stress and strains within the soil layers in the Mechanistic design approach.
124 The vertical stress and strain are limited to predefined critical limits. The critical stress
125 corresponds to the ultimate compressive capacity of the gravel layer while the critical strain

126 corresponds to the strain at which the gravel starts to loose structural integrity and degrades.
127 The modulus of resilience, required to define the elastic properties of the road material, can
128 be determined empirically using the AASHTO 1993 code, repeated load lab testing, or from
129 back-analysis of in-situ Falling Weight Deflectometer (FWD) testing.

130 **Design Philosophy**

131 The proposed philosophy of designing the thickness of the gravel wear surface subjected to
132 an extreme truck load is composed of fulfilling two compulsory requirements, and the
133 optional fulfillment of a third requirement;

- 134 • *Compulsory requirement No. 1: Maintain gravel cohesion and integrity.* This design
135 requirement is concerned with determining the minimum gravel dry density that will
136 prevent the loss of the gravel soil integrity under the combined action of tire load and
137 increased water content in the gravel layer.
- 138 • *Compulsory requirement No. 2: Prevent concrete deck cracking during the passage of*
139 *the design vehicle.* This design requirement is concerned with maintaining an un-
140 cracked concrete deck during the passage of the design vehicle at a constant speed
141 (i.e. primarily prevent punching shear of the concrete deck due to tire load).
- 142 • *Optional requirement No. 3: Minimize concrete deck cracking during the rare event*
143 *of truck braking.* Industrial traffic typically travels at a constant speed with a
144 predetermined frequency. No traffic jam or congestion is anticipated to occur in
145 industrial traffic. Braking of industrial traffic over the bridge would typically take
146 place in emergency events such as vehicle drifting. Depending on the site-specific
147 conditions and the bridge design criteria, the design engineers have to determine the
148 applicability of this design requirement and the necessity of implementing it in the
149 design of the bridge. This optional design requirement prevents excessive concrete

150 deck cracking and ensures that the crack width is maintained below the bridge code
151 design requirements during the braking event. Minimizing the concrete deck cracking,
152 rather than preventing it from happening, was determined as an appropriate
153 proportional response to the extreme rare event of vehicle braking.

154 The above mentioned design requirements were investigated analytically in this research. The
155 first design requirement was established using the Mechanistic Design approach. The second
156 and third design requirements were established via Finite Element simulation of the tire load
157 applied to a bridge wear surface. The detailed descriptions of the previously mentioned
158 approaches in relation to the design requirements are discussed in the following sections.

159 **Design Vehicle**

160 The work presented herein was conducted based on the vehicular characteristics of the CAT
161 797 (Caterpillar 2013), which is typically used in Canada's Oil Sand mining industry. The
162 623 ton haul truck represents the heaviest vehicle conveying ore and waste in Western
163 Canada. The configuration of the design vehicle is shown in Figure 1. The specified GVOW
164 of the two axle truck is 623 ton with a load per tire of 104 ton. The foot print area and tire
165 pressure represent two important elements in the design of wear surface depth. The tires of
166 the CAT797 truck (59/80R63), manufactured by Michelin or Bridgstone, have a foot print,
167 approximated as rectangle, of 1.15 m x 1.5 m and an inflation pressure of 600 kPa. The high
168 tire pressure places great stresses on the road surface while the large foot print area induces a
169 stress bulb extending deep into the wear layer resulting in the need for a well-designed and
170 well-compacted surface layer with sufficient bearing capacity and stiffness.

Design Requirement No. 1: Maintain gravel cohesion and integrity

The Mechanistic design approach was implemented to study the influence of varying both the thickness and the dry density (or water content) of the wear surface on the gravel cohesion. The fundamentals of this method, primarily used in the design of road pavement, are also applicable for the design of a gravel layer placed on a bridge concrete deck. The method controls the vertical stresses and strains in the gravel layer below critical limits. Two parameters are controlled by the Mechanistic Design approach; compressive stress and compressive strain in the gravel layer under the tire. The former parameter is concerned with the bearing capacity of the soil while the latter is concerned with the cohesion of the soil. In this context, cohesion is defined as the ability of the soil to maintain its integrity and it is controlled by the strain and stress state in the gravel wear surface layer. If the stress and/or strain exceed threshold values, the soil loses its cohesion and can no longer support the vehicle weight. The results drawn from this analysis will be used to suggest a minimum gravel dry density that is needed to sustain the functionality of the wear surface.

