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Editor-in-Chief SNC-Lavalin Technical Journal

Atkins Fellow, Professional Head of Bridge Engineering and Transportation Technical Director, Engineering Services

FOREWORD

Welcome to the sixth edition of our SNC-Lavalin Technical Journal, established to showcase the fantastic depth and breadth of our engineering expertise across a wide range of disciplines and domains and to demonstrate that technical excellence is at the heart of everything we do. This edition highlights the impressive work we have been doing from the planning of new assets for improved safety, sustainability and inclusivity of end-user experience, to the development of innovative designs and design methods and the optimisation of the operation of existing assets.

In the planning of new assets, we have increased the available data on LGBT+ travel behaviour and developed best practice guidance to facilitate uniform inclusive design by planning professionals. To address the safety of an increasing mix of road vehicles and light rail vehicles in transport, we have studied the severity of the consequences of side-on collisions using non-linear dynamic analysis to understand the level of risk to passengers and propose new guidance.

In design, we have assessed and applied the current state-of-the-art for use of innovative prefabricated systems and elements in bridge design to accelerate construction and limit traffic disruption. We have enabled the expansion of a landmark Hard Rock hotel through innovative design of fresh water, stormwater and wastewater facilities to minimise land take and allow continued operation of the existing hotel during construction. And on the Feeder 9 Gas Pipeline Replacement tunnelling project we have limited ground movements during tunnelling to prevent damage to a vulnerable operational high pressure gas pipeline through tightly designed control of tunnel boring machine face pressures.

In asset operation, we have evaluated adaptive algorithms in the U.K. to improve the efficiency and operation of highways ramp metering, which manages the number of vehicles joining a network at peak periods to prevent or delay traffic disruption on the main carriageway. For rail projects, we have proposed a new improved and simplified approach for assessing buckling risk of curved tracks, which builds on work published in our last Journal for straight track sections. And we have challenged traditional approaches to cyber-security through studies of human behaviour and manipulation and made recommendations for evaluating resilience with an attacker mindset.

The above examples provide only a small insight into the wealth of innovation that SNC-Lavalin creates day to day.

I hope you enjoy the selection of technical papers included in this edition as much as we have enjoyed compiling them.

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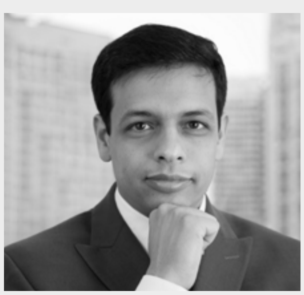

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The Seminole Hard Rock Resort
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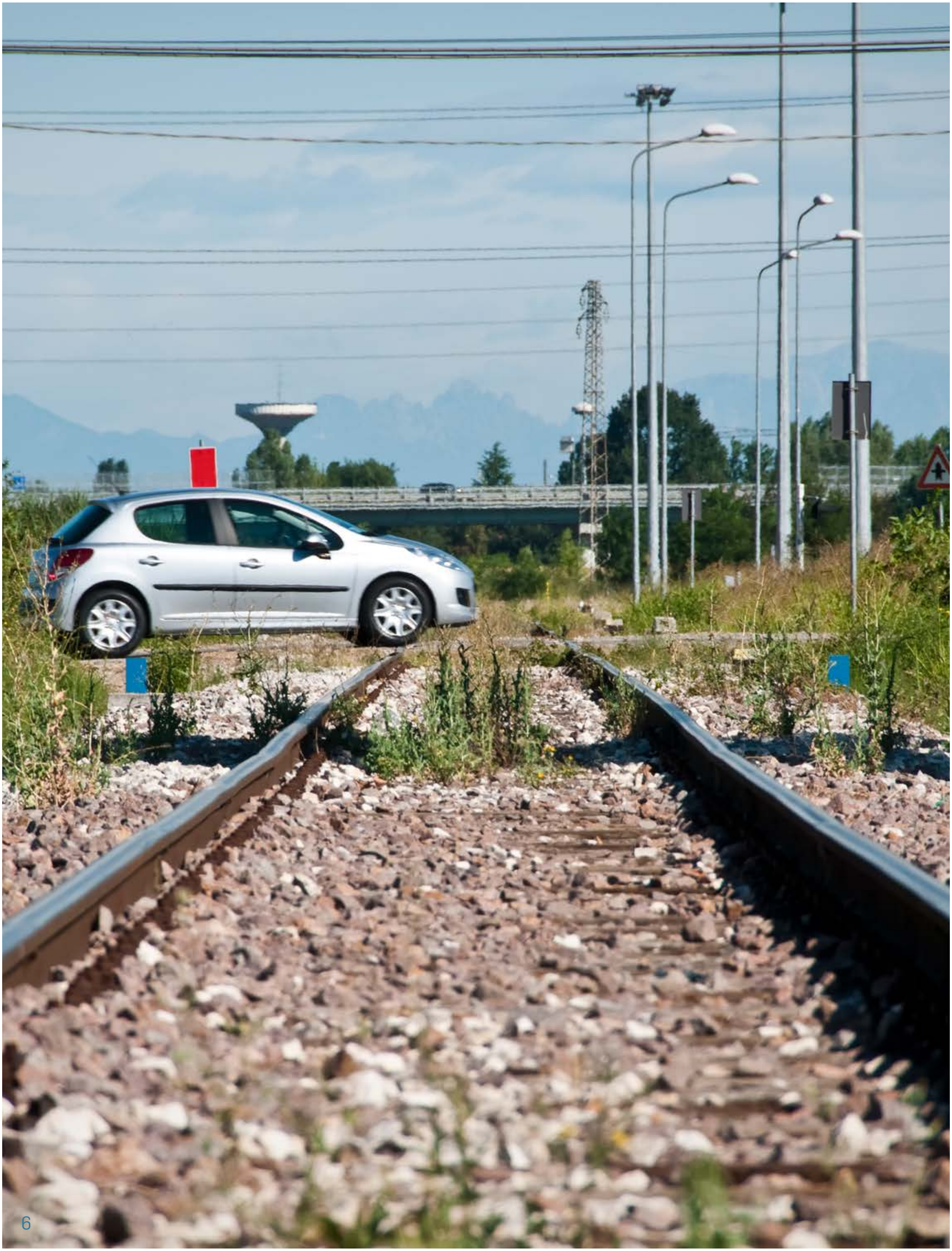


DR. JADEMOND KIANG

Senior Consultant Specialist, Engineering, Design and Project Management Sydney, Australia

01: TRANSPORTATION PLANNING, SYSTEMS AND ENGINEERING

LIGHT RAIL PASSENGERS - ARE THEY PROTECTED IN A CRASH?

ABSTRACT

This paper is a continuation of the work presented at the Light Rail 2019 Conference entitled "Creating crash-worthiness standards to protect light rail passengers". The increasing popularity of low-floor-height light rail vehicles (LRVs) is likely to result in higher accident numbers with road vehicles, including side-on impacts. High level LRV accident statistics from local and international sources are presented to anecdotally support this inference. The implication to Australian commuters is an increased risk of injury for LRV passengers. Local and international rolling stock car body design standards stipulate static load cases for assessment of side wall strength, which do not capture the relevant physics associated with a dynamic collision event. To capture the relevant physics associated with a collision event, the scenario can be accurately analysed using explicit dynamic finite element analysis (FEA) instead of static assessment. This analysis method has been regularly used by the rolling stock industry for frontal collisions and by the automotive industry for collision performance assessments. To assess the severity of the consequences of LRV-road vehicle collisions, a simulation of a side-on impact by a typical Australian road vehicle was undertaken using the explicit FEA method. The results of this simulation are presented in this paper. The LRV used for this simulation is based on a generic low-floor-height LRV representative of those found in the Australian urban light rail vehicle population. The simulations quantify and characterise the performance of the LRV, and more importantly, illustrate the severity of the consequences that side-on impacts might represent to passengers. With the rail industry and society increasingly embracing LRV technology, do we understand the level of risk to passengers and do design standards adequately mitigate these risks? This paper provides the Australian rail industry with insight into the answers to these questions.

KEYWORDS

Rail-vehicle collisions; Crash-worthiness; Light rail vehicles; Rolling stock; Safety; Risk; Finite element analysis

1. INTRODUCTION

The use of light rail vehicles (LRV) across many cities in Australia is increasing in popularity with new or expanding networks. This includes Sydney, Brisbane, Adelaide, Gold Coast, Canberra, Newcastle, Sunshine Coast and Perth. The fact that these LRVs often operate in urban mixed traffic environments, with potentially insufficient driver awareness of having to share the road with this new mode of transport, directly translates to an increased likelihood of collisions with road vehicles (thus risk to passengers).

Further contributing to the risk to passengers is the low-floor nature of these LRVs (often around 200-300mm off the ground); where the mass, centre-of-gravity and stiffness of road vehicles are at a height that corresponds to the weakest position of the LRV side wall (roughly quarter or half height), or at the most vulnerable components of passengers (waist or head level). Refer to Figure 1 for an example of low-floor-height LRV.

With these hazards inherent in this mode of public transport, it is reasonable to be curious about the potential outcomes of such collisions. Are passengers protected? What design standards, if any, cover side-on impact scenarios?

FIGURE 1

An example of low floor height LRV in mixed traffic environment (source: TfNSW)

2. STATISTICS

Melbourne has the largest light rail network in the world carrying 183 million passengers in 2012-13 [1]. Networks in other Australian cities have lower patronage as they are relatively new, less established and have less kilometres of track.

Statistics from Transport Safety Victoria [2] indicate that there is an increasing trend of road vehicles colliding with LRVs, with approximately 950 incidents in 2018 (Figure 2), the equivalent of two to three daily.

The proportion of these incidents with the LRV being the impacted vehicle is indiscernible from these statistics. However, these statistics indicate that even for a well-established network like Melbourne (where there is an established level of driver awareness/knowledge), there is still an increasing number of incidents involving road vehicles.

With less established LRV networks, it would be reasonable to expect the same trend to apply. In fact, the lack of driver awareness/knowledge (for example, in Canberra [4]) or confusion (for example, in Sydney [3]) may become a primary contributor to incidents as road users are still getting used to this new mode of transportation.

The other side of this argument is that the advent of auto-braking technology in modern road private/commercial vehicles may materially reduce, or limit the rise of, the number of collisions.

FIGURE 2

LRV/Tram collisions with road vehicles in Victoria [2]

A similar trend can also be observed for the USA, where there is an increasing number of incidents between LRV/street cars and road vehicles from 2011 to 2013 (Figure 3).

FIGURE 3

LRV/street car collisions with road vehicles in the USA [5]

-	‘11	‘12	‘13	AVG	TREND
Auto	414	421	453	429.3	---

3. CRASHWORTHINESS DESIGN STANDARDS

There are no specific rolling stock standards that address the structural dynamics of a side-on collision from a road vehicle. Rolling stock crash-worthiness standards, the most notable being EN15227 [6], mainly address frontal impact scenarios.

Local and international standards address side-on impacts indirectly with static load cases. The following are examples of such standards:

TABLE 1

Examples of local and international standards that address side wall strength

STANDARD	STATIC LOAD
ASME RT-1 (USA)	133kN side sill; 33kN belt rail
APTA PR-CS-S-034-99, Rev. 2 - Standard for the Design and Construction of Passenger Railroad Rolling Stock (USA)	178kN side sill; 31kN belt rail
RISSB AS7520.3 (Aust)	180kN sole bar; 30kN waist rail

However, assessing the static strength of an LRV does not capture the relevant physics. Static strength alone would indicate how strong a structure is under static loads. Are these loads appropriate? Are they representative of forces when a road vehicle impacts rolling stock?

It should be noted that the static loads specified in AS7520.3 are under the "roll over" section rather than specifically for side-on impacts.

Crashworthiness design standard EN15227 [6] states that the individual circumstances and collision risks of the operating environment (including mixed traffic and level crossings) need to be taken into consideration. Has the Australian rail industry considered the likelihood and severity of the consequences of road vehicle impacts? If so, how were the severity of consequences assessed? Were they based on static load cases?

Dynamic collision events require the following aspects to be captured over the time domain in order to be accurate:

- Momentum transfer;
- Mass and inertia;
- Energy dissipation;
- Large plasticity and deformation;
- Strain-rate effects;
- Friction between components in contact;
- Acceleration levels;
- Energy dissipation;

- Occupancy space intrusion;
- Post-yield and material fracture;
- Stress wave propagation; and
- Pre- and post-buckling response.

Some of these aspects are included in EN15227. However, as mentioned previously, this standard is mostly concerned with frontal impacts rather than side-on impacts from road vehicles. For side-on impact scenarios, road vehicle crash-worthiness standards such as ADR 72 [7], or engineering from first principles, may be more applicable.

In ADR 72, one of the requirements is the Head Performance Criterion, which is a function defining a limit for the allowable combined acceleration and duration acting on the passenger's head for an impact at 50km/h. Other criteria include setting limits on the force acting on the pelvis (6kN) and abdomen (2.5kN). Whilst this standard pertains to road vehicles with seated passengers, some aspects of this standard may be applicable for LRV passengers.

4. DYNAMIC COLLISIONS

As previously mentioned, the consequence of a collision, being a transient dynamic event, can be more accurately captured with simulations in the time domain, as opposed to static assessments. Simulations in the time domain are also known as dynamic simulations or dynamic FEA. What are the theoretical foundations of dynamic simulations?

4.1. Mathematical Theory of Dynamic Simulations

During static or non-dynamic events, loading is either constant or is applied slowly onto the structure, hence the dynamic effects mentioned above are either non-existent or insignificant. In such a case, the mathematical relationship between loading and structural response is simply:

$$\{F\}=[k]\{x\} \qquad \text{(Eq. 1)}$$

where
{F} is the external force vector
[k] is the stiffness matrix
{x} is the displacement vector

For a single degree-of-freedom (DOF) system (such as a linear spring loaded with a point force), all three quantities consist of single values. This is called a single DOF system.

For a more complicated system with 'n' DOFs, the force and displacement vector become a vector of dimension "n × 1". The stiffness matrix would have dimensions of "n × n".

The above system of equation can be solved by inverting the stiffness matrix ($[k]^{-1}$) and then re-arranging the equation as follows:

$$\{x\}=[k]-1\{F\} \qquad \text{(Eq. 2)}$$

Once the displacement vector is calculated, stress distribution throughout the structural system can then be computed.

In a dynamic system, the system of equation now includes the additional dynamic quantities mentioned previously, thus turning it into the following differential equation:

$$[m]\{a\}+[c]\{v\}+[k]\{x\}=\{F\} \qquad \text{(Eq. 3)}$$

where:
[m] is the mass matrix
{a} is the acceleration vector
[c] is the damping matrix
{v} is the velocity vector

Now that time is in the system of equation, the system of equation needs to be solved in the time domain as well as in the mechanical domain.

There are two mathematical schemes to solve this system of equations, namely the implicit and explicit schemes.

In the implicit scheme, the system of equations can again be solved by inverting the stiffness matrix and re-arranging the equation to obtain the structural response. For simplicity of discussion, if damping is taken out of the equation, the solution becomes:

$$\{x\}=[k]-1(\{F\}-[m]\{a\}) \qquad \text{(Eq. 4)}$$

This scheme is called the implicit scheme because the unknowns do not occur strictly on one side of the differential equation. An iterative approach is required to obtain the solution over both the time and mechanical domains.

One of the advantages of this scheme is its efficiency in solving the dynamic response of a system over a long timeframe because there is no theoretical limitation on the size of the time steps.

However, one of the major drawbacks is that the stiffness matrix needs to be inverted. Whilst this is no major issue for systems with a small number of DOFs, it is computationally expensive for detailed FEA models with large number of DOFs. Combining this with the need for multiple iterations at each time step imposes a limitation on the amount of detail that can be captured in the FEA model in practice.

The explicit scheme on the other hand is more efficient at solving FEA models with greater details (such as full train-on-train collisions), provided that the time-frame of the dynamic event is short (such as in a collision). This is because the explicit scheme does not involve the inversion of the stiffness matrix nor does it require iterations to find a solution at each time step. This makes it less computationally intensive than the implicit scheme (for a given amount of model detail).

Mathematically, unknown quantities in the explicit scheme are defined by known quantities and therefore the solution can be explicitly defined (hence the name). Therefore, no iterations are required to obtain the solution at each time step.

In the explicit scheme, the differential equation is solved by re-arranging it into the following format and solving for acceleration directly (again, damping is taken out of the equation for simplicity of discussion):

$$\{a\}=[m]-1(\{F\}-[k]\{x\}) \quad \text{(Eq. 5)}$$

The inversion of the mass matrix is a trivial task because a lumped mass matrix is usually used for explicit schemes.

Structural response of the system (such as velocity, acceleration, stress, and strain distributions) can then be calculated from the acceleration vector at each time step.

Further technical and theoretical details related to the finite element method can readily be found in FEA literature such as Bathe [9], Cook [10] or in journals papers such as Kiang et al [11].

4.2. Can FEA Accurately Predict Structural Response?

The output of crash analysis is largely dependent on the model's assumptions and accuracy of the input parameters.

Experienced engineers who are specialists in crash-worthiness engineering and FEA would be able to make decisions on relevant assumptions, level of model detail, and modelling methodology in order to achieve meaningful and accurate outcomes within a practical model run time.

Below is an example to demonstrate a crush tube of 60mm × 60mm × t2mm. The front of the tube is collided with a rigid mass weighing approximately 100 kg travelling at approximately 27km/h. This scenario is analysed in a FEA model and compared with test data presented in Zarei [14]. The results of this comparison are presented in Figure 4 and Figure 5.

As can be seen, deformation shape and structural response of the test article and FEA prediction are in good agreement. The correlation would be even better if the exact material parameters of the test article were known.

FIGURE 4

Force-displacement response of test and FEA

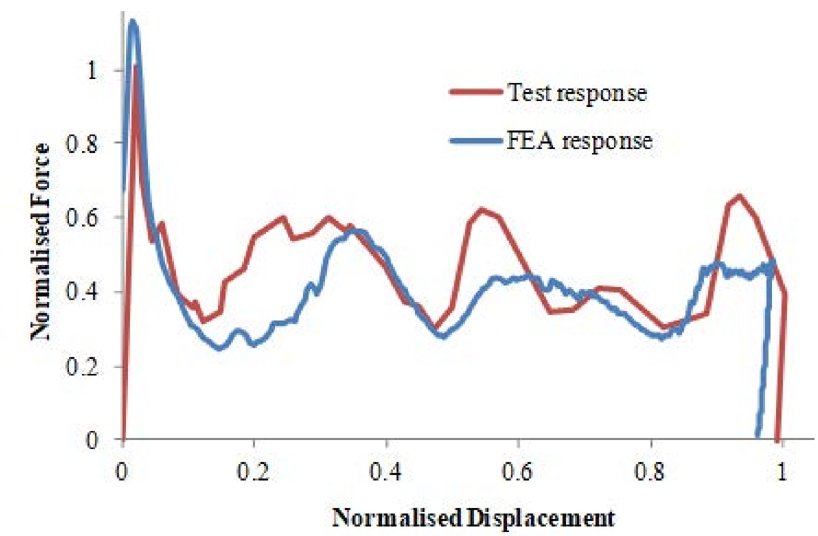
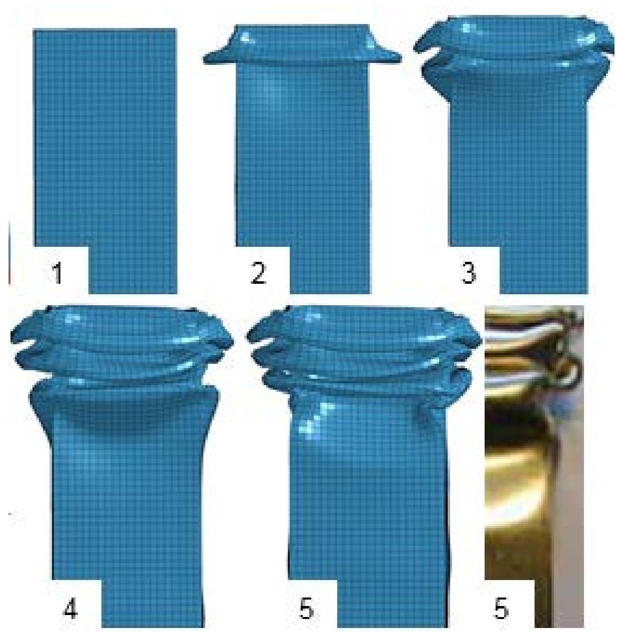


FIGURE 5

Progressive deformation of crush tube predicted by FEA compared with test (symmetric half shown)



The response of a structure in a collision, as predicted by FEA, can accurately represent the actual structure, provided that the FEA modelling approach is appropriate.

5. CONSEQUENCES OF A ROAD VEHICLE IMPACT

What happens when a road vehicle impacts the side of an LRV? To answer this question, a simulation model of a generic LRV typically found in the Australian urban vehicle population was set up. The LRV model was then impacted by a road vehicle typically found on Australian roads. The explicit FEA method was utilised and implemented using the LS-Dyna software.

Square-on impacts at 10km/h and 25km/h were simulated for this paper. Higher impact speeds and different impact orientations will be investigated in later publications.

FIGURE 6

Schematic of LRV used in this investigation; H = horizontal rotation articulation; V = vertical rotation articulation; T = torsional rotation articulation

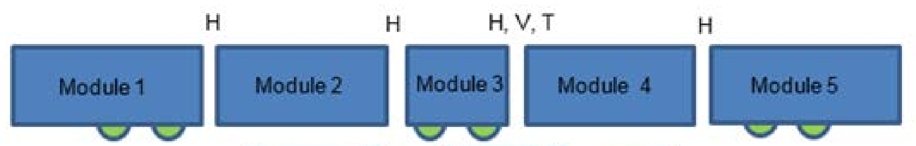


FIGURE 7

3D explicit dynamic FEA model

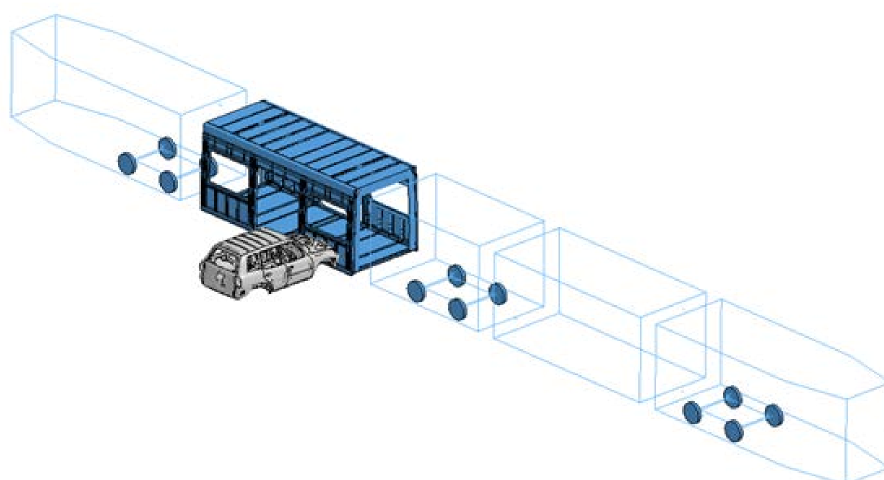
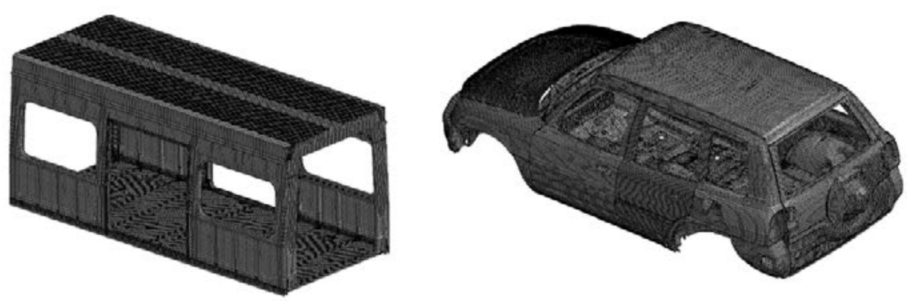


FIGURE 8

FEA mesh of LRV (Module 2) and Toyota RAV4 (not to scale)



5.1 3D FEA Model Setup

A 5-module LRV was selected. A schematic representation and 3D FEA model of the LRV are shown in Figures 6 to 8.

Typical and representative functional attributes of a 5-module LRV were used, including: mass, centre-of-gravity, rotational inertias, primary and secondary suspension, bump-stops, and inter-module articulations. The five module bodies, bogies and wheel-sets were included as separate entities in the model.

The length of the LRV is 32m with a total mass of 40 tonnes. The mass centres of the modules are between 1400mm to 1800mm above rail level (depending on the module).

Bogies are located at the first, third and fifth modules. The second and fourth modules are suspended modules.

Rotational articulation in the horizontal plane is allowed at all inter-module connections, except for one of the connections having all horizontal, vertical, and torsional rotation articulation freedom (refer to Figure 6). Centres of rotation are at the floor level.

Structural details of the second module were included. Structural details are representative of those typically found on stainless steel LRVs. The other module bodies are represented with rigid bodies.

The wheels of the LRV are supported in the vertical and lateral directions. Wheel-rail interface is not currently included in the model. This approximation may or may not be entirely appropriate depending on the tendency for wheel lift.

A Toyota RAV4 (original series) was selected as the road vehicle impacting the LRV. The Toyota RAV4 was selected not only because of their popularity on Australian roads, but also because of its high centre of mass, which is typical of increasingly popular SUV's in general. Only the body shell structural details were included. The body shell is tuned to have the correct mass, centre-of-gravity, and rotational inertias of the vehicle. The vehicle is supported at the suspension mounts in the vertical direction. The RAV4 LS-Dyna model was obtained from the National Highway Traffic Safety Administration (NHTSA) of the USA and was used as-provided except for the modifications indicated above.

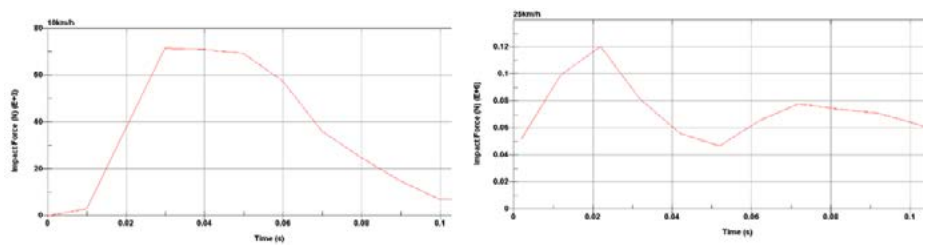
The effects of gravity were included. The model was first preloaded with gravity to pre-compress the suspension system, apply wheel loads, and to prestress the structure.

5.2 FEA Model Outcomes for 10km/h and 25km/h Impact Speeds

The peak impact forces were found to be 70 kN and 120 kN for the 10km/h and 25km/h cases, respectively. These magnitudes are above the 30 kN static load specified in RISSB AS7520.3 [12] for side walls at waist rail level. Is it time to provide further consideration to this design standard? If risk assessments of currently operating LRVs have been performed as per the requirement in EN15227, were the severities of consequences assessed based on static load cases?

FIGURE 9

Force of impact over the time domain



Impact forces over the time domain (derived from the deceleration of the RAV4) are shown in Figure 9.

For the 10km/h case, there is no tendency for wheel uplift. On the contrary, wheel loads increased during both impact scenarios (wheels “dig” into the rail). This can be attributed to the reverse rolling of the module bodies (cant rail rotates towards the impacting vehicle) rather than tipping over from the momentum of the impact. The phenomenon can be explained by the large offset in centre of mass between the LRV (1800mm above rail for Module 2) and RAV4 (800mm above ground).

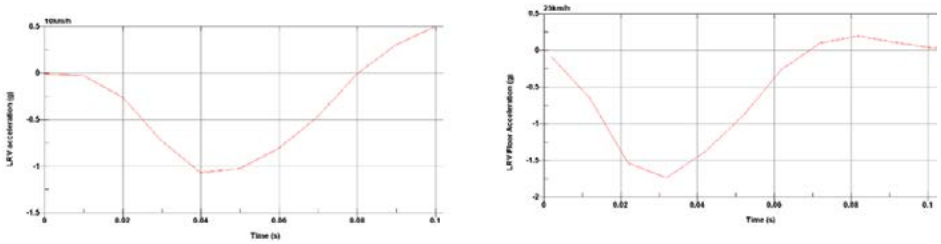
For the 10km/h case, the sum L/V ratio for the wheelset closest to the impact zone was found to be below 1.5 (acceptable criteria established in AS7509 [13]), hence likelihood of derailment is considered low and supports the boundary conditions assumption used.

However, for the 25km/h case, the sum L/V ratio was found to be over 1.5, which indicates a tendency for derailment. The results would therefore be more accurate if the wheel-rail interface contact condition was included for this impact speed.

Peak accelerations of the floor of the impacted LRV are 1g (10km/h) and 1.7g (25km/h) over a duration of approximately 80ms (Figure 10). These magnitudes of acceleration and duration can be considered benign. By comparison, the acceptance criteria for rolling stock frontal impacts are an average of 5 g or below (EN15227).

FIGURE 10

Lateral acceleration of the floor at the impact zone in time domain



Therefore, provided that passengers are not resting their heads on the side wall and that standing passengers are holding onto handrails at the time of impact, minor injury to passengers (if any) would be expected.

Maximum inward deformation of the LRV module at the impact zone was found to be 20mm (10km/h) and 70mm (25km/h). For the 10km/h case, the deformation is mostly in the elastic range. The side wall was found to have negligible residual plastic strain. For the 25km/h case, there is considerable yielding at the impact zone and base of the side wall. It should be noted that these results are based on generic structural details and thus cannot be construed as a definitive representation of actual modules. Peak stress plots are shown in Figure 11.

FIGURE 11

Plot of peak von Mises stress (MPa) (top = 10km/h; bottom = 25km/h)

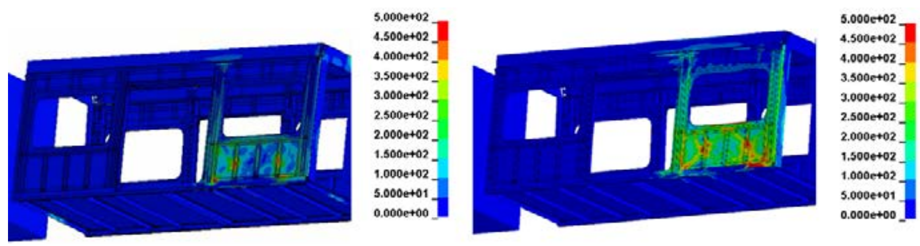
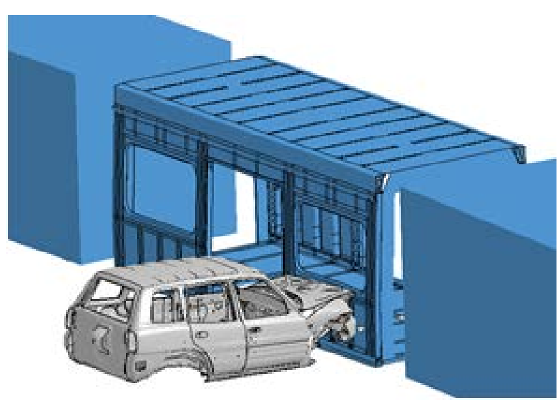


FIGURE 12

Peak deformation of the 25km/h impact scenario



The frontal compression of the RAV4 is approximately 70mm and 300mm for the 10km/h and 25km/h cases, respectively. The deformation of the RAV4 for the 25km/h case is shown in Figure 12. The deformation of the impacting vehicle and movement of the LRV suspension provided a “soft landing” for the collision energy thus sparing the LRV from significant damage.

6. DISCUSSION AND CONCLUSIONS

In both Victoria and in the USA, there is a confirmed statistical trend of an increasing number of collisions between LRVs and road vehicles. With the increasing popularity of LRVs in mixed traffic environments in Australia, coupled with human factors such as low driver awareness of this new mode of transport, it is inevitable that they will be impacted by road vehicles at some stage.

This paper has demonstrated a method of assessing the dynamics of out-of-standard side-on impacts from first principles. To investigate the severity of consequences of road vehicles impacting the side of an LRV, a 3D explicit dynamic FEA model was setup using the LS-Dyna software. A 5-module LRV (impact target) and a Toyota RAV4 (impacting vehicle) were selected as representative vehicles of the Australian urban vehicle population. The RAV4 was setup to collide with the side wall of the LRV square-on at 10km/h and 25km/h.

The peak acceleration of the floor of the impacted LRV module was found to be approximately 1 g for the 10km/h case, and 1.7 g for the 25km/h case. The likelihood of derailment is low for the 10 km/h impact as the sum L/V ratio for the most critical wheel-set is less than the acceptance criteria of 1.5 (as established in AS7509). In other words, the likelihood and/or severity of consequence from a passenger injury and infrastructure damage perspective is considered low for this impact speed.

For the 25km/h impact, there is a considerable amount of yielding in the LRV body structure, but the deformation is not significant. There is a high likelihood of derailment as the sum L/V ratio is greater than 1.5.

It was found that the dynamic impact force far exceeds the magnitude specified in RISSB AS7520.3 for side wall static strength assessment, even for a 10km/h impact. This should be noted as cause for concern.

From an LRV passenger safety perspective, the importance of understanding the effects of road vehicle collisions cannot be emphasised enough. There are currently no design standards that provide accurate design cases for such probable and conceivable scenarios. To provide the rail industry and the public with further insight, higher impact speeds (up to the ADR level of 50km/h [7]) at different impact angles and positions will be investigated and presented in future publications, as will the inclusion of anthropomorphic dummies for the purpose of personal injury assessment.

Passenger injury criteria on various parts of the human body (head, abdomen, pelvis, legs etc.) as defined by the automotive industry (such as in [8]) will be assessed for standing and sitting passengers in future publications.

The wheel-rail contact condition will also be included in future publications to capture the influence of derailment on the overall outcome of the collisions.

ACKNOWLEDGEMENTS

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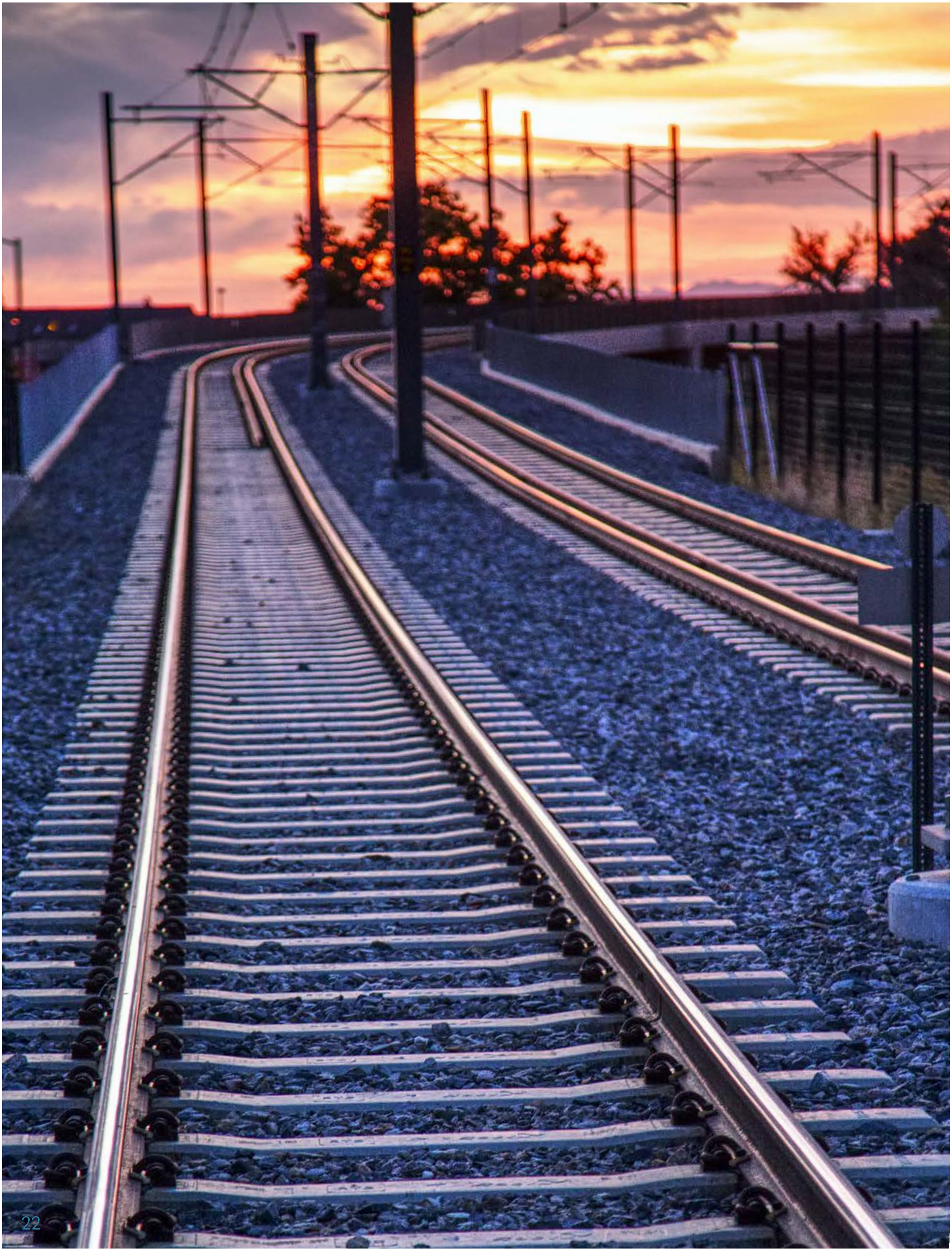


BUCKLING OF A BALLASTED CURVED TRACK UNDER UNLOADED CONDITIONS

NAZMUL HASAN

Principal track expert – Trackwork Engineering, Design and Project Management Burnaby, BC, Canada

ABSTRACT

There is no industry-accepted analytical model to compute the critical temperature differential for the buckling of an unloaded curved track in the engineering literature in North America. In this paper, the critical temperature differential for the buckling of an unloaded curved track is formulated by incorporating a value of unity for the factor of safety in the previously developed formula, which was developed considering thermal loading only. The factor of safety was the ratio between the resistance of a tie in an unloaded track against lateral displacement in the ballast and the lateral thermal load on a tie. The derived formula of the critical temperature differential for the buckling of an unloaded curved track is simple, as opposed to a complicated formula that has been endorsed in the European literature since 1969. The new formula is also validated in this paper. The critical temperature differentials for buckling of sharp and super-sharp curves have significant implications for track design and maintenance.

