UPGRADING THE TRACKS
of
MELBOURNE'S STREET TRAMWAYS

by

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INTRODUCTION:

The Melbourne and Metropolitan Tramways Board operates a fleet of about 685 *electric passenger tram cars over a street network comprising some 220 km of double tracks and 4 km of single track. (See Fig. 1) The Board also operates a fleet of about 290 *diesel buses over a network totalling about 270 street kilometres. Together the two systems carry over 120 million passenger trips each year.

The tram network is made up of 31 basic routes, most of which radiate from the central City area, and total some 326 route kilometres. The longest route, to East Burwood, is 18.2 km in length. The 3.4 km extension of this route during 1978, and the purchase of over 115 new Z class tram cars since 1975, indicates the important role that fixed rail electric street transit will continue to play in Melbourne's public transport scene in the future.

OPERATING CHARACTERISTICS:

All the passenger carrying trams are four-axle bogie cars for standard (1.435 m) gauge. They are double ended for two way operation and are always operated as single units. Power is 600 volt D.C. delivered from a single overhead trolley wire, with negative return via the rails. All axles are powered, and together may deliver up to 119 kW (W class trams) or 228 kW (Z class).

Tare weight varies between 16 and 19 tonnes, and a crush load of up to 160 passengers may add a further 10 tonnes. Therefore, operating axle loads are normally well below the design limit of 9.3 tonnes.

* A further 60 trams and 10 buses of the older types are in storage or set aside for training purposes, giving a total of 744 passenger trams and 300 buses. Approximately 530 trams and 235 buses are available for peak traffic requirements.

The new Z class trams are capable of accelerating at 1.8 m/sec^2 (empty) and can attain a maximum speed of 72 km/h. In an emergency they can brake at 3.7 m/sec^2 by use of four magnetically applied track brakes. Normal service braking is at the rate of 1.5 m/sec^2. Anti-slip devices are fitted for both acceleration and braking.

Axle centres on each bogie are 1.6 m (W) or 1.8 m (Z class). Bogie centres are 7.9 m (early W class) or 8.5 m (later W classes, and Z class).

Primary suspension on the early W class trams consists of helical springs onto an equalizer bar, and eliptical springs at the bogie bolsters. Later models of this class use eliptical springs as their primary suspension and helical springs at the bogie bolsters. The new Z class cars are fitted with chevron rubber primary suspension units and rubber suspension of the bogie bolsters.

Most of the W class trams are fitted with solid wheel-axle sets, but about 60 of the later ones are fitted with resilient wheels, as are all the Z class trams. Wheel diameters are either 680 mm (Z) or 710 mm (W classes), and flanges are nominally 14 mm deep by about 14-20 mm thick (See Fig. 10).
Density of tram traffic varies widely throughout the system. The busiest tracks are in Swanston Street and carry over 288,000 tram passes p.a. on each track. At their peak in 1942 - 1946 these tracks carried over 585,000 trams p.a. Current tram densities at outer suburban terminii range from 22,000 to 67,000 tram passes p.a. on each track.

Operating speeds are largely determined by the degree of influence of motor traffic sharing the road space, and (on the busier routes) by other trams.

About 85% of tram operations occur in City or suburban streets in which most of the inter-stop trackage is shared with motor traffic. Under these conditions the maximum inter-stop speed achieved is normally in the range of 40-50 km/h. Heavy street congestion in peak periods invariably reduces this speed, so that schedule speeds of 20 km/h are common. Wheel flats on W class trams, caused by skidding during braking, are another result of having to share the track area with motor traffic. Severe braking at tram stops, in an effort to make up time lost due to traffic congestion, leads to an increased rate of wear to the rail head at these locations. All trams are equipped with sanding gear to assist braking in wet or emergency conditions.

Some of the suburban operations (about 15%) have separate right-of-way with stops well spaced at 2 - 4 stops/km. Tracks in these areas may be of open ballast construction, or paved for the convenience of pedestrians and emergency vehicles. Under these conditions the trams are often able to exercise their full performance characteristics.