For well-compacted good quality gravel, the bearing capacity should not be a concern due to the low compressive stress applied onto the gravel layer. In fact, test results indicate a stress factor of safety around 6 for a typical crushed-aggregate surface layer (Tannant and Regensburg 2001). An upper compressive strain limit of 0.002 is generally adopted for design purposes while strains exceeding 0.0025 are usually associated with unacceptable structural performance (Tannant and Regensburg 2001).

A comprehensive sensitivity analysis was conducted to examine the influence of several design parameters on the variation of the vertical compressive strain in the gravel layer. The following parameters were considered in the sensitivity analysis: Concrete deck thickness, concrete compressive strength, gravel density, gravel layer thickness, and gravel-concrete

deck interaction. The concrete deck thickness ranges between 500 mm and 600 mm. The concrete compressive strength ranges between 40 MPa and 60 MPa. Three gravel dry densities were considered; 98% (target compaction level), 95% and 92%. The decrease in the gravel dry density simulates the poor quality compaction or increase in water content. The gravel layer thickness ranges between 200 mm to 1500 mm. Unlike the conventional design of haul mine design roads, the gravel layer is resting on top of a concrete deck in bridges. Two extreme conditions were considered to simulate the gravel-concrete deck interaction; Full adhesion and No adhesion. The former condition corresponds to the situation in which the stresses are fully transferable between the gravel and the concrete deck, while the latter corresponds to the situation in which there is no traction between the two layers. The latter condition is also applicable when water is trapped between the concrete and gravel layer due to poor drainage.

Mechanistic Design Approach

Geometry and Boundary Conditions

Two-D FE models were developed and used to examine the strain distribution as shown in Figure 2. The gravel layer subjected to the tire load of the rear axle was considered in the FE simulation since it represents the most critical region. Due to the symmetric nature of the wheel loading about the longitudinal axes of the vehicle, only two tires were modeled. The applied tire pressure was 600 kPa based on the maximum tire inflation pressure of 59/80R63 tires used in CAT 797 trucks. The boundaries of the FE model extended for 1.0 times the width of the tire measured from the outside edges of the tire foot print (Tannat and Regensburg 2001). The width of the FE model was determined based on a sensitivity analysis. The stress bulb vanishes near the side boundaries of the model, and hence, the model implicitly accounts for the confinement effect. Mesh sensitivity analysis was

conducted to optimize the mesh density. Fully integrated plane strain linear brick elements were used in modeling the system.

In the Full adhesion FE model, both the gravel layer and the concrete deck were modeled with a perfect bond at the gravel-concrete interface i.e. full transfer of stresses between the two layers. The concrete deck was supported by roller supports. In the No adhesion FE model, only the gravel layer was modeled and it was supported by roller supports to simulate the sliding of the gravel layer over a stiff surface i.e. concrete deck.

Material Constitutive models

The modulus of elasticity, Poisson's ratio, and unit density were 330 MPa (Tannant and Regensburg 2001), 0.4 (Tannant and Regensburg 2001), and 2150 kg/m³ (Van Wieren and Anderson 1990), respectively, for the gravel layer. The modulus of elasticity of the concrete deck was calculated as a function of the concrete compressive strength $4500 f_c^{1/2}$ (CSA-S6-14). The Poisson's ratio and unit density of the concrete material were 0.2 and 2400 kg/m³ (Wight and MacGregor 2007), respectively.

Results and Discussion

Varying the thickness and the compressive strength of the concrete deck was found to have negligible effect on the response of the models, and hence, their effect is not examined in the remainder of this study. The decrease in the unit dry density of the gravel layer and the concrete deck-gravel interaction have significant impacts on the system response. The variation of the vertical compressive strain in the gravel layer as a function of the gravel layer thickness and the gravel-concrete deck interface assumption are shown in Figures 3-5. Two curves were plotted in each figure; with concrete deck (full adhesion with concrete) and without concrete deck (no adhesion with concrete). Assuming that the applied stresses on the gravel surface fully transfers to the concrete deck yields 33%, on average, lower maximum

vertical strain than if the no adhesion between the two layers was assumed. The no adhesion with concrete curve represents the upper bound solution while the full adhesion represents the lower bound solution to the problem. It is believed that the real behavior is somewhat in between those two extreme boundary condition scenarios.

