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## Achieving carbon efficiency in construction & maintenance of railway turnouts, crossovers and diamonds

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### Abstract

Railway turnouts, crossovers, and diamonds are special track systems used to divert a train from a particular direction or a particular track onto other directions or other tracks. It is a structural grillage system that consists of steel rails, points, crossings, steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, steel or concrete), ballast and formation. Usually under dynamic and high-intensity impact loading conditions, structural components of the turnout tend to have relatively short lives compared with those of ordinary open railway tracks, resulting in frequent turnout reconstruction and maintenance (ranging from every 10 to 20 years). Such the activities emit greenhouse gas (GHG) that increasing air pollution and contributing to climate change. Although railway operation is the most sustainable and carbon-efficient mode of transport, its considerable construction and maintenance often produce large amount of greenhouse gas. This study aims at developing a practical guideline to achieve carbon efficiency in the construction and maintenance of railway turnout. It involves significant field-based surveys and monitoring of the critical and detailed data of CO<sub>2</sub> emissions from each task, process and activity across multi functions. The outcome of this study provides an alternative planning and decision-making tool taking into account environmental benefits and risk management for railway engineers.

**Keywords:** railway construction and maintenance, turnouts, crossovers and diamonds, greenhouse gas, CO<sub>2</sub> emissions

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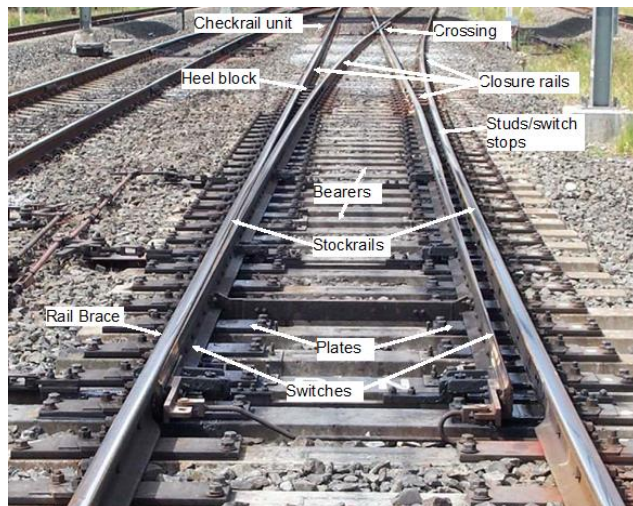
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### 1. Introduction

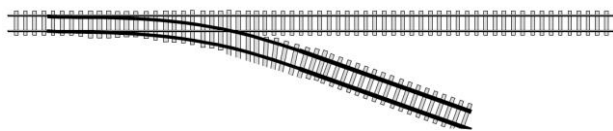
Railway turnouts, crossovers, and diamonds are special track systems used to divert a train from a particular direction or a particular track onto other directions or other tracks. It is a structural grillage system that consists of steel rails, points (or called 'switches'), crossings, steel plates, rubber pads, insulators, fasteners, screw spikes, beam bearers (either timber, polymer, steel or concrete), ballast and formation, as shown in Fig. 1 [1]. There are two types of turnouts, a conventional turnout and a tangential turnout. Standard conventional turnouts are designed typically for straight main line track. The combination of switch length, heel angle and cross rate defines the turnout type, and they all typically have the same components. Tangential turnouts are defined by the radius of the turnout. Components in a tangential turnout vary as manufacturers place their own designs over the standard configuration. The traditional turnout structure generally imparts high impact forces on to its structural members because of its blunt geometry and mechanical connections between closure rails and switch rails (i.e. heel-block joints).

A turnout is an inevitable structure in railway tracks whose crossing imparts a significant discontinuity in the rail running surface. The wheel/rail interaction on such imperfect contact transfer can cause detrimental impact loads on railway track and its components [1-4]. The transient vibration could also affect surrounding building structures. In addition, the large impact emits disturbing noises to railway neighbors [5]. The impact and ground-borne noises are additional to the normal rolling noise. Many previous studies have predicted impact forces and noise using numerical models<sup>5</sup>. However, only a few have implemented impact mitigation strategies in the field and

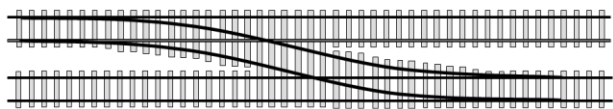
even fewer field trial reports are available in the literature [5-13]. The impact mitigation strategies at an urban turnout include wheel/rail transverse profiling and longitudinal profiling of crossings, increased turnout resilience and damping, changes to rolling stocks, external noise/vibration controls, etc.