TRACK GEOMETRY:

Situated on flat to undulating country, Melbourne is well suited to electric tram operation. Only 1% of the tracks have a gradient steeper than 1 in 15, the steepest (short) section being 1 in 11.

In the central City area the streets are 30 metres wide, straight, and intersect at right angles. Suburban streets vary in width from 20 to 60 m, and are generally laid out in a grid pattern.

Minimum curve radii occur at the intersections of 20 m streets. The absolute minimum radius (excluding depots) is 17.5 m, but wherever possible, curves of at least 30 m radius are preferred.

Maximum superelevation is limited to 50 mm in streets because of the need to provide for motor traffic crossing the track at right angles.

All horizontal curves have cubic parabola spirals at both ends to assist with the run-out of super-elevation. The maximum rate of change in super-elevation is 18 mm per 10 lineal metres. If switches are incorporated in the curve, or are likely to be at some time in the future, a switch spiral transition is substituted in place of a cubic parabola.

Track gauge is nominally 1.435 m but is widened by 3 mm on curves under 30 m radius, and reduced by 6 mm through rectangular crossings.

Minimum width of rail grooves is 29 mm on straight tracks, or 32 mm on curves.

The tracks are normally laid at 3.353 m (11 ft.) centres, with curves designed to ensure a minimum clearance of 380 mm between passing trams.

Horizontal alignment in streets is chosen having regard to existing (or planned) kerb lines and the best locations for kinks necessitated by inaccuracy in early Melbourne surveys. In some situations it also involves consideration of the longitudinal section, particularly where vertical curves and a change in direction are involved.

Vertical alignment of the tracks is very heavily dependent on the desired street cross-section for drainage and safety to motor traffic. It is therefore related to both the local council's kerb and channel profile as well as the Board's design limits on vertical curves and difference in levels between tracks. The minimum vertical curve radii permitted are : Convex - 260 m Concave - 305 m, and the maximum desirable difference in levels between tracks is 50 mm. Because of the many variables involved, vertical alignment is not computed by formulae, but is plotted on an exaggerated vertical scale as a series of straights and smooth curves. Proposed design levels are then tabulated and submitted to local councils for approval.

DEVELOPMENT OF TRACK STRUCTURE:

Prior to 1885, Melbourne's street public transport consisted of horse trams and horse buses. Cable trams, similar to those still operating in San Francisco, were then introduced, and by 1891 a fairly comprehensive system was in operation. The system extended about 5 or 6 km out of the central city area. Soon developing suburbs beyond this limit decided to build their own transport systems to link with the cable routes. Electric tramways were chosen because the new technology made the capital cost much less than for cable tramways. In addition, power was cheaper, travel faster and maintenance less than with the cable systems.

In the early 1900's several private electric tramway companies commenced operations. In most cases the track structure was merely a modified version of railway track - railways being well established in Victoria by that time.

In 1919 the Melbourne and Metropolitan Tramways Board was constituted to take over virtually all the existing horse, cable and electric tramways within a 16 km radius of the G.P.O.

During the 1920's and 1930's the newly formed Board undertook the conversion of most of the cable tram system to electric traction. The conversions, which ultimately involved about 62 km of double track, required the removal of the light-weight cable tracks and the laying of a heavier standard double track suitable for the new electric vehicles.

Since the cable tracks had a slot and tunnel along the centre of both tracks, sleepers had not been used to support the running rails. Instead the rails were laid on a 150 mm thick continuous concrete slab, and all running rails and slot beams were joined by steel tie rods at frequent intervals. Red-gum woodblocks 120 mm deep formed the street pavement. (See Fig. 3).

Some of the early paved ballast tracks acquired by the Board failed through faulty construction, so a more permanent track design for use on the more heavily trafficed routes was sought.

In 1925 - 1926, during the conversion of the St. Kilda Road tracks, the Board took the opportunity to test a track structure which was very similar in principle to that of the earlier cable tracks.