Requirement No. 1: Maintain gravel cohesion and integrity implies maintaining the strain range, bounded by the extreme boundary condition scenarios, below the critical strain limit of 0.002. The strain range is lower than the critical strain limit in both the 98% and the 95% dry density but higher than the critical strain for the 92% compaction. The change in the unit density is manifested by the reduction of the gravel modulus of elasticity (an 8% drop in dry density leads to a 37% drop in the gravel modulus of elasticity (Hopkins et al. 2007)). The increase in the thickness of the gravel layer has a minor effect on decreasing the strain range. The granular surface layer is recommended to meet the test requirements of MicroDeval loss test to ensure durability requirements. Furthermore, high resistance to impact and abrasion is a mandatory requirement for the selection and quality-control of the granular surface material.

It was concluded that varying the wear surface thickness has a negligible influence on its cohesion while the gravel unit dry density has the most significant impact on the response of the system. Consequently, the Mechanistic design approach does not predict a minimum gravel thickness. The wear surface granular layer is a manufactured product, and the water contact can be typically controlled to achieve a minimum of 100% to 98% compaction level. Nonetheless, severe weather conditions, poor drainage system, or poor bridge maintenance may increase the water contact in the wear surface layer, which leads to a drop in the compaction level. The analysis results suggest that the wear surface shall be compacted to at least a 98% compaction level, while the dry density of the gravel layer should not drop

267 beyond 95% of Standard Proctor maximum dry density at any time during the surface life of
268 the bridge.

269 **Design Requirement No. 2: Prevent concrete deck cracking during the**
270 **passage of the design vehicle**

271 A primary purpose of using a granular wear surface on the bridge deck is to distribute wheel
272 loads over a greater area in addition to providing continuity of surface with the haul road.
273 Load distribution is necessary to avoid areas of stress concentrations and punching shear
274 failure of the concrete deck due to elevated tensile stress within the concrete deck. Advances
275 in computational mechanics and in the computers available for performing the calculations
276 have greatly improved our ability to examine the road surface response under moving static
277 and dynamic vehicular load. Detailed FE analysis was conducted to determine the impact of
278 gravel thickness on the tri-axial stress state in the gravel layer and the concrete bridge deck.
279 Sensitivity analysis was conducted with regard to the concrete deck thickness, gravel layer
280 thickness, and concrete deck post-tensioning to develop design aids that server the purpose of
281 this design requirement.

282 **Finite Element Approach**

283 *Geometry and Boundary Conditions*

284 Representative FE models were developed using LS-DYNA software to examine the
285 application of the tire load on the response of the gravel layer and the concrete deck. The
286 geometry and the boundary conditions of the FE models are shown in Figure 6 and 7
287 respectively. The plane area of the FE models was 6 m x 6 m. The thickness of the concrete
288 deck varied from 300 mm to 500 mm, while the thickness of the gravel layer varied from 400
289 mm to 1500 mm. The bridge girder spacing was 3 m, which represents the typical girder
290 spacing in bridges used to transport industrial traffic. The vertical translational degrees of

freedom were constrained at two parallel lines at the deck soffit resembling the boundary condition imposed by the bridge girders. Similarly, roller supports were positioned at the transverse and longitudinal boundaries of the gravel layer in order to simulate the confining effect of adjacent gravel volume. The concrete deck and the gravel layer were modeled using constant stress solid elements with an hour glassing option. Mesh sensitivity analysis was used to determine the optimum number of elements in the model.

The Michelin 59/80R63 tire consists of a tread, carcass, belts, bead, and wheel ring. Only the tread, the belts, and the wheel ring were modeled since they control the stiffness and the response of the moving tire as shown in Figure 8. The wheel ring was modeled as rigid elements. The tread belts, and wheel ring were modeled using Belytschko-Tsay shell elements with two through-section integration points. The thicknesses of the tread, belt, and wheel ring were 127 mm, 20 mm, and 20 mm, respectively, based on design specifications (Bridgestone 2015). The truck was positioned in the middle of the gravel and concrete FE models to produce the maximum bending on the concrete deck.

The interaction between the concrete and gravel layers was modeled as a surface-to-surface contact with a coefficient of friction of 0.55 (Paikowsky et al. 2010). The coefficient of friction of the tire-gravel interface was 0.35 (Noon 1994). The equivalent post-tensioning stress applied to the concrete deck, as shown in Figure 7, is discussed in the Load Application section.