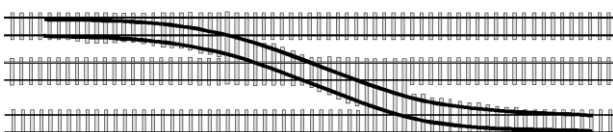
a) Typical components of a turnout



b) typical turnout structure



c) typical crossover structure



d) typical diamond structure



e) typical slips structure

Fig.1. Special Trackwork Fundamentals

Although a new method of geometrical design has been adopted for tangential turnouts, the transfer zone at a crossing nose in complex turnout system still imposes high-frequency forces to track components. Under static and high-intensity impact loading conditions, timber bearers have a long proven record that they can provide firm support to such turnouts. The structural timber bearers in turnout systems are usually in Strength Group 1 [11, 12] and the typical timber species are tabulated in Table 1. Based on the strength, the design dimensions of timber bearers in a variety of railway turnouts with nominal design spacing of 600mm (or between 500mm and 700mm) can be designed [11]. It is important to note that timber bearers for supporting points and crossing structures may be designed using the beam on elastic foundation analysis (similar to traditional railway sleepers) but one must take into account additional factors:

- Extra length of timber bearers in comparison with standard sleepers
- Centrifugal forces through curved pairs of rails
- Forces and bending moments induced from points motors and other signaling equipment
- Impact forces induced by wheel-rail interaction
- Mechanical rail joints (maximum spacing of bearers is 600mm)

Table 1 Timber species for railway turnout applications.

Group	Common Name	Scientific Name
Group 1	Ironbark Grey	E. Siderophloia
	Ironbark Grey	E Paniculata
	Ironbark Grey	E Drepanophylla
	Ironbark Red (broad leaved)	E Fibrosa
	Ironbark Red (narrow leaved)	E Creba
	Ironbark Red	E Sideroxyton
	Gum Slaty or Box Slaty	E Dawsonil
	Box White	E Albens
Group 2	Box Grey	E Microcarpa
	Box Grey	E Moluccana
	Tallow wood	E Microcorys
	Gum Grey	E Punctata
	Gum Grey	E Propinqua
	Gum Forest Red	E Tereticornis
Mahogany White	E Acmeniodies	

At present, most modern turnout systems install concrete bearers/sleepers to improve vibration performance and lateral resistance of railway tracks. However, there has been an incident cracking of a concrete bearer in several turnout systems within an urban railway network in Australia [14-16]. The concrete bearer cracked under a rail pad, the part which supports the rail, where the train wheel's shift over a diamond formation. It is also evident that a complex structural system induces a frequent failure of associated components and their fixtures (i.e. bolts, plates, rubber pads), which can often found

in railway network. These aggressive environments have led to a more frequent rate of renewal and reconstruction of turnout systems, compared to open plain tracks. The life cycle of turnout systems is between 10-20 years, depending on the turnout type, turnout structure and its components, operational condition, maintenance level and environmental loads. The emphasis of this study will be placed on the construction and maintenance issues related to turnouts, crossovers and diamonds. The life cycle analyses and failure analyses of the systems have been presented elsewhere [16-18].

## 2. Construction and Maintenance of Railway Turnouts, Crossovers and Diamonds

Railway operations have been used to transport passengers and freight for centuries. Railway transportation is a popular transport mode due to its capacity to carry more passengers or freight per journey when compared to other transport modes. The fundamentals of railway constructions have remained more or less the same for over a century; with trains travelling along steel rails, the rails distributing the load to the sleepers and the sleepers transferring the load to the ballast or sub-structure materials [19-20]. Materials improvements have contributed to increased traffic loads, increased tonnage per journey, faster train speeds and improved safety of railway transportation [21].