This track, known as stringer track, consisted of a continuous concrete slab with longitudinal red-gum stringers about 60 mm thick set into the slab beneath the foot of each rail. Anchor bolts cast into the slab passed through holes in the stringers, and held the rail in position by means of nuts and clips onto the rail foot. Tie rods at frequent intervals ensured correct gauge. Red-gum woodblocks or macadam formed the pavement.

More than half of the cable track conversions were constructed in this way. (See Fig. 3).

Contractors involved in the laying of stringer tracks found difficulty in keeping the rails vertical, so some sections were tried using timber sleepers cast into the slab. (Fig. 3)

This overcame the problem of keeping the rails vertical, but it was found that this 'sleeper track' required more maintenance than the stringer track, as the discontinuous support of the sleepers resulted in more cut-in than did the continuous wooden support of stringers.

In 1927 a track structure which used the best features of both designs was tried. Rails were bolted to thin (75 mm) sleepers known as timber ties. Steel sleeper plates were provided on each tie to reduce cut-in, and a 25 mm longitudinal timber pad was clipped beneath the foot of the rail between ties. This track skeleton was then cast into a continuous concrete slab up to the foot of the rail. Again, the usual form of pavement was woodblocks. (Fig. 3)

After 1936, with the development of mechanical methods of mixing concrete and the design of sheet asphalt pavements, this design was modified by bringing the concrete slab up to within 40 mm of the surface and laying an asphalt sheet on top to form the pavement. (Fig. 3). Much of the remaining cable track conversions were constructed in this way, and most of this track is still in service.

In 1937 a section of track involved in the conversions was laid using steel ties in place of timber ties (cast into concrete) but later conversions reverted to timber.

Concurrent with this work of converting the cable tracks to electric operation was the duplication of many single tracks constructed by the early private electric tram operations in the outer suburbs. Due to the lighter traffic loads in outer areas, most of these new tracks were of the conventional paved ballast construction, but in a few sections where the local councils had constructed the adjacent roadway on a concrete foundation the Board laid stringer tracks of the type mentioned before. Although most paved ballast tracks were laid prior to 1940, the practice continued until 1952. (Fig. 3).

During the early 1950's, as the final sections of the remaining cable tracks were being converted, the whole design of the track structure came under review. It was decided to adopt the above concrete design but to progressively reduce the anchorage attached to the foot of the rail.

The first step involved the extension of the concrete slab right up to the street surface in order to increase the contact area between rail and concrete. The timber ties and stringer pads were then eliminated, leaving only steel tie bars and anchor bolts fastened to the rails. (Fig. 3).

The second step eliminated the rail anchors, relying entirely on the bond between rail and concrete to hold the rail permanently in place. This design was first used in 1954, and apart from some minor changes, is the basis of the method still used for track construction in Melbourne. (Fig. 3).

Trials to determine the minimum acceptable cement content were carried out during the period 1954 - 56. A cement content as low as 5.0 bags/m^3 (4.2 bags/yd^3) was tried with only limited success, but a figure of 6.2 bags/m^3 (5.2 bags/yd^3) was then found to yield more satisfactory properties. This higher cement content enabled 7 day strengths of the order 24-28 MPa (about 3,500 - 4,000 psi) to be obtained. These results may seem slightly high by present day standards, but in those days the Board mixed their own concrete in a portable mixing plant which discharged straight into the trench, thus enabling very low slumps to be obtained. Unfortunately this method could only be used in the very wide (60 m) streets.

The concrete mix designs now used have been developed over many years of experience with the plant mix type of concrete delivered to the site in agitator trucks.

The most commonly used concrete mix now in use has a cement content of 315 kg/m^3 (530 lb/yd^3), which corresponds to 6.8 bags/m^3 (5.7 bags/yd^3) A minimum 7 day compressive strength of 17.5 MPa (about 2,500 psi) is specified, but strengths in excess of 21 MPa (about 3,000 psi) are frequently obtained.