Material Constitutive Models

The gravel was modeled using the Drucker-Prager material model. The model takes into account the confining effect in enhancing the gravel capacity and enables the shape of the surface to be distorted into a more realistic definition for soils. The gravel density was set to 2200 kg/m³ (CSA-S6-14). The elastic shear modulus, Poisson's ratio, and angle of friction

315 were 69 MPa, 0.25, and 1.0122 rad (Reid et al. 2004), respectively, while the cohesion value
316 was 0.05 MPa (Wu and Thomson 2007).

317 The response of the gravel material model was validated using FE simulation against
318 experimental behavior of granular soils subjected to the tri-axial state of stress conducted by
319 Verdugo and Hoz (2006). Series of Isotropically consolidated drained (CID) triaxial
320 compression tests were conducted at confining pressures in the range of 200 to 600 kPa on
321 samples with height/diameter ratio of 2. Tests were conducted in strain-controlled manner
322 with a deformation rate of 0.1%/min. The samples were prepared by the method of wet
323 tamping using distilled water in a proportion of 5% in weight, and were compacted to an
324 initial relative density of 70-80%. The cylindrical samples were modeled using constant
325 stress solid elements with an hour glassing option using the above mentioned material
326 mechanical properties. The results of the FE gravel model are compared with the
327 experimental test results in Figure 9. The FE and experimental data were plotted in terms of
328 deviatoric stress versus axial strain. The stiffness, strength, and ultimate strain of the FE
329 simulation are, in general, in good agreement with the experimental test results. The Drucker-
330 Prager material model along with the assigned mechanical properties were, therefore,
331 validated against the mechanical response of compacted granular material under tri-axial state
332 of compressive stresses.

333 The concrete was modeled using the Winfrith Concrete Model, which is a basic plasticity
334 model that includes strain softening in tension, strain rate effects, and confining effects. The
335 assigned concrete density was 2400 kg/m³ while the Poisson's ratio was 0.2 (Wight and
336 MacGregor 2009). The assigned concrete compressive strength was 60 MPa and the modulus
337 of elasticity was 32.1 GPa (CSA-S6-14). The material model was validated against the
338 response of concrete cylinders subjected to confining pressure as detailed in Schwer (2010).

The tire tread was modeled as an elastic material with a density of 910 kg/m^3 , modulus of elasticity of 50 MPa, and Poisson's ratio of 0.3 (Reid 2001). The steel belt and the wheel ring were modeled as elastic materials with a density of 7800 kg/m^3 , modulus of elasticity of 200 GPa, and Poisson's ratio of 0.3 (Reid 2001).

Load Application

Oudah and Norlander (2016) conducted extensive sensitivity analysis to examine the dynamic response of bridge systems subjected to extremely heavy mining trucks. The analysis results recommended a Dynamic Load Allowance (DLA) value of 0.19 for the design of bridges conveying CAT 797 trucks. In this study, the specified GVOW of the CAT 797 was factored up by 19% to account for the dynamic response of the moving vehicle over the bridge surface. One-sixth of the factored GVOW was assigned to the wheel ring.

The wheel inflation and application of tire self-weight, gravel self-weight, concrete self-weight, and transverse concrete post-tensioning were applied during the explicit dynamic relaxation phase. The explicit dynamic relaxation phase is a transient analysis phase that precedes regular transient analysis and is typically used to preload a model before onset of transient loading. The explicit dynamic relaxation phase terminates and the solution automatically proceeds to the transient analysis phase when the distortional kinetic energy is sufficiently reduced, i.e. the solution undergoes a form of damping during this phase.

The wheel inflation was conducted using AIRBAG_SIMPLE_PRESSURE_VOLUME card in LS-DYNA. The applied inflation pressure was calculated as follows:

$$Pressure = \beta \frac{CN}{Relative Volume}$$

(1)

$$\text{Relative Volume} = \frac{\text{Current Volume}}{\text{Initial Volume}}$$

(2)

The constant CN was set to 0.00032 (Reid 2001), while the scale factor β was set to unity.

The concrete deck is typically composed of concrete panels connected to each other and post-tensioned longitudinally and transversely. Three scenarios were considered with regard to the concrete deck post-tensioning; zero post-tensioning, post-tensioning with 12.7 mm 7-wire 1860 MPa strands spaced at 300 mm and post-tensioned to 70% at transfer, 12.7 mm 7-wire 1860 MPa strands spaced at 150 mm and post-tensioned to 70% at transfer. The former and latter post-tensioning levels correspond to uniform stresses of 1 MPa and 2 MPa, respectively, applied uniformly on the transverse face of the concrete deck as shown in Figure 7. The post-tensioning was applied during the explicit dynamic relaxation phase.