The result of improved railway technology had seen more efficient use of materials and the development of cost effective structures and trackwork [22]. The most commonly used track bed system globally is ballasted track due to its cheaper initial construction cost and relative ease in material availability [23]. Recent technological developments had seen increased popularity in the selection of ballastless track bed systems; which achieved reduced contact noise, increased axle loads, faster train speeds, increased train frequencies and reduced maintenance on track beds [24].

Other advances in materials in the railway industry include composite polymer-concrete sleepers, double headed rails and ballastless slab track systems [25-28]. Increased complexity of railway systems had seen increased reliance on special trackwork such as turnouts, crossovers and diamonds to increase train frequency and reduce network delays [29-30].

Railway turnouts, crossovers and diamonds are special trackwork that allow trains to pass from one track to a diverging path [31]. Railway trackwork is expected to experience impact loadings as regular contact occurs at the wheel and rail interface [32]. In special trackwork, these impacts can be considerably more than mainline track as the specialised components (switch rail etc.) are frequently in contact with train wheels and heavy axle impact loads [33]. Railway maintenance is a periodic activity performed to ensure track components are effective and to extend the life of the railway infrastructure. Understanding the maintenance and re-

construction of turnouts is of great interest to engineers as cost savings and increased life expectancy can be achieved [11-13]. The environmental impact of turnout, crossover and diamond re-construction projects needs to be considered to understand the contribution of CO<sub>2</sub> emissions from railway maintenance activities in the railway transportation sector; with strategic planning implemented to reduce future emissions from railway maintenance activities. Management to minimise carbon emissions depends on information related to the project process and activities. However, not all information necessary is readily available. In particular, the construction methodology, machinery usage, machinery fuel consumptions and the materials used in special trackwork re-construction projects. With this data, the CO<sub>2</sub> emissions from railway re-construction projects can be estimated. A literature review found no published works investigating the environmental impacts of the maintenance and re-constructions of turnout, crossover or diamond trackwork.

The National Greenhouse Accounts factors (NGA) [34] are designed to assist individuals and companies to estimate CO<sub>2</sub> emissions. The National Greenhouse Gas and Reporting Scheme (NGER) [35] was introduced to provide data and accounting in relation to greenhouse gas (GHG) emissions in relevant sectors. It is the responsibility of NGER to ensure that Australia's Kyoto protocol targets and maintained and achieved.

In 2010, the transportation sector emitted 15% of the total emissions emitted from Australia. Carbon dioxide (CO<sub>2</sub>) is the primary greenhouse gas which is considered to be the major cause to climate change [36]. Carbon dioxide equivalent (CO<sub>2</sub>-e) is defined as the mass of GHG emissions that is emitted then is multiplied by its global warming potential to convert greenhouse gas emissions to an equivalent quantity of CO<sub>2</sub> emissions [37].

Literature regarding the construction and subsequent CO<sub>2</sub> emissions from new railway infrastructure are well published [26, 38-41]. The literatures investigated the CO<sub>2</sub> emissions from new railway construction projects in Europe, Asia and the United States of America.

The purpose of this study was to estimate the CO<sub>2</sub> emissions from turnout, crossover and diamond special trackwork and reporting on solutions to reduce CO<sub>2</sub> emissions from the railway maintenance sector. This study was the first to investigate the CO<sub>2</sub> impacts of maintenance and re-construction of turnouts, crossovers and diamond trackwork; providing decision makers, designers, planners and engineers the estimates of CO<sub>2</sub> emissions which can be used in strategic planning in reducing future CO<sub>2</sub> emissions in the railway industry.

The aim of this paper is to develop a better understanding of the construction methodology, machinery and material requirements and estimate the CO<sub>2</sub> emissions from turnout,

crossover and diamond special trackwork re-construction projects.