The total depth of the concrete slab has also changed over the years. In the early days, slabs were 340 mm deep at track junctions and crossings, but increased to 390 mm at track junctions and crossings. Experience with Melbourne's ground conditions has since enabled the Board to reduce the slab thickness to 270 mm for all trackwork. (See. Fig. 7).

Another result of experience is that steel reinforcing mesh is now only used in the slab at rail joints, unless ground conditions are very poor, or the reconstruction of an old concrete foundation track results in a top slab thickness of less than 150 mm, in which case the entire top slab is reinforced.

In the construction of concrete-to-surface tracks, the design of the longitudinal construction joints has also changed with experience. (Fig. 3) Ever since the days of timber sleepered track the Board has been responsible for maintaining the road pavement to 460 mm (1'6") beyond the outer rails. Due to this requirement the early concrete-to-surface tracks incorporated a concrete-to-surface margin, against which the Council's asphalt roadway abutted. Difficulties in matching exactly the levels (or proposed levels) of the roadway (especially at steep cross falls) and the gradual opening up of the longitudinal joint where concrete and asphalt abutted, led to the development of the "dropped margin" design now in use. The level of concrete in the margins is held down by 50 -100 mm to permit an overlay of asphalt which is easily shaped to match the adjacent council pavement. The resulting stepped joint is sufficiently strong to prevent reflection cracks appearing in the pavement above the outer limit of the concrete margin. In many cases local councils lay their wearing course of asphalt across the whole distance from kerb to rail, and the Board reimburses them for that portion across the track margin. The result is a very durable and attractive marriage of concrete and asphalt pavements.

A similar 'stepped' joint is also used in the forming of the concrete pavement between tracks. The earlier method, which was to pour an inner concrete-to-surface 'margin' concurrent with the pouring of the first track, resulted in a vertical construction joint between (and parallel to) the two tracks. The action of motor traffic eventually caused fretting of the surface concrete along this joint.

Use of 'stepped' joints in both applications therefore results in all construction joints surfacing at a rail interface; improving both durability and appearance, while also reducing formwork costs.

Many changes have also occurred in the rails themselves. Some of the early electric tracks were laid with 80 lb T-head rail fitted with lengths of special bolt-on flange to form the groove, while others were laid using a British Standard 90 lb tramway rail, with the groove rolled as an integral part of the section. In 1927 a similar 102 lb section was rolled for use in Melbourne and Adelaide. With a few minor alterations this rail became the Austrlian Standard Tramway Rail, (Fig. 10), and was used in most of Melbourne's track construction work until 1975. At that time B.H.P.'s rolls for 102 lb rail wore out and they were not prepared to continue production for the Board. Grooved tramway rails manufactured overseas were considered but proved too expensive, so it was decided to develop a checkless, or T-head, rail which would be particularly suited to concrete-to-surface construction. The result is a non-symmetrical rail having a deep head, and weighing 43 kg/m (See Fig. 4). As with the previous tramway rails it is made of medium manganese steel. This rail has been used in most track reconstruction work since April 1975. On straight track the groove next to the running edge is slip-formed into the concrete surface, but on curves under about 600 m radius a steel guard plate is fixed to both rails. This is described in more detail later in the paper.

The earliest method of joining rails was the conventional one, using a pair of fishplates bolted together through the rail web. The presence of a street pavement made regular tightening of the fishbolts a major exercise, so the practice of seam welding the fishplates to the rail was begun.

The use of fishplates in a rigid or semi-rigid track proved to be quite unsatisfactory even with seam welding because of rail web failure (cracks propagating from either the first or second fishbolt hole).

With the advent of thermit welding, the technique of joining rails changed again (around 1930). Both "combined" and "full fusion" types of thermit joint were tried. Thermit welded joints proved satisfactory on timber-supported rails but despite much research the resulting joint was found to be unsatisfactory in rigid track. Even though the hardness of the weld material could be made to closely match that of the parent rail, the heat affected zone to each side was invariably of a different hardness. In rigid track this resulted in rail head batter, and the eventual formation of 'cupped heads' at each joint. The lack of a suitable alternative meant that thermit welding continued until 1968. As a result the repair of thermit joints in rigid track continues today at the rate of about 3,000 cupped head repairs each year. (The total number of rail joints throughout the network is about 65,000).