Results and Discussion

The results of the sensitivity analysis are presented in terms of design aids developed specifically to facilitate a practical design procedure of the gravel wear surface in accordance to the Design Requirement No. 2: Prevent concrete cracking during the passage of the design vehicle. The design-aid diagrams in Figures 10-12 are illustrated in terms of the concrete tensile stress level at the bottom of the concrete deck versus the thickness of the gravel layer. Three figures were generated corresponding to the previously mentioned concrete deck transverse post-tensioning scenarios. For each post-tensioning level, three concrete deck thicknesses were considered; 400 mm, 450 mm, and 500 mm. Linear interpolation between the figures is permitted should the desired post-tensioning level and/or the concrete deck thickness do not fall within the ones included in the figures.

383 The design curves shown in Figures 10-12 were developed based on the FE analysis results
384 and factored up for design purposes in accordance to the following procedure. The curves
385 were developed as the summation of the FE results and three standard deviations ($FE+3\sigma$).
386 The addition of three standard deviations to the mean value of the FE results establishes a
387 99% level of confidence in the design of the gravel wear surface thickness, assuming a
388 normal distribution of the FE results. This procedure accounts for the variance between the
389 FE analysis results, given the assumptions adopted in developing the models, and the actual
390 behavior of concrete bridge decks. The variance corresponds to a coefficient of variation of
391 0.05 (Ellingwood et al. 1980). Thus, the $FE+3\sigma$ represents a more reliable measure for design
392 purposes.

393 Based the proposed design-aids, design engineers shall follow the following steps in
394 designing the thickness of the gravel wear surface to satisfy the Design Requirement No. 2:

- 395 1. Select the design post-tensioning level (graph ordinate).
- 396 2. Select the concrete deck compressive strength f'_c .
- 397 3. Select the concrete deck thickness (graph abscissa).
- 398 4. The intersection of the inclined concrete deck thickness curve with the horizontal line
399 representing the concrete capacity suggests the minimum thickness of gravel wearing
400 surface for design purposes.

401 For example, for a 450 mm thick concrete deck, 60 MPa concrete deck compressive strength,
402 and 12.7 mm 7-wire 1860 MPa strands spaced at 300 mm and post-tensioned to 70% at
403 transfer (1MPa reaction stress), the minimum design gravel thickness that is needed to avoid
404 cracking in the concrete deck under vehicle load is 450 mm.

Design Requirement No. 3: Minimize concrete deck cracking during the rare event of truck braking

The concrete deck-wear surface-vehicle dynamic interaction during the braking event of CAT 797 vehicle is a complex phenomenon due to the involvement of several influential parameters in the dynamic response of the system. As such, advanced nonlinear Finite Element simulation was conducted to examine the response behavior of the wear surface gravel layer to fulfil the optional Design Requirement No. 3. The objective of the FE analysis was to propose a gravel thickness design factor that satisfy the philosophy of the Design Requirement No. 3. The design factor shall be applied to the gravel thickness determined based on Design Requirement No. 2.

Typical configuration of concrete thickness, gravel thickness, and transverse post-tensioning designed in accordance to the Design Requirement No. 2 (refer to design aids shown in Figure 10-12) were considered in the FE simulation. The configuration has 450 mm concrete deck, 500 mm gravel layer, and 1 MPa equivalent transverse post-tensioning.

Finite Element Approach

Geometry and Boundary Conditions

The geometry and the boundary conditions of the FE braking model were similar to those used in examining Design Requirement No. 2, except for the longitudinal dimension of the concrete deck and the gravel layer. The length of the two layers were extended for 60 m as shown in Figure 13.

Material Constitutive Models

The material constitutive models of the concrete deck, gravel wear surface, and tire were similar to those used in conducting the FE analysis pertaining to Design Requirement No. 2.

428 *Load Application*

429 The concrete self-weight, gravel self-weight, tire load, and concrete deck transverse post-
430 tensioning were applied during the explicit dynamic relaxation phase. Additional pulse force
431 generated due to the tendency of the vehicle to overturn about its center of gravity, referred to
432 as the pitch effect, was applied in the proceeding transit dynamic phase. The pitch force was
433 calculated using simple mechanics given the dimensional properties of the vehicle, speed, and
434 surface friction. The pitch force was found to be 0.57 times the vehicle's weight distributed to
435 the front axle. The wheel ring was subjected to an initial translational velocity and angular
436 velocity about the rotational axis corresponding to the maximum truck speed (18.8 m/s) in the
437 transit phase.