KEYWORDS

Buckling of track; Buckling load; Ballast resistance; Critical temperature differential; Rail neutral temperature; Thermal load

1. INTRODUCTION

A couple of field tests were conducted on tangent track from 1932 to 1966 to determine buckling load [1]. Esveld, and Hasan suggested analytical formulae to compute buckling load of a tangent track [2,3]. There is little work on buckling load of a ballasted curved track in recent literature. An analytical formula of the critical temperature differential, ΔTc, for buckling of a curved ballasted track is reviewed; this formula from 1969 is endorsed by Lichtberger [4].

Hasan presented formulas for track stability analysis against displacement in terms of factor of safety under four loading scenarios [5]. The factor of safety was the ratio between the resistance of a tie against lateral displacement in the ballast and lateral load on a tie. The loading scenarios were

Case I: Under vehicle and compressive thermal load,

Case II: Under vehicle and tensile thermal load,

Case III: Under vehicle load only (no thermal load), and

Case IV: Under thermal load only (no vehicle load).

The loading scenario in Case IV is the most critical for track shifting and buckling, as the resistance of an unloaded track is much lower than that of a loaded track. Thus, the loading under Case IV is the most relevant for studying the critical temperature differential or critical buckling load of an unloaded track. The factor of safety was the ratio between the resistance of a tie in an unloaded track against lateral displacement in the ballast and the lateral thermal load on a tie.

ΔTc for the buckling of a curved unloaded track is derived by incorporating a factor of safety equalling unity in the formula presented in the previous work for the loading scenario under Case IV so that the corresponding criteria for track design, maintenance and evaluation can be formulated. The stability of the track needs to be enhanced if ΔTc is lower than the available temperature differential, ΔT. Rail buckling temperature, sum of ΔTc and stress neutral temperature, would help to determine hot weather patrolling temperature to ensure safety of rail traffic. A track may be qualified as weak or strong depending on the value of ΔTc. The previous formula for ΔTc in the literature and its computed value are compared with the derived formula and the resulting computed value of ΔTc in this work. Both formulas are found to be functionally similar. Three reasons are offered as to why the newly derived formula is more suitable than its previous counterpart. A brief comparison is made between the new and existing formulas for the critical temperature differential of a ballasted curved track. Then, the proposed formula is applied for the different minimum radii suggested by various codes and agencies in North America and for super-sharp curves typically used in light rail transit maintenance and operation yards across Canada.

The following formula from recent literature is used to compute the critical temperature differential of a curved track [4,6]:

$$\Delta T_c = -\frac{8 \times I^*}{\alpha \times R \times f^*} + \sqrt{\left(\frac{8 \times I^*}{\alpha \times A \times R \times f^*}\right)^2 + \frac{16 \times I^* \times F_{QVW}}{\alpha^2 \times A^2 \times E \times I^*}} \quad \text{(Eq. 1)}$$

The critical buckling load is calculated by [2]

$$F_0 = A \times E \times \alpha \times \Delta T_c \quad \text{(Eq. 2)}$$

The following assumptions and data are used to calculate ΔT_C [4]:

f^* = 2cm (assumption)

Rail profile: UIC 60 (weight 60.34 kg/m, 121.64 lb/yd)

Concrete tie: B 70 W (pre-stressed concrete tie at Germany)

I^* = $2200 cm^4$

A = $2 \times 76.9 = 153.8\ cm^2$

F_{QVW} = 10 kN/m = 100 N/cm

R = 500m = 50000 cm

E = $21 \times 10^6\ N/cm^2$

α = 0.000012/°C

Equation 1 is applied with the aforementioned data for different curve radii. The results appear in Table 1

TABLE 1

Application of Eq. 1

R (M)	DOC	F_{QVW} (N/CM)	I (CM^4)	f^*(CM)	ΔT_C (°C)
50	34.9°	100	2200	2	12.8
75	23.3°	100	2200	2	19.1
100	17.5°	100	2200	2	25.1
125	14.0°	100	2200	2	31.0
150	11.6°	100	2200	2	36.6
200	8.7°	100	2200	2	47.0
250	7.0°	100	2200	2	56.2
300	5.8°	100	2200	2	64.4
500	3.5°	100	2200	2	88.2
700	2.5°	100	2200	2	102.9
Note: Rail UIC 60, A=2x76.9=153.8cm^2 in the equation 1					

An axial compression force of 2040 kN (1020 kN in each rail) may be enough to buckle a track [1]. Seven field tests on a tangent track yielded ΔT_C of 42.5–50°C corresponding to a track buckling load of 1730–2000 kN; the lower buckling load was observed on geometrically imperfect test tracks [1]. Esveld (2001) computed a critical buckling load of 2018 kN for a misaligned tangent track with UIC 60 rail exhibiting a constant lateral shear resistance of 10 kN/m; [2] the ballast resistance and rail section were same as those in the aforementioned calculation example provided by Lichtberger [4]. Temperature load of 50°C corresponds to 1800, 1906, and 2130 kN for 115 RE, UIC 60 and 136 RE rail respectively; buckling load is expected to be more but not significantly due to track grid effect. In context with aforementioned discussion, a ΔT_C of 50°C may be taken as a conservative value for buckling of a real– life tangent track. Interestingly the actual rise in temperature, ΔT, amounts to 45–50°C considering the deviations that occur in practice when rails are tensioned [2]. Buckling of a tangent track is very unlikely if the available temperature differential, ΔT is less than ΔT_C. Thus, risk of thermal buckling may be reduced or removed by setting an appropriate rail neutral temperature considering the anticipated maximum rail temperature and ballast resistance.

According to Table 1, a curved track of radius ≤ 200m exhibits a critical temperature differential of < 50°C, which seems logical and is therefore acceptable. It also appears that a curved track of radius > 200m is thermally more stable than the tangent track; however, this is confusing; ΔT_C is expected to be less than or equal to that of a tangent track i.e., ≤ 50°C. With the increase of radius, thermal load on a tie reduces but ballast resistance remains same; thus the ΔT_C for a mild or shallow curve might exceed 50°C. However, stability of a mild or shallow curve is not a concern.

A value of the equivalent moment of inertia of the UIC 60 rail track grid, I^* is given without computation [4]. Probably I^* is estimated by using beam deflection theory with assumed value of span and deflection of a buckled track beam under assumed end support condition. The equivalent moment of inertia of the UIC 60 rail track grid, I^* is estimated to be $2200cm^4$, whereas the moment of inertia of two UIC 60 rails (2I) is $1026cm^4$. This implies that the lateral stiffness of the track frame increases by 114%. The huge increase of 114% in lateral stiffness due to track grid effect is not in harmony with the following facts.

The longitudinal resistance of a track equals its lateral resistance;[4] implying that lateral bending stiffness makes no significant contribution toward the lateral resistance of the track, and almost all of the resistance is provided by the ballast. In fact, according to the American Railway Engineering and Maintenance-of-Way Association (AREMA), the longitudinal load developed by the combination of thermal stress in a continuously welded rail and due to traffic is restrained by the mass internal friction of the ballast [7]. Dogneton showed that 23 factors influence the lateral resistance of a track, and he mentioned that tie spacing has little or no influence [8]. Zarembski also compiled a list of 23 parameters that influence lateral displacement resistance, and the list excluded tie spacing [9]. Logically, the track grid cannot influence ballast resistance significantly when tie spacing does not. The torsional rigidity of the track grid exerts a minor influence on lateral resistance [9]. The stiffness of the rail–tie structure does not play a very important role in the lateral rigidity of the entire track. The track frame contributes 5–10% of the lateral resistance of the track [2]. It has been estimated that an increase in the ballast resistance by 10% is sufficient to compensate for the differences in stiffness of tested track panels [10]. The calculated moment of inertia of a track grid, I^* of 2200cm^4 is not in agreement with the recent findings that the lateral resistance is equal to the longitudinal resistance of a track and that the track frame contributes 5–10% of the lateral resistance of a track. Thus, the author intends to use the moment of inertia of two rails, $2I$, as the equivalent moment of inertia of the track grid, I^*, to study the effect on the critical temperature differential. Thus, the moment of inertia of two UIC 60 rails (1026cm^4) is applied to Eq. 1 (see Table 2), assuming that the track grid makes no contribution toward the lateral stiffness vis-à-vis the lateral resistance.

TABLE 2

Application of Eq. 1 with modified input of equivalent inertia of 1026cm^4

R (M)	DOC	F_{QVW} (N/CM)	I (CM^4)	f^*(CM)	ΔT_C (^{0}C)
50	34.9°	100	1026	2	12.7
75	23.3°	100	1026	2	18.8
100	17.5°	100	1026	2	24.5
125	14.0°	100	1026	2	29.8
150	11.6°	100	1026	2	34.7
200	8.7°	100	1026	2	43.2
250	7.0°	100	1026	2	50.3
300	5.8°	100	1026	2	56.1
500	3.5°	100	1026	2	71.5
700	2.5°	100	1026	2	80.0

Note: Rail UIC 60, A=2x76.9=153.8cm^2 in the equation 1

A comparison of the values of ΔT_C (°C) in Tables 1 and 2 reveals that the track grid has little effect on the buckling load for a radius of up to 300 m. This reasoning is supported by the aforementioned literature. As the curvature decreases the ΔT_C is expected to converge towards the ΔT_C of a tangent track. Thus, the computed critical temperature differentials over 50°C in Tables 1 and 2 are questionable. It appears that the curved tracks of radius ≥ 250m are thermally more stable than the tangent track; however, this result remains confusing. However, engineers are concerned with the stability of sharp curves, not mild or shallow curves. A critical temperature differential over 50°C might be an incorrect value for a curved track, but it indicates a stable track. The issue is further investigated with a new formula, as derived below.

2. DEVELOPMENT OF A FORMULA FOR ΔTC OF AN UNLOADED TRACK

The following formula was derived to check the status of an unloaded curved track under thermal load in the context of stability in terms of factor of safety [5]:

$$FS = \frac{500 \times R \times R_S}{S \times A \times E \times \alpha \times \Delta T} \quad \text{(Eq. 3)}$$

A minimum factor of safety of 2.5 is recommended for an unloaded curved track [5]. The longitudinal thermal force in the rails exerts a lateral force on the ties along a curve. The equilibrium under a factor of safety (FS) of one (i.e., assuming that the thermal load on a tie is equal to its lateral resistance) is unstable, which may cause buckling or radial displacement in case of sharp curve. The temperature differential or the corresponding load on the track is designated as the critical temperature differential or critical load, respectively. A small increase in load over the critical value can cause a significant misalignment.

Thus, incorporating FS = 1 in Eq. 3 results in the following formula expressing ΔT_C for buckling of a curved track:

$$\Delta T_C = \frac{500 \times R \times R_S}{A \times E \times S \times \alpha} \quad \text{(Eq. 4)}$$

Discreet values of sleeper resistance, R_S (kN) from panel test often do not come with sleeper spacing, S (m) and/or maintenance condition of track. The recommended values of unit resistance (kN/m) are available in codes and literature [2,4,11].

Thus, discreet value of sleeper resistance is converted to unit resistance. Replacing R_S (kN)/S (m) by F_{QVW} (N/cm) and adjusting the units, Eq. 4 may be rewritten as

$$\Delta T_C = 50 \frac{R \times F_{QVW}}{A \times E \times \alpha} \quad \text{(Eq. 5)}$$

Note that A is the area of a single rail in Eq. 5, whereas in Eq. 1, A denotes the area of two rails. The assumption underlying Eq. 5 is that the buckling mode is in the horizontal plane. The computation results for ΔT_C using Eq. 5 are presented in Table 3 and compared with the values in Table 1, which were calculated using Eq. 1.

TABLE 3:

Application of Eq. 5 for comparison with Eq. 1

R (M)	DOC	F_{QVW} (N/CM)	ΔT_C (°C) BY THE EQ. (5)	ΔT_C (°C) BY EQ. (1) REF: TABLE 1	DIFF (°C)
50	34.9°	100	12.9	12.8	0.1
75	23.3°	100	19.4	19.1	0.3
100	17.5°	100	25.8	25.1	0.7
125	14.0°	100	32.3	31.0	1.3
150	11.6°	100	38.7	36.6	2.1
200	8.7°	100	51.6	47.0	4.6
250	7.0°	100	64.5	56.2	8.3
300	5.8°	100	103.2	64.4	38.8
500	3.5°	100	129.0	88.2	40.8
700	2.5°	100	180.6	102.9	77.7

Note: Rail UIC 60, A=7690mm^2 in the equation (5)
Rail UIC 60, A=2x76.9=153.8cm^2 in the equation (1)

Both Eqs. 1 and 5 provide practically equal values of ΔT_C for radii up to 200m. Both formulae indicate that curves with radii > 200m are thermally more stable than the tangent track; again, this reasoning might be questionable. Thus, although the critical temperature differential over 50°C seems to be a confusing value, it is inconsequential because the actual rise in temperature, ΔT, amounts to 45–50°C considering the deviations that occur in practice when rails are tensioned[2], and thus, this value may be regarded as safe. Hence, Eqs. 1 and 5 can be said to be functionally similar.

Track standards across Europe dictate that continuous welded rail (CWR) should not be installed on tracks with radii tighter or less than 500m. This standard is mandatory for new constructions; however, it also recognizes that tracks with radii of up to 100m exist in all networks. The UK standards mention that CWRs should not be installed on tracks with radii < 250m due to the increased chance of track buckling. North America has no specific mandated rules on curve radius for CWR tracks. Different manuals and agencies suggest various maximum degree of curvature, the examples of which are cited below.

For new light rail transit (LRT) construction, AREMA recommends a curvature of no more than 23° (R = 76m) [7]. AREMA also notes that the curvature should not exceed 19° (R = 92m) for new heavy transit systems [7]. The Transit Co-operative Research Program recommends a maximum curvature of 12° (R = 145m) for lead tracks and industrial side tracks [12]. A mainline curvature of 10° (R = 175m) is regarded as the nominal maximum for designing commuter railroads. Burlington Northern and Santa Fe (BNSF) Railway recommends that the curvature be limited to 9° 30′ (R = 184m) for industrial tracks [13]. TCRP recommends that the curvature should not exceed 9° 30′ (R = 184m) for LRT track design [12]. The Canadian National (CN) Railway recommends a maximum curvature of 9° (R = 195m) for industrial tracks [14]. The aforementioned minimum radii are probably based on curve resistance and/or the ability of rolling stock to negotiate a curve. Among aforementioned values of radius, the minimum value of recommended radius is 76m by AREMA. Thus, a super-sharp curve is defined as a curve with radius, R ≤ 75m in this paper. Modern LRT vehicles can even negotiate 35m curves. Super-sharp curves are not used on the main line. The minimum radius of a ballasted curve should be based on the thermal stability of the unloaded track.

A 34m curved track with regular concrete ties and without tie anchors (tie spacing = 685mm and 100 ARA-A rail) and a shoulder ballast width of 600mm has been constructed in the Oliver Bowen Maintenance Facility (OBMF) in Calgary, Canada. A curved track with an 80m radius, regular concrete ties with a tie spacing of 750mm, and 54 E1 rails (without tie anchors) has been constructed in the operation and maintenance (OMC) yard of the Canada Line Project in Richmond, BC, Canada.

Kerr uses a resistance of 80 N/cm (800 kgf/m) for wood tie tracks [15]. The Paris Metro Agency uses a resistance of 90 N/cm (0.9 tonne/m) for wood tie track. It is estimated that for a track to remain perfectly stable after the passage of several hundreds of thousands of tons, the ratio of the resistance to axial displacement should be approximately 1200 daN/m for the track i.e., 120 N/cm [8]. Esveld considers a longitudinal resistance of 100–200 N/cm (10–20 kN/m) to compute the breathing length of a continuously welded rail track; [2] it seems that the range of resistance covers the wood-to-concrete tie track. Some railways (e.g., the German Railway (DBAG) and the Norfolk Southern (NS)) consider a same ballast resistance value (k) of 200 N/cm for unloaded tracks (assuming that the ties in the ballast are well maintained) [15].

Using the aforementioned minimum radii recommended by different agencies, two radii from the field, and a ballast resistance of 100–200 N/cm for concrete ties, the critical temperature differentials are computed and presented in Table 4.

TABLE 4:

Application of Eq. 5

R (M)	DOC	RAIL PROFILE	A (MM^2)	F_{QVW} (N/CM)	ΔT_C	SITE/AGENCY
34	51.4°	100 ARA-A	6357	100 - 200	10.6 - 21.2	OBMF example
76	23.0°	115 RE	7232	100 - 200	20.8 - 41.7	AREMA
80	21.8°	54 E1	6977	100 - 200	22.7 - 45.5	OMC example
92	19.0°	115 RE	7232	100 - 200	25.2 - 50.5	AREMA
145	12.0°	115 RE	7232	100 - 200	39.8 - 79.6	TCRP
175	10.0°	115 RE	7232	100 - 200	48.0 - 96.0	-
184	9.5°	115 RE	7232	100 - 200	50.5 - 101.0	BNSF
195	9.0°	115 RE	7232	100 - 200	53.4 - 107.0	CN

If the available temperature differential, ΔT, is less than the critical temperature differential, ΔT_C, computed in Table 4 using Eq. 5, then the curve would be thermally stable; thus, a correct assessment or choice of the ballast resistance value based on ballast consolidation is very important. Table 4 shows that the recommended minimum radii by CN Railway and BNSF Railway are safe for a CWR track even if the ballast resistance is as low as 100 N/cm. It is preferable to avoid a ballasted track if ΔT exceeds the value of ΔT_C computed using Eq. 5; otherwise, tie anchors should be used to augment lateral resistance.

The 34m radius curve without tie anchors at OBMF, Calgary, Canada, has been found to swing by approximately ±20mm. The maximum, minimum, and stress neutral rail temperatures are 58.3°C, –40°C, and 20°C, respectively. This implies a maximum temperature differential of 38.3°C in summer and 60°C in winter in the field. The curve swings as the temperature differential in the field is higher than the critical temperature differential of 21.2°C (see the first row in Table 4). It is evident that an excessive wide shoulder (e.g., 600mm) does not help to increase the lateral resistance. A photo is provided in Fig. 1.

FIGURE 1

Thirty four (34) meter radius curve without tie anchor at OBMF, Calgary, Canada

The 80-m radius curve at the OMC in Richmond, BC, Canada has exhibited no visible lateral swing since its construction. The maximum, minimum, and stress neutral rail temperatures are 50°C, –20°C, and 20°C (+3°C, −6°C), respectively. This implies a maximum field temperature differential of 42°C in summer and 43°C in winter. The curve might or might not swing, as the calculated critical temperature differential of 22.7–45.5°C (see the third row in Table 3) may be more or less than the temperature differential in the field depending on the ballast resistance it encounters; the curve has never buckled since construction.

Super-sharp curves should be avoided where ties cannot be installed too closely or where the ties cannot be equipped with tie anchors to ensure an ample FS against lateral displacement [5]. Mono-block standard concrete ties may be replaced by scalloped ties or frictional ties to enhance lateral resistance. An experiment was conducted on a track with and without frictional ties and its result showed that the lateral resistance of the railroad increased by 64% by using frictional ties [16]. Compared to mono-block ties, bi-block ties have greater resistance to lateral actions and lighter weight [2,17]. The specific lateral resistance values, in case of an unladen track, are equal to 11 kN in monoblock tie and 14 kN/m in bi-block ties [17]. Some railways (e.g., the German Railway (DBAG) and the Dutch Railway (NS)) consider a ballast resistance value of 20 kN/m for unloaded tracks with standard mono-block ties assuming that the ties in the ballast are well maintained [15]. The use of tie anchors increases the lateral displacement resistance and helps achieve sufficient resistance to track buckling in long welded rails, even at critical locations [4]. Following experimental research by Prof. Eisenmann, the German railways have recently normalized the use of Vossloh SN anchoring device which is able to increase the track stability especially in the bridge transition zone and in curves with a small radius [17]. The experimental curves have pointed out a growing increase of the lateral resistance values linked to the sliding rise; especially the shifting values equal to 2mm show a resistance increase equal to 47% [17].

The author has designed several super-sharp curves of radii < 65m for lengths of up to 25m with scalloped concrete ties and tie anchors at the Eglinton Maintenance and Storage Facility (EMSF) yard of the Eglinton Crosstown Light Rail Transit (ECLRT) Project in Toronto, Ontario, Canada; the maximum, minimum, and stress neutral rail temperatures are 55°C, –35°C, and 23±5°C, respectively. No specific formula was used to compute stress neutral temperature which was fixed on the basis of local experience. Photos of a 30m radius curve with three tie anchors on each tie appear in Figs. 2 and 3.

FIGURE 2

Tie with tie anchors at EMSF yard in Toronto, Canada

FIGURE 3

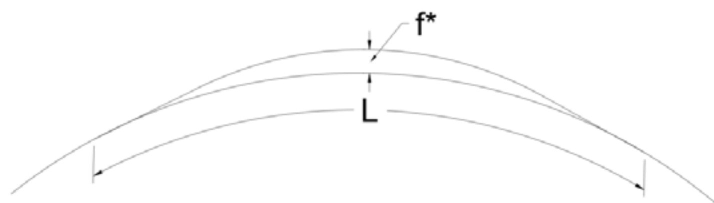
30m radius curve with tie anchors in EMSF yard in Toronto, Canada.

3. DISCUSSION ON EQUATIONS 1 AND 5

Equation 5 shows that ΔT_C is directly proportional to the radius, but Eq. 1 depicts a nonlinear relation between ΔT_C and the radius, which is theoretically plausible. If radius R in Eq. 1 tends to infinity, ΔT_C is calculated to be 157°C. However, buckling of a curved track due to a temperature differential above 50°C does not sound acceptable, because a tangent track may be regarded as a curved track with an infinite (practically large) radius. Moreover, Eq. 1 was derived while assuming a modal track shape and a critical load, as seen in Fig. 4.

FIGURE 4

Critical track position defect in curves (adopted from Lichtberger (2005))



The modal shape of a buckled track is a half sine wave, but on a shallow curve, the modal shape might take the form of a full sine wave, as observed for tangent tracks. Thus, Eq. 1 does not seem to be applicable for all radii. The same is true for Eq. 5.

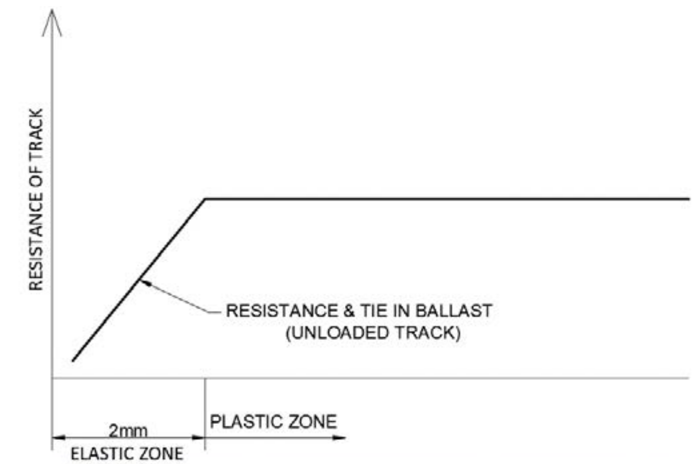
It is apparent that both equations offer sensible values of ΔT_C (< 50°C) for sharp and super-sharp curves. The computed value of the ΔT_C is acceptable so long as $\Delta T_C \leq 50$°C. $\Delta T_C > 50$°C is theoretically unacceptable but inconsequential, because the actual rise in temperature, ΔT, amounts to 45–50°C, considering that deviations occur in practice when rails are tensioned [4]. However, the limiting value of the radius for the applicability of Eqs. 1 and 5 can be determined by setting $\Delta T_C = 50$°C in these equations for a given ballast resistance.

The functional similarity of Eqs. 1 and 5 has already been noted. The latter is better than Eq. 1 for at least three reasons: (i) it is simpler than Eq. 1, (ii) it does not contain the term for the equivalent moment of inertia of the track grid, I^*, whose value is not sensitive to the critical temperature differential and depends on many assumed and subjective parameters (e.g., rigidity of the connection between the tie and the rail, end support conditions of the track grid, length of the assumed track grid, deflection, etc.), and (iii) it is not affected by the assumed critical misalignment value,

f^*, which cannot be calculated by any method. The force value arising from tie displacement by 2mm is typically considered as the lateral displacement resistance. In situations with higher displacements, the tie begins to slide as the static friction changes to sliding friction [4]. This fact is illustrated in Fig. 5.

FIGURE 5

Lateral displacement resistance diagram



The assumed value of critical misalignment, f^*, namely 2cm (20mm), seems to be high compared to 2mm (Fig. 2). At present, there is no suitable theoretical model to compute the critical misalignment [18]. The critical misalignment may be any value above 2mm in the plastic zone.

The proposed formula is based on a well-maintained curved track. The critical temperature differential of a misaligned curved track would be less than that of a properly aligned curved track. Codes usually specify acceptable limit of deviation from uniform profile. For example, Federal Railroad Administration specifies different values of deviation from uniform profile at mid-ordinate of 31, 62 feet chords for different class of tracks. Periodic track maintenance would take care of lining alone with surfacing and gauging to ensure ride comfort and safety which is adequate to guard against thermal instability of a curved track.

4. CONCLUSION

The critical temperature differential of an unloaded curved track is formulated in a simpler way; one need not resort to assumptions about the critical misalignment value, which cannot be calculated by any method so far, and the moment of inertia of the track grid, which is not sensitive to the critical temperature differential. The stability of sharp and super-sharp curves is a real concern, and the proposed formula offers sensible values of critical temperature differential for buckling. If the critical temperature differential is less than the available temperature differential then the lateral resistance of a curve shall be augmented to ensure stability. If the computed value of the critical temperature differential exceeds 50°C, then the curve may be assumed to be stable.

Notation

The following symbols are used in this paper:

A	sectional area of a rail (mm^2)
E	Young's modulus (210000 N/mm^2)
F_0	critical rail pressure force (N)
f^*	critical track defect (2–2.5cm)
F_{QVW}	lateral displacement resistance (N/cm)
I	moment of inertia of a single rail (mm^4)
I^*	moment of inertia of the track grid (cm^4)
R	curve radius (m)
R_S	tie resistance from a panel displacement test (kN)
S	spacing of ties (m)
α	coefficient of expansion (0.0000118/°C)
ΔT	temperature differential (°C)
ΔT_C	critical temperature differential (°C)

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Hampstead Heath 24
LTZ 1026
LX53 OBD

RICHARD ADAMS (HE/ HIM)

BA(Hons) AssocRTPI
Transport Planner
Engineering, Design and
Project Management
Birmingham, UK

LINDSEY STACK (SHE/HER)

BSc(Hons) CMILT
Principal Consultant
Engineering, Design and
Project Management
Birmingham, UK

QUERYING MOBILITY: TOWARDS A BETTER UNDERSTANDING OF LGBT+ TRAVEL BEHAVIOUR AND IMPLICATIONS FOR DESIGNING INCLUSIVE PUBLIC TRANSPORT SYSTEMS

ABSTRACT

Current understanding of LGBT+ transport users is limited to the occurrence of hate crimes and the key barriers to travelling on public transport. Whilst this has a profound impact on LGBT+ transport experience, it does little to situate the practitioner in the eyes of the user and the underlying processes that impact the way they travel. Crucially, limited understanding of LGBT+ users ignores the agency these people have in making choices and choosing/avoiding travelling in a particular way. How can we design inclusive public transport systems in principle without engaging with the people it is designed for? Catering for LGBT+ transport needs (and other minority groups) requires new perspectives and ways of understanding transport experiences; this is offered through the 'LGBT+ mobility' paradigm. This paper also addresses the lack of data on LGBT+ travel behaviour by conducting a national LGBT+ travel survey. The final section brings together theoretical debates and analysis of the survey findings, alongside discussions with various stakeholders, to reflect on best practice and develop key development items for practitioners.

KEYWORDS

Public transport; Social research; Behavioural insight; Inclusion and diversity; LGBT+

1. INTRODUCTION

The impetus for this paper arose following a discussion between two transport planning colleagues during LGBT+ history month. One identifies themselves as gay, the other is a behavioural research specialist. They both realised there was a significant gap in our understanding of LGBT+ travel behaviour, which prompted further investigation.

The issue of personal safety in public spaces is something both authors – as LGBT+ and female, are acutely aware of in their own day-to-day and professional lives. This was brought into sharp focus with the killing of Sarah Everard in London, which prompted a huge public debate on women's safety and shed light on just how pervasive violence and discrimination is.

This is also reminiscent of the widely publicised incident nearly two years earlier, where a lesbian couple were assaulted in London [1]. Sadly, issues such as these are not isolated and although they may vary in severity and nature, they are generally on the rise. Data from the Home Office [2] indicates a 144% rise in the rate of homophobic crime since 2014.

This is of obvious concern, but since the attack on a lesbian couple took place on a bus; naturally, one questions whether the transport industry is doing enough to protect LGBT+ people and cater to their travel needs? Furthermore, is there crossover with the myriad of other minority and vulnerable groups and the issues they face when using the transport network? Could this paper offer much needed insight into the design of inclusive transport systems?

Firstly, our current understanding of LGBT+ transport users is largely limited to the occurrence of hate crimes and identifying key barriers to travel, including personal safety concerns. Whilst this is important, and safety remains a key component of LGBT+ travel, little is known about the methods of travel and the underlying processes that drive the travel decision making process. Ultimately, this requires more data on LGBT+ public transport users, which was a primary motivation for this paper.

Crucially, it is important to stress that LGBT+ people have agency in their travel behaviour and are not merely subject to forces beyond their own control. It is important to understand transport systems from a user perspective and how they interact with the environment around them, although arguably we lack the tools, knowledge and resources to do so. This will likely be resolved through greater depth of understanding through qualitative approaches that seek to understand how our individual persona's navigate and negotiate the transport system.

To frame this research topic, this paper argues that decision making is a complex interaction of objective and subjective drivers of travel behaviour. The former can be considered factors that exist independently of the user, such as journey time, reliability and cost; the latter includes the often less tangible factors that directly relate to the user's personal characteristics.

Mobility studies research has made significant progress on theorising subjective drivers of travel behaviour, by developing an understanding and language around people's movements and how it is deeply rooted in our social identities i.e. the most intimate and intrinsic characteristics that make us who we are. However, this is yet to translate into mainstream transport planning practice, whose appraisal techniques do not fully engage with user experience of the network.

In short, there appears to be little merit in designing the perfect transport system for people in principle, if the human element in practice results in actions that don't engage with this system. Catering for LGBT+ transport needs (and other minority groups for that matter) require new perspectives and ways of understanding transport experience – which is offered through the 'LGBT+ mobility' paradigm.

To address the current gap in industry knowledge and practice, the purpose of this study is to better understand LGBT+ travel behaviour and provide new insight that will assist practitioners in planning inclusive public transport systems. A mix of primary and secondary data was collected to provide insight to answer the overarching research question. The remainder of this paper is structured as follows:

- Section 2: Current data and evidence that exists around LGBT+ experiences and perceptions relating to using public transport.
- Section 3: Findings from an online survey with LGBT+ public transport users as well as the outcomes from discussions with key stakeholders.
- Section 4: A review of the implications and lessons learnt from the research and recommendations for the transport industry.

2. LITERATURE REVIEW

2.1. Understanding LGBT+ Travel Behaviour and Experiences

2.1.1. What proportion of the UK population identify as LGBT+?

Those identifying as LGBT+ are likely to make up a considerable proportion of the population, however it is more challenging to ascertain the true number. Outputs from a recent Office for National Statistics (ONS) survey (2018) [3] estimates that 2.2% of the UK population over 16 years identify as lesbian, gay or bisexual. This equates to approximately 1.2 million people, or equivalent to the entire population of Birmingham.

The exact number of trans people is unknown with no robust data on the UK trans population currently in existence. However, the ONS tentatively estimate that there are approximately 200,000-500,000 trans people in the UK [4].

Over recent years, there has been significant progress in LGBT+ visibility in mainstream society. Whilst everyone's experience will vary, it is likely more individuals will self-report as it becomes more socially acceptable and part of public discourse. Estimates vary on the true number of LGBT+ individuals, but collectively they make up a large demographic group which arguably has been under-reported and poorly understood in the past.

2.1.2. What do we currently know about LGBT+ people's experience of public transport?

Transport for London (TfL)'s diversity reports [5] [6] have investigated LGBT+ peoples' experience of public transport and what their key concerns were in relation to other demographic groups [7]. The survey found that many LGBT+ public transport users experience the same principal concerns as the wider population, such as overcrowding, cost and unreliability and crime.

In terms of LGBT+ specific barriers to travel, respondents mentioned fear of intimidation and/or abuse as a barrier to travel, although this is likely to vary significantly from person to person depending on the individual's persona, past experience, and perceived visibility of LGBT+ characteristics (TfL, 2012) [5].

Furthermore, data obtained from the national LGBT survey (Government Equalities Office, 2018) [8] found that public transport was one of the most commonly cited locations where respondents were not open about their sexual orientation, for fear of negative reaction from others, which demonstrates that a large proportion of LGBT+ people self-police behaviour in order to protect their personal safety.

2.1.3. How prevalent is violence against LGBT+ people on public transport?

Sadly, hate crimes against LGBT+ people are still commonplace. In England & Wales, there were 15,835 recorded hate crimes where hostility or prejudice against sexual orientation was a factor, making up 15% of total recorded hate crimes (Home Office, 2019/2020) [9]. For transport settings, data is collected by the British Transport Police. In 2019/2020, there were 626 recorded hate crimes reported that had sexual orientation as a factor. Hostility/prejudice against sexual orientation was the second most common factor (18%), which broadly aligns to the figures reported nationally. However, it is acknowledged that a significant number of crimes could be unreported, and official figures may be underestimating the problem.

2.1.4. What are the types of violence and what safety concerns do LGBT+ individuals experience?

LGBT+ safety is a complex issue; fear and occurrence of violence is a fluid interaction between different social identities, not least gender and sexuality, which makes it difficult for practitioners to target. A study by Lubitow et al. (2017) [9] found that gender non-binary and self-disclosed 'feminine' identities report more harassment, and Mason-Bish (2014) [10] found that lesbians, bisexual women and trans women report disproportionate levels of discrimination in numerous settings. This indicates that these particular groups face 'double discrimination', as they deviate from heteronormative and masculine identities.

On the other hand, Berrill (1992) [11] reports that gay men are usually more prone to physical violence than lesbians, who are more likely to suffer verbal attacks. Statistically speaking, men are more likely to suffer from violent crime than women, despite the fact the women report feeling less safe – which demonstrates how perception of violence as well as its actual occurrence is important in governing personal safety (ONS, 2019) [12].