Fortunately, in 1968, a rail joint designed to suit concrete-to-surface construction, and having none of the problems of thermit joints, was evolved by the Board. Known as the Kirby joint, (Fig. 5), it avoids any welding in the vicinity of the rail head. All welding is done at the foot and (if necessary) the web of the rail. The joint relies on being cast into concrete to prevent it opening up at the surface when the wheel load is away from the joint. The bond with the reinforced concrete surrounding each joint also relieves much of the tensile force to be borne by the joint itself. Prior to welding considerable effort is made to ensure that the two rail head running surfaces are firmly butted against each other with no gap. This is achieved by positive undercut of the 'vertical' rail ends. Once subjected to tram traffic the joint can often prove difficult to locate, as 'flow' of the surface steel serves to seal the joint permanently. Failure of a Kirby joint is very rare, but the few that have occurred may be attributed to poor concrete quality around the joint. After many years of service, even on routes carrying dense tram traffic, the Kirby joint has proved to be completely satisfactory. Details of this joint appear later in the paper.

THE CASE FOR RECONSTRUCTION:

Most of the tracks laid during the 1920's and 1930's have progressively deteriorated due to the actions of tram traffic, motor traffic, water and time. The failure of the tracks may occur simply as worn out rails, but more often the ingress of water from the street surface has led to rotted sleepers or stringers and (in some cases) failure of the sub-grade as well. (Fig. 16). The resulting movement of the rails under load causes the road pavement (whether wood-blocks, macadam or asphalt) to break up - first near the rails, then extending through the action of motor traffic.

Wood-block pavements in particular are expensive to maintain once this has occurred. In dry weather the blocks shrink, and motor traffic may sometimes dislodge a few blocks, allowing the rest to progressively fall over like dominoes. Road silt falls between the blocks when they are dry, and sometimes manages to work its way beneath them so causing them to lift slightly. When wet the blocks expand causing some silted areas to bow upwards, creating a hollow domed effect. Wood-block pavements located at low points or in flat streets are also likely to rot.

Macadam or asphalt pavements laid next to a rail which moves under load fail as a result of the pumping action of the rail. Road silt and water form a slurry which lies inside the broken open joint alongside the moving section of rail. The downward movement of the rail head pumps this slurry sideways under the pavement skin, forcing the pavement upwards. This "mushrooming" of the pavement is particularly common at old fishplated rail joints, or may indicate a group of rotted sleepers or a rotted length of stringer.

Track in poor condition (Fig. 16) also causes severe transverse movement of the tram body leading to a substantial reduction in passenger comfort. Fig. 2 illustrates the lateral and vertical accelerations recorded on a fixture located over the kingpin of an SW6 (W class) tramcar. This is the point of minimum deflection when body movement is set up by track condition. The records were taken over two sections of track:

(a) A typical section of paved ballast track in poor condition, and requiring major maintenance within 12 months.

(b) A typical section of concrete-to-surface track in good condition. This particular section of track was laid over 20 years ago and is still of a standard similar to a newly constructed track.

Lateral and vertical accelerations recorded over the paved ballast track (a) were approximately 500% higher than those recorded over the concrete-to-surface track (b). Frequency at 32 km/h (20 m/h) was approximately 1 cycle/sec.

The maintenance necessary to upgrade a paved ballast track such as track (a) above would involve:

i) excavation and removal of the road pavement in the track area
ii) replacement of rails having a corroded foot or web
iii) repairs to defective rail joints
iv) replacement of rotted sleepers and respiking of others
v) repacking of ballast to provide good top and line for rails
vi) replacement of the road pavement.

As most of these operations are labour intensive with only limited opportunity for mechanisation, the cost of major maintenance such as this usually represents about 70% of the capital cost of complete reconstruction in concrete-to-surface using new rail.