### 3. Methodologies: Observation, Review, Expert Interview and Assessments

The objective of this study was to determine the construction methodology, the fuel consumptions, machinery use and material requirements of special trackwork re-construction projects; then estimate the CO<sub>2</sub> emissions emitted from the special trackwork re-construction projects. This study involved field based surveys in which the construction methodology, fuel consumptions from machineries and track bed materials from special trackwork re-constructions were investigated and the CO<sub>2</sub> emissions estimated from embodied energy consumption, materials requirements and fuel consumptions. The CO<sub>2</sub> emissions from individual turnout, crossover and diamond re-construction projects were then compared to a bulk turnout renewal; consisting of three turnouts and two crossovers, to investigate if bulk renewal projects were successful in reducing overall CO<sub>2</sub> emissions from special trackwork projects.

#### 3.1 Data collection

The data collection included construction methodologies, fuel consumption of machineries used and material quantities of actual field based special trackwork re-construction projects including a turnout re-construction, a crossover re-construction, a diamond re-construction and a bulk renewal. The details of the re-construction projects are shown in Table 2.

**Table 2** Summary of re-construction projects A to D.

Project	Detail	Scale
A	Turnout renewal	122m
B	Crossover renewal	101m
C	Diamond renewal	99m
D	Multi-unit turnout renewal	352m

#### 3.2 Inclusions and exclusions of the study

Engineers involved in organising re-construction projects are faced with many considerations regarding the construction practices and project delivery. The following considerations were made in this study:

- Initial construction earthworks were not considered as this study is focusing on the re-construction as part of maintenance projects only.
- Ballasted track bed is the only track bed considered.
- HDEC (heavy duty 30 tonne capacity – cast-in shoulders) concrete sleepers are only considered; with 600 mm maximum sleepers spacing's observed.
- Fuel emissions and distances travelled from crew vehicles and transport of vehicles to site.

- Energy use to construct the machineries.
- Recycling at the end-of-life have not been considered as it is assumed that they are used in less frequented locations.
- Access and ease of access to site has not been considered.
- Financial cost of maintenance activities.
- Alternative transport arrangements (usually bus transportation) whilst re-construction activities are being carried out.
- Track possessions are not considered whilst re-construction activities are carried out.
- Labour requirements, including project support personnel and safe working personnel.

#### 3.3 Assessment of CO<sub>2</sub> emissions from machineries

Diesel powered machineries are used in the re-construction of special trackwork to reduce the demands on physical labour and construction times. The environmental impact of the machineries needed to be considered to ensure the life-cycle CO<sub>2</sub> emissions are accurate and strategic planning can be implemented to reduce the CO<sub>2</sub> emissions from the railway maintenance sector.

The site survey determined the machineries used in the re-construction projects. Machine operators ensured the machines were delivered to site with full petrol tanks (it is common practice to send machines to site with full tanks). The machine operators were then followed up after works completion to determine the amount of fuel used for the re-construction project. Fuel estimates that could not be collected were estimated from the same machine use on similar projects.

The CO<sub>2</sub> emissions for the machineries used in railway re-construction projects were evaluated employing the National Greenhouse Gas and Reporting Scheme [34-35] technical guidelines database and the Australian National Greenhouse Accounts Factors. The NGA [35] determined that the emissions from a given fuel be estimated using Equation 1:

$$E_{ij} = (Q_i) * (EC_i) * (EF_{ij}) \quad (1)$$

where:

- $E_{ij}$  (kg) is the emissions of gas type  $j$  for fuel type  $i$ ;
- $Q_i$  (kg) is the quantity of type  $i$  fuel consumption;
- $EC_i$  (GJ/kL) is the energy content factor of type  $i$  fuel;
- $EF_{ij}$  (kg/GJ) is the gas  $j$  emission factor for fuel  $i$ .