Furthermore, violence against LGBT+ people often interact with other forms of discrimination. For example, Fogg-Davis' (2006) [13] research demonstrates how LGBT+ people of colour suffer disproportionate levels of violence due to the interplay of sexual and ethnic identities.

2.1.5. How do LGBT+ people respond to violence and safety concerns?

Not only is LGBT+ safety complicated by other factors affecting one's social identity, but practitioners also need to consider the agency of LGBT+ individuals themselves and the actions they take to avoid violence and discrimination.

For example, Lubitow et al's (2017) [9] study on public transit use in Portland, Oregon, masculine gender identity and presentation was a key factor identified by trans individuals for avoiding harassment on public transport, which involved exercising their male and white privileges. Trans public transport users also reported to use proactive strategies, such as scheduling rides on certain routes and during daylight hours, to minimise the likelihood of harassment and violence; familiar routes also offered a sense of safety.

Furthermore, it is worth acknowledging a key point raised by Browne et al's (2011) [14] study on LGBT+ community safety, that many LGBT+ people may not recognise or categorise abuse in the same way; rather, many normalise the abuse they experience as a strategy for dealing with day-to-day life. Therefore, it is likely that this leads to incidents being under-reported, and the figures above likely to not tell the full story.

It is also unlikely that perceptions of safety are spatially and temporally static. As discussed by Newton (2014) [15], a wide range of practical constraints contribute to a person's experienced fear of violence and crime in public transport, such as the time of day, mode of transport, level of security provision, as well as past personal experiences and attitudes (Weintrob et al., no date) [7]. Lubitow et al. (2017) [10] also note how particular environments, especially enclosed transit settings such as carriages, can heighten feelings of exposure and vulnerability - akin to having a 'captive audience' or feeling trapped as participants noted. Ultimately this is why transport operators should take a responsibility above and beyond wider activities to tackle LGBT+ discrimination as the environment they control can be a determining factor.

2.1.6. Does being LGBT+ affect travel behaviour?

The evidence suggests that being LGBT+ does not necessarily affect travel behaviour, but research that is available demonstrates how for certain groups and settings, transport behaviour can be significantly impacted for LGBT+ individuals. It is worth noting however that LGBT+ transport behaviour is not simply a case of avoiding violence or overcoming structural inequalities, but it can also be an empowering and desirable practice.

As Smart and Klein's (2013) study into 'neighbourhoods of affinity' show, in areas with a high percentage of coupled gays and lesbians, gay men were observed to have significantly reduced trip lengths both for work and non-work purposes. This was also observed for women (straight and lesbian) and straight males, although to a lesser extent.

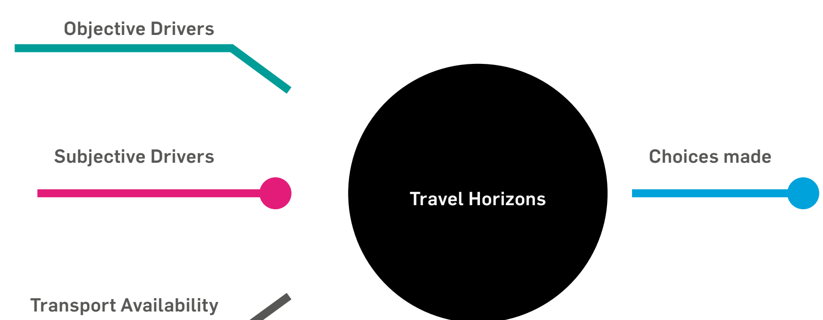
Co-location of LGBT+ individuals is a trend that has been traditionally seen through the 'gay village' phenomenon in the 20th century; mainly inner-city enclaves which became powerful draws for disparate LGBT+ populations (Nash and Gorman-Murray, 2014 [16]. Whilst research is limited, Smart and Klein (2013) work demonstrates just how important social networks are in governing people's movement in particular areas, where the need and desire to travel can be significantly altered.

2.2. Travel Horizons – The Outcomes of the Decision - Making Process

The term travel horizons is a qualitative means of capturing the capabilities of someone to travel beyond their home location on particularly modes and/or routes to potential destinations. For example, someone who is considered transport disadvantaged is likely to have much shorter travel horizons.

This term was coined by the Social Exclusion Unit (2003) [17] and has been explored in the context of transport poverty (Lucas et al., 2016) [18], a combination of accessibility deficits that reduce someone's ability to reach certain land uses. Crucially, travel horizons not only capture people's inability to access the transport network but also their unwillingness to do so and use it to their full advantage.

This paper calls for greater consideration of the most intimate of personal factors such as gender and sexual identity in determining someone's travel horizons, as these parameters form the foundation of what makes a person 'them' and have profound impact on one's ability to travel the way they do.



2.3. What Is LGBT+ Mobility? Why Is It Important and Can It Help Practitioners?

To improve understanding of subjective drivers of travel behaviour and how they might impact one's travel horizons, this paper uses the term 'LGBT+ mobility' to develop novel approaches for transport practitioners, drawing up LGBT+ and gender theories which try and capture people's lived experience of transport.

Key to a 'LGBT+' approach to transport planning is understanding that one's social identity interacts constantly with the world around them, so it is subject to constant negotiation with environment cues. Depending on the nature of this interaction, the person may adapt their behaviour and/or appearance accordingly. This may not be purely reactionary, but cumulatively over time can de-construct and reconstruct aspects of the individual through this constant feed of environmental information.

This understanding of social identity can be attributed to gender theorist Judith Butler (1990) [19], who proposed that gender is constructed through repetitive actions. The ability for someone to be comfortable in their surroundings involves a constant processing of environmental stimuli, with feelings of vulnerability aroused by feeling exposed or 'standing out' if that environment does not feel safe or inclusive of their social identity. The extent of someone's travel horizon is one such impact of this.

2.3.1. It's more than just about getting from A to B: journey experience is important

As Cresswell (2008) [20] emphasises in Gendered Mobilities, how people move is inherently influenced by their gender, and this is affected by other social characteristics by extension. People's mobility is heavily influenced by cultural structures and hierarchies in public space, which affect a number of transport user groups (Lubitow et al. 2017) [9]. In this the case of LGBT+ populations, public spaces – including public transport – are traditionally gender normative, masculine and heterosexual domains, which are reconstructed through wider social norms, people's experiences and perceptions and environmental cues.

Mobility should be not only be thought of as getting from A to B, but also the negotiations, decisions and actions people have to make to complete those movements. As noted by (Weintrob et al) [7], transport planners need to address the 'complexity of differences' in how people travel across different social groups. To better tackle hidden barriers to travel for disadvantaged groups, such as LGBT+ populations, practitioners need to be equipped to understand the content and meanings behind people's journeys which ultimately impact upon their decision making.

As called for by Browne et al. (2011) [14], we need to move beyond purely incidents of hate crime in isolation and consider the wider effects this has on people's lives and their behaviour. Due to the complex nature of LGBT+ transport experience, this might require new analysis techniques that better capture data on the issues raised in this paper.

2.3.2. Overcoming binaries and biases: a call to practitioners

Furthermore, practitioners can often fall victim to heterosexist and binary gender bias (Bettinger, 2010) [21], which can be described as 'conceptualising human experience in strictly heterosexual terms' and assuming that gender exists in two mutually exclusive categories of male and female respectively (Herek et al., 1992) [22]. To make the transport network truly inclusive, there is a need to disrupt existing relationships between social identity and how people perceive and experience the places around them.

3. SURVEY AND STAKEHOLDER ENGAGEMENT FINDINGS

3.1. Survey of LGBT+ Travel Behaviour and Experiences

The research methodology involved collecting primary data via an online survey during May 2021 to understand people's experiences of travelling on public transport, as well as how public transport can be made more inclusive for all users. Due to COVID-19 at the time of this study, respondents were asked to focus on their travel experiences prior to March 2020.

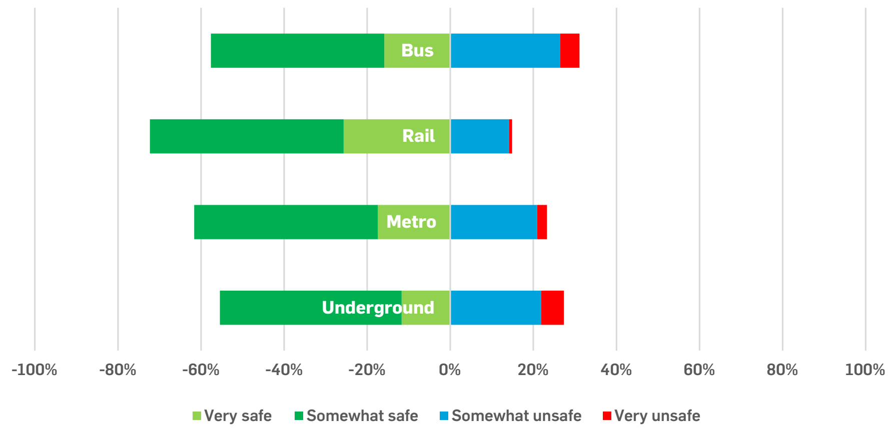
At the time of writing, a total of 156 respondents completed the survey and the results are summarised within this section. Of the responses received, 139 participants (90%) identified as being LGBT+. A total of 24 responses were received from participants who identified as being a trans person. A range of responses were received from across England and Scotland, and also from across a variety of age groups. Thirty-five percent of respondents noted that they had a physical or mental health condition/ illness that was expected to last 12 months or more.

3.1.1. How safe do people feel on public transport?

Respondents were asked how safe they feel using public transport. Additionally, if respondents did not regularly use a transport mode, they were asked how safe they perceived this mode to be. On the whole, more respondents considered all modes of public transport to be safe than unsafe. That said, a notable proportion of respondents considered public transport to be unsafe. Bus had the highest proportion of respondents that felt it was unsafe (32%). This compares to 29% underground, 25% metro and 15% rail.

FIGURE 1

How safe do users feel when travelling on public transport?



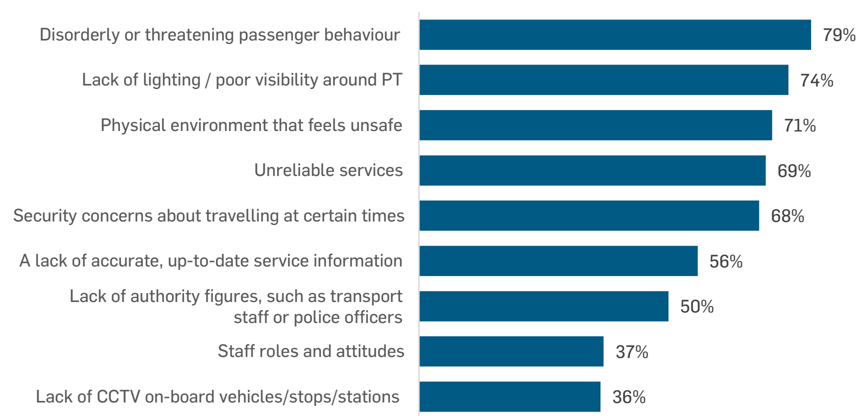
Base: 156 respondents ('neither safe nor unsafe' is not shown for presentation purposes)

Responses were also analysed by different user groups to understand whether some users were felt disproportionally safe compared to others. The results were intriguing and showed a great variance by user type. For all modes, the proportion of respondents that felt somewhat/very unsafe on public transport was higher for LGBT+, female, trans and non-binary users in comparison to all participants. A higher proportion of females felt unsafe using public transport compared to all respondents, however this difference was most noticeable for metro (36% females noting they felt unsafe compared to 25% overall). Although comprising a relatively low base, trans people and those identifying as non-binary, felt disproportionally more unsafe on public transport compared to overall respondents.

Respondents were asked what elements concern them in relation to the usage of public transport. A list of options was presented to the respondent and they were asked to rank each on a scale of 1 (very much so) to 5 (not at all).

FIGURE 2

What issues are the biggest concern to public transport users?



Base: 156 respondents (only showing factors that were ranked 1 or 2 – the most concerning)

Of biggest concern to respondents was disorderly or threatening behaviour from other passengers, with 79% respondents ranking this as a 1 or 2 (most concerning). Respondents were invited to provide comments on their response to this question, with many remarking that it was the element of not knowing who you might encounter, highlighted by being in an enclosed space, which concerned them - *"It depends so much on who else is on the train or bus and I cannot control that". Several respondents also commented that they had previously experienced incidents which has affected their feelings of safety - "I avoid public transport as much as possible... I've been sexually assaulted in broad daylight on a train and have spent hour long bus journeys being homophobically and transphobically abused."* This is similar to findings by Lubitow et al. (2017) [9] who found that enclosed transit settings can heighten feelings of exposure and vulnerability.

The second highest area of concern was a lack of lighting / poor visibility at bus stops, stations and car parks, with 74% scoring this as the most concerning for them (1 or 2). As well as this, 71% of respondents also were concerned about physical environments that feels unsafe e.g. long subways, isolated bus stops, enclosed/disorientating spaces. Within the open response section, it was clear that these physical environment issues were heightened while travelling at night, with some respondents stating that they avoid travelling at night altogether - *"when I need to travel in the dark, I am more alert to danger".*

Interestingly, some of the more 'traditional' concerns that we often try to address as transport planners, such as unreliable services and a lack of accurate, up to data service information, were considered to be a much lower concern for respondents.

3.1.2. What are people's experiences of physical/verbal incidents when travelling by public transport?

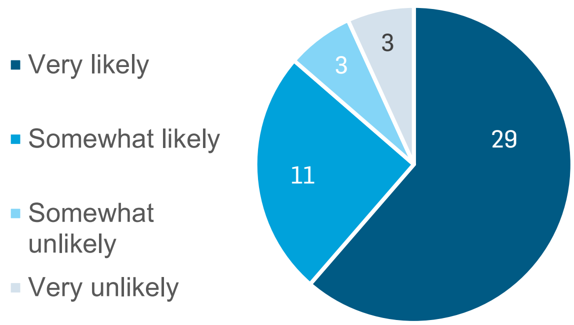
Respondents were asked whether they or a person they were travelling with had been physically/verbally attacked or threatened whilst using public transport in the past five years. The results showed that in the last five years, 55 respondents (37%) said they or the person they were travelling with had been physically/verbally attacked or threatened whilst using public transport. Of these 55 respondents, over half said they had experienced multiple incidents within the last five years.

Respondents were asked how likely it was that the last incident that occurred was either partly or completely because of their perceived gender or sexuality. A total of 44 out of 55 respondents (83%) said it was somewhat or very likely, with this figure being even higher for LGBT+ respondents only

(85%). 13 out of 14 respondents who identify as trans, said it was likely the last incident that occurred was due to their perceived gender or sexuality.

FIGURE 3

Likelihood the last incident that occurred was partly or completely because of the respondent's perceived gender or sexuality



The survey found that most of the respondents who had experienced an incident did not report it to transport staff/police. Only eight out of 55 respondents that had experienced an incident said they had reported. Of these eight respondents, six said they were dissatisfied with the way the incident was handled.

The overwhelming reason for not reporting the incident was because the respondent thought 'I did not think they could/would do anything'. On a similar theme, many respondents considered the incident to be 'too minor/ not serious enough/didn't occur to me'.

Sadly, there were many comments relating to experience of homophobic abuse and sexual harassment on public transport, with many commenting this was commonplace. There was an acceptance that nothing would change, and it is society's view in general.

Survey respondent comments

"The way that it was dismissed left me feeling like I shouldn't have bothered reporting it. After this I never felt safe on a train."

"There should be conductors whose job it is to support safety and not just to check that people are paying fares."

"These are issues that are too large for public transport operators to be able to fix."

For some, they felt incidents they reported were not taken seriously enough, and some felt too scared to report for fear of reprisal. This highlights the similar findings made by Browne et al's (2011) [14] study on LGBT+ community safety, who suggested that many LGBT+ people the abuse they experience as a strategy for dealing with day-to-day life, leading to incidents being underreported.

3.1.3. How comfortable do LGBT+ users feel about being open about their sexuality and/or gender identity when using public transport?

The national LGBT survey revealed [8] that public transport was one of the most commonly cited locations where respondents were not open about their sexual orientation, due to fear of a negative reaction from others. Similarly, a poll commissioned by Pride in London (2016) [23] found that 77% of LGBT+ respondents felt uncomfortable being their true self in public, against 23% of the general population. They also found that 41% of gay men would think twice about holding a partner's hand in public, dropping to 5% amongst the general population.

To understand the extent this was the case for public transport users, respondents were asked whether they had ever avoided being open about their sexual orientation on public transport due to fear of a negative reaction from others (for example, avoiding public displays of affection). Of the 139 respondents who identified themselves as being LGBT+, 77% responded that they had avoided being open about their sexual orientation on public transport.

Respondents commented that they did not feel safe or comfortable being open about their sexual orientation e.g. holding hands with a partner and they considered it safer to 'blend in' and not draw attention to themselves. Respondents also noted previous experiences where they had been open about their sexuality but had experienced a negative response from other passengers. Other respondents commented that they simply did not feel safe in being open about their sexual orientation whilst travelling.

Survey respondent comments

"I always 'play it straight' and try to avoid any behaviour or conversations that might give me away."

"People stare and make me feel uncomfortable about expressing my affection or sexuality on public transport."

"I am worried about physical attacks and people using weapons such as knives."

Respondents were also asked whether they had ever avoided being open about their gender identity on public transport due to fear of a negative reaction from others. Of all the respondents, 27% said they had avoided being open about their gender identity. This figure was even higher for LGBT+ respondents (30%), and higher again for trans people: 17 out of 24 trans respondents said they had avoided being open about their gender identity on public transport.

Survey respondent comments

"I have previously avoided clothing or items that may out me or give others an impression of my gender/sexual identity. For me, public transport is an enclosed microcosm where harassment cannot easily be walked away from."

"If I am having to travel late at night on my own, I will often wear more androgenous (rather than feminine) clothing so as to avoid unwelcome attention."

3.1.4. Do people feel obliged to change their travel behaviour due to safety concerns?

This analysis found that 60% of respondents had changed their travel behaviour due to personal safety concerns. The same proportion of LGBT+ respondents (60%) reported that they had changed their behaviour, but it was much higher for female respondents (70%) and higher again for trans respondents (79%).

The majority of comments were from respondents who said they were most likely to change their behaviour when travelling at night. This was discussed by Newton (2014) who commented that a wide range of practical constraints contribute to a person's perceptions of safety, including time of day. Many of the respondents commented that night time was when they were most likely to change their behaviour, with some avoiding travel at this time altogether – "I often chose to walk home late at night to avoid travelling on a night bus".

Respondents noted some of the ways they changed their travel behaviour and this included:

- Moving train carriages or getting off the bus at an earlier stop - "I've often changed train carriage or got off one bus and onto another. This is usually due to perception of the potential for trouble due to other passengers."
- Avoiding travelling alone at night / choosing a busier route
- Taking a public transport service at a particular time
- Taking a taxi / walking to avoid travelling by public transport completely
- Covering up clothes and/or avoiding drawing attention to oneself
- Other safety measures such as calling a friend, or sharing location via phone

Such a large proportion of respondents noting they feel they have to change their behaviour to stay safe, is disappointing. Similar findings were presented in the Get Home Safely toolkit

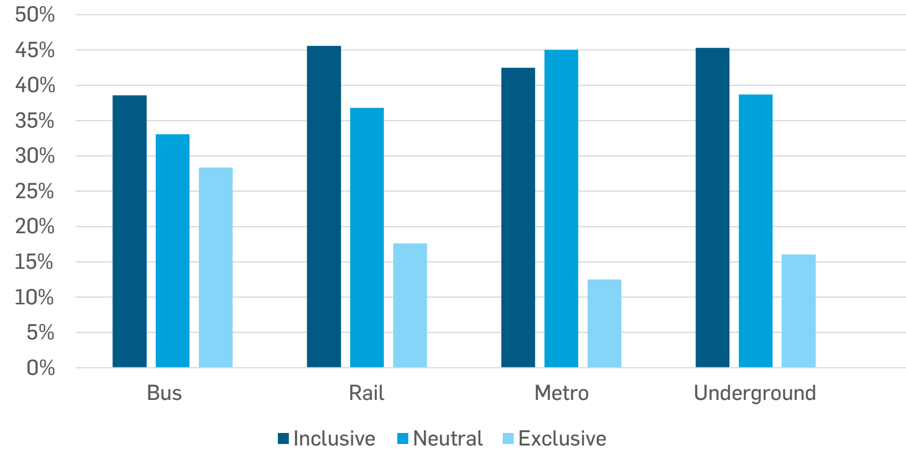
(Cary, Evans, Matthews, 2021) [24] which found that a large proportion of women feel the need to change their travel behaviours to stay safe.

3.1.5. How inclusive do people feel public transport currently is?

This research aspired to determine how inclusive people feel public transport is at present. Rail had the highest proportion of respondents considering it to be inclusive (49% overall vs 45% LGBT+ users). However, bus had the highest percentage of respondents who felt it was not inclusive (27% overall vs 29% LGBT+ users).

FIGURE 4

How inclusive do you consider the following modes of transport to be?



Base: 139 LGBT+ respondents

3.1.6. What can we do to make public transport more inclusive?

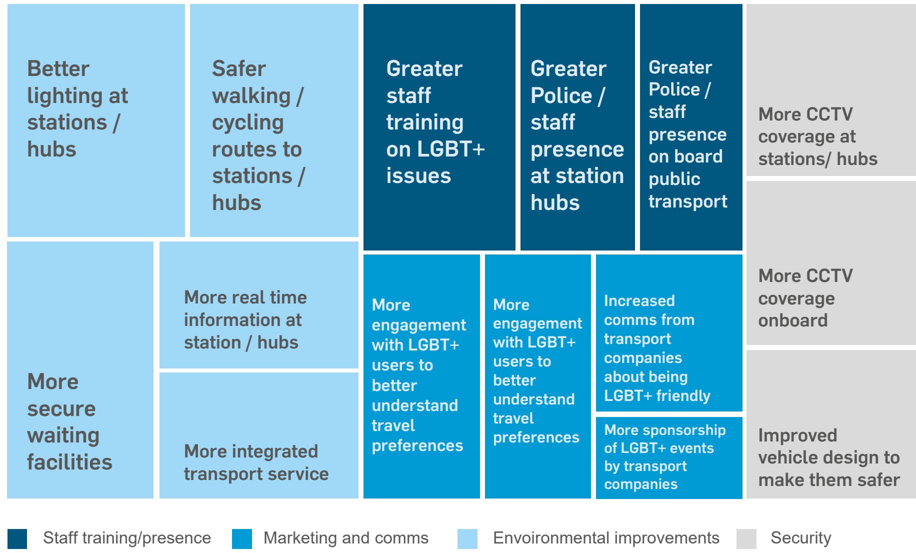
Respondents were asked what could be done to make public transport more inclusive for all users. Respondents were presented with a list of potential initiatives and asked to select those that they felt would make public transport more inclusive for LGBT+ users.

Some of the initiatives to improve the physical environment for transport users received the highest amount of responses. This included the provision of ‘better lighting at stations/hubs’ (109 responses), safer walking/cycling routes to stations and hubs (102 responses) and more secure waiting facilities (96 responses).

Alongside these physical improvements, respondents also selected initiatives relating to staff training and presence to help make public transport more inclusive for LGBT+ users. More specifically, this included greater staff training on LGBT+ issues (97 responses) and greater police/staff presence at stations and hubs (74 responses).

FIGURE 5

Which of the following initiatives would make public transport more inclusive for LGBT+ users?



Base: 156 respondents

3.1.7. Final thoughts from survey respondents

The final part of the survey invited respondents to leave any last thoughts on the topic of public transport safety and inclusivity for LGBT+ users. Firstly, there was the reiteration from some respondents that unfortunately prejudice against the LGBT+ is commonplace in society and some felt this was a deep-rooted, nationwide societal issue which isn't just specific to public transport. One respondent in particular noted "Public transport just tends to be an especially unsafe place for us because of the close proximity to strangers and inability to get away from them.". However, the key point here is that while many respondents feel these issues are a reflection of society in general, the key differentiator is the environment is not of their control. This we feel, is an opportunity for the public transport industry to do better and recognise they have a duty of care to their passengers and can lead the way in pushing society to better attitudes and actions.

In addition to the previous suggestions to improve inclusivity of public transport, many respondents noted that they would like to see greater messaging and campaigns from transport operating companies about how they take a zero tolerance approach to hate crimes, and also the ways that hate crimes can be reported in action to the police and/or a non-police organisation/charity – "I think it needs to be made clear to ALL that there is zero tolerance to any harassment to anyone!".

> **"When we improve the transport system for one group, we actually improve it for everyone"**

There was also the acknowledgment, that whilst this survey has specifically focussed upon the LGBT+ community, these issues relating to feelings of safety are often quite similar to other transport users and vulnerable groups.

3.2. Stakeholder Engagement

A number of stakeholders were engaged in this research, including Joanna Ward (Freelance transport planner and influencer), Martyn Loukes BEM (HRH honoured creator of #RidewithPride & London's rainbow crosswalk, bus, taxi, train & UK LGBT traffic lights), Transport for London, National Express, Rachel Evans (Stations as Places Programme Lead for West Midlands Stations Alliance & Head of Cities at Atkins), West Midlands Rail Executive and Pollyanna Gannaway-Pitts (Gloucestershire Community Rail Partnership).

One of the key takeaway points from the discussions with stakeholders concerned the scalability of interventions to improve LGBT+ travel experience, namely the tension between the granular nature of individual schemes (such as environmental improvements at a station), the need to appraise journey experience at the personal level, and developing a consistent and coordinated approach across the network and industry actors.

"Mainstreaming diversity" was highlighted by Martyn Loukes BEM as a key strategy to developing best practice across the industry. This involves appreciating the customer as a heterogeneous group, whose transport needs and experiences vary across time and place, which has been highlighted through the LGBT+ mobility approach. Ultimately, this will require new appraisal techniques and data sets that better account for this difference and identify the key points of intervention in the design of truly inclusive transport systems.

Whilst this ultimately requires further research as to how the approaches advocated in this paper can be applied in real life transport planning settings, conversations with stakeholders have already identified potential strategies that could be adopted into mainstream practice. For example, community organisations such as Community Rail Groups provide key gatekeepers to a diverse range of customers and are already embedded within the planning process. "Public transport decision makers need to physically get out and about in the real world on rail, bus and tram services with a diverse cross section of customers, including LGBT +, to understand how their needs and rights can be better met" Rachel Evans - Head of Cities Discipline at Atkins

"We can really start to tackle these issues through representation of different voices in our organisations and meaningful public consultation with around design, operations of services and making safe and accessible spaces, allowing marginalised voices like the LGBTQ+ community to advocate for their needs and have a seat at the table" - Pollyanna Gannaway-Pitts - Gloucestershire Community Rail Partnership. Better engagement with these groups, for example through the consultation process, could unlock new knowledge and disseminate best practice through a grassroots approach to public transport design.

4. SUMMARY AND RECOMMENDATIONS

4.1. Summary of Findings

4.1.1. What do we know about the LGBT+ population and their travel behaviour?

- The ONS (2018) approximates that 2.2% of the UK population over 16 years identify as lesbian, gay or bisexual. This equates to approximately 1.2 million people. The ONS tentatively estimates that there are approximately 200,000-500,000 trans people in the UK.
- Despite large numbers of LGBT+ people living in the UK, there is a lack of available data on LGBT+ people's experience of using public transport.
- The National LGBT survey (2018) found that public transport is one of the most commonly cited locations where respondents were not open about their sexual orientation, due to fear of a negative reaction from others.
- Similarly, a Pride in London survey (2016) found that 77% of LGBT+ respondents felt uncomfortable being their true self in public, against 23% of the general population.
- This survey found that 77% LGBT+ respondents said they had avoided being open about their sexual orientation on public transport for personal safety reasons. Thirty percent of LGBT+ respondents had avoided being open about their gender identity to avoid a negative reaction from others. For trans respondents, 17 out of 24 stated that they avoided being open about their gender identity on public transport.
- These findings demonstrate that a large proportion of LGBT+ people self-police their behaviour to protect their personal safety. We also need to be aware of LGBT+ people using their agency to 'avoid' being subject to a crime.

4.1.2. How frequently do LGBT+ public transport users experience crime whilst travelling?

- In England & Wales as a whole, there were 15,835 recorded hate crimes where hostility or prejudice against sexual orientation was a factor, making up 15% of total recorded hate crimes in 2019/2020.
- For transport settings, there were 626 recorded hate crimes reported that had sexual orientation as a factor in 2019/2020. Hostility/prejudice against sexual orientation was the second most common factor (18%), which broadly aligns to the figures reported nationally.
- This survey found that 37% (55 respondents) said they or the person they were travelling with had been physically/verbally attacked or threatened whilst using public transport in the last five years. Of these respondents, over half said they had experienced multiple incidents.
- 44 out of 54 respondents said it was somewhat/very likely that the incident was due to their perceived gender or sexuality. 13 out of 14 respondents who identify as trans, said it was likely this had been the case.
- A study by Lubitow et al. (2017) found that gender non-binary and self-disclosed 'feminine' identities report more harassment, and Mason-Bish (2014) found that lesbians, bisexual women and trans women report disproportionate levels of discrimination in numerous settings. This indicates that these particular groups face 'double discrimination', as they deviate from heteronormative and masculine identities.

4.1.3. How safe do the LGBT+ community feel on public transport?

- A notable proportion of respondents to this survey considered public transport to be unsafe. Bus had the highest proportion of respondents that felt it was unsafe (32%). This compares to 29% underground, 25% metro and 15% rail.
- Results also varied by user. A higher proportion of females felt unsafe using public transport compared to all respondents, with this difference being most noticeable for metro (36% females noting they felt unsafe compared to 25% overall). Although comprising a relatively low base, trans people and those identifying as non-binary, felt disproportionally more unsafe on public transport compared to overall respondents.
- The survey findings show that the biggest concern to respondents was disorderly or threatening behaviour from other passengers. In particular, 'not knowing who you might encounter' coupled with being within an enclosed space, caused great concern for many of the survey respondents.

- Additionally, lack of lighting / poor visibility at bus stops, stations and car parks also caused concern. In addition to physical environments that feel unsafe e.g. long subways, isolated bus stops, enclosed/disorientating spaces.
- All of these drivers of feelings of unsafety were heightened while travelling at night, with some respondents avoiding travelling at night altogether.

4.1.4. Do LGBT+ people change their behaviour to feel safe?

- This analysis found that 60% of respondents had changed their travel behaviour due to personal safety concerns. For females this increased to 70% and even higher again amongst trans respondents (79%).
- Other ways people travel changed their behaviour included moving carriages/getting off at an earlier stop, travelling at a particular time and avoiding drawing attention to oneself where possible. Some respondents noted that they often take a taxi/walk/get a hotel to avoid travelling at night completely.
- Research undertaken in the development of the Get Home Safety Toolkit (Cary, Evans, Matthews) found similar behaviours amongst women, with a large proportion feeling the need to change their travel behaviours to stay safe. In a snap poll as part of this study, 91% of people said they have altered their behaviour to account for actual or perceived safety issues in public spaces.

4.1.5. To what extent do we think any incidents occurring on public transport are reported?

- From Home Office data, we know the numbers of hate crimes that are reported in general society and also on public transport. However, this survey found that the majority of respondents that had experience a verbal/physical attack, did not report it to staff or police.
- Reasons for lack of reporting include perceptions that nothing could/would be done. Others felt the incident was ‘too minor/not serious enough’ to report.
- This survey’s findings, alongside research such as Browne et al (2011), found that many LGBT+ people normalise abuse they experience as a strategy for dealing with day-to-day-life. There is a general acceptance that this is how society is and nothing will change.

- Not only that, but LGBT+ people are routinely using their agency to 'avoid' being subject to a crime. The above leads to incidents being underreported, with the crime statistics likely not revealing the full extent of the true issue.

4.1.6. How inclusive is public transport now and what could be improved?

- This survey found that rail had the highest proportion of respondents considering it to be inclusive (47% overall vs 45% LGBT+ users). However, bus had the highest percentage of respondents who felt it was not inclusive (27% overall vs 29% LGBT+ users).
- Initiatives to improve the physical environment for transport users were well supported by respondents. This included the provision of 'better lighting at stations/hubs', safer walking/cycling routes to stations and hubs and more secure waiting facilities.
- What the presented research really highlights is the distinct lack of data on LGBT+ people's travel behaviour, which means ultimately the industry is poorly equipped to understand and respond to their travel needs. It is not only the lack of quantitative data which is the issue, but also the appreciation and understanding of the complex social factors that influence how people move and make travel choices.

4.2. Recommendations for Practitioners and Future Research

This is clearly a nascent area of research and will require further input from practitioners to develop into mainstream planning practice. Nevertheless, by way of conclusion, this section summarises seven key development items, informed by theoretical insights, data collections and conversations with industry representatives.

This is a crucial opportunity for public transport providers and transport planners to do better by LGBT+ transport users, whilst leading society by example through mainstreaming diversity in public transport provision. The key recommendations are as follows:

ACKNOWLEDGEMENTS:

We would like to thank our Atkins Transport Planning colleagues for their valued input, enthusiastic encouragement and overall support in the development of this study. We would also like to extend our appreciation to the stakeholders who gave up their time to speak with us and provide fruitful discussions to enrich our work. This paper was originally accepted for publication at the 19th Annual Transport Practitioners' Meeting, UK, 7-8 July 2021.

ENVIRONMENTAL DESIGN

- Removing blind stops and making environments feel more openand welcoming, to ensure that people don't feel like they haveto adapt their behaviour and/or appearance in order to feel safe
- Visibility and natural surveillance are key parameters in designingsafer environments, particularly at night.
- Engagement with urban designers and landscape architects will be key.

TRANSPORT SCHEME APPRAISAL TECHNIQUES

- Improve the tools available to transport planners to assess journey quality and account for the diversity of transport users.
- Expand the scope of equality and diversity impact assessments of transport schemes.
- Develop associated guidance for practitioners to ensure consistent best practice

ZERO TOLERANCE APPROACHES

- Although progress has been made, more could be done to address hate crimes on public transport and improvements made in the reporting process.
- There should be a 'code of conduct in place for passengers using public transport, so that all passengers should know what is expected of them, right from the moment they buy a ticket. They should be made clear on what behaviour will not be tolerated and the repercussions should this occur. Public transport operators should adopt a zero-tolerance approach towards incidents when this behaviour isn't adhered to (such as the Transport for London 'Together Against Hate Crime' campaign.
- In addition, reporting systems could be improved and processes need to be promoted to passengers. We need to instil a culture that no incident is too small to report and tackle the normalisation of hate crimes against LGBT+ (and other) users.

EMPOWERING TRANSPORT STAFF

- Staff roles go beyond the function of making transport operate to making sure it works for everyone. Staff are knowledgeable and empowered to act upon safety issues

CONSULTATION PROCESSES

- Greater community buy-in, engagement and knowledge sharing to ensure that transport schemes best serve the people that use them. Communrty/chartty organisations as gatekeepers for hard-to-reach groups.

POLICY MANDATES

- To achieve greater buy-in from industry actors, incentivise improvements in service provision and achieve wider scale best practice. Develop outcome driven approaches to public transport planning.

FURTHER RESEARCH

- It is recommended that further research focus on the mechanisms that would make public transport work for everyone. Further research should be conducted to greater understand the issues that LGBT+ public transport users face. Further research could also involve working with transport operators to test interventions, whilst also investigating further initiatives have been successful elsewhere.