If considering the cost of maintenance over the years, discounted at 10%, a complete reconstruction in concrete may break even after about 9 years and over a period of 40 years may yield a Benefit-Cost ratio of about 1.3.

Furthermore, if a value (for example 0.75 cents per passenger-kilometre) is attached to passenger comfort disbenefits arising from a decision to retain the paved ballast track by continued maintenance, then a typical reconstruction in concrete may pay for itself after about 7 or 8 years and may yield a Benefit-Cost ratio of about 1.4 over 40 years.

These figures are fairly typical of those encountered but each case is treated on its merits. All sections of track are regularly inspected to establish the condition of the rail, pavement and foundation. The Board uses this information to establish its own priorities for reconstruction, but other factors such as public opinion, the desire of local councils or other road authorities to reconstruct their portion of the roadway, and the availability of funds, also influence the decision as to when reconstruction will proceed.

To date approximately 130 street-km (or 60%) of the Board's paved tracks have been laid or reconstructed in concrete-to-surface. Reconstruction is currently proceeding at the rate of about 5 km (or 2¼%) of double track each year.

TRAFFIC OPTIONS DURING RECONSTRUCTION:

The reconstruction of tracks through major intersections is always done at weekends, as motor traffic volumes at other times are generally too high to enable detours to function properly. Usually the reconstruction of tracks through major intersections is done before the bulk reconstruction between these intersections is commenced.

Every effort is made to choose the most appropriate method of track reconstruction having regard to minimizing the overall inconvenience caused to the travelling public (including motorists), commercial vehicles, local businesses and local residents.

To the layman the most obvious solution might seem to be the complete replacement of trams by buses during the whole period of reconstruction of each section of track. Whilst the use of buses is often possible on weekends or even after 6.30 p.m. on weeknights, this option requires too many extra buses (and bus crews) for it to be practical during a weekday. These extra buses (about 40 or 50) would have to be bought and set aside especially for the purpose of operating the route in which the reconstruction was located. If fewer buses were bought and only operated over a part of that route many passengers would suffer inconvenience by having to change between tram and bus, perhaps twice in the one journey. Most tram depots provide trams for several different routes, so many of the tracks also provide access to a depot from other routes. Reconstruction of these tracks by substituting buses would be virtually impossible.

It is, therefore, most desirable to continue to operate the service by use of trams whenever physically possible. Depending on factors such as: width of the street, the environment (private dwellings, shops, factories or mixed) the motor traffic pattern and the frequency of the tram service; various techniques may be employed to enable the continued running of trams.

i) Temporary Track:

The most common method of gaining occupation of a track involves the laying of a temporary tram track on top of the adjacent council roadway. The length of temporary track required varies from job to job, but is normally in the range 0.5 - 1.0 km.

The chief advantage in using temporary track is that it enables the reconstruction crew to take occupation during daylight hours, thereby minimizing noise disturbance at night. The method also permits use of the cheaper concretes having a relatively low cement content, and generally leads to a higher quality result, it being easier to lift and line rails in day light. It is also easier to get men to work dayshift rather than nightshift, and the total cost of the job is usually less than by any other method.

A typical job involving the reconstruction of 0.8 km of double track normally takes 20 to 25 working days, with an average gang strength of 45 to 50 men (including Foremen, Plant Operators and Welders). Every day saved not only reduces the cost to the Board, but also improves public relations, so temporary track is used whenever possible.

In the narrow (20 m) streets the temporary track occupies all the roadway between the track under construction and the footpath, (Fig. 17), so motor traffic travelling in that direction must be diverted around the works area. When one track has been reconstructed the temporary track is transferred to the opposite side of the road, and the direction of motor traffic travelling through the works area is reversed. Access to properties within the works area is thus maintained.

In the wider (30 m) streets there is usually sufficient room to allow a single lane of motor traffic through between the temporary track and the footpath. In such cases it is often more efficient to avoid shifting the temporary track to the opposite side after reconstruction of the first track. Instead temporary reverse curved connections are made at both ends of the newly constructed track enabling trams in the opposite direction to use it while the second track is being reconstructed. This method is particularly well suited to those wide streets in which local businesses relying on passing trade are predominantly located on one side only.