438 **Results and Discussion**

439 The FE braking model was first validated against a simple mechanics-based analytical
440 solution. Given the vehicle dimensions, mass, and tire-to-gravel friction, the braking
441 deceleration and distance were calculated as 5.4 m/s^2 and 32.6 m, respectively, based on the
442 mechanics-based analytical solution. The percentage difference between the aforementioned
443 values and the ones obtained from running the FE braking model was 4% and 9% for the
444 braking deceleration and braking distance, respectively. Therefore, the FE braking model was
445 reasonably accurate in predicting the response of the gravel, concrete, and tire interactions.

446 Analysis results show a significant increase in the stress level at the deck soffit as illustrated
447 in Figure 14 for a travel time of 1 second. Snapshots of the braking event are also shown in
448 the figure for multiple time periods. The static stresses were increased by 110% at the peak
449 braking force. This is attributed to the fact that the dynamic impact force generated by
450 braking of the CAT 797 is approximately 114% times the static force. This elevated vertical
451 force is due to the pulse induced by the pitching effect on the front wheels.

The gravel thickness and/or the concrete deck thickness required to maintain an un-cracked concrete deck is extremely large in the event of vehicle braking. Preliminary results indicate a minimum gravel thickness of 1850 mm required to maintain an un-cracked 500 mm thick concrete deck. This extraordinary thick gravel layer will place tremendous dead weight on the structure and results in significant material and construction costs even though the probability of a truck braking hard over the bridge is extremely low. As such, the design criterion under braking action is stated as follows:

Localized cracking at the bottom of the concrete deck is allowed to occur under the extreme event of braking given that the crack width is maintained below the maximum crack width at serviceability limit state specified by the bridge code CSA S6-14.

The maximum crack width permitted by CSA S6-14 for a prestressed concrete deck at the serviceability limit state is 0.15 mm (Clause 8.12.3.1). Based on the strain gradient in the concrete deck, the analysis results indicate a minimum gravel thickness of 700 mm to maintain crack widths below the maximum limit. Thus, a design factor of 1.55 shall be applied to the gravel wear surface thickness determined based on the Design Requirement No. 2, if the design engineer decides to fulfil the optional Design Requirement No. 3.

Conclusions and Design Recommendations

In the absence of scientific-based studies for determining acceptable depths of a gravel wear course over concrete bridge decks under heavy haul truck traffic, this article outlined a detailed rational approach aimed at providing a basis to optimize the wear course layer thickness. A design philosophy composed of satisfying two compulsory design requirements and one optional design requirement was proposed. Advanced structural analysis including Mechanistic design and nonlinear Finite Element modeling were conducted to develop design

aids pertaining to the proposed three design requirements. The design requirements and the developed design aids are outlined as follows:

- *Compulsory Design Requirement No. 1: Maintain gravel cohesion and integrity.*

This design requirement is concerned with determining the minimum gravel dry density to maintain the integrity of the wear surface. The gravel layer shall be compacted to 98% of Standard Proctor maximum dry density. The water content shall not drop beyond 95% during the service life of the bridge.

- *Compulsory Design Requirement No. 2: Prevent concrete deck cracking during the passage of the design vehicle.*

This design requirement is concerned with maintaining an un-cracked concrete deck during the passage of the design vehicle at a constant speed. The design-aid diagrams shown in Figures 9-11 shall be used to determine the minimum gravel thickness.

- *Optional Design Requirement No. 3: Minimize concrete deck cracking during the rare event of truck braking.*

This requirement accounts for the behaviour of the bridge deck in the rare event of vehicle braking. The design engineers shall determine the applicability of this requirement based on the project-specific design criteria. A factor of 1.55 shall be applied to the gravel thickness determined based on Design Requirement No. 2.

The above-mentioned design philosophy and design requirements are recommended for consideration by the related code committees of the North American pavement and bridge design codes (CSA-S6, AASHTO LRFD, and AASHTO) to account for the increasing number of bridges designed to transport extremely heavy mining trucks. The design approach is rational-based and provides a simple tool for bridge engineers to design the thickness of bridge granular wear surface.

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Tire = Tread + Belt + Wheel Ring

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