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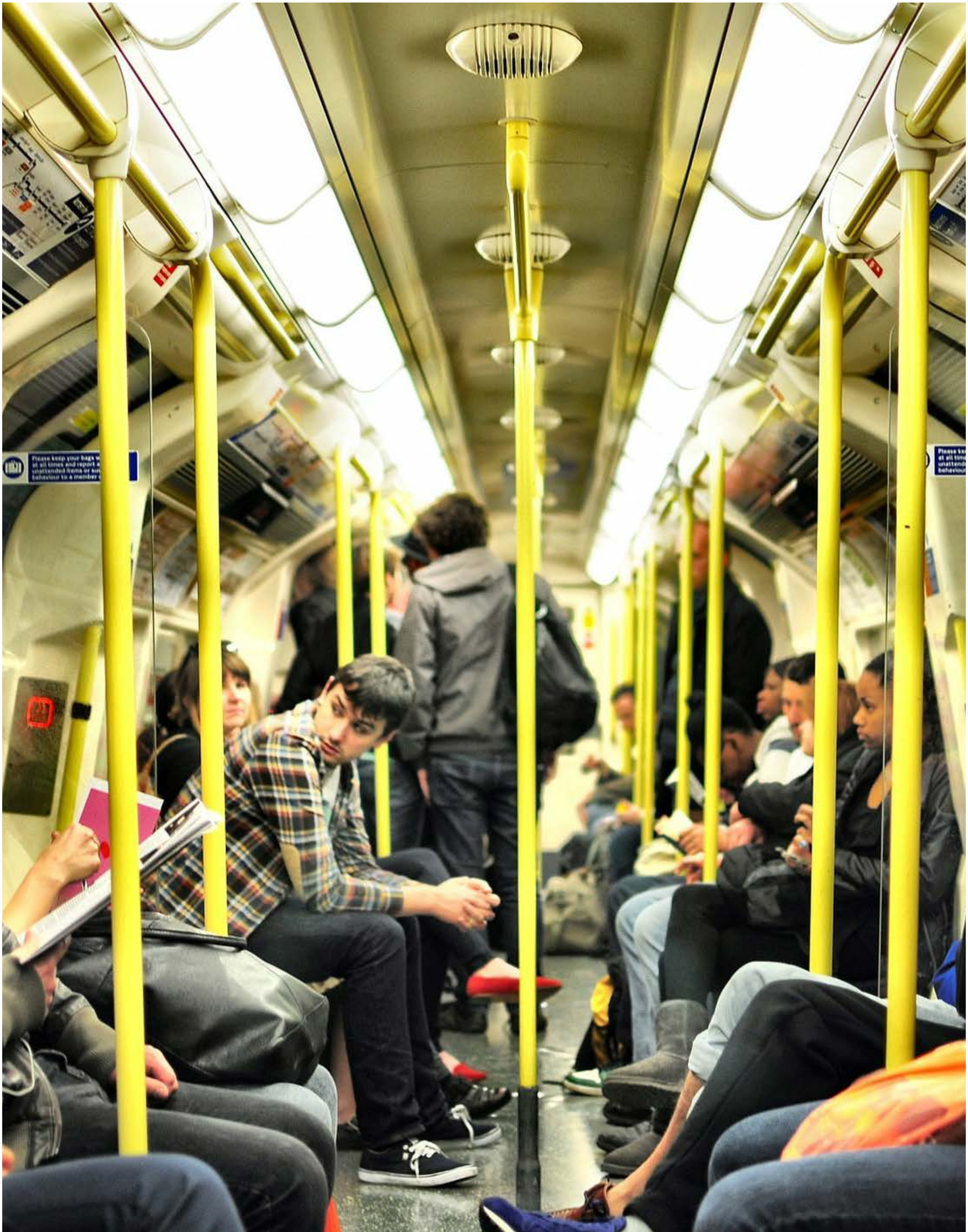


SIGNAL
UNDER

ADAPTIVE RAMP METERING ALGORITHMS IMPLEMENTED IN ENGLAND SHOW IMPROVED TRAFFIC BEHAVIOURS

PETER KIRBY

Principal Consultant
Engineering, Design and Project Management
Manchester, UK

JILL HAYDEN

Technical Director
Engineering, Design and Project Management
Manchester, UK

ABSTRACT

National Highways, formerly Highways England, specified and deployed a second-generation ramp metering system (2GRM) with advanced features and trialled the operation at two locations. The system operation includes the provision of three adaptive traffic control algorithms which have been designed to optimise system performance and the response to traffic. Ad-ALINEA, Ad-POQM, and Ad-Release have been monitored, evaluated, and confirmed to provide useful functionality which will cater for variations observed between AM and PM peak periods and improve the experience of road users. The adaptive traffic control algorithms will provide business benefits by reducing the need for ongoing system calibration and the level of knowledge necessary for day-to-day operations.

KEYWORDS

Ramp metering; Adaptive algorithms; Traffic control algorithms

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1. INTRODUCTION

Ramp metering is a traffic management technique which manages the number of vehicles joining a network at peak periods in order to prevent or delay the onset of flow breakdown on the main carriageway.

National Highways, formerly Highways England, began the implementation of a wide scale deployment of ramp metering in 2006. The system was effective but required periodic calibration to account for changes in traffic patterns and network improvements.

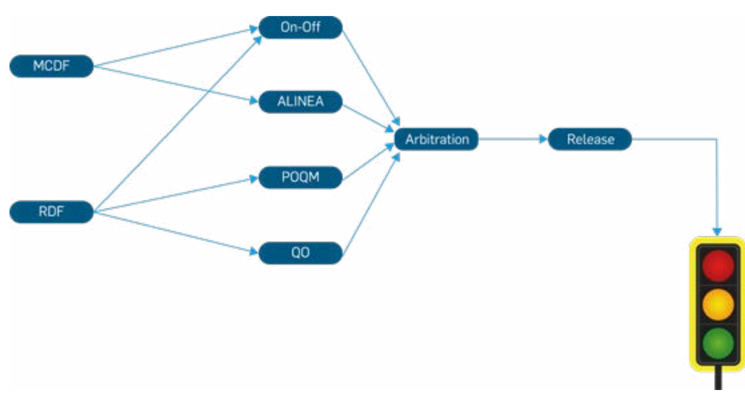
National Highways specified and deployed a second-generation ramp metering system (2GRM) with advanced features and trialled the operation at two locations (M25 J13 clockwise and A3 Dennis Roundabout). The new 2GRM system brought advances in system functionality and technology, a more maintainable and safe design, improved system interfacing, and three new adaptive algorithms designed to optimise system performance and the response to traffic. This paper describes the function and results from the adaptive traffic control algorithms.

2. BACKGROUND

The original ramp metering system uses eight core algorithms as shown in Figure 1 below.

FIGURE 1

Schematic of original algorithms



A high-level review of their relevant function is as follows (from right to left):

- Release – looks up the signals timings associated with the requested hourly flow rates provided by the Arbitration algorithm.

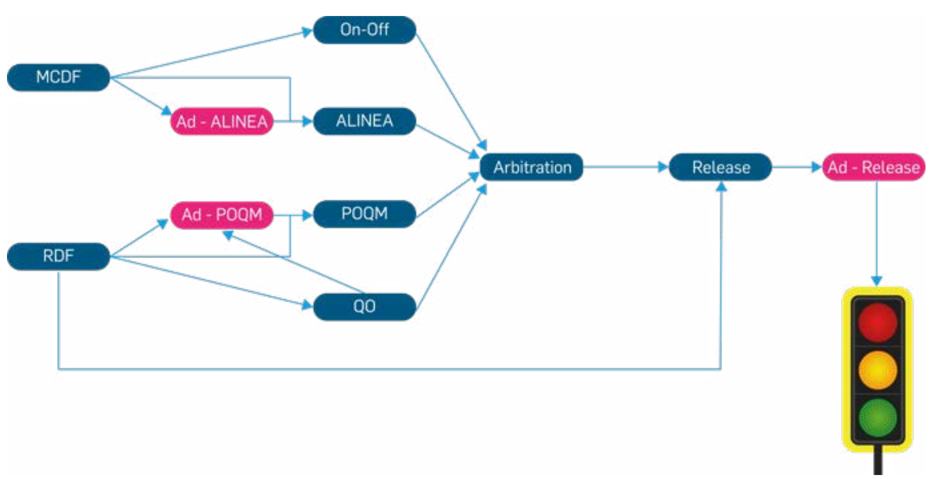
- Arbitration – takes the requested flow rates from the four "main algorithms" and outputs the highest flow rate to the Release algorithm.
- On-Off – turns the system on and off in response to real-time speed and occupancy measurements. On-Off uses flow rate as an output metric.
- ALINEA – requests a flow rate which seeks to maintain mainline downstream occupancy in order to maximise downstream flow.
- POQM (Proportional Occupancy Queue Management) – requests a flow rate which seeks to maintain a slip road occupancy which represents a certain length of queue.
- QO (Queue Override) – Requests a maximum flow rate when a queue is present at the slip road entrance. Requests a minimum flow rate at all other times.
- MCDF and RDF (Main Carriageway and Ramp Data Filtering)- filters the sensor data from the mainline and the slip road, respectively, to avoid noisy readings for the operation of the algorithms.

The 2GRM system provides three new adaptive algorithms which seek to optimise the mainline, queue management, and signal timings algorithms. These interface with the existing algorithms and are in illustrated in Figure 2.

The operation and results of each of the three adaptive algorithms is provided in subsequent sections.

FIGURE 2

Schematic of original algorithms with Adaptive functionality incorporated



3. MAINLINE ALGORITHM (ALINEA AND AD-ALINEA)

ALINEA is an algorithm that ramp metering utilises to select the release level required on the slip to maintain the mainline occupancy close to the critical occupancy, to maximise the mainline flow.

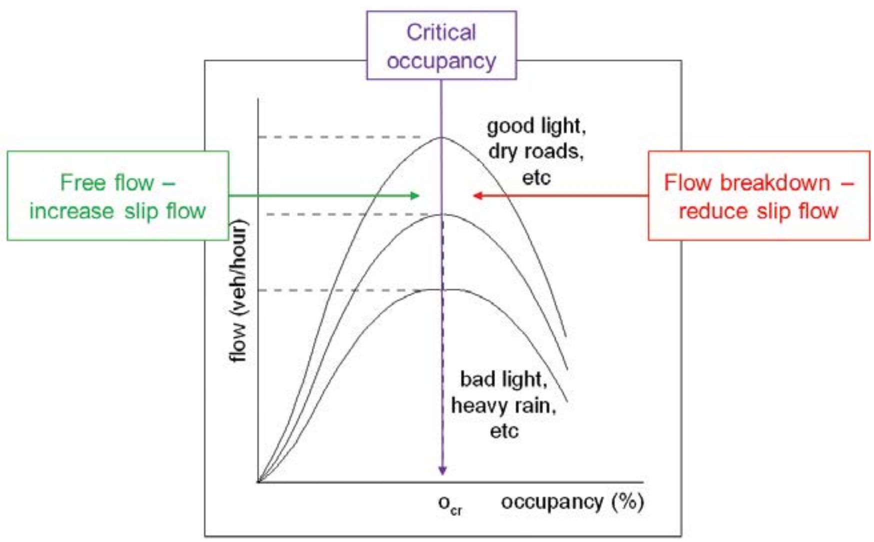
The ALINEA algorithm calculates the release rate (rAl) by multiplying the difference between the desired occupancy (oDes) and the measured (downstream) occupancy (oDs) by a constant gain factor (kAl), increasing the ramp flow rate if the measured downstream occupancy (oDs) is less than the desired occupancy (oDes) and vice versa. The ALINEA algorithm is expressed as follows:

rAl(k) = rAl(k-1) + kAl (oDes – oDs(k-1))

The critical occupancy is the occupancy for which the flow in the mainline is at its maximum. If the flow (in vehicles per hour) is plotted against occupancy for the mainline, the resulting flow-occupancy curve presents an inflexion point: as occupancy increases so does the flow until it reaches the critical occupancy, after which there is a reduction in flow and/or flow breakdown as occupancy increases. The principle of ALINEA's operation is shown in Figure 3.

FIGURE 3

Typical flow vs. occupancy plot



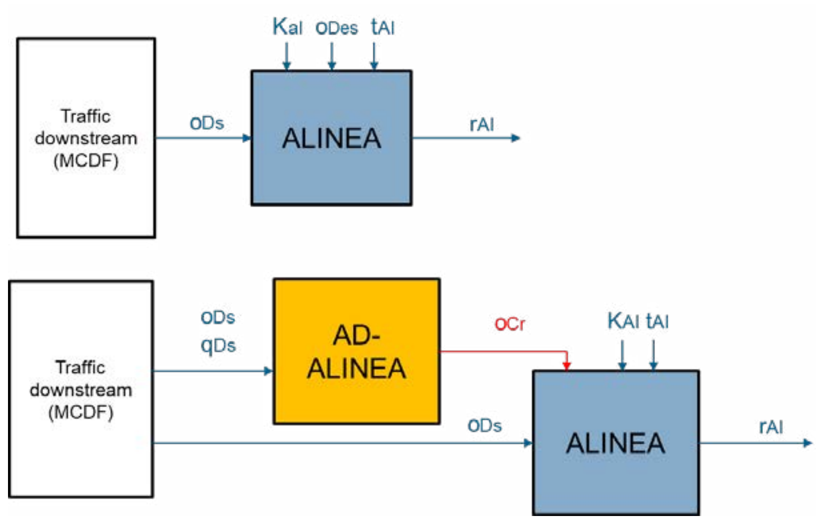
In order to maximise the performance of the ALINEA algorithm, the desired downstream occupancy (oDes) is pre-specified as close as possible (or slightly below) to the critical occupancy, based on traffic data and observations during calibration.

However, the critical occupancy may change in real time due to fleet composition, application of control measures, and environmental factors. To enable automatic real-time estimation of the critical occupancy, 2GRM introduces Adaptive ALINEA (Ad-ALINEA).

Ad-ALINEA continuously estimates the critical occupancy of the mainline downstream of the merge, based on the current flow (qDs) and occupancy (oDs). The value of the critical occupancy calculated every iteration by Ad-ALINEA (oCrKf) is in turn used as the desired occupancy (oDes) by the ALINEA algorithm. The inputs, outputs, and variables used by ALINEA and Ad-ALINEA are illustrated in Figure 4.

FIGURE 4

ALINEA and Ad-ALINEA algorithms



Ad-ALINEA estimates the critical occupancy by measuring the gradient of the flow-occupancy curve to determine where the maximum flow occurs, i.e., where the flow-occupancy gradient is: dqDs / doDs = 0. Ad-ALINEA uses the Kalman filter to produce a smooth estimate of the gradient (dKf).

The Kalman filter is an algorithm that can effectively calculate the state of a system in the presence of uncertainty due to noisy sensor data or random external factors. It obtains a smoothed value by using a weighted average between a predicted value and the actual measurement, with a higher weight towards values with lower uncertainty. The weights are calculated from the covariance, a measure of the estimated uncertainty of the predicted state.

For an estimated critical occupancy (oCrKf):

- If Ad-ALINEA calculates a positive or negative gradient (dKf), the critical occupancy (oCrKf) will be increased or decreased by a small amount (deltaKf), respectively.
- If Ad-ALINEA calculates a gradient dKf that is close enough to 0, critical occupancy value does not change.

In addition, the algorithm initialises every day by dropping the value of the estimated critical occupancy (oCrKf) to its minimum while traffic conditions are free flowing and ramp metering is not operational. This caters to different performances in AM and PM peak conditions. If the difference between the measured occupancy and the estimated critical occupancy (oCrKf) is more than a tolerance value pOcc (i.e., the calculated occupancy is far enough from the critical occupancy) for a number of iterations (kIncEst), the algorithm decreases the estimated critical occupancy. This prevents Ad-ALINEA from starting the peak with a critical occupancy that is too high.

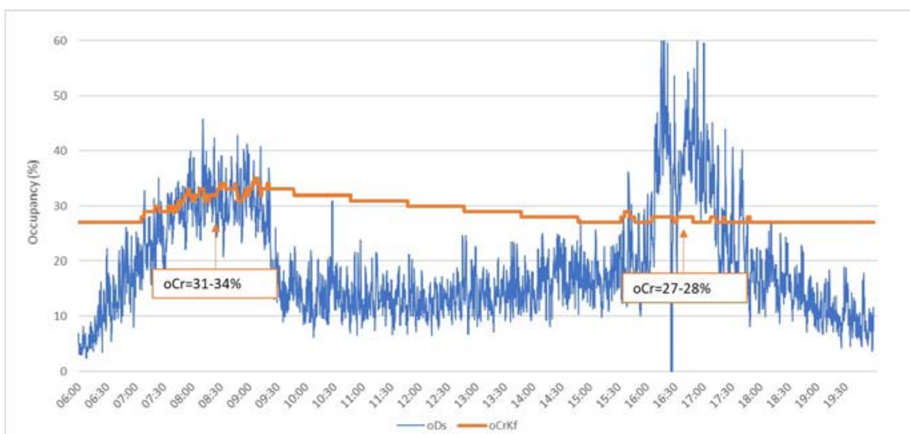
3.1. Commentary and Results from A3 Dennis Roundabout Site

Once the algorithm parameters were set up to respond to changes in the traffic, Ad-ALINEA showed a good response. Note that sometimes (especially in the AM peak) it was difficult to find the negative slope due to traffic characteristics leading to a relatively flat flow-occupancy curve. Defining adequate limits for the algorithm prevented the calculated critical occupancy downstream from creeping upwards.

Figure 5 below shows a typical time series plot of downstream occupancy and oCrKf as calculated by Ad-ALINEA. It can be observed that, for the A3 site, the AM peak shows a higher critical occupancy than the PM peak. A review of multiple (approximately 80) flow-occupancy curves confirmed that Ad-ALINEA predicted the critical occupancy range for all peaks assessed.

FIGURE 5

Changes in critical occupancy throughout the day (07/01/2019) at A3 site



4. Queue Management Algorithm (POQM and Ad-POQM)

Proportional Occupancy Queue Management (POQM) is the algorithm which proportionally increases the release rate requested from ALINEA as a queue is building up on the slip road. POQM maintains the queue length within acceptable limits, allowing arriving platoons to be stored without extending the queue to the local road network.

The POQM algorithm calculates the release rate (rpoqm) by multiplying the difference between the measured occupancy (oCq) and desired occupancy on the slip (oDesCq) by a constant gain factor (kpoqm). This amount is added to the release rate calculated by ALINEA. The POQM algorithm is expressed as follows:

$$rpoqm(k) = rAl(k-1) + kpoqm\ (oCq(k-1) - oDesCq)$$

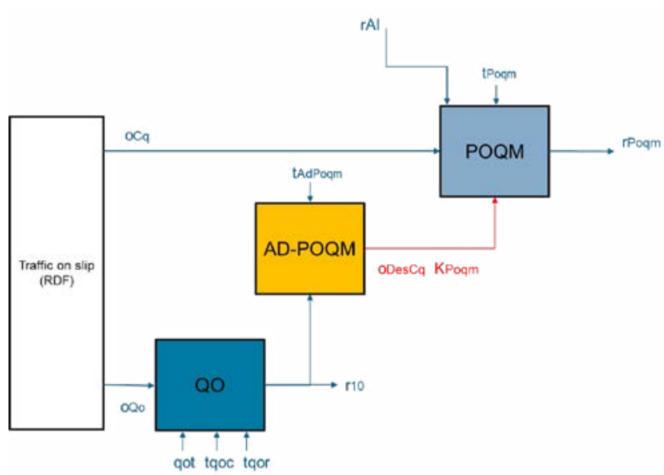
In standard POQM, the value of oDesCq is defined by the user and corresponds to the occupancy when the slip has a desired queue length, usually around a value of approximately 20-30%. When the slip is full, the measured occupancy (oCqQO), which is determined by observations of the traffic on site, is usually around 60%.

In order to maximise the performance of POQM, the desired slip occupancy value (oDesCq) should be as high as possible without resulting in the queue extending to the point where queue override is triggered too frequently.

Adaptive-POQM (Ad-POQM) varies the value of oDesCq to increase the length of the acceptable queue as long as queue override is not being triggered too frequently. A change of oDesCq also requires a change to the associated gain factor so Ad-POQM varies the kpoqm gain factor, too. The values are in turn used by POQM, as shown in Figure 6.

FIGURE 6

POQM and Ad-POQM algorithms



4.1. Commentary and Results from A3 Dennis Roundabout Site

With Ad-POQM enabled, a much better behaviour was observed on-street as the queue management was able to make use of fluctuations in queue length and modify its desired occupancy accordingly.

Figure 7 illustrates the changes in system values as a result of Ad-POQM throughout a typical AM peak period. The blue lines represent Queue Override and the yellow lines are the release levels requested by the system. Kpoqm (grey) and oDesCq (orange) are optimised by Ad-POQM. With Ad-POQM enabled, Queue Override was triggered less frequently, and the system was better able to vary its requested release rate in response to queue length fluctuations.

FIGURE 7

Ramp metering behaviour at A3 site with Ad-POQM

Ad-POQM behaved as expected after careful set up of the parameters. As a general observation, it was found that the algorithm could be quite aggressive and, therefore, it is important to understand the behaviour of POQM and Queue Override before enabling Ad-POQM and to observe Ad-POQM's behaviour during the first days to set up the algorithm properly.

It was also found that, where the slip road flows are very high, Ad-POQM significantly improved the behaviour of Queue Management and Queue Override.

5. SIGNAL TIMINGS ALGORITHM (RELEASE AND AD-RELEASE)

Ramp metering uses 10 release levels that are defined during calibration. Each release level delivers a particular slip road flow rate. The release levels are equally spaced and are chosen based on the range of peak hour slip road flow rates for a given site. The main carriageway and slip road algorithms request flow rates between the site-specific minimum and maximum value. Each of the release levels are associated with a specified green time and red time (starting and leaving ambers are the same and fixed for every cycle). The ramp metering algorithms use feedback loops which help with error correction; however, the system will perform optimally if the flow rate requested by the system is actually delivered across the stop line. During calibration, checks are made to confirm the green and red timings actually deliver the flow rates requested by the traffic control algorithms.

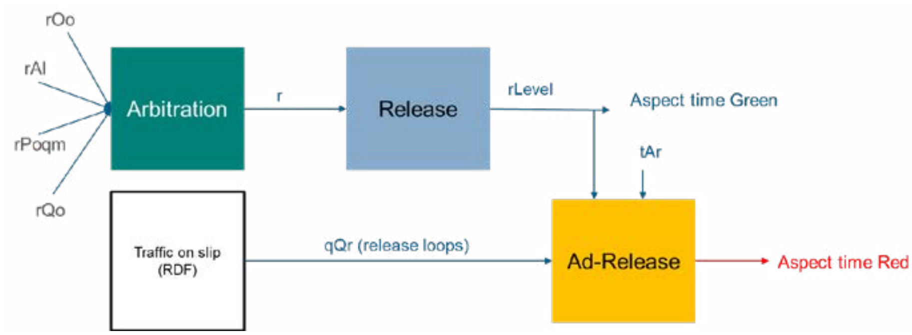
Adaptive release (Ad-Release) optimises the red signal timings for each release level based on the measured flow released from the stop line. This aims to ensure that the system actually delivers the required flow for each release level. The algorithm architecture is shown in Figure 8 below.

Over a period of time, if the average measured flow rate from the release level is greater than the required flow rate, the red time increases to reduce the flow by having fewer signal cycles per hour. Similarly, if the historic average measured flow rate from the release level is lower than the required flow rate, the red time decreases which increases the flow by creating more signal cycles per hour. To avoid confusing drivers with excessively short red periods, the best-practice minimum red time (a constraint for Ad-Release) is set to three seconds. The Ad-Release algorithm only operates when the following is true:

- A queue exists to deliver the flow rate required by the system; and
- The merge area beyond the stop line is sufficiently clear to allow the vehicles an unrestricted access to the mainline. Or, more specifically, the presence of stationary or slowly moving vehicles beyond the stop line does not interfere with the release of vehicles from the stop line.

FIGURE 8

Release and Ad-Release algorithms



5.1. Commentary and Results from M25 Junction 13 Site

The algorithm optimised the red times for those release levels that were calculated as being inaccurate. Ad-Release worked well, making small adjustments to the red signal timings, without any major oscillations or major departures from the manually entered values. Table 1 below shows the optimised red times (dark red cells) by release level over a small number of broadly consecutive days.

TABLE 1:

Red signal timings during calibration of Ad-Release for M25 J13

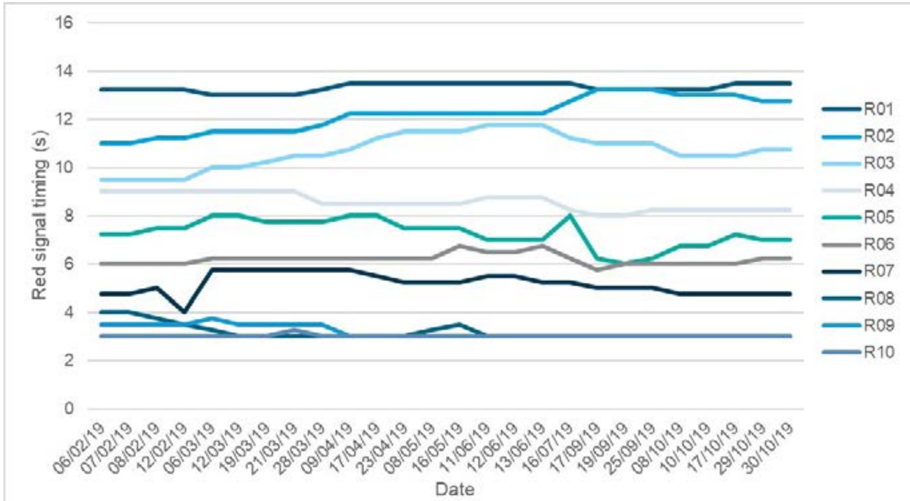
Non-adaptive			6/2/19	7/2/19	8/2/19	12/2/19
Release level	Green (s)	Red (s)	Red (s)	Red (s)	Red (s)	Red (s)
1	2	13.25	13.25	13.25	13.25	13.25
2	2	10.75	11	11	11.25	11.25
3	2	8.5	9.5	9.5	9.5	9.5
4	4	9	9	9	9	9
5	4	7.25	7.25	7.25	7.5	7.5
6	4	6	6	6	6	6
7	4	4.75	4.75	4.75	5	4
8	8	4.75	4	4	3.75	3.5
9	8	3.5	3.5	3.5	3.5	3.5
10	8	3	3	3	3	3

A longer-term review of the progression of the red signal timings demonstrated that the algorithm behaves as expected and adapts successfully to changes in traffic conditions as shown in Figure 10.

It is noted that by April, the three higher release rates merged into a single minimum red value. This suggests that for an eight-second green (the longest green time currently configured within the system) and three-second red, the release flow that can be achieved at this site is approximately that associated with release level eight. It is suggested that the green times for the high release levels are increased to give more range to Ad-Release to accommodate high flows.

FIGURE 10

Changes in M25 J13 red signal timings from February to November 2019



6. SUMMARY AND CONCLUSIONS

Each of the adaptive algorithms have been demonstrated to work effectively. Implementation of these algorithms will provide an improved response to traffic conditions, cater for variations observed between AM and PM peak periods, and improve the experience of road users.

To ensure that the adaptive algorithms are optimised, the rate and boundaries within which they are permitted to perform need to be correctly configured and appropriately understood.

The adaptive algorithms will bring benefits through reducing the need for on-going system calibration and the level of knowledge necessary for day-to-day operations.

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BALANCING TUNNEL BORING MACHINE FACE PRESSURES IN CHALLENGING CONDITIONS: A CASE STUDY FROM THE FEEDER 9 GAS PIPELINE REPLACEMENT TUNNELLING PROJECT

ALEX GREEN

Tunnel Engineer
Engineering, Design and Project Management
London, UK

ABSTRACT

The Feeder 9 Gas Pipeline Replacement tunnelling project faced a number of significant engineering challenges, including difficult geological conditions and large tidal variations in groundwater pressures. These factors, combined with tunnelling in shallow, highly variable material along sections of the alignment, compounded the challenge of controlling tunnel boring machine (TBM) face pressures and limiting ground movements local to major assets. This paper highlights how planned mitigation measures were successfully executed by a skilled contractor-consultant team to prevent damage to an operational high pressure gas pipeline when large ground movements were recorded during TBM transit. Details of the theoretical approach used to specify face pressures, and how this was applied in practice to inform on-site proposals, are outlined. The solutions developed and recommendations provided to minimise ground movements and allow the TBM to advance underneath the pipe with a high level of confidence are also discussed.

KEYWORDS

Tunnelling; TBM face pressures; Limit Equilibrium method; Damage assessments

1. INTRODUCTION

1.1 Project Overview

The purpose of the Humber Feeder 9 Gas Pipeline Replacement project was to replace one the UK's major natural gas pipelines, which ran across the Humber estuary east of Hull and carried approximately 25% of the UK's natural gas supply. A study by National Grid (NG) identified critical vulnerabilities to the existing Feeder 9 pipeline, which was installed in a trench in the bottom of the estuary. Over time, scour of the riverbed had left it exposed in sections, making it vulnerable to accelerated degradation and accidental damage from marine ship anchors. To install the new pipeline, a 5km long tunnel, utilising a precast concrete (PCC) segmental lining, was designed and constructed to act as a conduit through the bedrock. The tunnel was the first to be constructed underneath the Humber estuary. Figure 1 shows a long section through the tunnel, displaying the local geology.

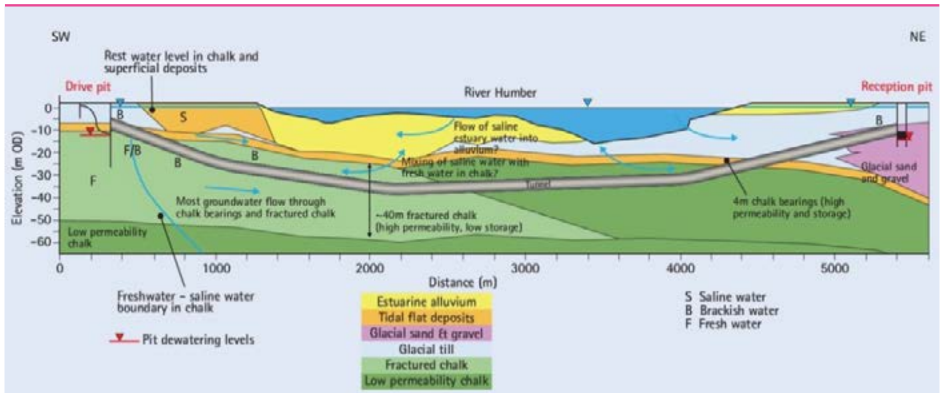


FIGURE 1

Geological long section through the Feeder 9 Tunnel alignment; Note. section of Alluvial Deposits at reception shaft not shown (Champkin, 2021)

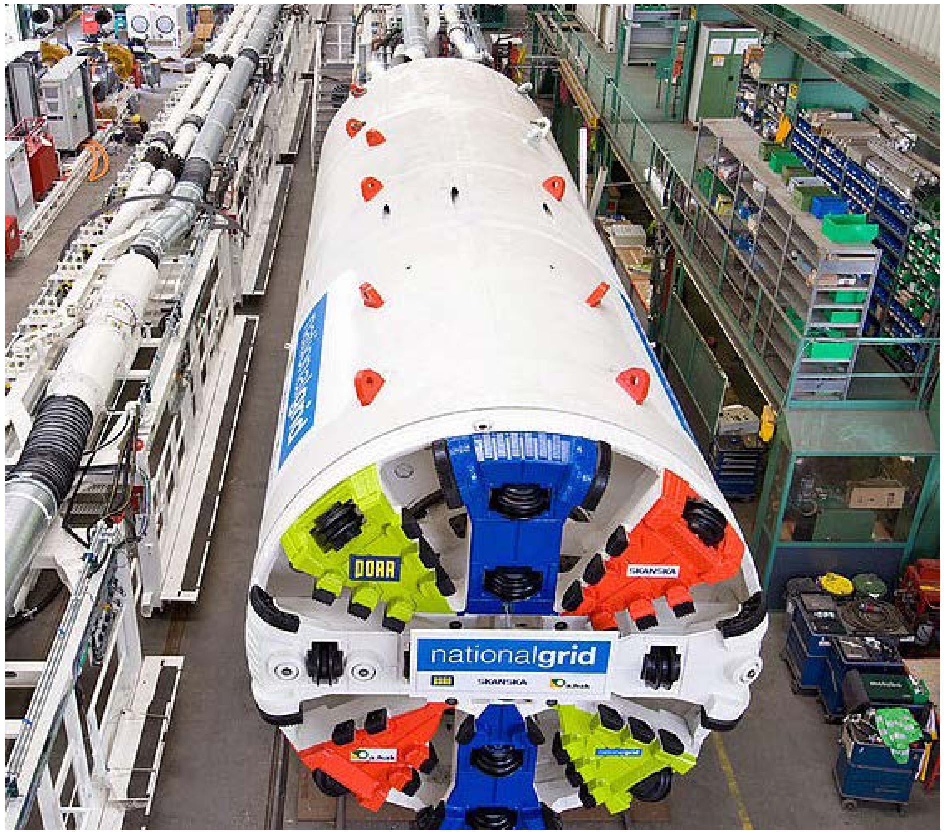
Humber Pipeline Tunnel Joint Venture (HPT JV), a joint venture formed from tier 1 Contractor Skanska, tunnelling specialists PORR, and pipeline specialists A. Hak was appointed by NG to undertake the works. HPT JV commissioned Atkins to deliver the tunnel design, ground investigation and geotechnical modelling, environmental assessment and third-party interfaces, and local highway design. Atkins also provided support to HPT JV for a variety of issues that arose during the tunnel construction works.

1.2 Construction of the Feeder 9 Tunnel

A slurry shield tunnel boring machine (TBM) was used to construct the tunnel (see Figure 2 for image of TBM "Mary"), which launched from Goxhill on the south bank of the Humber estuary in April 2018, and finished its journey at Paull on the north bank in September 2019.

FIGURE 2

Slurry TBM "Mary" used to construct the Feeder 9 Tunnel (Herrenknecht AG, 2018)



A slurry TBM operates by providing face support through a pressurised bentonite slurry suspension, which is regulated by the inflow (feed line) and outflow (return line). The excavation head is completely sealed, providing a barrier against water ingress, and the excavated material is suspended in the slurry allowing it to be pumped out of the tunnel and processed at the surface. A slurry TBM was selected to construct the Feeder 9 Tunnel due to the high groundwater pressure present across the alignment (in particular the sections of ground directly under the estuary) and the local geology, which consisted of Marine Alluvium, overlying mixed Glacial Deposits, overlying a bedrock of Structured and Unstructured Chalk.

2. CALCULATION AND SPECIFICATION OF TBM FACE PRESSURES

2.1 Overview of TBM Face Pressures

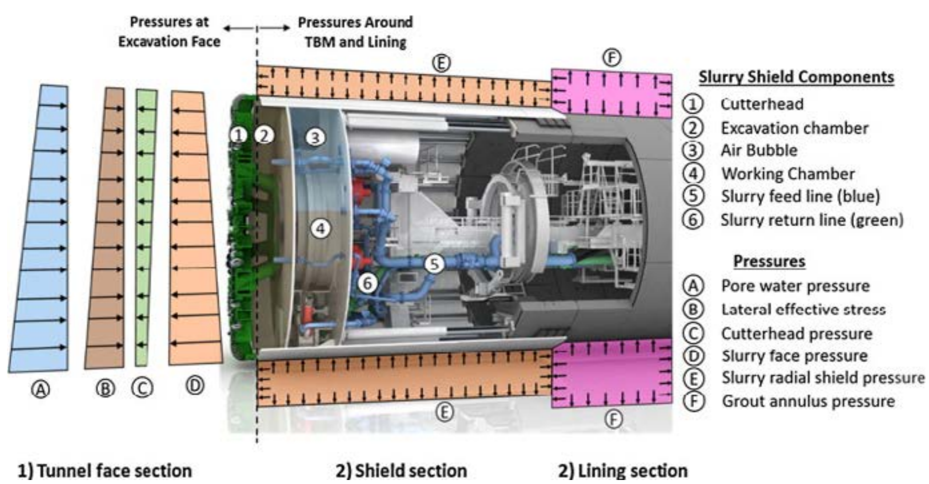
Prior to TBM launch, the designer undertook the Category III check of the TBM face support pressures, which were originally produced by a specialist geotechnical consultant. TBM face pressures are key operational parameters required by the TBM operator to ensure the excavation face remains stable under changing geological/hydrological conditions. Face pressures are typically expressed as minimum and maximum values at regular intervals across the tunnel alignment. The primary objectives of face pressure controls are:

- Ensure face pressures are above a minimum value, below which there is a risk that the excavation face may collapse and/or water and fines may wash into the TBM, leading to excessive ground settlement; and
- Limit the face pressures below a maximum value, above which there is a risk that excessive ground heave or blow-out can occur.

Many methods exist for calculating face pressures, including analytical, empirical and numerical methods. The choice of method depends primarily on the nature of the ground: certain methods favour drained (granular) soils whilst others are more suitable for undrained (cohesive) soils. The maximum limiting pressure is calculated relatively simply using the weight of the ground and groundwater above the tunnel. Calculation of the minimum pressure typically requires a more sophisticated approach that considers a failure mechanism of the soil at the tunnel face; although for competent rock it is often based on groundwater pressure only. Figure 3 displays the key pressures that require balancing for slurry TBM operations.