The tracks along one of the very wide (60 m) streets in Melbourne were reconstructed by laying two parallel temporary tracks along the one side of the road while the reconstruction crew worked from the other side. Motor traffic was still able to flow past on both sides.

This however, was an exceptional case. Most reconstruction work now being done falls into the narrow (20 m) category, so much of the following description applies only to these narrow streets.

Temporary tracks naturally require a temporary overhead trolley wire on each side of the road. These are erected first, usually in conjunction with the erection of the temporary floodlights provided above all track openings. The temporary trolley wires are supported from the existing (lateral) span wires which support the permanent trolley wires. The permanent trolleys are not cut, but are connected to the temporary trolleys at both ends of the job by means of a diagonal cross wire and a pair of 'frogs'.

The temporary track is prefabricated in panels 13.7 m long and transported to the site by semi-trailers. Each panel consists of a pair of grooved 102 lb rails connected by angle-iron tie-rods and steel tie-bars (alternating) connected to the rail webs. The centre-most angle-iron tie is fitted for lifting. The rail foot rests directly onto the surface of the council roadway except where minor timber packing may be required. All joints are fishplated with provision for expansion at every fourth joint. One rail is connected by copper bonds tack welded across each joint in order to maintain continuity for the negative return current. Horizontal alignment is maintained by the use of timber toms wedged against the council kerb.

At each end of the job the temporary track is connected into the permanent track by a set of prefabricated reverse curved 'swings'. (Fig. 18). These are made from British Standard 96 lb tramway rail which features a thicker check than 102 lb rail (96lb rail has been widely used for curves and special-work fabrication in Melbourne, but is now largely superseded by 43 kg/m rail fitted with a separate guard plate). The 'swings' must be fairly flexible in both horizontal and vertical directions. In the vertical direction, each swing must accommodate both a summit and a sag vertical curve in order to join the rail head of the temporary track (about 170 mm above the pavement) to that of the permanent track (at pavement level). In order to avoid excavation of the council roadway or ramping up of the temporary track the 'swings' should be not much greater in depth than the temporary track itself. (Earlier 'swings' fabricated on conventional timber sleepers were a problem in this respect). In the horizontal direction, each swing should be able to adjust slightly to match job-to-job variations in the offset to the temporary track. The location of the council kerbline in relation to the permanent track, as well as the proximity of roadside trees, poles and shop verandahs, will determine the best position for the temporary track in the range 3.2 - 3.6 m offset from the permanent track.

To meet all these requirements, and to facilitate packing with timber where the 'swings' rise out of the trench, flat steel sleeper plates only 12 mm thick were chosen. These are fixed to the rail foot by Pandrol clips. Standard 20 mm dia. steel tie-bars are alternated with the sleeper plates. This arrangement allows sufficient flexibility in the 'swings' while still performing properly during handling and in service. The three sections of each 'swing' are arranged so that each 'swing' is reversible. This enables the sections to be re-arranged on the opposite side of the road to create a mirror image of their original layout. Earlier 'swings' were not reversible, so that when the temporary track was shifted across the road the 'swings' had to be transferred to the opposite ends of the job. The 'cutting in' of the swings to the permanent track is done during nightshift between the last tram (usually about 1.00 a.m.) and the first tram (about 6.00 a.m.). The bulk of the excavation for this operation is done during the day prior in order to minimize the noise on nightshift. Delays to the first tram are frowned upon, and seldom occur.

Along the length of the temporary track, vehicular access to side streets and private driveways is maintained by constructing crossings of crushed rock topped with cold-mix asphalt level with the top of rail. Street drainage along the council kerb and channel is maintained by first laying a steel pipe in the gutter at each driveway crossing. Passenger loading platforms at tram stops are similarly built up to be level with the top of rail. As the removal of the old permanent track proceeds the resulting trench between the temporary and remaining permanent track is bridged at each vehicular crossing. Prefabricated arch bridges of steel and timber are used, usually in pairs. As the various stages of the work move past, these bridges are readily removed and replaced by crane. The clear arch beneath each bridge enables them to be placed over freshly concreted track.