Since CO<sub>2</sub> is the largest contributor to GHG emissions (Carbon Neutral, 2011), only this gas type has been considered in the current study. The fuel used by the machines for the trackwork investigated in the current study was diesel. The  $EC_{diesel}$  value is 38.6 GJ/kL according to NPA [35], and the  $EF_{diesel-}$

CO<sub>2</sub> value is 69.2 kg CO<sub>2</sub>-e/GJ [34-37], where kg CO<sub>2</sub>-e/GJ stands for kilogram of CO<sub>2</sub> emission per gigajoule of energy. Hence for estimating CO<sub>2</sub> emission by diesel fuel, Eq. (1) can be written as:

$$E_{diesel-CO_2} = (Q_{diesel}) * (EC_{diesel}) * (EF_{diesel-CO_2}) \quad (2)$$

$$E_{diesel-CO_2} = 2671.1 * Q_{diesel} \quad (3)$$

### 3.4 Assessment of CO<sub>2</sub> emissions from materials

The material requirements per metre of track in ballasted special trackwork are shown in Table 3. The materials requirements were determined from construction drawings and verified during the on-site installation [42-45]. Turnout, crossover and diamond materials are dependent on

- The gradient of curve;
- Length of turnout, crossover or diamond;
- The number of normal, small bearers and long bearers used (was ascertained from the actual on-site installation) and the sleeper spacing's used.

**Table 3** Materials and quantities of turnout, crossover and diamond materials.

Material	Nominal weight	Required material (kg/m)
Subballast	2200 km/m <sup>3</sup>	1272
Ballast	1700 km/m <sup>3</sup>	2067
Concrete sleepers	330 kg each	561
Small turnout bearers	574 kg each	975
Long turnout bearers	1065 kg each	1810
Steel rail (each)	60 kg/m	60
Pads	0.10 kg	1.02
Fastening systems	0.80 kg	5.44
Insulators	0.04 kg	0.68

## 4. Results and Discussions

The machineries, machine description, size of machines used and amount of machines used on site in each re-construction projects are shown in Table 4. The total fuel consumption per re-construction project is shown in Table 5.

The total CO<sub>2</sub> emissions from machineries and materials are shown in Tables 6 and 7. The results show that the crossover re-construction emitted 4 % less CO<sub>2</sub> emissions when compared to the turnout re-construction. The diamond re-construction emitted 9 % less CO<sub>2</sub> emissions when compared to the turnout re-construction. The diamond re-construction emitted 5 % less CO<sub>2</sub> emissions when compared to the crossover re-construction. The total CO<sub>2</sub> emissions bulk turnout renewals total emissions was divided by 5 (as 3 turnouts and 2 crossovers were replaced); with the average re-construction in the bulk renewal

having 34 %, 31 % and 28 % less CO<sub>2</sub> emissions when compared to turnout, crossover and diamond re-constructions respectively.

**Table 4** Type and number of machines used in re-construction projects of turnouts, crossovers and diamonds.

Item	Project A	Project B	Project C	Project D
Front end loaders	4	3	4	5
25t Excavator				1
16t Excavator	1	2	3	4
5t Excavator	2	1	1	3
Drott	2	2	2	2
15t Dump truck	3	1	3	10
5t Dump truck	1	1	1	2
Bobcat				2
Smooth drum roller	1	1	1	2
Desec (turnout transporter)	1	1	1	
PEM/LEMS				6
Tamper	1	1	1	2
Regulator	1	1	1	2
Road transportation	1	2	1	1

\*\* records from railway projects in NSW, Australia

**Table 5** Quantity of fuel consumptions in projects A to D.

Project	Detail	Fuel Consumption (litres)
A	Turnout renewal	3347
B	Crossover renewal	3370
C	Diamond renewal	3371
D	Multi-unit turnout renewal	11611

\*\* records from railway projects in NSW, Australia

**Table 6** Embedded carbon emissions from construction materials in projects A to D.

Project	Detail	Carbon Emission (kg CO <sub>2</sub> -e)
A	Turnout renewal	59156
B	Crossover renewal	56326
C	Diamond renewal	53188
D	Multi-unit turnout renewal	39101

\*\* records from railway projects in NSW, Australia

The results of this field based study show the estimated CO<sub>2</sub> emissions from special trackwork re-construction projects. Previous studies and life-cycle assessments have investigated the impact of CO<sub>2</sub> emissions on new railway constructions but have based maintenance CO<sub>2</sub> emissions on assumptions or a percentage of construction CO<sub>2</sub> emissions. This study provides designers, decision makers and engineers an actual field based

comparison of the CO<sub>2</sub> emissions associated with special trackwork re-construction activities.