FIGURE 3

Schematic of a slurry TBM and pressure components (Mooney et al., 2016)



2.2 Methods for Calculating Minimum Earth Pressure

For tunnelling in granular soils, several analytical methods based on the Mohr-Coulomb law of failure have been developed to approximate the earth pressure component of minimum TBM face pressure. The first failure mechanism was proposed by Horn (1961), based on a sliding wedge failure at the tunnel face loaded by a rectangular prism above. Anagnostou & Kovari (1994) developed this three-dimensional mechanism further for use in TBM tunnelling, and included Janssen's silo theory (1895) to take into account vertical arching of the soil, thus resulting in lower earth pressures acting on the tunnel face. DIN 4085 is another widely-used method, which assumes failure of a three-dimensional spherical body of earth proposed by Piaskowski & Kowalewski (1965). The tunnel face is split into horizontal plates, with the earth pressure calculated at each plate and summed to find the total earth pressure; however, it does not consider vertical soil arching, therefore producing more conservative results (Lantinga, 2018).

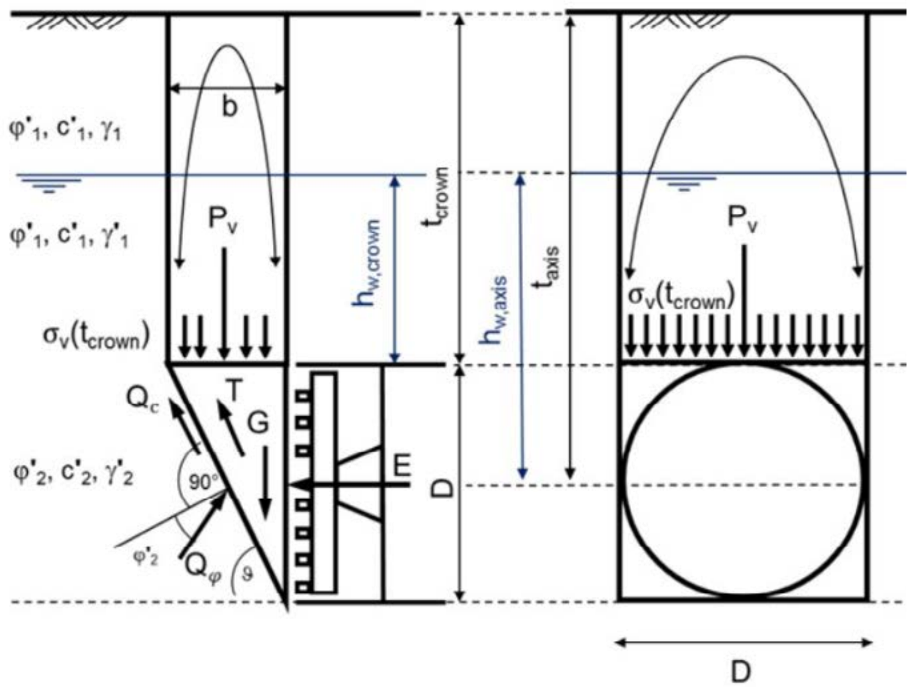
For tunnelling in cohesive soils, both analytical (Davis et al., 1980) and empirical (Broms & Bennermark, 1967) approaches use a 'critical stability ratio' to calculate minimum face pressures, which is typically a function of overburden height and tunnel diameter. Due to the mixed geology found along the Feeder 9 Tunnel alignment, cohesive soil methods were not considered as part of the specification of face pressures for the project and are not discussed further.

2.3 Limit Equilibrium Method

The DAUB (German Tunnelling Committee) produced a guide titled 'Recommendations for Face Support Pressure Calculations for Shield Tunnelling in Soft Ground' (2016), which outlined the 'Limit Equilibrium' method – based on Anagnostou & Kovari's (1994) failure mechanism – as the recommended approach for calculating minimum face pressures in both granular soils and where a combination of granular and cohesive layers is present. The Limit Equilibrium method has the advantage over other methods (such as DIN 4085) as the effect of soil arching can be included when tunnelling in competent ground, thus resulting in a smaller minimum pressure and hence a wide range of allowable face pressures to be specified. Additionally, the effect of soil cohesion is much lower for the Limit Equilibrium approach, thus resulting in less variation in the minimum pressures calculated; whereas cohesion has a much greater influence on the DIN 4085 method (Karl, 2015). As a result, the Limit Equilibrium method was selected for undertaking the Category III check of the TBM face pressures for the Feeder 9 Tunnel. Figure 4 displays a schematic of the model, extracted from the DAUB guide.

FIGURE 4

Schematic of Limit Equilibrium failure mechanism (DAUB, 2016)



For this method, a critical wedge angle (ϑ_c) must be determined for which the highest earth pressure force ($E_{max,re}$) is calculated (see Eq. 1). The calculation considers both stabilising forces (shear resistance due to friction and cohesion, T) and destabilising forces (weight of wedge, G; and vertical load from prism, P_v).

$$\textbf{Eq. 1} \quad E_{max,re} = \frac{(G + P_V) \cdot \left(sin\vartheta_c - cos\vartheta_c \cdot tan\varphi'_2\right) - 2T - c'_2 \cdot \frac{D^2}{sin\vartheta_c}}{sin\vartheta_c \cdot tan\varphi'_2 + cos\vartheta_c}$$

To calculate P_v, the effective vertical stress at the tunnel crown ($\sigma'_{v,crown}$) must be found, which is a function of overburden depth (H_{crown}) and soil unit weight. When H_{crown} is less than or equal to twice the tunnel diameter (D), full effective overburden is taken. However, based on silo theory, if H_{crown} is greater than 2D, a reduced effective overburden is taken to account for arching of the soil above the wedge, using Eq. 2.

$$\textbf{Eq. 2} \quad \sigma'_v = \left(\frac{\frac{A}{U} \cdot \gamma_r - c'}{K_{prism} \cdot tan\varphi'}\right) \cdot \left(1 - e^{-\frac{U}{A} K_{prism} \cdot h \cdot tan\varphi'}\right) + \sigma_s \cdot e^{-\frac{U}{A} K_{prism} \cdot h \cdot tan\varphi'}$$

For the stabilising forces, the shear resistance force is made up of two components: friction force (T_r) and cohesion force (T_c). Calculating T_c is relatively simple (see Eq. 3); however, assumptions must be made when defining T_r (Eq. 4), which is a function of the lateral earth pressure acting on the wedge (Broere, 2001).

$$\textbf{Eq. 3} \quad T_C = \frac{c' \cdot D^2}{2tan\vartheta_c}$$

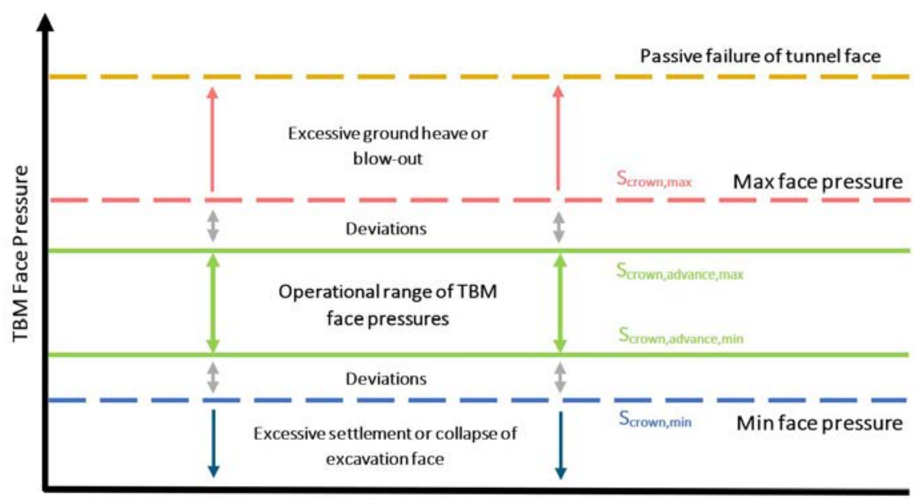
$$\textbf{Eq. 4} \quad T_R = tan\varphi' \cdot K_{wedge} \cdot \left(\frac{D^2 \cdot \sigma'_{v,crown}}{2tan\vartheta_c} + \frac{D^3 \cdot \gamma_r}{6tan\vartheta_c}\right)$$

The water pressure acting on the tunnel face is calculated separately, based simply upon the height of water above tunnel axis level. Factors of safety are applied to the earth pressure and water pressure (1.05 and 1.5 respectively), with the factored pressures summed. The minimum support pressure at tunnel crown ($s_{crown,min}$) is determined by accounting for the beneficial support provided by the slurry medium. Support pressure deviations (specified by the TBM manufacturer) are then incorporated, to determine the minimum TBM face support pressure at the tunnel crown for regular advance ($s_{crown,advance,min}$).

To calculate the maximum face support pressure, the minimum total vertical stress at the tunnel crown ($\sigma_{v,crown,min}$) is calculated, using the lower-bound unit weight of the soil layers. A factor of 0.9 is applied, to give the maximum support pressure at tunnel crown ($s_{crown,max}$). Support pressure deviations are included, to determine the maximum TBM face support pressure at the tunnel crown for regular advance ($s_{crown,advance,max}$). An operational range whereby the TBM can operate in full slurry advance is then defined, as shown in Figure 5.

FIGURE 5

Allowable operational face pressure range for full TBM advance (DAUB, 2016)



Limitations exist with the Limit Equilibrium approach (and other analytical methods previously discussed) when tunnelling in multi-layer soils. In scenarios where cohesive layers overlay a granular tunnel face, it is difficult to estimate the reduced overburden due to soil arching, as the method incorporates a drained analysis. Another limitation concerns tunnelling in heterogenous 'mixed-soil' faces. For cases where the face is granular and cohesive, the DAUB guide (2016) recommends viewing the whole tunnel face as granular and using the Limit Equilibrium method. Where multiple granular layers are present, but the properties of each layer vary significantly, common practice is to use a weighted average of the different soil properties.

2.4 TBM Face Pressures in the Context of the Feeder 9 Tunnel

When tunnelling in Structured Chalk, which the design team deemed to be self-supporting due to its high strength/stiffness, minimum face pressures were set to balance groundwater pressures only. For TBM transit through Unstructured Chalk, Glacial Deposits and Marine Alluvium, the Limit Equilibrium method was used. However, a conservative approach was taken whereby no reduction in overburden due to soil arching was assumed, thus resulting in greater minimum face pressures; primarily due to the lack of confidence in the drained nature of the Glacial and Alluvial Deposits.

Minimum face pressures were specified at regular intervals along the tunnel alignment for two additional cases: 1/2 slurry drawdown (1/2 compressed air) and full slurry drawdown (1/1 compressed air). These were specified to allow for operator access into the excavation chamber, which would be carried out to facilitate inspection and repair works on the TBM cutterhead.

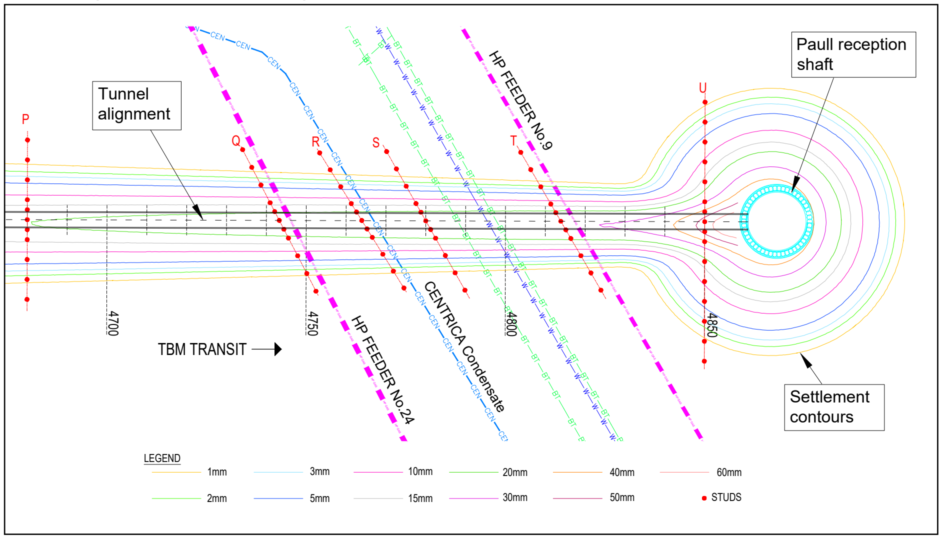
3. TBM TRANSIT UNDER THE EXISTING FEEDER 9 HIGH PRESSURE GAS PIPELINE AT PAULL

3.1 Damage Assessment and Ground Monitoring Provisions for the Transit

On the approach to the reception shaft at Paull, the tunnel alignment passed under several third-party assets which were deemed to lie within the Zone of Influence (ZOI) of the TBM. One high risk asset identified was a section of the existing Feeder 9 high pressure gas pipeline, which was required to remain fully operational during tunnelling. Prior to the start of tunnelling activities, the likely impact on these utilities due to tunnelling-induced ground movements was reviewed and an instrumentation and monitoring (I&M)

plan which would be used to monitor settlement and prevent damage to the assets was subsequently designed. An extract from one of the I&M drawings is shown in Figure 6.

FIGURE 6



Extract from an I&M drawing; displaying positions of assets and surface monitoring transects in relation to tunnel alignment and reception shaft, and predicted settlement contours

Trigger levels for individual assets and for ground surface movement – using transects carefully positioned to monitor ground movements and TBM performance prior to entering the ZOI of each asset – were also recommended; see Table 1 for Feeder 9 pipe and Transect T trigger levels for vertical ground movement.

TABLE 1:

Recommended trigger levels for Feeder 9 pipe and Transect T (+ve = settlement, -ve = heave)

UNITS (MM)	GREEN	AMBER	RED	BLACK
Feeder 9 (pipe level)	14	27	33	38
Transect T (ground level)	15	29	36	43

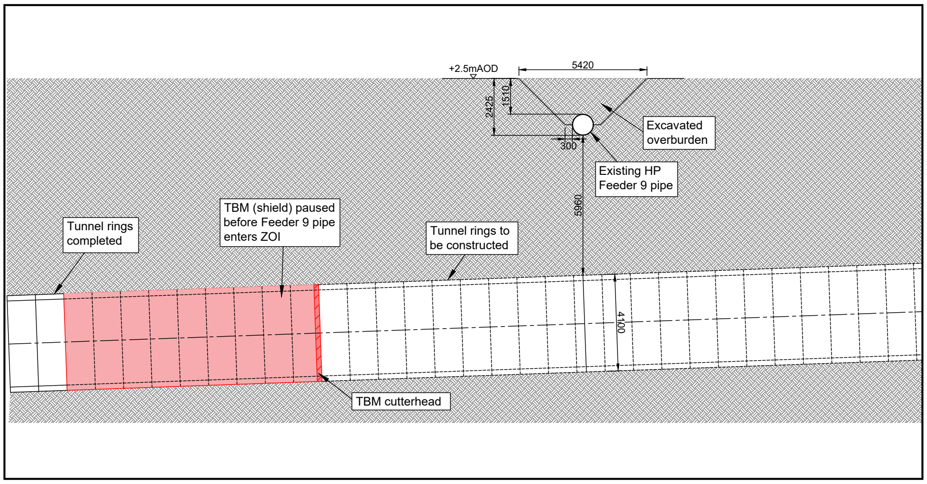
3.2 High Volume Loss Experienced on the Approach to Feeder 9 Pipe

Measured/actual ground movements (Transects R, S) on the approach to the Feeder 9 transit (Transect T) were larger than expected, due to the ground experiencing high volume loss. This was likely caused by pockets of very weak Alluvium within the Glacial Deposits in this section of the alignment – a key geotechnical hazard identified prior to tunnelling. To mitigate against the potential risk of excessive settlement damaging the Feeder 9 pipe, the contractor stopped tunnelling prior to entering the Feeder 9 pipe ZOI, until additional clarification on the potential settlement-induced impacts on the pipe was provided. The width of the settlement trough was calculated –

based on settlement monitoring data from previous transects – and the deflection of the pipe under varying (and zero) ground load was analysed. Results demonstrated that with no overburden, the pipe would likely span over the settlement trough and would therefore not exceed its strain limit. Following this, overburden was removed above the Feeder 9 pipe for a 20m length section. Figure 7 is a cross-section which displays the stationary position of the TBM and cover to the exposed Feeder 9 pipe.

FIGURE 7

Cross-section of exposed Feeder 9 pipe in relation to stationary TBM position and tunnel alignment



3.3 Risks of Controlling TBM Face Pressures in Difficult Environments

Balancing face pressures through this transit was vitally important for two reasons: to ensure excessive settlement or heave did not occur in close vicinity to the pipe; and to control the width of the settlement trough to limit the spanning length of the pipe. Control of face pressures is particularly difficult when sudden changes in ground level/overburden are experienced (e.g. at rivers, cuttings) and when tunnelling in shallow ground, where the acceptable range of face pressures (between minimum and maximum) reduces. A similar scenario was encountered at Crossrail Puddling Mill Lane Portal, where the TBM was launched immediately under the River Lea (reduced cover). Solutions were successfully developed to mitigate the foreseen risks, including the construction of a cofferdam in the canal to increase overburden, soil grouting to solidify the ground and careful TBM face pressure control; ultimately allowing the TBM to advance without affecting the cables (due to tunnelling-induced settlements) and blowing-out the river base.

The hazards associated with tunnelling under an operational high pressure gas pipeline coupled with reduced overburden and tunnelling in unfavourable ground conditions resulted in this becoming a high risk activity

As the TBM had stopped and the tunnelling works were on the project critical path, there were also significant time pressures involved to develop and execute a strategy whereby the TBM could safely pass underneath the Feeder 9 pipe. As such, the collaborative relationship between the designer and contractor was key in providing quick and accurate solutions to inform on-site proposals. This subsequently provided the end client (and asset owner) with confidence and assurance that that there would be minimal impact on the Feeder 9 pipe.

3.4 Measures Implemented to Protect the Feeder 9 Pipe

Initial face pressure specification for tunnelling under the existing Feeder 9 pipe had to be revised to account for the significantly reduced overburden at this location. The designer and contractor worked closely to create a solution whereby suitable minimum and maximum face pressures could be specified to allow tunnelling to commence. Along the 20m exposed section of pipe, three inspection pits were excavated where pipe welds were present to allow NG to undertake a condition survey of the welds to ensure the pipe had no undetected vulnerabilities (see Figure 8). The initial face pressure specification had to be modified to account for the reduced overburden at the inspection pit locations, where trenches 600mm below the pipe were excavated.

FIGURE 8

Exposed Feeder 9 pipe at location of excavated inspection pit

Multiple scenarios were checked for the face pressure calculations, based on varying levels of backfill (assumed to act as a surcharge at ground surface); results for the no/shallow backfill cases verified there would only be a very narrow range of face pressures for TBM operation. Consequently, it was decided that the inspection pits must be backfilled to increase the amount of overburden in the region of the Feeder 9 pipe. A temporary works solution that added overburden back onto the ground to prevent excessive heave/blow-out when the TBM transited, whilst also avoiding adding weight on top of the Feeder 9 pipe to prevent additional settlement, was developed. An in-house face pressure calculation tool (developed by the author), allowed various backfill arrangements to be tested and optimised in a short timeframe. The final stepped trench solution, developed to minimise differences in overburden across the trench (within the TBM's ZOI), comprised backfilling the inspection pits with sand to pipe invert level, followed by backfilling the trench either side of the Feeder 9 pipe through use of cement/ sand bag walls to retain the backfill (see Figure 9).

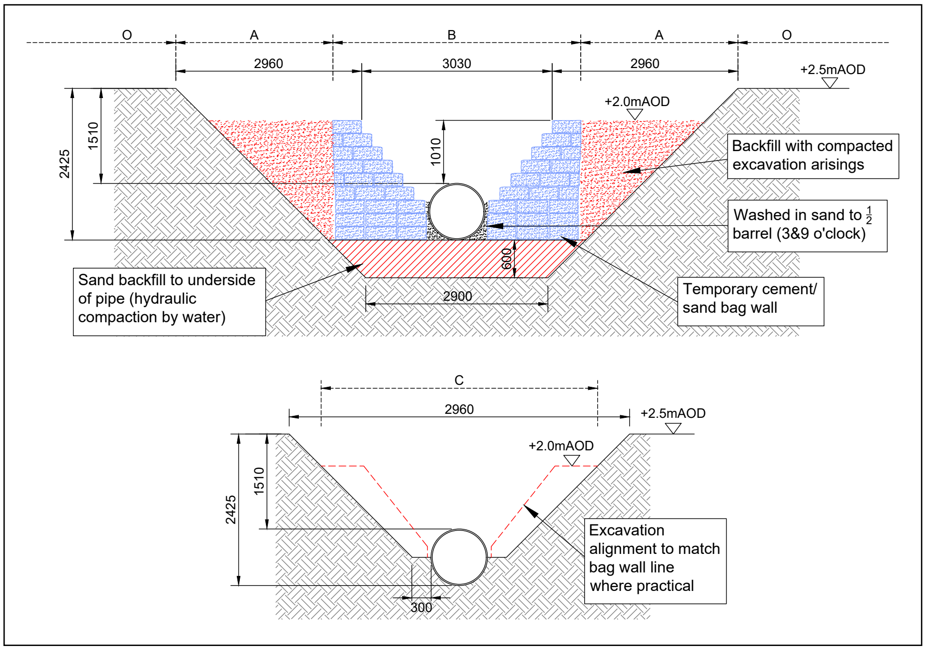
FIGURE 9

Temporary works trenched solution for section of exposed Feeder 9 pipe

Several cases were identified to be present for the reduced overburden scenario and were individually assessed. Figure 10 displays cross-sections of the final trenched solution at both inspection pit locations (full trench) and remaining sections of the exposed Feeder 9 pipe (partial trench), including the cases assumed for face pressure analyses. Due to the uncertainty in how the groundwater would respond to the unloading (due to excavation), an extreme range of groundwater levels which could have been present during the TBM transit were considered. An operational range of face pressures was identified which would allow the TBM to operate safely in full advance (slurry pressure supporting) across all cases considered.

FIGURE 10

Cross-sections of final trenched solution at inspection pit locations (full trench excavation) [top] and remaining exposed pipe locations (partial trench excavation) [bottom]; face pressure analyses cases (O, A, B, C) shown



This reduced the potential for TBM operator error, as transitioning between different pressure ranges (for the different cases) as the TBM advanced underneath the trench would not be required. The minimum/maximum face pressures and a factor of safety (FoS) for each case are shown in Table 2, with the recommended operational range highlighted.

TABLE 2:

Min/max face pressures and operational range calculated for the Feeder 9 pipe reduced overburden scenario

CASE	WATER LEVEL [M AOD]	MIN. FACE SUPPORT PRESSURE ($S_{CROWN,ADVANCE,MIN}$) [BAR]	MAX. FACE SUPPORT PRESSURE ($S_{CROWN,ADVANCE,MAX}$) [BAR]	FOS (η_{RAISE})
O	1.11	1.06	1.28	1.21
A	1.11	1.04	1.20	1.16
	0.28	0.97	1.20	1.24
B	1.11	1.06	1.27	1.20
	0.28	0.97	1.20	1.23
C	1.11	1.05	1.24	1.18
	0.28	0.97	1.18	1.22
Operational Range	-	**1.06**	**1.18**	**1.11**

3.5 Additional Constraints and Recommendations

The minimum face pressures required for full (1/1 air) and half face (1/2 air) draw down of the slurry were found to exceed maximum pressures, due to the narrow operational face pressure range specified. A key recommendation outlined that drawdown of the slurry and/or interventions to access the excavation chamber/cutterhead could not be carried out; a typical constraint in shallow ground. Owing to concerns on the potential for blow-out and liquefaction of material, the following recommendations were made:

- Inspect the bottom of the trench prior to backfilling to check for signs of high permeability columns (i.e. fissures, gravel channels) and grout to plug any observed feature that could provide a flow path for the TBM slurry to surface;
- Approach the crossing at the minimum face pressure, increasing pressure sparingly (if required) whilst regularly monitoring pipe movement and inspecting the trench to check for slurry leakage; and
- Increase slurry density to reduce the risk of slurry leaking to the surface, by creating a more stable filter cake at the face to help contain slurry within the TBM excavation chamber.

3.6 Successful transit of the TBM

On 4-5th September 2019, the TBM successfully passed underneath the Feeder 9 pipe, following the tunnelling controls established by the designer. Regular monitoring of the Feeder 9 pipe before, during and after TBM transit showed that the pipe did not exceed its green trigger limit at any point; whilst monitoring of Transect T identified maximum ground settlements just below the amber trigger limit (Table 1). These results supported the hypothesis that the pipe would deflect with the ground to a certain degree and then bridge over the ground settlement trough, resulting in limited further deflection (i.e. only deflection due to self-weight).

In addition to the face pressures specified by the designer, the skill and judgement required by the TBM crew to balance face pressures and react to the unpredictable and challenging ground conditions was key to the successful crossing. Real-time monitoring and expert communication between the surface and sub-surface teams was vital in ensuring the TBM advanced whilst minimising the risk of excessive settlement/heave.

4. SUMMARY

The successful crossing of the TBM underneath the Feeder 9 pipe highlights that the Limit Equilibrium method is an acceptable approach for specifying face pressures in low overburden environments. Nevertheless, engineering judgement and a detailed understanding of the mechanisms involved was required to specify a suitable range of face pressures for TBM operation that represented the site-specific scenarios.

Several observations were made following the specification of face pressures for the Feeder 9 pipe transit. Whilst Anagnostou & Kovari (1994) recommend using a reduced overburden (due to vertical soil arching) in all scenarios (regardless of ground cover), the author agrees with recommendations from the DAUB guide (2016) to take full overburden where cover is less than 2D, and would extend its use to locations of mixed-soil (granular/cohesive) overburden. Whilst this is a more conservative approach, this paper demonstrates that it is an appropriate measure when tunnelling in difficult geological conditions, such as the sections of Alluvial and Glacial Deposits found along the Feeder 9 Tunnel alignment.

Another observation concerns the complexities of heterogenous (mixed-soil) tunnel faces, a key limitation of the Limit Equilibrium method and other analytical approaches. This paper documents how a simplistic approach of solely considering the properties of the weaker material for the entire failure wedge at heterogenous face locations was adopted. However, the author recognises that opportunities exist to refine assumptions. Although the use of three-dimensional finite element numerical modelling to determine limiting face pressures is common in academia (e.g. Kirsch (2010)), examples demonstrating the behaviour of heterogenous tunnel faces, particularly in industry, are limited. Further studies to understand the correlation between analytical and numerical methods, validated by actual TBM operation data, at challenging locations such as heterogeneous tunnel faces and/or shallow overburden should be explored.

A number of key takeaways from the Feeder 9 pipe transit, specifically in terms of mitigation measures employed to limit risk and provide assurance to the client, are highlighted:

- A robust I&M plan to verify and check TBM performance was designed;
- Procedures were appropriately and timely followed to mitigate foreseen risks;
- An innovative yet simple trenched solution for protecting the Feeder 9 pipe was successfully developed and executed;
- TBM face pressures were balanced with skill (theory) and surface observations (practice) to overcome the challenges of tunnelling in difficult, variable geology; and
- The collaborative relationship between the designer and contractor was key in the design and implementation of mitigation measures to protect the Feeder 9 pipe.

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Tunnel Exit
1230 MTS

ACCELERATED BRIDGE CONSTRUCTION TECHNIQUES USING PREFABRICATED AND PRE-ASSEMBLED STRUCTURAL SYSTEMS

ADEL R. ZAKI

Vice-President/Chief Engineer
Engineering, Design and
Project Management
Montreal, Canada

SEVAK DEMIRDJIAN

Vice-President, Major Projects
Engineering, Design and
Project Management
Montreal, Canada

ABSTRACT

Accelerated Bridge Construction Techniques are currently being implemented by many government agencies responsible for bridge rehabilitation, replacement, and new construction around the world. This paper presents state-of-the-art advances within the international infrastructure network describing the use of innovative prefabricated systems and elements in modern bridge construction. The entirely prefabricated bridge systems offer the maximum advantage for accelerated construction and depend on a range of prefabricated bridge elements that are transported to the work site and assembled in a rapid-construction process. The main objective is to limit traffic disruption during the construction, replacement or rehabilitation of bridges, and to minimize the impact of construction activities on the environment.

KEYWORDS

Accelerated Bridge Construction; Composite Action; Integral Deck System; Sustainability; Rehabilitation

1. INTRODUCTION

The purpose of this paper is to identify the different approaches for the design and construction of bridges by adopting Accelerated Bridge Construction (ABC) techniques. An overview of the evolution of the ABC technique is also presented. Some of the topics that will be covered include:

- Prefabricating and pre-assembling structural systems with speedy bridge construction techniques
- Preparing prefabricated bridge elements that are transported to the work site and assembled in rapid-construction process
- Using high performance concrete and steel innovation solutions
- Implementing light innovative equipment during construction
- Determining the objective, procurement process, and business model in detail for innovative structural system, sustainable concepts and materials, and cost-effective solutions.
- Several case studies will be presented related to state-of-the-art rapid construction techniques and their application for highway, railway and foot bridges. Overcoming obstacles to ABC implementation was a paramount goal of the rapid renewal projects that will be described.

2. RATIONALE FOR IMPLEMENTING ABC TECHNIQUES

Accelerated techniques for bridge construction should be used where the benefits have effects on the construction costs and impacts of the project. Prefabricated and pre-assembled systems/elements limit traffic disruption during construction and minimize the impact of construction activities on the environment.

The savings in accelerated bridge construction techniques are found in several aspects of the total project such as time, equipment use and labour.

Decisions to use accelerated bridge construction techniques should be made after considering the following factors:

- Temporary roadways and bridges
- Temporary retaining structures
- Environmental impacts
- Sustainable development
- User costs
- Social and financial prerogatives

- The length of detours
- Modern technology and innovative concepts
- Means and methods

In order to become competitive with "in-place construction" of concrete bridges, prefabricated systems must provide benefits such as:

- Cost-effectiveness
- Faster installation
- Design flexibility
- Easy handling and transportation of components
- Reduced superstructure depth
- Greater durability
- Reduced maintenance

3. BRIDGE DECK COMPOSITE ACTION

3.1 Overview

The common type of composite action comprises a reinforced concrete continuous slab supported by either steel plate girders or pre-cast pre-stressed concrete girders. In a composite action, the individual materials are used efficiently since concrete slab is strong in compression. This type of bridge deck facilitates speedy erection of prefabricated girders and considerably reduces the cost of form work.

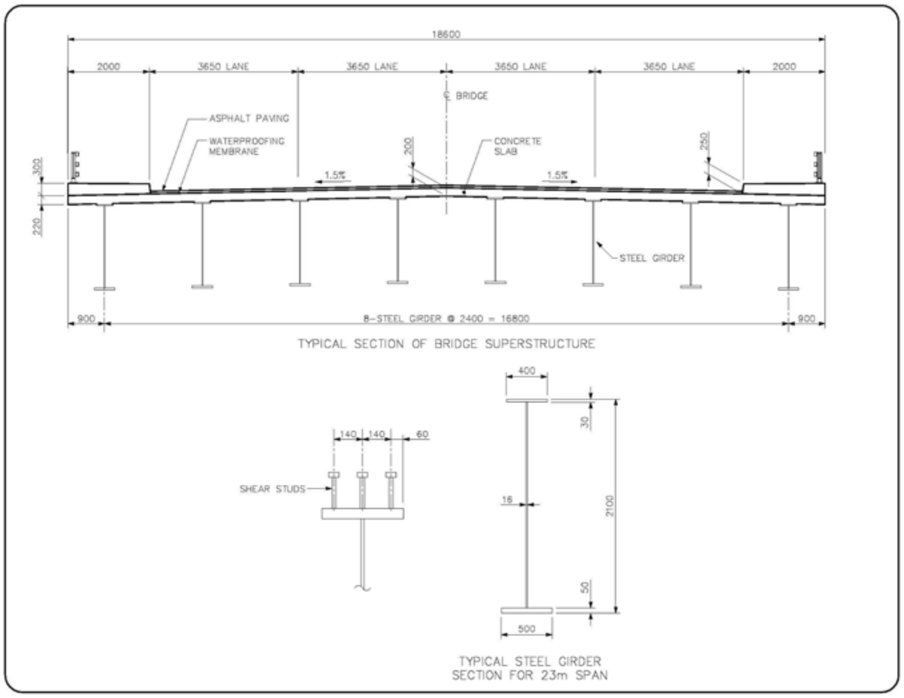
3.1.1 Traditionally Cast-in-Situ Concrete Deck Supported by Steel Plate Girders

The Composite construction in the bridge deck refers to the interaction between in-situ reinforced concrete and structural steel (see Figure 1). The main economic advantages are:

- For a given span and loading system a smaller depth of girder can be used.
- The cross-sectioned area of the steel top flange can be reduced since the concrete is part of it.
- Transverse stiffening for the top compression flange of the steel girder is reduced because the restraint against buckling provided by concrete deck.

FIGURE 1

Traditionally cast-in-situ deck - steel girders

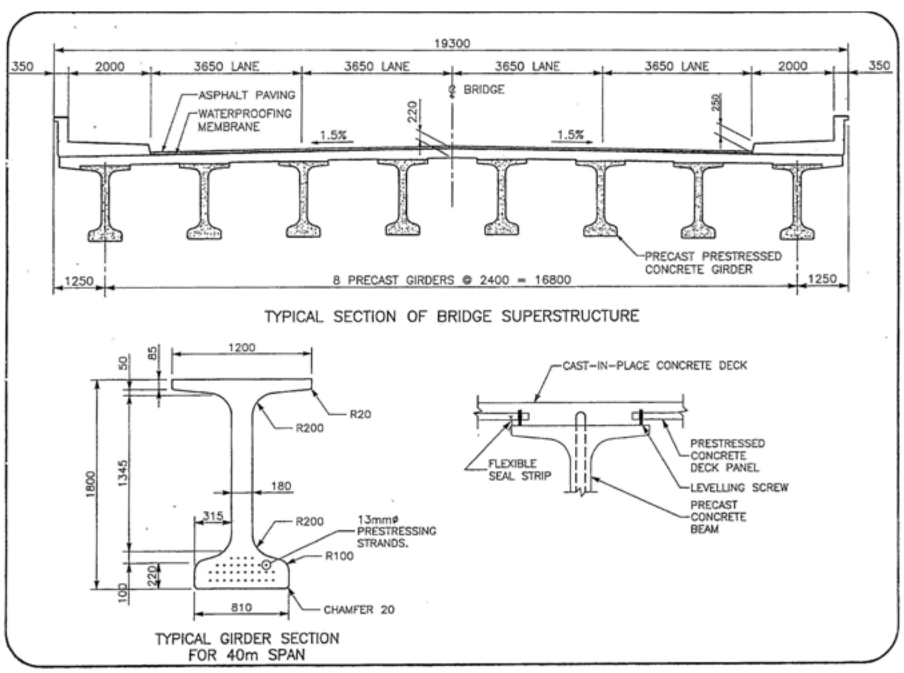


3.1.2 Traditionally Cast-in-Situ Concrete Deck Supported by Standard Pre-cast Concrete Girders

The interaction between in-situ reinforced concrete and pre-cast concrete girders provides the same composite feature as the interaction with steel girders (see Figure 2). In this case, a pre-cast concrete deck panel is installed over the concrete girder's flanges and will be considered as a permanent form work system.

FIGURE 2

Traditionally cast-in-situ deck – Standard pre-cast concrete girders



4. VARIETY IN BRIDGE DESIGN: EXAMPLE FROM THE AUTHOR'S PRACTICE SHOWING TRADITIONAL COMPOSITE ACTION

4.1 Bridge Structure Crossing a Main River

The bridge measures 370m in length, crossing a river and two adjacent roads, and 18.80m in width to accommodate 4 lanes of traffic, a sidewalk, and a bicycle path.

The mandate was to design and construct the new bridge and to demolish the deteriorated existing structure while maintaining the traffic without interruption. A demolition/construction staging scheme was implemented, leaving one lane from the old bridge in operation and using the second lane from the new bridge. The newly constructed portion was to be used for road traffic while demolition and reconstruction work continued on the rest of the structure. In addition, new bridge piers had to be constructed at a different footprint, while keeping the existing ones in place to support the remaining portion of the existing superstructure.

The main spans consist of a cast-in-situ concrete deck supported by eight longitudinal steel plate girders. The approach spans consist of a cast-in-situ concrete deck supported by standard pre-cast pre-stressed concrete girders. Both structural systems were constructed to ensure a composite action for carrying live load. (Figures 3, 4, 5, and 6).

FIGURE 3

Bridge structure elevation crossing a main River

FIGURE 4

Staging construction

FIGURE 5

Principal main steel plate girders with shear studs

FIGURE 6

Pouring concrete deck inside temporary shelter during winter season

4.2 Elevated Roundabout

This is a complex geometry project located in a highly urbanized area. The project includes relocation of public utilities, demolition of existing structures, construction of new structures and new roadways, and preparation of temporary roads and alternate itineraries for highway traffic, public transport and pedestrian traffic. The elevated structure was constructed over a major highway in phases to maintain traffic flow.

Driven by the need to reconstruct the elevated roundabout without disturbing the traffic flow, the site work included construction of a temporary flyover, overnight demolition of the old, elevated structures and staged construction of the new elevated structures. The design of the new elevated structures within the site's physical and environmental constraints offered many unique challenges that required the adoption of the ABC technique. The new roadway alignment required numerous horizontal and vertical curves to fit with the different access ramps. (Figures 7, 8, 9, 10 and 11)

FIGURE 7

Curved plate girder segments

FIGURE 8

Lifting girders by pairs

FIGURE 9

Installation of structural segments

FIGURE 10

Curved plate girder segments

FIGURE 11

Lifting girders by pairs

5. FULL DEPTH PRE-CAST PANELS

An alternative to using cast-in-place decks is the use of full-depth pre-cast concrete deck panels.

- Panels are constructed off-site under controlled conditions and brought to the site ready for installation.
- Using pre-cast deck panels can significantly reduce construction time.
- Increases work zone safety by reducing the number of and exposure time of workers operating near moving traffic.
- Reduces environmental impacts by minimizing the site access footprint.
- Improves the constructibility of bridge designs.

FIGURE 12

Full depth pre-cast panels

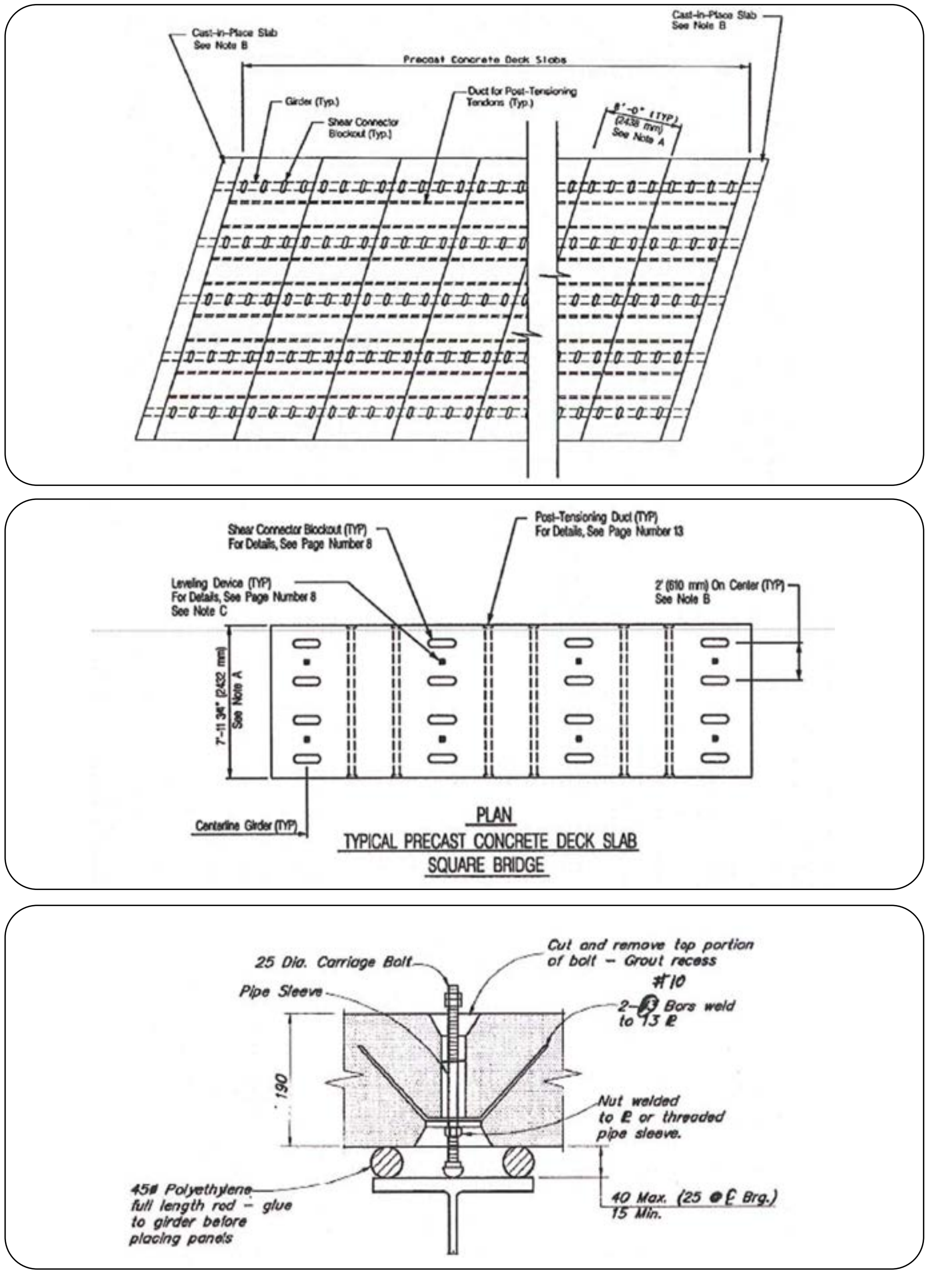


FIGURE 13

Installation of pre-cast panels

6. INTEGRAL BRIDGE SUPERSTRUCTURE

6.1 Short and Medium Span Bridges

The application of a pre-cast concrete integral deck system became the chosen state-of-the-art solution for a comprehensive design in short and medium span bridges. The main objective is to reduce on-site construction time for bridges in heavily congested urban areas.

6.1.1 Short-Span Bridges: Pre-cast Elements

The rationale for selecting an integral superstructure system is based on achieving standardized pre-cast units, thus reducing the construction cost. The bridge span length will drive the structural choice. The pre-cast elements geometry for short-span bridges is shown in Figures 14, 15, 16 and 17.

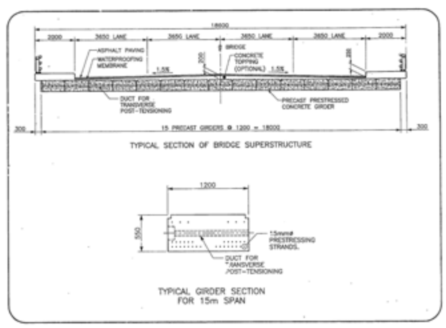


FIGURE 14

Pre-cast pre-stressed concrete slab

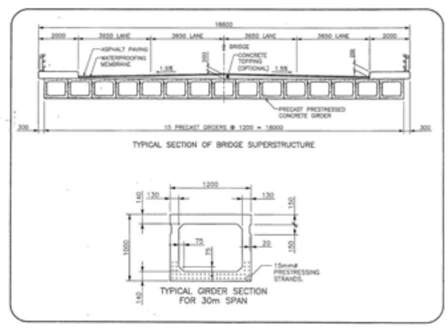


FIGURE 15

Pre-cast pre-stressed concrete box type

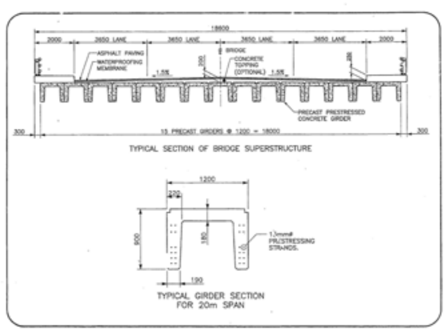


FIGURE 16

Pre-cast pre-stressed concrete channel type

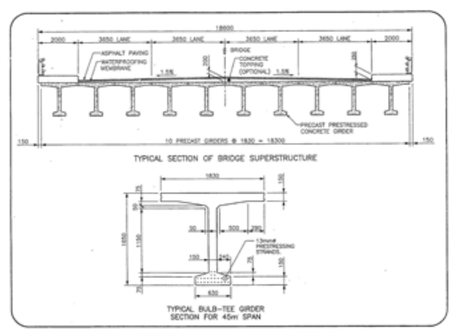


FIGURE 17

Pre-cast pre-stressed concrete bulb-tee girder

6.1.2 Conceptual Design for Medium Span Length – the Splice Girder Technique

A spliced girder is pre-cast, pre-stressed concrete member that is fabricated in several relatively long pieces (i.e., girder segments) that are assembled into a single girder for the final bridge structure. Post-tensioning is generally used to achieve continuity between girder segments (Figures 18, 19, 20, 21 and 22). The main advantage of using spliced girders is to minimize the number of intermediate piers, thus offering a cost-effective solution.

FIGURE 18

Transverse post-tension between segments

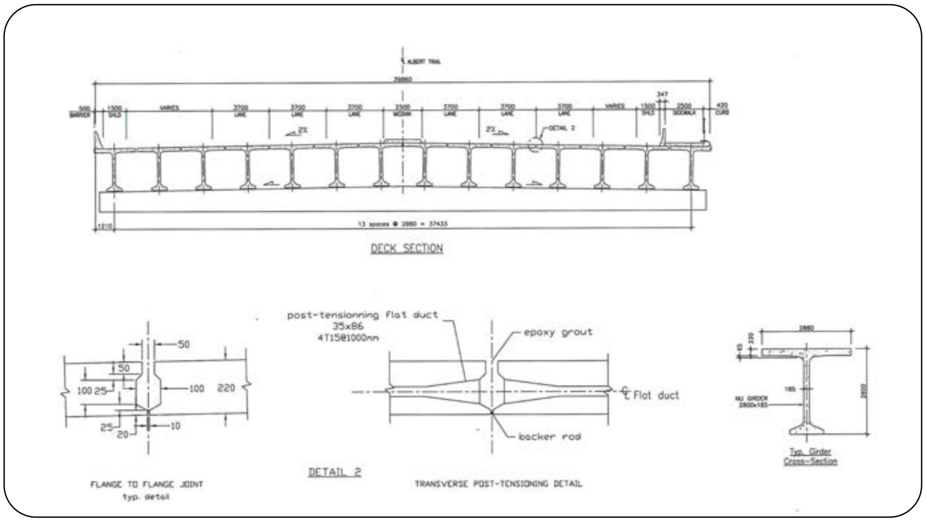


FIGURE 19

Temporary shoring and longitudinal post-tension

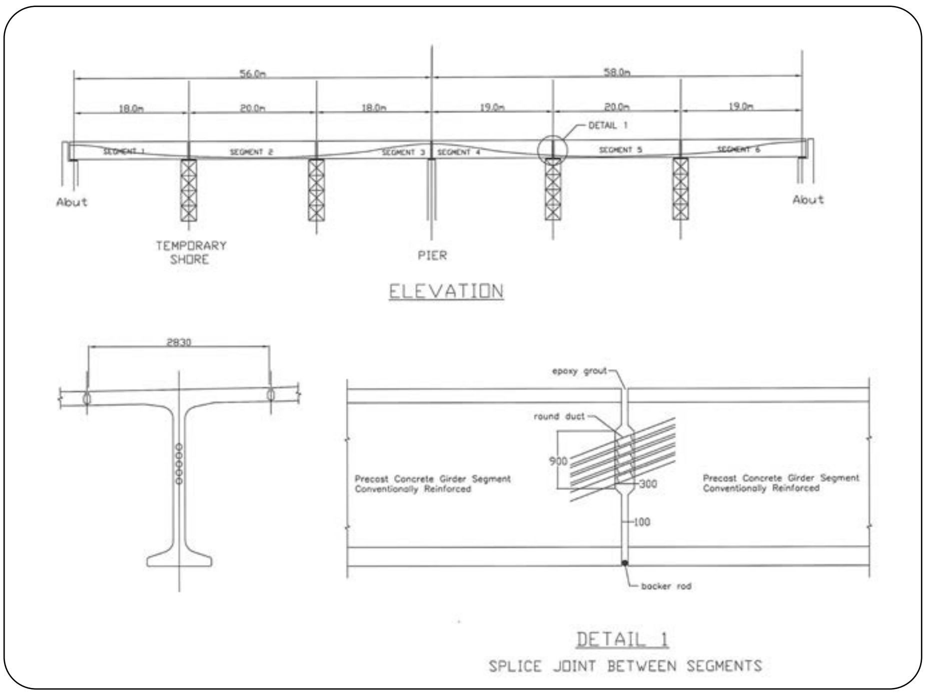


FIGURE 20

Pre-cast concrete segment detail

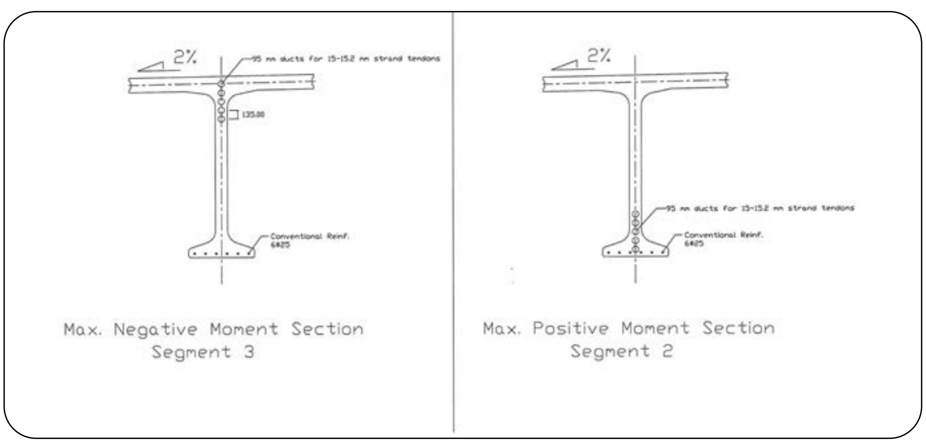
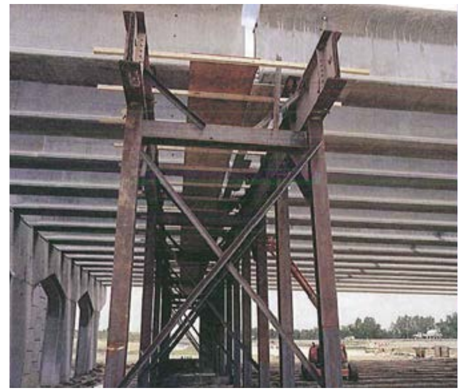


FIGURE 21

Segment installation over temporary shoring

FIGURE 22

Temporary shoring detail



7. INTEGRAL BRIDGE SUPERSTRUCTURE: FOOTBRIDGE EXAMPLE

The existing footbridge, crossing a six-lane highway (3 lanes in each direction plus a central median and 2 shoulders), was examined for structural assessment. The original concrete footbridge (Figure 23) showed signs of significant concrete deterioration and reinforcement corrosion. A decision was taken to replace the bridge and an ABC technique comprised of high-performance concrete (HPC) pre-cast elements offered the most economical solution.

Figure 24 shows the cross section of the new pedestrian bridge made with HPC. The bridge spans 35m centre-to-centre of the neoprene bearings. The cross section consists of two Z-shaped pre-cast girders shaped to provide a bottom ledge to support the pre-cast panels for the deck slab. Each of the Z-shaped girders was pre-tensioned with 40 – 15 mm Φ strands. The depth of the pre-cast pre-tensioned girders is 1370mm and the widths are 250mm. Figure 25 shows the reinforcing details.

One of the key features of the design was the need for rapid erection to cause the least amount of disturbance to the traffic flow under the pedestrian bridge. The girders were erected in one evening to limit the disruption of traffic. The Z-shaped girders are structurally interconnected at both supports and at mid-span by casting concrete in 300 mm thick reinforced concrete closure strips. These closure strips produce a U-shaped cross section at these locations and serve as structural diaphragms. The diaphragms served to connect the girders to enable sharing of vertical loading and to interconnect the Z-shaped girders to aid in resisting torsion. The pre-cast concrete panels were pre-tensioned with 13-mm Φ strands and were supported by the lower ledge of the girders. Demolition and construction steps are shown on Figures 26, 27, 28 and 29.

FIGURE 23

Original pedestrian bridge

FIGURE 24

Footbridge cross-section

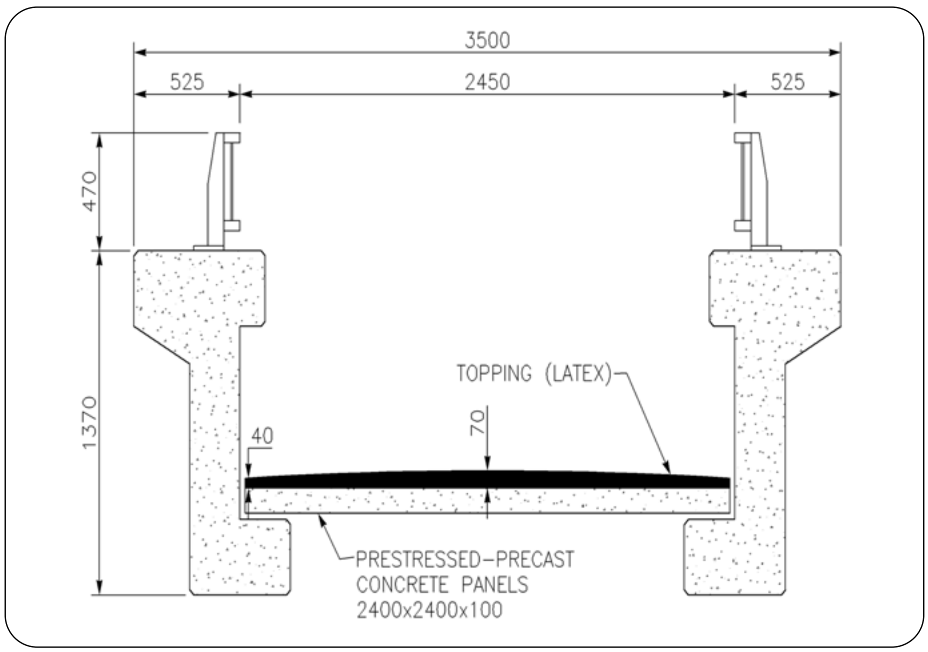


FIGURE 25

Reinforcing details

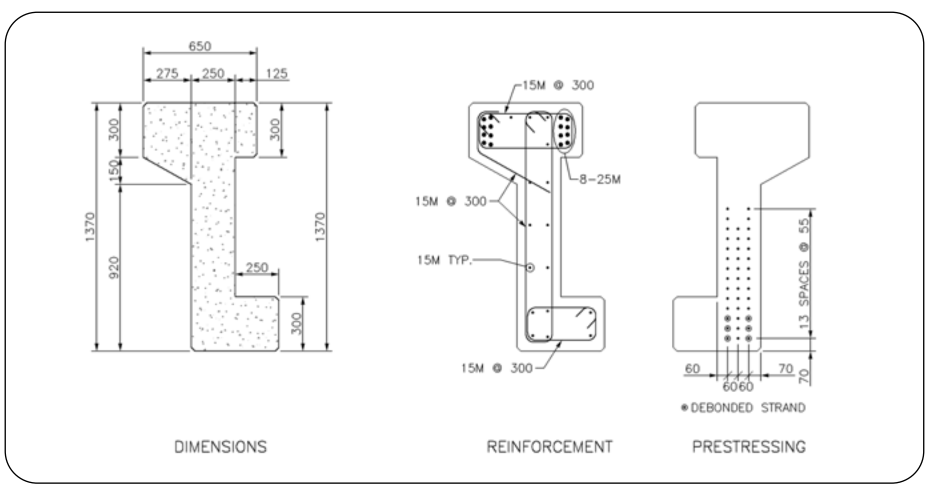


FIGURE 26

Handling and shipping of pre-cast girders

FIGURE 27

Demolition of existing structure during night

FIGURE 28

Erection of new pre-cast girders

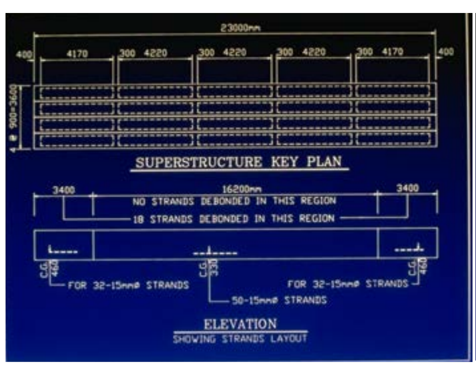
FIGURE 29

Final installation of pre-cast girders and slabs

8. INTEGRAL BRIDGE SUPERSTRUCTURE: RAILWAY BRIDGE EXAMPLE

During a periodic inspection of the bridge structure, it was found that the open deck bridge steel span, built in 1914, had become severely corroded and immediate replacement was needed.

The new single-span, simply supported bridge spans 23.0m and was designed for E-85 Railroad Loading. Comprising four pre-cast concrete box girders, this represents the longest pre-cast, pre-stressed span ever used by the railway company. The girders were tied together with 26 mm diameter DYWIDAG threaded bars, (See elevation of new bridge, typical span section and superstructure key plan in Figures 30 and 31. Construction details are shown on Figures 32, 33, 34 and 35.



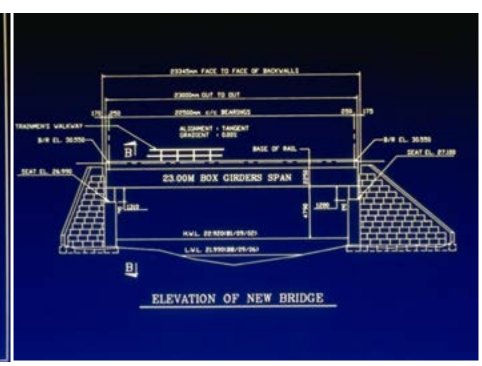


FIGURE 30

Structural system

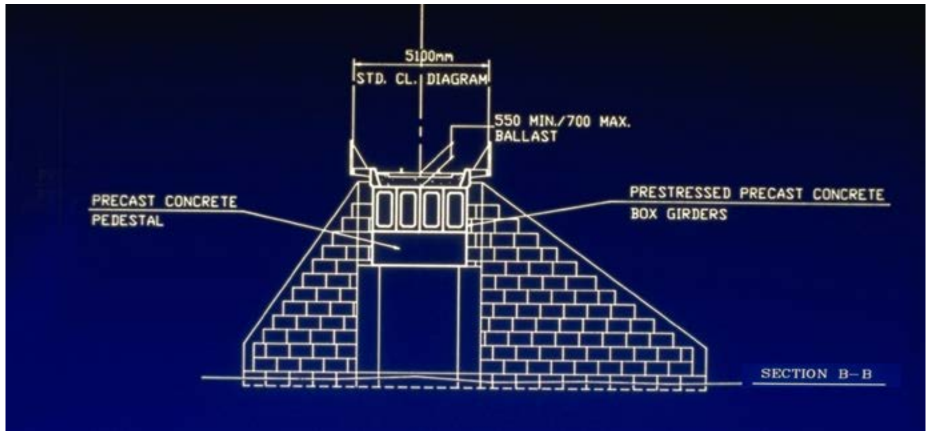


FIGURE 31

Cross - Section at abutment

FIGURE 32

Original bridge structure to removed

FIGURE 33

Rail mounted crane used
during construction

FIGURE 34

Erection of pre-cast
concrete box girders

FIGURE 35

General view of the new bridge

9. CASE STUDY: BRIDGE DECK REPLACEMENT PROJECT – INTEGRAL DECK FLOATING SYSTEM (DESIGN/BUILD CONTRACT)

9.1 General Description

Measuring 2.70 km long, crossing a major river, with five lanes of traffic, this bridge carries more than 43 million vehicles every year making it one of the busiest bridges in North America on a per lane basis (Figure 36).

The combined effects of age (much of the existing deck is more than 71 years old), the increase in weight and number of truck transits each year since its inauguration in 1930 and the severe deterioration of concrete has led to undertake a complete replacement of the existing deck.

The ABC Technique for deck replacement was developed based on the following main objectives:

- Minimize inconveniences to as many users as possible
- Construct a new highly durable deck (design service life greater than 50 years)
- Ensure safety of both users and workers
- Minimize negative impacts to the environment

These requirements led to the decision to undertake the replacement of the existing non composite reinforced concrete deck originally supported by steel stringers by a new deck system made of pre-cast, pre-stressed, HPC integral deck panels. The design-build method of delivery was retained to carry out this project.

FIGURE 36

Bridge view

The new deck consists of a series of deck spans, typically 7.67m long. Each span is made of four pre-cast, pre-stressed concrete panels installed side-by-side (Figure 37) for a total width of 23.5m. Each panel has a 180 mm thick slab and possesses three integral stems with variable moment of inertia which are reinforced with four 15 mm Φ draped pre-stressing strands (Figures 38 and 39). The concrete barriers are also integrated with the outside panels. Following the installation of a certain number of panels which are supported by existing floor beams, the transverse and longitudinal post-tensioning was applied.

FIGURE 37

Bridge Deck Cross Section

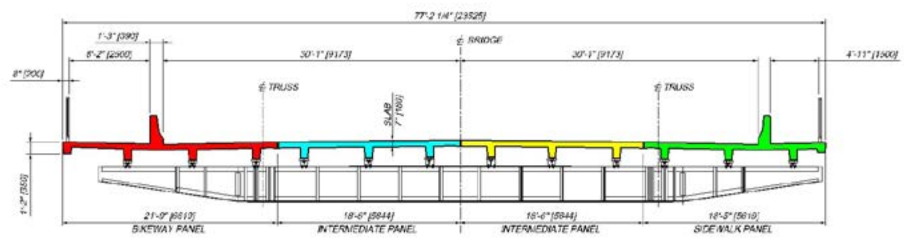


FIGURE 38

Panels Configuration

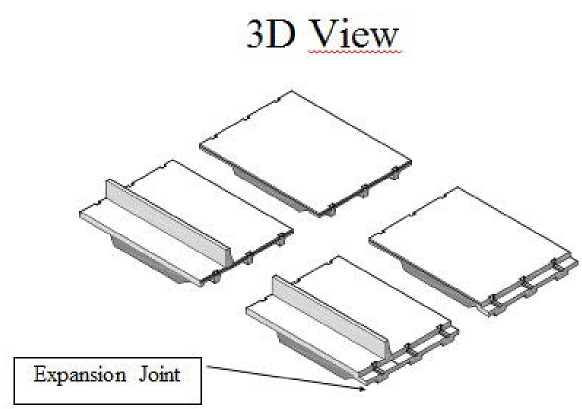


FIGURE 39

Typical Deck Panel

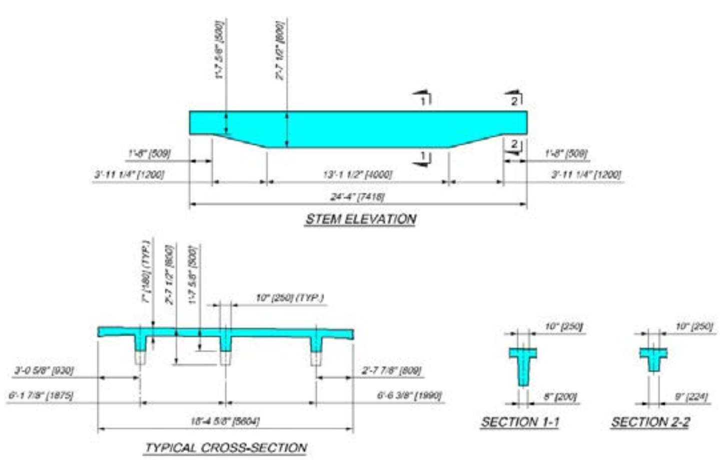


FIGURE 40

Geometry of Strands

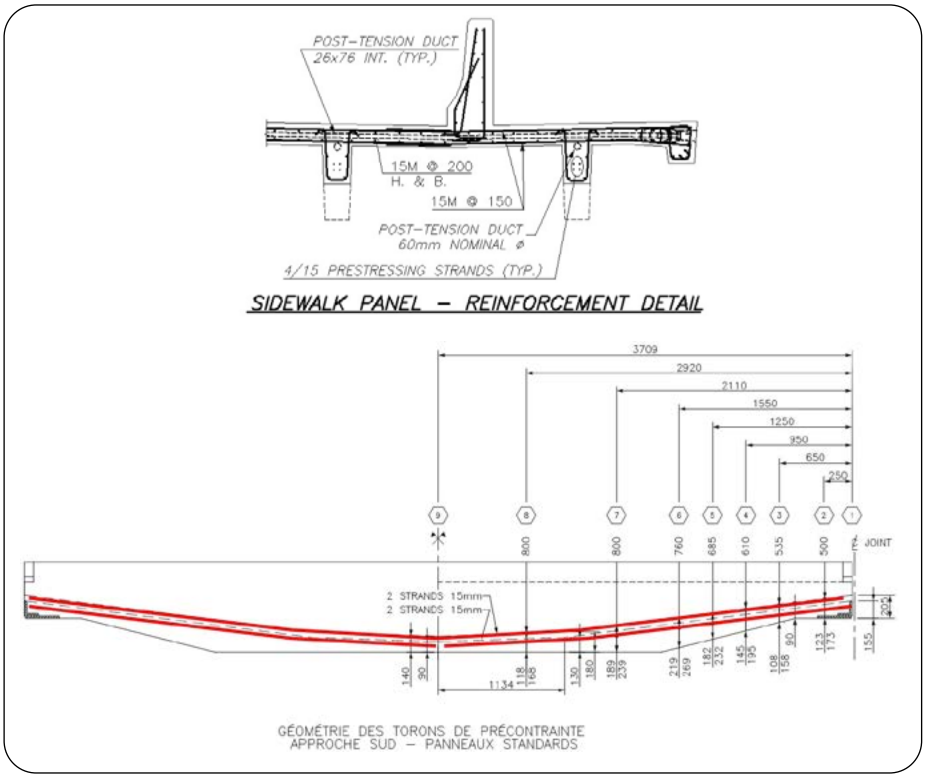


FIGURE 41

Pre-assembled Reinforcing Steel Cages

9.2 Construction Activities

Deck replacement work involves six principal types of construction activities which include:

- Steel works incorporating floor beam repair, strengthening and installation of new bearing assemblies to support the panels (Floating system)
- Pre-casting of HPC deck panels
- Removal of existing deck sections
- Installation of new panels (1680 pre-cast panels were installed)
- Joint mortar placement and post-tensioning works
- Installation of expansion joint armours, cast-in place expansion joint dams, and waterproofing and paving work

Construction activities are shown in Figures 42 to 46.

FIGURE 42

Lifting panels

FIGURE 43

Tractor-trailer

FIGURE 44

Set-up for removal and installation of new deck panels

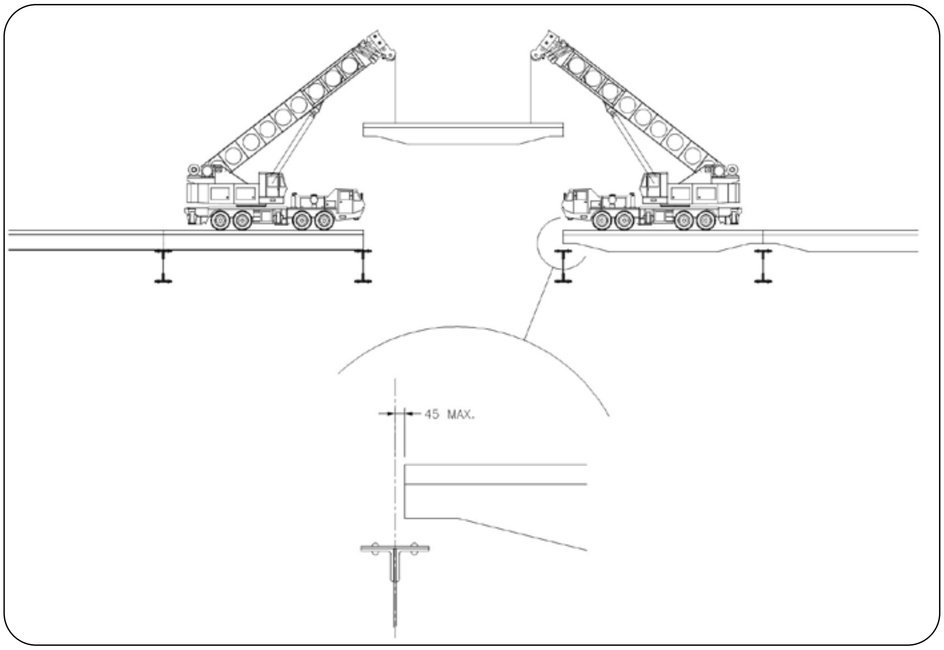
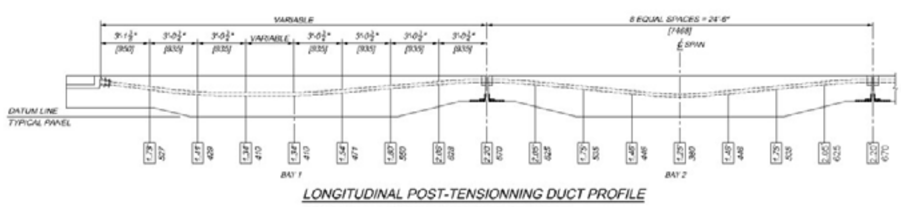


FIGURE 45

Installation of new deck panel

FIGURE 46

Longitudinal post-tensioning duct profile



10. CASE STUDY: BRIDGE DECK REPLACEMENT PROJECT – INTEGRAL DECK, COMPOSITE ACTION (DESIGN/BUILD CONTRACT)

10.1 Bridge Configuration

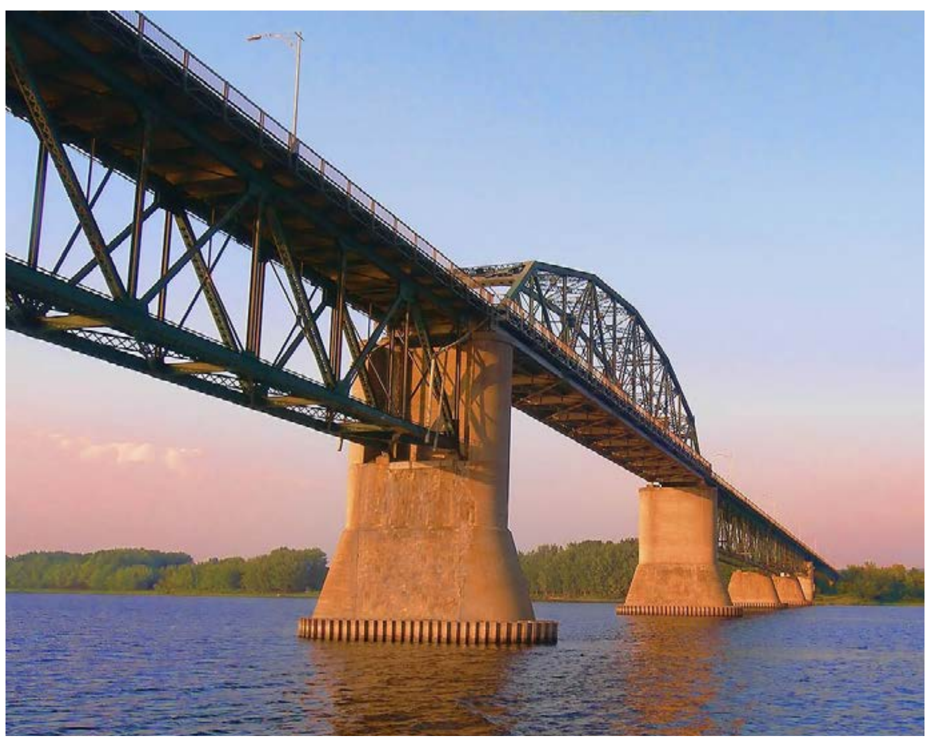
The Princess Margaret Bridge provides an elevated crossing over a major river, measuring 1097m in overall length. A bridge layout is shown in Figures 47 & 48. It is a high-level structure supported on tall slender piers in order to provide the required 23±m clearance for the centre navigation span. The roadway is supported by 9 deck truss spans, one through-truss navigation span, 7 Plate Girder spans and 6 Rolled Beam approach spans. Support for the steel superstructure is provided by 8 main river piers, 14 land-based piers and 2 abutments.

FIGURE 47

Bridge layout

FIGURE 48

Bridge configuration



The bridge was approaching its 50th anniversary and signs of aging were starting to appear. The concrete deck and the floor beams were in poor shape and needed replacement.