The results show that the CO<sub>2</sub> emissions from the fuel consumptions of the machineries used in turnouts, crossovers and diamond re-constructions are very similar in nature, which is primarily due to a similar amount of construction machineries used and the same contractor carrying out the re-construction works. The difference in CO<sub>2</sub> emissions from turnouts, crossovers and diamond re-constructions was less than 1%, showing very little difference in CO<sub>2</sub> emissions from the fuel consumption of special trackwork re-construction projects.

**Table 7** Total carbon emissions in projects A to D.

Project	Detail	Carbon Emission (kg CO <sub>2</sub> -e)
A	Turnout renewal	68097
B	Crossover renewal	65328
C	Diamond renewal	62193
D	Multi-unit turnout renewal	225317
	Average per turnout	45064

\*\* records from railway projects in NSW, Australia; \*\*\*take into account all logistics and transportation emissions.

**Table 8** Construction duration (track possession) in projects A to D.

Project	Detail	Track possession (hours)
A	Turnout renewal	48
B	Crossover renewal	48
C	Diamond renewal	48
D	Multi-unit turnout renewal	120

\*\* records from railway projects in NSW, Australia

The results of the machinery use on CO<sub>2</sub> emissions shows that the machineries emitted between 8,941 kg CO<sub>2</sub>-e for turnouts, whilst crossover re-constructions emitted 9,002 kg CO<sub>2</sub>-e and diamond re-constructions emitted 9,005 kg CO<sub>2</sub>-e. This results show that the CO<sub>2</sub> emissions from machinery use in single re-construction projects are in good agreement, however, the bulk renewal showed that the average CO<sub>2</sub> emissions from fuel consumption from the 5 projects were 5,961 kg CO<sub>2</sub>-e. This represented a 34% reduction in the CO<sub>2</sub> emissions per project when compared to a single project. The bulk turnout renewal was carried out over a 5 day period; which is typically 2.5 times longer than a typical weekend single re-construction project.

The results from the bulk re-construction project showed that if more than one re-construction project was carried out at one time, CO<sub>2</sub> emissions could be reduced as the same machines are used to fulfil the multiple projects, thus also leading to the possibility of financial as well as environmental savings. The impact on train services needs to be considered when carrying out bulk renewals; as the extended construction time may impact existing train and freight services as shown in

Table 8. Access and distance apart between special trackwork are other important considerations.

By carrying out a bulk turnout and crossover renewal, the average turnout / crossover in the bulk renewal achieved 34%, 31% and 28% less CO<sub>2</sub> emissions when compared to the individual turnout, crossover and diamond re-constructions projects respectively. This shows that by strategically carrying out re-construction works on multiple special trackwork in parallel, the CO<sub>2</sub> emissions can be reduced per project [46].

## 5. Conclusion

This study assessed the CO<sub>2</sub> emissions from the re-construction of special trackwork in railway construction and maintenance activities; which are performed periodically to mitigate the deterioration of components. The study carried out site investigations, cost review and expert interviews, which surveyed the construction scales, materials, machineries and the construction methodologies used for turnout, crossover and diamond re-constructions. The results show that when comparing turnout, crossover and diamond re-constructions works; the machineries used in special trackwork re-constructions emitted 15 % to 17 % of the total CO<sub>2</sub> emissions when compared to material CO<sub>2</sub> emissions. There was less than 1 % difference in total fuel consumption CO<sub>2</sub> emissions from turnout, crossover and diamond re-constructions; mainly due to the same construction methodologies, similar machinery usage and materials used.

This study then evaluated a multi-unit turnout renewal (3 turnouts and 2 crossovers) and found that by carrying out re-construction works in bulk, there was a 34%, 31% and 28% reduction in fuel consumption CO<sub>2</sub> emissions per maintenance activity when compared to individual turnout, crossover and diamond re-construction projects respectively. However, the bulk turnout renewal project typically took 2.5 times longer period to complete than a single re-construction project. The results of this paper show that it is more carbon efficient to carry out multi-unit services or bulk renewal in a single maintenance project than single service in multiple projects. This information can be used in maintenance scheduling to achieve the optimum outcome per maintenance project.

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