10.2 Bridge: New Deck - Composite Solution

A composite section was created between the deck slab and the steel members. This composite action tremendously improved the capacity of those members and therefore reduced the need for the strengthening.

› Composite actions were created between the deck panels and top chord steel truss.
› A typical detail of pre-cast panel is shown in Figure 49.
› Deck Truss panels were pre-tensioned transversally and post-tensioned longitudinally, which created a challenge to create the composite action. The composite actions to the steel members are achieved as follows:
› For both deck truss and plate girder, a spine beam was detailed to connect either the Plate Girder top flange or the Deck Truss top chord to the deck panels after the post-tensioning operations, as shown in Figure 50
› Composite actions were created between the deck panels and the following steel bridge members

FIGURE 49

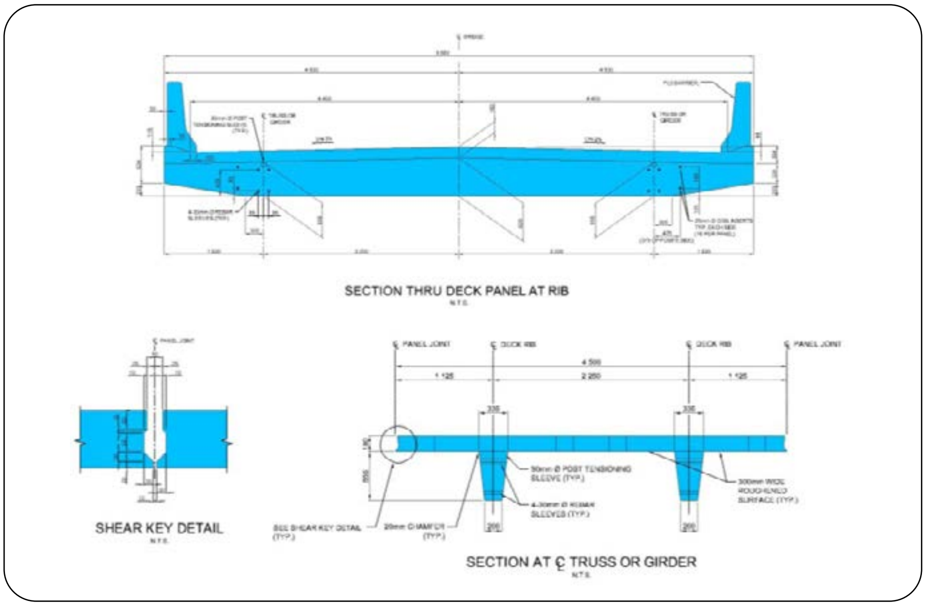
Composite action between the Pre-cast Deck and either the plate girder top flange or the deck truss top chord through the construction of a concrete spine beam

FIGURE 50

Saw cut locations for deck removal

FIGURE 51

Typical detail of a pre-cast panel



10.3 Construction Activities

The construction activities for the deck replacement work involve twelve principal types of construction activities which include:

- Remove electrical lighting system, drainage system and hand railing.
- Remove bolted connection between floor beam and deck truss/plate girder.
- Saw-cut and remove the existing concrete deck and asphalt.
- Sandblast top of cover plate and install anchor studs.
- Install new pre-cast deck panels on steel superstructure.
- Install spine beam reinforcing steel, post-tensioning duct and formwork.
- Grout shear key between deck panels, place post-tensioning strands and tension.
- Pour the self-consolidated concrete for spine beam.
- Install cast-in place expansion joint assemblies, including troughs and downspouts.
- Install cast-in-place PL3 concrete barrier.
- Install lighting and traffic signals.
- Place asphalt wearing surface.

Construction activities are shown in Figures 52 to 60.

FIGURE 52

Deck panel geometry

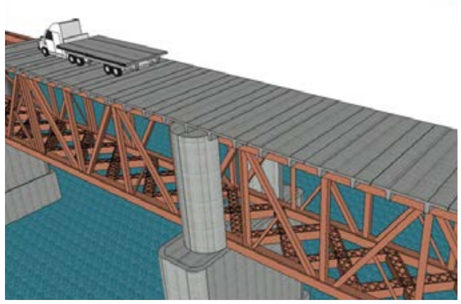


FIGURE 53

Special Lifting equipment

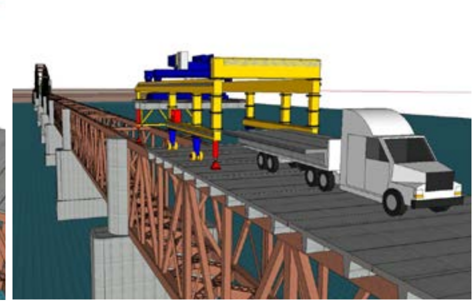


FIGURE 54

Deck removal

FIGURE 55

Transport, install new panels, and haunch reinforcement

FIGURE 56

Post-tensioning

FIGURE 57

Trough truss-deck installation

FIGURE 58

Pre-cast concrete pier cap installation

FIGURE 59

Pier cap connection

FIGURE 60

**East approach spam –
pre-cast deck installation**

11. CHAMPLAIN BRIDGE RECONSTRUCTION

A final example is the construction of a replacement of the Champlain Bridge. The new bridge is a Cable-Stay structure 3.4 km long, with two decks supporting three lanes of highway traffic in each direction; a third, central deck supporting a mass transit system; and a multi-use path. The substructure is made of an all pre-cast concrete pre-assembled in-situ (Figure 61).

FIGURE 61

Construction of the new bridge

12. CONCLUSIONS

Accelerated Bridge Construction (ABC) techniques have the potential to minimize traffic disruptions during major bridge construction work and deck replacement / reconstruction. The concept of composite action offers a cost-effective solution and facilitates speedy erection through an all-pre-assembled structural system.

The ABC technique was developed based on the following main objectives:

› Minimize inconveniences to as many users as possible
› Construct new highly durable bridge components (design service life greater than 50 years)
› Ensure safety of both users and workers
› Minimize negative impacts to the environment

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JEREMY REIDERMAN, PE

Senior Civil Engineer
Engineering, Design and Project Management
Melbourne, FL, USA

SEMINOLE HARD ROCK RESORT: COLLABORATION AND INNOVATION TO ENGINEER EFFECTIVE WATER MANAGEMENT SYSTEMS

ABSTRACT

The Seminole Hard Rock Resort in Hollywood, Florida celebrated the grand opening of their $1.5 billion dollar expansion October 24, 2019. The expansion included a hotel tower in the shape of a guitar surrounded by blue water and cabanas. At night, the neck of the guitar directs lasers into the sky, and the face of the guitar is used to give a nightly light show. This expansion was proposed by the architectural firm Klai Juba Wald (KJW) as a way for architecture to draw tourism. Atkins, as the civil engineering firm, enabled this previously fully developed site to be doubled in capacity and made this project feasible through three innovative approaches. First, land was created for the expansion by eliminating an existing stormwater pond and reducing the footprint of the required stormwater treatment. Second, new water systems from another water provider were designed to allow the expansion. Third, the wastewater was redesigned and split to different off-site force mains to allow the expansion, when the existing wastewater treatment plants could not handle the expected flows.

KEYWORDS

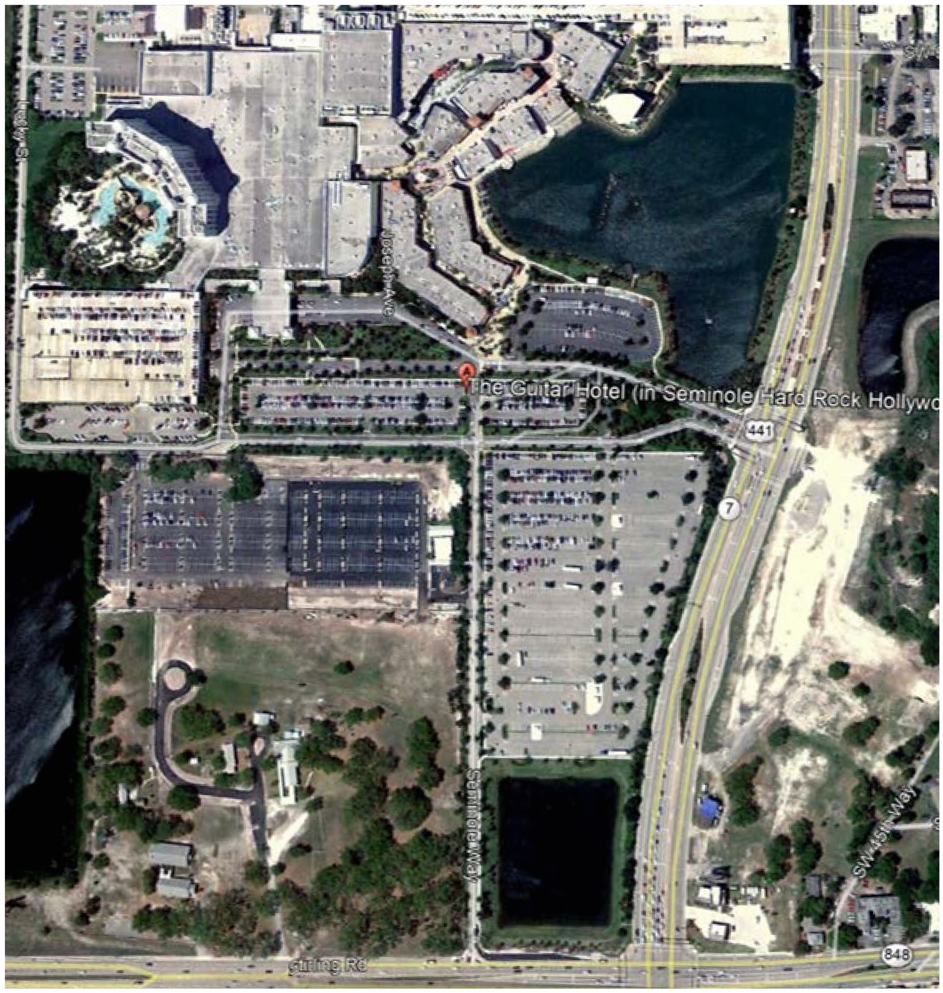
Hotel expansion project; Stormwater management; Water transmission; Sanitary sewer systems; Construction administration

1. EXISTING CONDITIONS

The original Seminole Hard Rock in Hollywood (SHRH) consisted of a hotel and casino built in 2004. This original SHRH site plan was designed by PBS&J, which was acquired by Atkins in 2010. The SHRH is located on the Seminole Tribe of Florida (STOF) Hollywood Reservation. The Town of Davie is located to the north of the site, the City of Hollywood to the east, and the Turnpike to the west.

FIGURE 1

SHRHC circa 2013



2. MASTER PLANNING

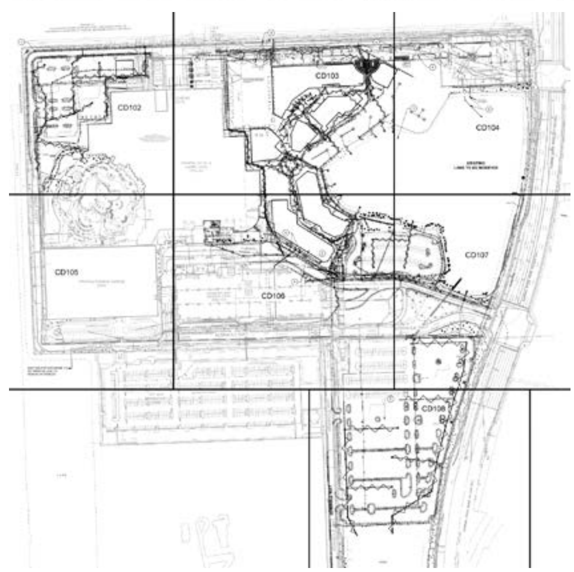
The idea of a guitar-shaped hotel was proposed by architectural firm Klai Juba in 2008. The Atkins Melbourne, Florida office contracted with Seminole Gaming and Development to produce master planning design documents at that time. The guitar tower concept didn't progress forward due to the economic recession, but it was this initial design development that helped demonstrate the need for increased parking and other infrastructure improvements. The civil design of the Winner's Way Garage was completed around 2010. Additional water and sanitary sewer planning efforts were started with STOF's Public Works Department (PWD) in 2011. In 2014, master planning began with the architect for what ultimately became the resort that exists today. This planning effort showed that parts of the existing 10.5-acre stormwater lake would need to be filled in to make room for the expansion. Figure 2 is an architectural rendering of the existing site as it stood in 2015. Figure 3 is the overall civil demolition plan, with all the items proposed to be demolished in bold. Most of the buildings east of the existing casino low rise were demolished. This included the previous Hard Rock Live venue, the outdoor shopping area called Seminole Paradise, and the 10.5-acre stormwater lake.

FIGURE 2

Architect's plan showing existing buildings in 2014

FIGURE 3

Civil demolition plan from 2015. (Bolded items to be demolished)



The Seminole Gaming Association (SGA) reinitiated master planning with consultants in 2014. Out of these meetings and charettes came the concept of expanding the site to have approximately 3.2 million square feet of development including a 36-story (450 ft) guitar-shaped hotel (GT) and Pool Tower (PT) surrounded by a Bora Bora paradise experience, a large Low-Rise Expansion, a larger Hard Rock Live Theater, a Valet Tunnel, two new grand covered entrances, and the supporting utility infrastructure. The resort environment included an Oasis Paradise East Pool (EP) to be modeled after the resort island Bora Bora, as shown in Figure 4.

Executing these goals would require overcoming challenges with the existing infrastructure. The site's challenges included: limited space, inadequate water supply, inadequate sanitary sewer support, stormwater management restrictions, traffic constrictions, and maintenance of traffic. The casino, hotel and Hard Rock concert venue would all also have to remain open and profitable.

FIGURE 4

Architect's rendering of Guitar Tower and Bora Bora Oasis area

3. PROGRAMMING IMPROVEMENTS

The engineering firm worked with STOF and Seminole Gaming to develop the civil programming improvements necessary for improving the infrastructure of the site.

Table 1 shows the services that were provided. This article will focus on stormwater management, water transmission (including potable and fire protection) sanitary sewer systems, and construction administration.

TABLE 1:

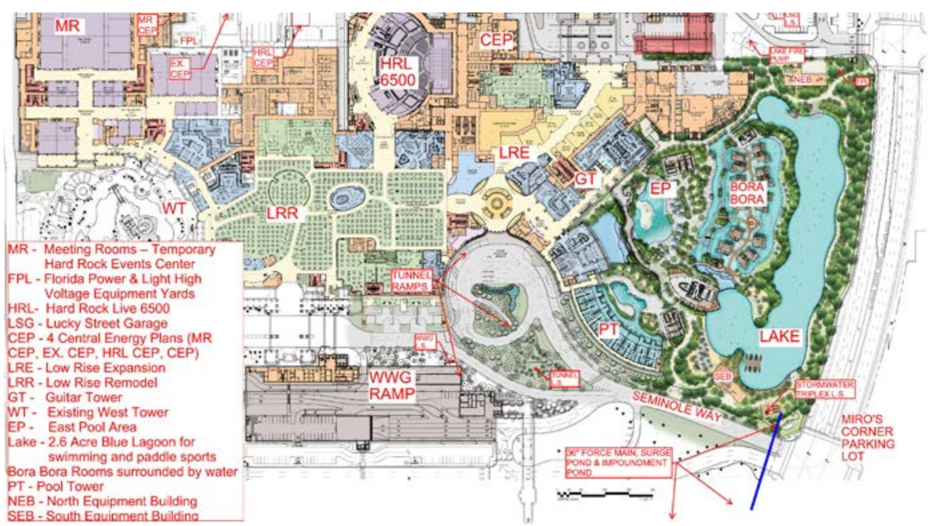
Services provided

Site Civil (Grading, Drainage, Stormwater Management, Site Planning)	Water & Wastewater Transmission
Structural (Site and Transportation)	Electrical Engineering of pump stations
Survey & Bathymetric data collection	Transportation Planning
Dive team inspections	Environmental Surveys & Testing
Traffic Engineering & Planning	Construction Administration

The engineering firm provided extensive construction administration throughout the expansion. This was due to the phasing plan proposed by the contractor/owner team, which commenced before all elements of site or building design were completed. The project required multiple construction project teams and the management of construction and demolition limits, all while maintaining a fully functional, profitable, and open-to-the-public resort. Coordination also had to factor in the schedule constraint of a ribbon-cutting in time for Hard Rock Stadium's 2020 Super Bowl. The engineering firm worked with General Contractor Suffolk Yates and the Site Contractor, American Engineering Development Corporation (AEDC), the MEP engineers from Giovanetti Shuh and Associates (GSA), and the architects at KJW. Figure 5 below demonstrates the number of hotel rooms, concert seats, CEPs, pool areas, port cocheres, low rise area and other amenities were virtually doubled. The previous room count was 465. Now it has 1,271 rooms with the addition of the Guitar Tower and the Pool/Oasis Tower. Hard Rock live seating capacity went from 3,500 to 7,000. New pools, restaurants, clubs, stores entrances and low-rise areas were added. There were over a dozen different architecture projects that needed to be coordinated with the civil improvements.

FIGURE 5

Building and site improvement projects



4. STORMWATER MANAGEMENT

Doubling the capacity of the site required reducing the footprint of the existing stormwater management system and rerouting many existing pipes under garages and active roads. The expansion resulted in an impervious area increase of 12.5 acres. This reduced the amount of allowable soil storage as calculated by the South Floridan Water Management District (SFWMD) criteria. The elimination of most of the surface parking lots also eliminated further stormwater storage since the allowance of surface ponding in parking lots during larger storm events would no longer be feasible.

Original design charrettes proposed the existing stormwater pond to the north be only partially filled where the GT is currently located. This design would have allowed the existing lake fire pumps to work by drafting from the pond near the Lucky Street Garage. Keeping a pond connection between the Lucky Street Garage and Seminole Way would have maintained the necessary stormwater hydraulic grade line for several onsite pipe systems. This was important since conveying stormwater from the northwest corner of the site to the expanded pond at the southeast leg of the site would have been a distance of over 3,000 feet. The existing roads have low points around 7.0+/- NGVD29 and the ponds staged up to 5.0+/- NGVD29 in the 10-year 24-hour storm. To avoid flooding at upstream inlets, an average HGL of 0.067% would have been required. This flat of a HGL does not provide cleansing velocities in the pipes. The existing system was based on an existing casino finished floor of 9.00 NGVD29. The ponds had a top of bank of 8.5 NGVD29, a normal water level of 2.4 NGVD29, and a total attenuation volume of 120+/- acre-feet. These elevations are only a few feet above sea level.

The site discharges to a Florida Turnpike pond which drains to a SFWMD canal. SFWMD restricts allowable discharge for the canal to only 40 cubic feet of discharge per square mile for the 25-year 72-hour storm (13.5 inches of rain). For Hard Rock's 85 acres, this meant an allowable discharge of only 5.3+/- CFS, which is a very small allowable flow rate for this site. This canal has a large stormwater lift station located further downstream to the north near US 441. To limit offsite discharge, exfiltration trenches were designed near the meeting rooms (first phase of construction). This increased the amount of infiltration and decreased the required amount of stormwater storage. Installing more exfiltration systems was thoroughly modeled but deemed uneconomical as the ground water models showed diminishing returns in reducing the needed attenuation volume. Also, the crowded utility corridors on-site did not allow room for exfiltration systems, which would inevitably need access for servicing in the future.

After permitting the previously discussed design concept, and during the construction of the new meeting room convention center and early utility work, the client revisited the desire to transform the remaining stormwater pond into a pool of blue water surrounding the Guitar Tower. Stormwater ponds in Florida cannot be used for swimming due to health concerns. This meant that the existing northern stormwater pond/lake system, which originally was only going to be partly filled, would need to be eliminated and replaced with a swimming lake (a.k.a., lagoon). This new 2.3-acre swimming lake would be additional impervious area with only 6 inches of attenuation storage, which is not adequate for the 25-year 72-hour storm rainfall amount of 13.5 inches.

With the elimination of the northern stormwater pond, the lake fire pump would not be functional. Also, the longer storm pipe runs from the northwest corner to the expanded pond in the southeast, would have caused the roads in the northwest to flood. The stormwater Interconnected Pond Routing design models showed that even eliminating the entire south parking lot for stormwater storage would not meet the design criteria. This was due to reducing the amount of attenuation volume, which prevented satisfying pre-vs-post discharges and stages for the SFWMD 25-year 72-hour storm and the Florida Department of Transportation's (FDOT) critical storm analysis.

Despite the design constraints, the client pressed forward with their vision to have the lagoon. To achieve this goal, the client offered to allow stormwater to be discharged to the land they owned east of US441, a major highway, which was not on the STOF Reservation. After investigation, the designer determined that this land did not have a positive outfall other than infiltration. Stormwater would have been required to be pumped under the road and back again to maintain the historical discharge location at the Turnpike pond. This, in conjunction with scheduling concerns due to environmental and permitting challenges, rendered this option not feasible. Instead, the engineering firm proposed a more feasible idea to the client for stormwater management which met the following design constraints:

- Eliminate the north pond.
- Maintain a feasible hydraulic grade line to furthest reaches of the site.
- Reduce the required footprint of the southern pond to maximize parking.
- Satisfy pre-vs-post discharges and stages for SFWMD and FDOT required storms.

FIGURE 6

SHRH's stormwater user's guide

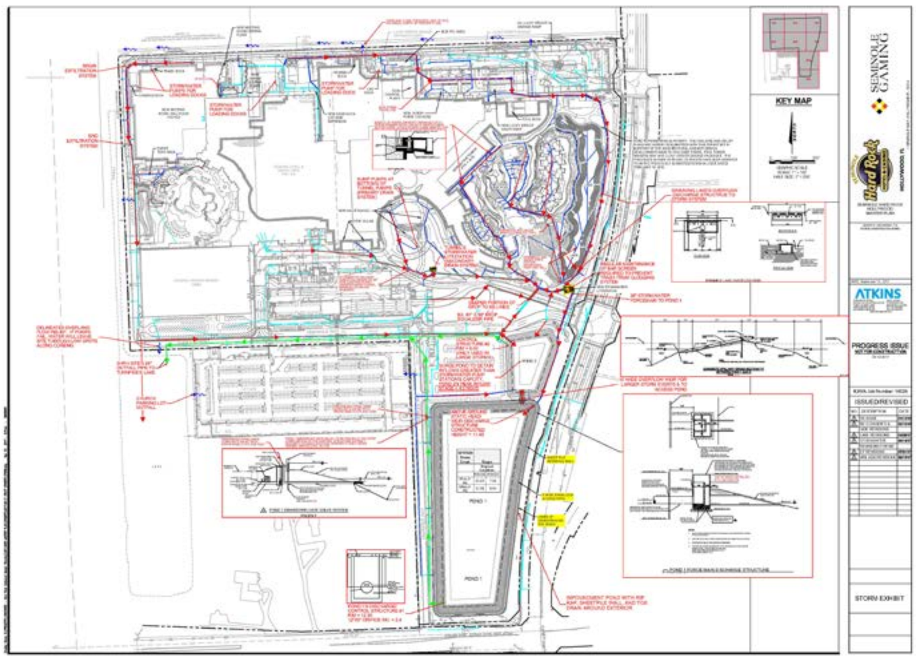


Figure 6 is a user guide created for Hard Rock that shows the many parts required for this stormwater management system to meet the above criteria. A stormwater lift station was needed to allow the northern lake to be filled and redirect stormwater over 1,000 feet to the south pond. The lift station improves the hydraulic grade lines of the existing system to ensure there is no flooding at the upstream northwest corner of the site. The lift station also allowed the footprint of the southern pond to be reduced, by attenuating runoff up to 4 feet above the normal grade elevation into an impoundment pond surrounded by sheet pile cutoff and retaining walls. The southern impoundment pond footprint was reduced to the maximum extent possible by designing to the upper limits of a minor impoundment pond criteria per the SFWMD. This was important because the SFWMD was apprehensive about allowing a major impoundment pond near a highway and urban area. A dam break analysis was provided to mitigate SFWMD concerns.

The new stormwater system includes a stormwater tri-plex pumping station, a surge pond, and an impoundment pond, a discharge structure, an emergency overflow spillway, and a pumped drawdown pipe. The impoundment pond is comprised of a 20-foot-tall sheet pile cutoff wall with a toe drain system surrounding it. The top of the sheet piles are at 15.0 NGVD. These are encased in concrete with a top at 16.0 NGVD, and a pond top of bank of 8.4 NGVD. Langan, as the geotechnical engineer, designed these walls to meet groundwater flow analysis requirements and to meet the Florida building code that requires the system to withstand wave action from hurricanes. The project team evaluated the strength of the stormwater system during a hurricane that impacted southern Florida in 2018. The system endured with no issue.

The second wet detention pond serves as a surge pond for the stormwater system. This pond allowed the size of the needed pumps to be reduced to three 130 HP pumps, since the site's peak runoff rates (580 CFS 100-year 72-hour) could be attenuated to 90 CFS. It also allowed the existing 6 feet equivalent ERCP under the main entrance to be reused. This would have required the SHRH's main entrance to be closed, which was not acceptable to the client. The surge pond maintains similar storm stages as the previous system.

Once treated, the stormwater leaves the impoundment pond with a final discharge into the FDOT drainage Canal 300, which is adjacent to the property. The Soils Conservation Service (SCS) Unit Hydrograph Method Computer Model was used to estimate the stormwater runoff hydrograph. Per the design criteria outlined by SFWMD, the ponds must be able to provide for water quantity and water quality. Modeling scenarios were performed with Streamline Technologies Advance Interconnected Channel and Pond (adICPR Version 3.2) Model. The model provided a 1D hydrologic and hydraulic model with a quasi-2D groundwater module called PercPack. This program allows an interaction between surficial aquifer systems and surface water bodies.

5. WATER IMPROVEMENTS

The capital improvements proposed for the property required extensive infrastructure changes to support it. This included the need for a new water supply system from STOF PWD. A new transmission system and water treatment plant were required. The sanitary system required a new 12-inch force main and wastewater treatment plant. Both of these new treatment plants were located over a mile south from the Hard Rock (see Figure 7). These improvements needed to occur in coordination with the Hard Rock improvements and over several phases. The lack of immediately available infrastructure resulted in the need for supporting utility agencies to invest in their own facilities expansion and increase their transmission capacity to serve the Hard Rock site.

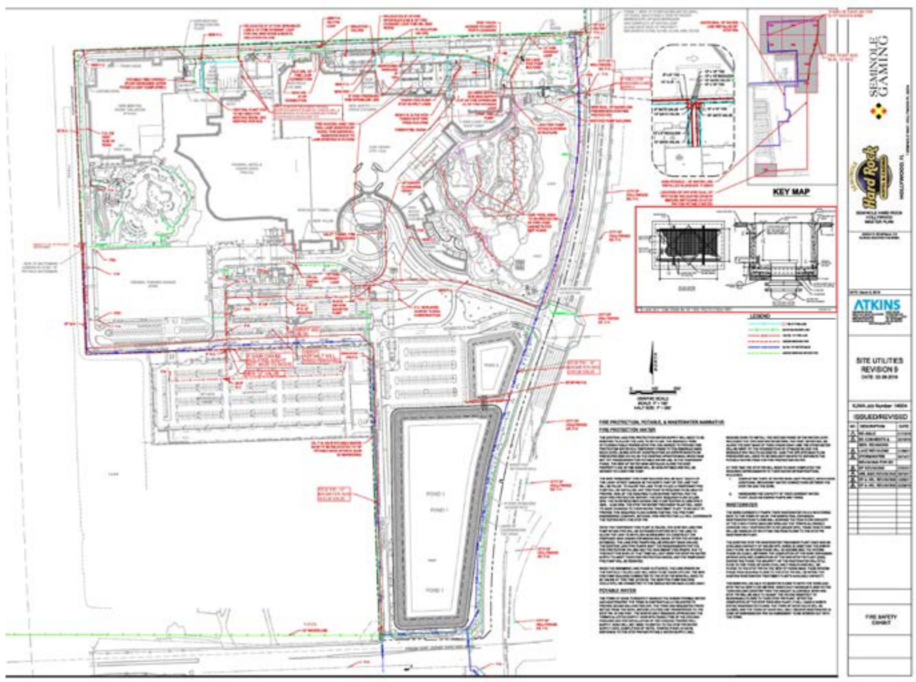


FIGURE 7

SHRH's stormwater water infrastructure

Figure 7 shows relevant on- and off-site water mains for Hard Rock. The Hard Rock property has separate water mains for potable, fire hydrants, and high-pressure fire sprinklers demand. Originally, potable water was supplied by a 12-inch dead-end main from an adjacent municipality, the Town of Davie to the north of the site. Through an ongoing agreement with the Town of Davie, the Hard Rock was allowed 500,000 gpd and used approximately 350,000 gpd on average. With the improvements, the average daily water demand would double to over 700,000 gpd. The Town of Davie could not improve their water main to meet the needed water volume, flow rate, and pressure demands, so the Hard Rock would have to switch to the STOF Public Works for utilities.

Hard Rock and the designer began working with STOF PWD to improve the Hollywood Reservation water infrastructure to allow the STOF to better supply their own reservation and the Hard Rock's anticipated potable and fire supply demand needs. The STOF PWD would need a new 2.0 million gallons per day (mgd) water treatment plant (WTP) that could serve the Hard Rock expansion. This work was performed under a partnership between STOF PWD and Seminole Gaming and Development. STOF PWD was responsible for bringing two 16-inch water mains to the Hard Rock property line under a separate contract. The Hard Rock site contractor was responsible for installation of the backflow preventers at the property line and the 16-inch transmission line within the Hard Rock property. The designed 16-inch transmission lines were installed via directional drill and open cut. This design also included permitting a long directional drill under the Florida Turnpike, which required a 24-inch casing pipe.

The first phase of the expansion required one of these 16-inch water mains to be installed for fire flow protection so the lake fire pumps could be taken offline while the lake was being modified. During this first phase, due to the lack of daily demand, the water in the main would be non-potable and an off-site backflow preventer was required.

In collaboration with STOF PWD, a water network model was created to show that the single water main could provide the needed fire flow rate during the first phase and the final configuration. The model showed that the STOF PWD water mains could provide the required fire flow demands of 2,000 gpm. Two points of connections were designed on-site to provide a redundant loop, as required by fire code. This redundant loop would be necessary during construction to maintain fire flow protection. The fire code required a fire flow duration for the site of 4 hours, resulting in a needed firefighting volume of 480,000 gallons. This volume was previously provided by the stormwater lake, which was going to be filled in to make room for the GT and Oasis hotel towers and Bora Bora area. The STOF PWD originally was concerned that the water storage tanks at their plant could not supply the needed daily water demand and fire protection volume. The STOF PWD wanted to require a 2.0-million-gallon water tank to be installed on the very crowded and valuable Hard Rock property. The engineering firm worked with the STOF PWD, the fire protection engineer, the STOF FD, and the swimming lake designer to allow the existing lake pumps to be reused to provide the needed fire protection volume.

The existing lake fire pumps would be connected to the swimming lake and fire protection mains to provide the required fire protection volume, thus eliminating the need for an onsite water tank.

The existing single on-site potable water main was looped, by installing a new 16" watermain from Stirling Road at the southwest corner and connecting to the existing main near the northwest of the site. Another 16" watermain was ran along the eastern side of the site and connected near the Town of Davie meter in the northeast corner. The analysis demonstrated that the additional piping on- and off-site would need to be constructed concurrent with the onsite expansion in order to be pressure tested and ready to serve the facility as certain phases went live, the GT in particular. The Town of Davie connection would continue to serve as a backup.

6. SANITARY SEWER SYSTEM

The sanitary sewer system consists of a combination of gravity systems, force mains, lifts stations, and grease traps. The projected demand capacity required is over 700,000 gpd. The gravity system includes 6-inch laterals all the way up to new 15-inch sewer lines entering the farthest downstream lift station. There are approximately 11 grease trap locations designed to handle the many kitchen locations associated with the existing and proposed facilities. Locating these grease traps posed a few challenges due to 1) lack of back of house locations, 2) the need to reduce grease trap depth by locating them as close as possible to the source, and 3) the number of locations needing service by vacuum truck. The smaller tanks are approximately 2,500 gallons and the larger ones are 12,000 gallons.

The original main lift station is located under the Lucky Street garage in the northeast corner of the property. Originally, the sanitary peak flows were limited by a 6-inch force main which traveled over a mile north to the Town of Davie before increasing in diameter. The peak flow rates from the expansion would more than double the existing peak flow rates and would increase pipe velocities beyond the capacity of the existing 6-inch force main from the Town of Davie. A connection was established to STOF PWD's existing 12-inch force main near the southeast corner of the site. This was installed with long directional drills under Stirling Road and Seminole Way at the main entrance to reduce disruptions. STOF PWD's new wastewater treatment plant will not be completed until 2023, three years after Hard Rock's grand opening. STOF PWD's existing plant does not have capacity for Hard Rock's entire wastewater discharge.

The solution was to split the wastewater flows between the Town of Davie and the STOF PWD. Each force main has a magnetic flow meter that is monitored by its respective utility provider.

The engineering firm helped resolve other challenges such as:

› A Valet Tunnel that required two lift stations (storm and wastewater).
› Phased construction plans for the tunnel to enable maintenance of traffic of the Hard Rock's main entrance.

7. CONCLUSIONS

The project was successfully completed on time and a letter of appreciation was received from the client (Seminole Gaming Association). The project costs were closed out with the client's approval. The design team managed all of these project constraints effectively while interacting well with the outside consultants and client representatives, all of which ultimately contributed to the success of this project by encouraging an open exchange of ideas and problem-solving dialogue.

BEYOND MURPHY'S LAW: APPLYING WIDER HUMAN FACTORS BEHAVIORAL SCIENCE APPROACHES IN CYBER-SECURITY RESILIENCE

NICOLA FAIRBURN

Principal Human Factors Consultant
Engineering, Design
and Project Management
Silchester, UK

ANDREW SHELTON

Human Factors Consultant
Engineering, Design and
Project Management
Bristol, UK

FRANCES ACKROYD

Human Factors Consultant
Engineering, Design and
Project Management
Bristol, UK

RACHEL SELFE

Senior Human Factors Consultant
Engineering, Design and Project
Management Aldershot, UK

ABSTRACT

Traditional approaches to cyber security resilience, assuring the overall socio-technical system is secure from immediate known attacks, and routes to potential future attacks, have relied on three pillars of people, process, and technology.

In any complex socio-technical system, human behaviour can disrupt the secure and efficient running of the system, with risk accumulating through individual and system-wide errors, and compromised security behaviours that may be exploited by actors with malicious intent.

Practitioners' experience and use of different assessment methods and approaches to establish cyber security vulnerabilities and risk are evaluated. Qualitative and quantitative methods and data are used for different stages of investigations in order to derive risk assessments and access contextual experience for further analyses. Organisational security culture and development approaches along with safety assessment methods are discussed in this case study to understand how well the people, the system, and the organisation interact.

Cyber security Human Factors practice draws on other application areas such as safety, usability, behaviours and culture to progressively assess security posture; the benefits of each approach are discussed. This study identifies the most effective methods for vulnerability identification and risk assessment, with focus on modelling large, dynamic and complex socio-technical systems, to be those which identify cultural factors with impact on human system interactions.

KEYWORDS

Human factors; Cyber security; Behavioural science; Organisational security culture; Socio technical cyber resilience; Safety assessment.

1. INTRODUCTION

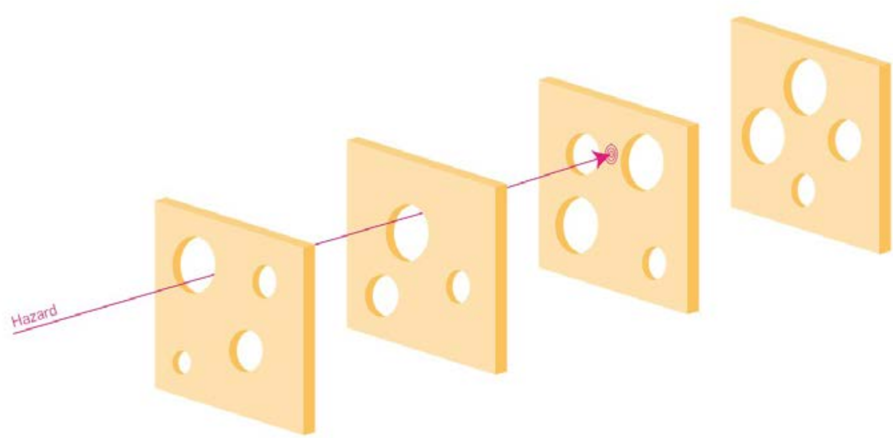
Traditional approaches to cyber security resilience, that is assuring the overall socio-technical system is secure from immediate known attacks and routes to potential future attacks, have relied on three pillars of people, process, and technology. Historically greater emphasis has been placed on technology solutions with reduced attention placed on the human element; now human behaviours, culture and organisational human factors are considered in every cyber resilience improvement programme.

There are multiple different understandings of “human factors” (HF). The International Ergonomics Association (IEA) defines human factors as “...the scientific discipline of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human well-being and overall system performance” (IEA 2016). Part of these human-system interactions involve understanding the drivers for behaviours e.g., the capability, opportunity and motivation. It also involves; ensuring the design supports the needs of the user, identifying where the user will find the system complex to interact with, ensuring the design minimises the likelihood of human error and ensuring the design maximises the opportunities for error tolerance.

In any complex socio technical system, the significant risk of certain “human factors” disrupting the secure and efficient running of the system is now widely recognised. The accumulated effect of individual and system-wide human errors and compromised security behaviours lead to vulnerabilities that may be exploited by threat actors, or attackers, with malicious intent. Identifying those vulnerabilities; assessing the risk arising from them; and evidencing the argument for making improvements is critical to developing cyber resilience.

FIGURE 1

Reason’s (1997) “Swiss Cheese” model demonstrates how multiple defensive layers of security prevent hazards becoming incidents

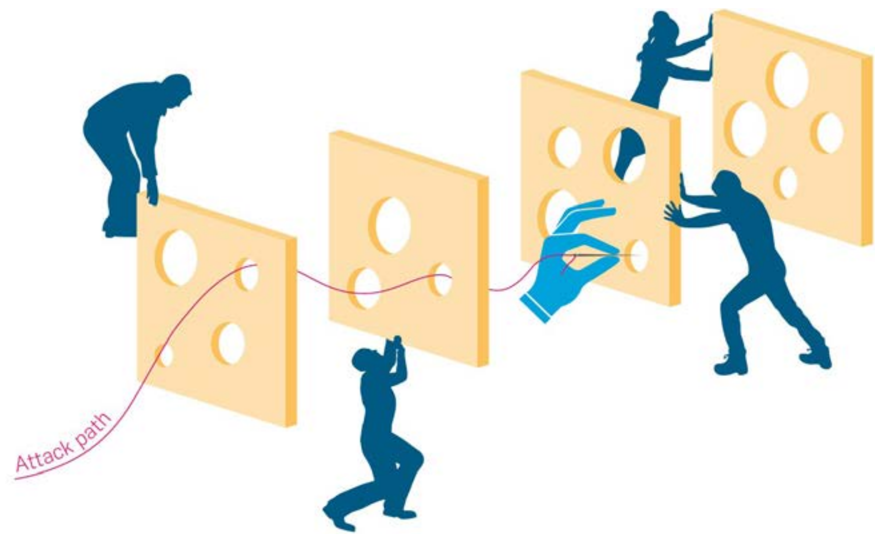


Within safety, James Reason's (1997) "Swiss Cheese" model of accident causation is used in risk analysis and risk management, where the risk of a hazard causing harm in the system is reduced as layers of defence are added. For straightforward security compromises, where layers of defence prevent the risk from developing, this model still applies to security, as demonstrated in Figure 1.

However, in cyber security a threat actor seeks to attack targeted systems and can manipulate these layers to exploit any vulnerabilities within the wider socio-technical system to create an attack path. Furthermore, rather than a linear path of circumstantial failure, threat actors can actively weave their way through defences to engineer a system failure as demonstrated in Figure 2.

FIGURE 2

Manipulation of vulnerabilities by a threat actor



The Murphy's law adage stresses that "what can go wrong will go wrong," with acknowledgement that it is often considered in reality as a case of "what can go wrong might go wrong at some point." However, in cyber security assurance it is necessary to go beyond Murphy's law as "what can go wrong will be actively sought out and manipulated to make it go wrong."

When considering "the human" and human behaviour in a large, complex socio-technical system, a distinction should be made between the different roles adopted by humans as "end-users," attackers, defenders, and bystanders. While the threats posed by individual threat actors, with the intention of actively creating and exploiting vulnerabilities, are well documented, they can be emphasised at the expense of potential vulnerabilities posed by humans in the system carrying out their everyday work tasks.

In order to understand the human centred activities a key element of the investigation activities focused on the day-to-day tasks of all humans in the organisation as they interact with the system. Drawing on both goal-orientated and social interactions enables the identification of vulnerabilities which can be exploited by the threat actors, and recommendation of human-centred mitigations to increase security.

From working within high hazard domains, HF have a pedigree in understanding and identifying the potential vulnerabilities within a system, in sharing knowledge across domains, and transferring best practices to create a more rigorous cyber security process.

Comparisons have been made across both safety and cyber security, drawing on HF practitioner experience. On the surface, safety hazards and cyber attack paths look very different and the processes used to identify the underlying vulnerabilities within the system are also different. A cyber threat is often perceived as an adversary deliberately targeting a system, however that is not the only way to assess vulnerabilities in a cyber security context. As stated by Dekker (2014) "...people in safety critical jobs are generally motivated to stay alive, to keep their passengers, their patients, their customers alive. They do not go out of their way to deliver overdoses; to fly into mountainsides..." The majority of people want to do a good job both in a cyber security and safety context. One of the most striking similarities within both domains is the requirement to understand the human element of risk and what drives risky behaviours. Most people do not intend to undertake risky security behaviour, but multiple factors can influence their actions such as time pressure, outdated system or task design, or deliberate manipulation through social engineering, all of which can result in workarounds, lapses and behaviour that leads to people unintentionally compromising security.

As HF practitioners, assessing the human cyber risks within a system requires a shift in focus from the malicious outsider threat, to incorporating a wider focus to include social engineering, organisational culture and system design that can create the opportunity for attack paths.

In the socio technical system of interest it is the vulnerabilities that are sought out. In terms of cyber security, a vulnerability is an element of the system which has the potential to be exploited as part of an attack path and is assessed with an associated risk of compromise.

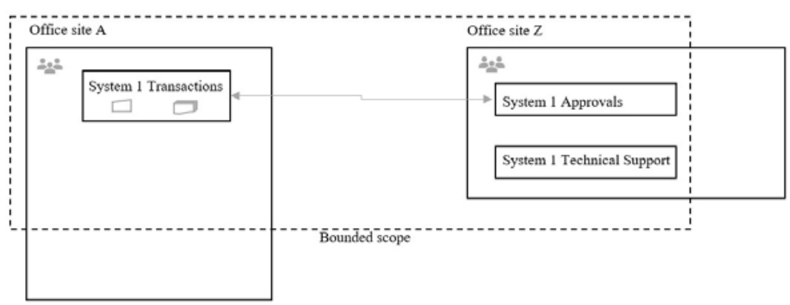
2. CASE STUDY

This paper introduces the case study activities experienced by the authors and their organisation with a number of clients in different sectors. It explores the overlaps and differences from across domains and discusses how this knowledge can be applied to a risk investigation to identify the widest set of human-based and system vulnerabilities. The method and processes described draw upon existing best practices in technical, cyber security and behavioural science safety approaches into one homogenised methodology.

Cyber security investigations have been conducted into a variety of systems, ranging from single technology applications, for example an app on a mobile phone, to multiple interrelated systems, with interactions from multiple parties, based in different locations. For the purpose of this paper, an example transactional system "System 1" is accessed and interacted with from two office sites, and the investigation scope is identified accordingly, as shown in Figure 3.

FIGURE 3

Example diagram showing System 1 usage across office sites A and Z



People and processes are intrinsically interwoven with technology throughout its design, manufacture, installation, use and maintenance, and ultimately disposal. Cyber security risk is therefore assessed for each of these stages, and for all interactions, within the socio-technical system in order to identify vulnerabilities which could enable an adversary to gain access to the information contained within. In the example above, authorised access to System 1's transactions by users in office sites A and Z would be examined, along with the cases where System 1 users required approval by senior users, or needed technical support in order to complete a transaction. In addition, unauthorised use of System 1's connection between office sites, would also be a plausible vulnerability line of enquiry. Note that other systems and interactions in both office sites are beyond the scope boundary of this investigation.

3. "MATERIALS" - RECOGNISED HUMAN FACTORS APPROACHES

3.1 A Cross-Disciplinary Approach

Human Factors practitioners adopt a human centred approach to work across different industries and with multi-disciplinary teams. This wide range of work allows us valuable access to a range of tools and techniques. The following sections draw upon and pull together experience using HF processes within the technology domain, the safety domain, behavioural science and cultural assessment and following a human centred assessment approach. Collating best practices from each of these domains has allowed the creation of a bespoke approach for cyber security HF investigations to date, combining the best techniques from across multiple domains in high hazard industries.

3.2 HF Adoption of Formal Cyber Security Methods

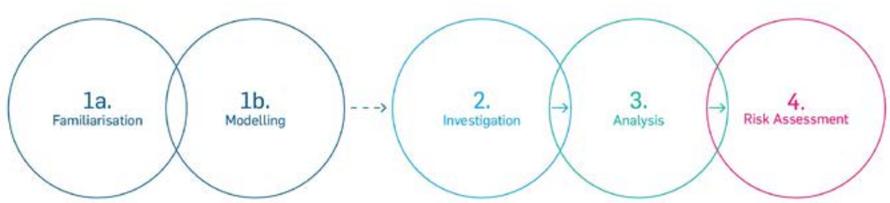
When investigating an organisation's security defences against a potential cyber security attack, it is important that the system is considered in its entirety and that potential vulnerabilities are assessed from the mindset of an attacker. This section outlines the existing methods and practices drawn on by HF and cyber security domain experts for investigating and identifying cyber security vulnerabilities.

The aim of the reviews, investigations and assessments is to develop an accurate, 'real world' view of the socio-technical system. These are required to produce a detailed analysis of the vulnerabilities which may lie within. The focal point of an investigation could be narrow, such as a piece of technical equipment, or broad, such as an establishment or group of people.

A typical security project is divided into phases namely: Familiarisation & Modelling, Investigation, Analysis and Risk Assessment. These phases are demonstrated in Figure 4 and outlined below.

FIGURE 4

Typical phases of a cyber-security investigation



FAMILIARISATION AND MODELLING

The aim of the initial phases of the investigation is to gain a primary understanding of the socio-technical system under investigation by gathering existing technical and process material, and engaging stakeholders. It is important to confirm the scope of the process and the boundaries of the socio-technical system that will be explored, and ultimately analysed.

Modelling provides a central focal point for all information found to date and reflects the initial high-level analysis of the critical components within the system, this allows the team to discuss identified high level impacts associated with those components.

INVESTIGATION

Investigation of a socio-technical system is planned and conducted in order to progressively discover and identify likely areas of potential vulnerability. After initial identification, further qualification through deep dive exploration of all candidate areas reveals the extent of the vulnerabilities that may exist. Data is collected through a range of quantitative and qualitative methods and analysed to evaluate technical security assurance, along with security and organisational culture. As the data accumulates, a developed picture of the initial assessment outcomes and the potential impacts of vulnerabilities on the system as a whole, is made.

ANALYSIS AND RISK ASSESSMENT

During the “Analysis” phase the accumulated data is analysed from the perspective of an adversary in order to establish how the vulnerabilities could be exploited and manipulated into potential attack paths to infiltrate the system. Following this, risks are quantified during the ‘Risk Assessment’ phase according to their likelihood of occurrence and the impact on the organisation. Again this overlaps with, and leads directly into, the next phase where risk mitigation strategies are formulated and proposed.

3.3 HF Practitioner Experience

In undertaking HF activities on complex systems, HF practitioners are experienced in the application of structured, rigorous methodologies, and providing strong substantiation arguments in support of safety and security cases which are presented to regulators. This experience afforded the opportunity to select, learn, and create best practice in translating methods, and rigour to new domains such as cyber security assurance. The following outlines some of our learning:

- System scope – the importance of bounding the system that is being assessed.
- Work-as-imagined and work-as-done – the identification of the differences which can appear between work-as-imagined and work-as-done.
- Risk and Resilience – The likelihood that some form of unintended outcome will have an impact on the organisation.

SYSTEM SCOPE

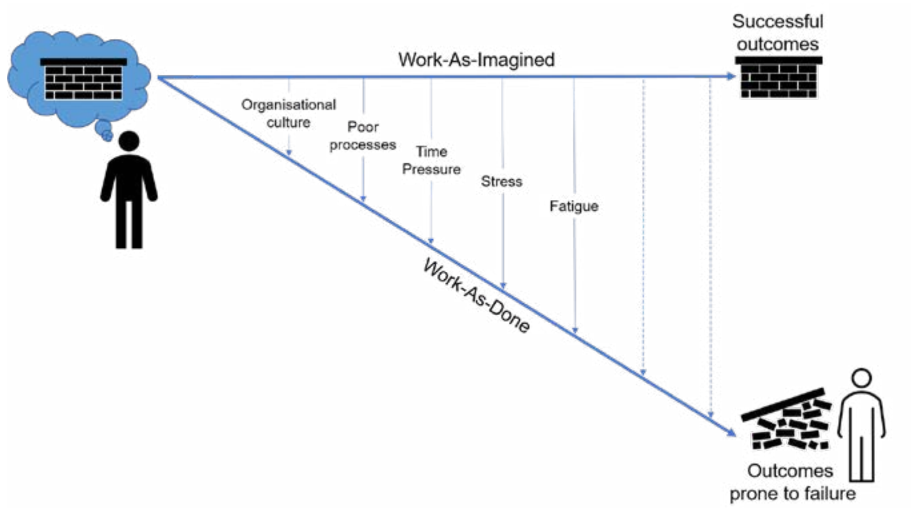
It is important to ensure the scope of the system is fully bounded and the practitioner assessing the system fully understands how the system is used by means of developing a task analysis to identify human interaction with the system under investigation. For example, a technical system may have limited human interactions compared with a site which may have multiple digital systems within scope. From experience gained in the cyber security domain, a system of systems approach has been adopted looking at the individual technological system and the context in which it operates. The system of approach proposed here incorporates the features of a typical HF system of systems approach but goes beyond it in order to evaluate the scope of the accumulated risk and attack paths. Therefore, to undertake a successful cyber investigation, the scope of the system should be clearly defined and the human interactions within the system understood and documented.

WORK DONE VS WORK IMAGINED

From investigating human error, a significant part of the HF input is to review, understand and analyse how work is intended to be carried out (work-as-imagined) compared with how work is conducted in reality (work-as-done) (Hollnagel 2006). This approach involves utilising task analyses, hierarchical and tabular task analysis (HTA, TTA) for example, behavioural and system modelling, and engagement with end-users through interviews and focus groups. In addition, observations are carried out to review “work-as-done,” including any workarounds to cyber security procedures that may pose a greater risk. Evaluating the differences and variation between work-as-done and work-as-imagined, will help the client's understanding of the interaction of many factors in the overall system, such as organisational pressure, poorly written or out of date procedures, and inadequate training to name a few. As will be discussed later, the gaps between "work-as-done" and "work-as-imagined" are a good indicator of where system weaknesses or potential vulnerabilities may lie that could be exploited by an adversary.

FIGURE 5

"Work-as-done" vs. "Work-as-imagined"



RISK AND RESILIENCE

Definitions of risk in cyber security vary; for the purposes of this case study, it can be conceived as a form of unintended outcome that has the ability to impact the mission, whether in a commercial or defence environment. These impacts are loss of finance, reputation, operational capability and, in some contexts, loss of life.

The risks of cyber security attack paths and vulnerabilities being exploited are established against a standard risk matrix of risks, the impact of the unintended outcomes, and the likelihood. The level of risk however varies for each case and for maximum effectiveness, is aligned with the risk appetite of the organisation. Some may have a conservative, low security risk-appetite whereas others may be more risk tolerant in a security context. The risk-benefit analysis (RBA) is therefore unique for each organisation and system.

Furthermore, there may be a set of risks associated to system "A," for instance a mobile phone, which may be deemed to be acceptable, and another set of risks associated to system "B," let's say a server room, which are also deemed to be acceptable. However, when the mobile phone is in the server room the accumulated risks of the larger, combined, systems will be different, and may become unacceptable. In this context a system of systems approach can be recognised and the importance of clearly defining the boundaries of the targeted system and the scope of the investigation at the outset are highlighted.

3.4 Culture

In order to understand how well the people and systems in an organisation interact, it is increasingly important to recognise and assess how the organisational and security environment affects the operation of work done and work-as-imagined. Organisational cultures where blame is high for security breaches or those where operational focus is consistently prioritised over security issues, could be exploited as potential vulnerabilities.

By collecting data on both the security culture and organisational culture throughout the investigation process and timeframe, it is possible to standardise some responses as a basis for assessing risk, and to identify anomalous areas for further indepth interviews. This is achieved through incorporating questions and commentary into all interviews, surveys, observed group discussions and tasks, and making use of security culture questionnaires and pulse surveys for climate. In addition, organisational change and development methods can be utilised to improve the security implications of cultural factors. Furthermore, readiness or baseline assessments of the impact of cultural factors can then be incorporated into an overall strategy for cultural change development.

Expected human computer interactions, flows of information and security decision making points can be identified on the socio technical systems model, even where complex systems are in use. Identifying cultural factors that alter or interrupt those interactions, information or decisions across the breadth of the target system yielded effective vulnerability identification and risk assessment. These models and factors are then overlaid with complementary security data using robust assessment frameworks developed for the organisation.

Qualitative and quantitative methods and data were used for different stages of the investigation in order to derive risk assessments and access contextual experience for further analyses. For example, exposure to the risk of social engineering was assessed using ‘direct’ questions, whereas expectations of blame for an incident was asked ‘indirectly’ with opportunities to comment.

The primary focus of the approach is to assess the impact of cultural factors on cyber security risk. Potential vulnerabilities can be exploited in a direct attack on an identified cultural weakness, or by engineering the situation to take advantage of cultural factors.

In activities that focus on modelling large, dynamic and complex socio technical systems, identifying cultural factors that affect human interactions across the breadth of the system were most effective for vulnerability identification and risk assessment.

3.5 SAFETY ASSURANCE APPLIED TO SECURITY

Safety assurance is a formal and systematic process which aims to demonstrate that an organisation, functional system, plant or process are tolerably safe. Safety assurance can result in risks being effectively managed and lead to improved system performance. HF forms an integral part of the safety assurance process. With HF specialists working alongside safety specialists to help to ensure the “human” element of risk is identified and effectively managed throughout the safety assurance process.

HF are integrated into safety assurance in multiple industries such as aviation, nuclear, defence and rail. Some of the worst major accidents have highlighted the complex role of the “human” within the wider complex socio technical systems. These major accidents have helped to demonstrate the combination of system failures and human failures perfectly aligning to result in some of the worst disasters (for example, Piper Alpha, Chernobyl and Herald of the Free Enterprise). Having HF effectively integrated within the safety assurance process can help to identify human failure within the complex socio technical system where the human is an integral part of the complex system and come up with effective mitigation solutions to minimise the likelihood of human error from occurring.

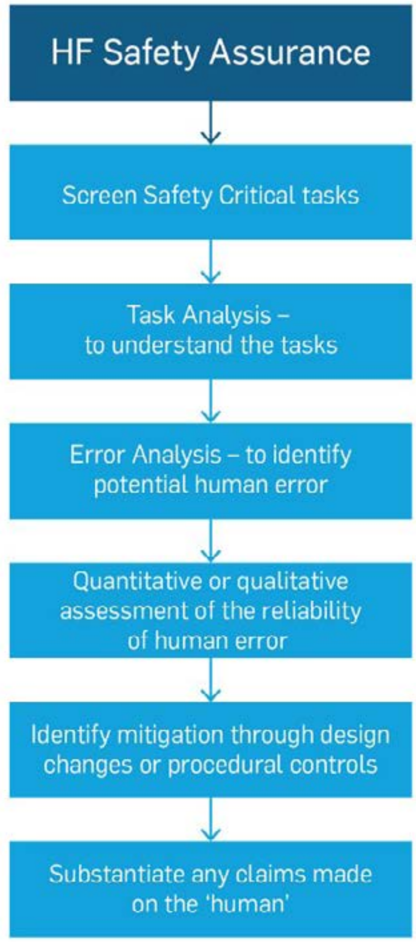
Providing HF safety assurance within a complex socio technical system is detailed and a proportionate approach must be adapted depending on the level of "risk" involved. A typical approach to HF safety assurance is presented in Figure 6. This approach is systematic, detailed and can be time consuming. Focusing HF efforts in the areas of highest risk such as safety-critical, safety-related or complex tasks ensures efforts are proportionate to the risk. Once the overall set of these tasks are identified, task analysis is conducted on each to analyse the task detail undertaken by operators and maintainers. Error analysis is conducted to identify credible human error. The extent to which human errors are quantified with the derivation of human error probabilities (HEPs) depends on the requirements from the safety case. Regardless of whether it is done numerically or quantitatively, HF practitioners indicate the likelihood of error occurrence and identify the performance shaping factors (PSFs) that will make that error more or less likely to occur.

A key part of the process is to identify opportunities to mitigate the human error. The "as low as reasonably practicable" (ALARP) approach is adopted within HF safety assurance. Therefore, whilst eliminating human error is the preference (based on the ERICPD[1]), several factors are considered including cost of proposed change, consequence and likelihood of the error occurring. One option, which is used particularity within operational plants where engineered changes are more costly, is to derive procedural controls such as human based safety claims (HBSCs) to protect against system and human error. Procedural controls rely on operators or maintainers to form a key layer of defence against an unintended consequence (see Figure 1 to highlight layers of defence against an unintended consequence). Therefore, any HBSCs made will need to be qualitatively substantiated to ensure the necessary arrangements are in place to demonstrate that the HBSCs form a reliable layer of defence against an unintended consequence.

1 Eliminate, Reduce, Isolate, Control, Personal Protective Equipment and Discipline.

FIGURE 6

A typical HF safety assurance process



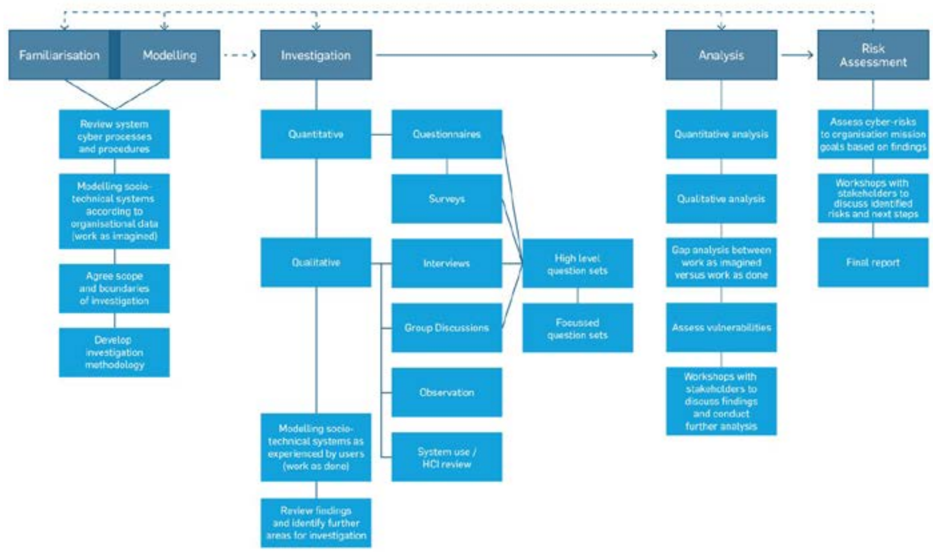
This HF assurance approach utilises a number of HF tools and techniques, including hierarchical and tabular task analysis (HTA, TTA), error analysis, walk throughs and talk-throughs with operators and maintainers, desk top reviews of documentation such as operating procedures, derivation of HEPs and qualitative substantiation of HBSCs. These HF tools and techniques are not unique to HF safety assurance and can be utilised across any domain to support HF assessment work. In addition, whilst this traditional approach to HF safety assurance has been presented here this approach can be adapted to suit a range of different domains such as cyber-security to ensure HF are integrated and "human" remains a key focus in identifying human failures or vulnerabilities and any potential defence and solution can be delivered consistently and reliably.

4. METHODOLOGY

From the previous sections it is apparent that there are multiple HF qualitative and quantitative methods available for HF practitioners to use when undertaking a cyber security review. The following section outlines the process utilised by HF for cyber-security investigations drawing upon the knowledge and techniques applied across wider domains. It should be recognised the process defined below is iterative throughout, with further investigation or analysis being conducted as required, until all parties are satisfied that the socio-technical system has been analysed in full.

FIGURE 7

Cyber-security HF investigation process



FAMILIARISATION

Assurances of stakeholder and user confidentiality are made during initial contact in this stage. As outlined in Section 2.1 the output of the familiarisation stage summarises the "what and why" of the existing socio technical system as well as any vulnerabilities that immediately emerge.

The methods that are used include literature reviews and internal briefings, as well as reviews of security processes, procedures and documentation regarding the existing systems. The reviews include training records, cyber security training, organisational charts and technical processes in order to establish the "work-as-imagined" and facilitate the development of investigation strategies unique to that system.

MODELLING

Human system interactions are identified to develop the initial socio technical model which will act as a baseline for the investigation which is updated as the process evolves. The methods used include; task analysis, system modelling and behaviour modelling.

INVESTIGATION

All interactions are examined using a number of methods including quantitative questionnaires and surveys along with qualitative interviews, discussions and observations of behaviours, work environment and system use which could include assessments of usability and human computer interaction (HCI).

After the initial engagement, thematic analysis is conducted in order to prepare a focused question set developed to encapsulate themes enabling further exploration in subsequent engagements. The data produced is used to build up a picture of how the socio-technical system actually operates and where potential vulnerabilities may lie.

ANALYSIS

Wider practitioner experience is employed to create a full understanding of the data set by applying theory, skills, knowledge and expertise along with external application of guidance, standards and recommended good practice. Utilising a number of human factors methods enables a comprehensive overview of system vulnerabilities to be captured.

Methods include quantitative and qualitative analysis of interviews as well as gap analysis between identified "work-as-imagined" and "work-as-done" processes. The emergent gaps indicate where vulnerabilities may lie, such as security shortcuts and workarounds, as processes are not carried out as intended. Workshops may be held with users and stakeholders to confirm the accuracy of the models.

RISK ASSESSMENT

Based on the findings from accumulated investigation data, the overall risk matrix is evaluated for impact and likelihood of human system vulnerabilities leading to attack paths. Methods include: human risks assessment matrix, assessed individually and as part of the wider system. The resulting matrix is then validated across the team for interrater consistency and socio technical risk mitigations.

5. RESULTS, DISCUSSION AND LESSONS LEARNED

The following section discusses the findings from utilising the defined process to identify vulnerabilities within a defined system.

RECOGNISE THE DIFFERENT HUMANS IN THE SYSTEM

In large, complex cyber security socio technical environments, it is important to consider the full range of different human roles and tasks, rather than honing in on one group. Behaviours vary for different humans in the system depending on whether they are attacker, defender, or end users of systems with either specific tasks, or occasional use. By expanding the perspective beyond the traditional focus of preventing the harm caused by threat actors alone, the security and day-to-day work behaviours can be placed at the centre of a resilient cyber security system.

GO BEYOND THE “TECHNOLOGY-ONLY” APPROACH

By adopting a broad HF-led human-centred approach, vulnerabilities and risks can be identified earlier than a technology first approach would yield. Even in the most technologically complex environments, there are always some human task related interactions that contribute to vulnerabilities.

EARLIER HF ENGAGEMENT LEADS TO WIDER SYSTEM SCOPE

In early practitioner activities, HF were invited, after the initial project engagement, to review problems that were deemed beyond the bounds of the technical system. This resulted in the need to ask questions of the wider socio-technical system retrospectively, in order to identify the causes of vulnerabilities rooted in social and cultural issues. Wider understanding of the impact of human factors on the system have been incorporated into further developments of the models since, that reflect the full scope of the socio-technical system, not just the technical element.

EARLIER APPRECIATION OF THE USER TASK

Understanding of the user task could have been further developed earlier in the process, depending on the system scope, which would have helped when assessing risk.

ITERATIVE MODEL DEVELOPMENT AND VALIDATION

Building models and assurance arguments from which to generate further areas of investigation and risk mitigations, provided artefacts for discussion and feedback at stakeholder workshops. In addition, ongoing validation of re-usable instruments and tools for future investigations and to evidence recommendations were evaluated and reviewed with teams. This construction of models and validation with stakeholders can be an iterative process depending on project design. The accuracy of the model needs to be agreed and accepted by all parties, with sufficient evidence to explain differences to key stakeholders. Further data collection to confirm this accuracy of models and to eradicate discrepancies may be required at times. On other occasions, evidence may surprise individuals within the organisations being assessed who take a more macro view of operations and processes, when micro system intricacies are identified of which they may have been unaware.

INTEGRATING CYBER AND HF APPROACHES

A key to the success of the investigation practice set out in this study has been the adoption of cyber security domain expertise and the integration of HF processes into the cyber security investigation team, in order to fully assess the risks within complex socio technical systems. HF, as a discipline, have a long standing history of successfully integrating into receptive multidisciplinary teams, for example working closely with safety specialists as part of safety assurance activities; and now a close one-team approach with cyber security domain teams. Integrated contributions to potential vulnerabilities, system and attack path modelling, and risk assessments were produced as a collaborative effort across disciplines.

Initially the scope of some clients' work allowed for limited integration activities, but it was important for HF to be a fully integrated part of the cyber team in order to elicit the relevant information from end-users. Effort was put into integration and collaboration activity, ensuring that HF maintained an independence but contributed practices which would support and complement the exercise as a whole. For example, HF introduced the development of a consistent, transparent positive investigation environment, where people were able to speak out, aware of the exercise ethics, confidentiality and actions for their reports, which has been critical to the success of each investigation.

- Terminology presents a barrier - Another reason for ensuring participants were put at ease was because it was found that some cyber security terms and the general use of "cyber" could be confusing for participants outside the security domain.
  The term 'cyber' wasn't generally understood, it was too ambiguous and somewhat misleading when in reality, the process was to analyse a complex socio technical system. More problematic still was the term 'investigation', which immediately implied wrongdoing and that a perpetrator was being sought out. It was important to overcome these barriers for the participants to invest fully in the process.
- Introduction of HF ethics to investigations - The importance of clear ethical briefings was highlighted to all investigation teams, and to participating interviewees, explaining informed consent, use and handling of data, the boundaries of anonymity and that participants could be identifiable if they divulged information that only they could know. Participants were informed that if they revealed information that could do harm to themselves or others, the team would be obliged to report it.
  A key benefit of offering a safe and anonymous environment for participants to communicate their experiences is that they have the opportunity to speak freely about the workings of the system, without fear of it reflecting badly on them and damaging future prospects. Therefore, known bad security practices or potential for vulnerabilities are more likely to be revealed in the absence of the worry of reprisals.
  A further benefit is an understanding by all of the reasons for processes not being carried out as envisaged and the remedial actions required.
- Aligning understanding of "Work-As-Done" - Gap analysis between "work-as-done" and "work-as-imagined" reveals system weaknesses or potential vulnerabilities that could be exploited by an adversary. Both senior and security management may hold out-of-touch or over idealised views of work in their organisation, not aligned with reality or work-as-done and they value feedback on behaviours that reveal gaps in processes. Highlighting these areas to management enables them to improve the security and efficiency of their processes.

QUALITATIVE AND QUANTITATIVE METHODS

The importance and purpose of adopting individual quantitative or qualitative methods for analyses of different data is acknowledged in HF practice. Within cyber security HF investigations, both qualitative and quantitative data can be utilised throughout all phases of the process. This enables investigators to derive risk assessments and access contextual experience for further analyses. For example, exposure to the risk of social engineering was assessed using 'direct' questions, whereas expectations of blame for an incident was asked "indirectly" with opportunities to comment.

Experience has shown there are significant benefits to be gained from utilising a mixed methods approach for some stages of the investigation process. For example, recording observations and behaviours, as well as self-reports of stated intention, e.g., visual cues of people looking to the locations of a password crib can be compared with their stated password practice.

- Value of Quantitative Investigation Methods - The use of quantitative surveys and questionnaires has enabled the effective sampling of large populations, and provides the opportunity for statistical measurements of trends and cultural attitudes as well as validation to evidence findings. Quantitative methods are important for measuring the extent and risk of a human centred problem and for comparison with other wider populations and overall security culture, where available.
- Value of Qualitative Investigation Methods - In order to capture the socio behavioural system in its entirety, qualitative methods, including interviews, discussion groups and observations, were also widely utilised. These methods provided valuable insights into the unique experiences of groups and individuals within the system. For example, a participant who appeared visually frustrated during discussion, not speaking due to their seniors' presence in the room, proved to be a great source of information when interviewed alone. Comments made during discussions revealed a rich level of detail that often led to the revelation of significant vulnerabilities which may otherwise have remained undiscovered.
- Use of Mixed Methods - The benefits of using mixed methods, that is collecting both quantitative and qualitative commentary responses for analysis, were significant for identifying, developing and quantifying areas for further investigation and potential vulnerabilities. Analyses

were also enhanced by adopting alternative perspectives, from a cognitive approach focusing on the person purely as a rational information processing individual,
to evaluating stimuli-response drivers of security behaviours. Interview texts were examined through the lens of discourse analysis (Tileaga & Stokoe 2016), and primarily phenomenological approaches, using thematic analysis of first person interviews to explore the lived experiences of individuals (Langdridge 2007) within the socio-technical system.
This was highly successful in facilitating deeper analysis, producing rich findings and a nuanced understanding of the investigation environment. Rather than asking questions that would only require quantitative, binary style "yes" or "no" responses, it was found that using open ended questions, which were deliberately designed to elicit deeper responses, would provide personal insights that were invaluable to a holistic understanding of the socio-technical system.

A lesson learned was that utilising a survey covering a broad range of potential issues and vulnerabilities at the outset of an investigation, is effective in narrowing the lines of enquiry to those of most concern before physical engagements with users and stakeholders commence.
By doing so, valuable interview time is maximised during initial interviews and discussion groups, resulting in greater efficiency and better evidence results being collected.

- Stakeholder workshop feedback - Workshops held with the users and stakeholders can be a critical part of the investigation process. Once systems have been analysed, models constructed, and vulnerabilities identified, returning to the people operating within the system to validate the findings and gather end-user feedback on recommended courses of actions was important to moving forward. There would often be comments such as “you should speak to [this person]” or “you may want to look at [this information]” which would lead to further insight and data collection for review. It may also be that findings are disputed by a stakeholder, in which case further evidence would be collected to either bolster or alleviate the findings. Furthermore, the risks arising from some vulnerabilities discovered may be mitigated by other processes, so diminish in significance. Workshop feedback is an iterative process until all avenues have been explored within the boundaries of the system that were established at the outset.

6. CONCLUSION

Adopting a defined and systematic process from the start of any investigation, and ensuring that the system under investigation is well bound continues to be important for effectiveness. In addition, creating a robust HF data capture plan, before any investigations start is valuable to later success.

It remains important also that HF practitioners do not just utilise the existing technical process in place but bring their knowledge from other domains to support and develop existing practices and enable full integration and knowledge sharing with the multi-disciplinary team.

Adopting a mixed methods approach and drawing from methodologies beyond a purely cognitive approach can add richness and insight from experience to the data collected from those who operate within the socio technical system daily. This enables a wider data set and deeper analysis to be conducted, from which a more extensive range of vulnerabilities can be identified.

The most secure assessments of risk and resilience require evidenced analysis from both observations, and self reports, in order to access the widest data set; and to generate, support and evidence the analysis argument for risks to resilience.

A significant take away, is ensuring the social element of the socio-technical system is investigated, by developing robust human system models of interaction and by identifying the impact of organisational and security culture issues on vulnerabilities and risk. Risks can be mitigated, cyber-security resilience and security culture improved, once the impact of cultural issues in the organisation are identified.

Finally, it should be noted that whilst selective adoption of relevant approaches from the safety and cyber security realms is effective, threat actors are actively seeking out vulnerabilities in order to manipulate and weave a path through them. Outcomes therefore shift from unintended failures to intended failures. This subtle difference changes the dynamic of the approach to evaluating resilience with an attacker mindset. Practitioners need to go beyond “Murphy’s Law” to analyse how vulnerabilities, the “holes in the cheese,” could be exploited, and how humans could be manipulated to unwittingly align them, aiding attack path navigation.

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SNC·LAVALIN

snclavalin.com

Contact Information
Akshaye Sikand
Manager, Knowledge Management
akshaye.sikand@snclavalin.com