When the first track has been reconstructed in concrete the nightshift gang move in and dismantle both 'swings'. New straight rail is laid at each end, putting the reconstructed track into service by first tram that morning. At this stage about 40 m of the track at each end awaits concrete but is in service. It is temporarily supported on un-dogged timber sleepers (paved ballast reconstruction) or hardwood blocks (concrete foundation), and all Kirby joints are temporarily reinforced by fishplating. One joint is left unwelded and open for expansion. On the evening of that same day (usually after 6.30 p.m.) buses replace all trams on that part of the route. The concrete gang, working an afternoon shift, move in behind the last tram and prepare the two 'cut-ins' for concrete. Sleepers (or packing blocks) and fishplates are removed and all welding of joints is completed.

(The last joint on each rail must be butt welded). After lifting and lining the rail, concreting commences. A specially designed high early strength concrete is used which enables concreting to be continued until no later than 5 hours before the first tram next morning. Concrete design details are provided later in this paper.

The next major step is the shifting of the temporary track to the opposite side of the road. Fishplates are released and a swivelling 'Cap' crane travelling near the centre of the road lifts each panel of track and swings it across the road into its new position. A well organized crew, working nightshift with all motor traffic diverted, can transfer the entire temporary track and 'cut-in' the swings during the one shift.

Reconstruction of the second track then proceeds as above, except that concreting of the pavement between the two tracks is also (preferably) done before taking the temporary track out of service.

ii) "Jump-Up" Cars:

For some reconstruction jobs it may not be practical to use temporary track. Such situations can arise if the length of the job is less than 0.5 km, or particular difficulty is encountered in diverting motor traffic around the works area. In one case, the permanent overhead wires were supported by cantilever arms on centre poles (between the tracks), so that temporary overhead trolley wires could not be erected.

In these cases, and when extensive work at night is out of the question because of proximity to private dwellings, most of the work must be carried out during the day under tram traffic.

Advantage is taken of the reduced frequency of the tram service between the morning and evening peak periods. On tracks served by a single route the off-peak headway between trams is usually about 12 mins. By introducing an extra tram, or "jump-up" car, into the service the time available for changing rail may be doubled to about 24 mins.

The "jump-up" car is introduced into the service as an empty car travelling immediately behind a regular (service) car. After both cars have passed through the works area the second (empty) car waits on the departure side, and rail changing begins. About 12 mins. later, when the next service car arrives, its passengers are asked to walk forward past the work to the waiting car, which then sets off in the other's place. The (now empty) car on the arrival side waits, while the reconstruction crew continue to work on ahead of it renewing the rails. About 12 mins. later the next service car pulls up behind the waiting car, and passengers are again transferred onto the leading car. Normally, after the 24 minutes have elapsed, the reconstruction crew has managed to make good the section of track involved and both cars travel forward slowly over the new track. The second (now empty) car waits on the departure side, and the whole procedure is repeated.

On routes having headways less than about 12 minutes, two "jump-up" cars may be used in order to gain a track occupancy of three times the headway. Use of more than three "jump-up" cars is rarely justified as too many passengers are inconvenienced by having to transfer.

To date the above technique has only been used in the reconstruction of tracks having a concrete foundation. (It may well be possible to adapt the method to paved ballast tracks, but it is hardly necessary because the work involved in changing rail laid on sleepers does not involve nearly as much noise disturbance as does the breaking out of concrete to release the timber stringers cast into a concrete foundation track. Rerailing of paved ballast tracks may therefore proceed at night if required.)

As rerailing proceeds all rail joints are temporarily fishplated and tie-bars fixed. The rails have to be supported by hardwood blocks at close spacings and rigidly tommed to the sides of the excavation to prevent crippling the rail under traffic. Welding of Kirby joints follows, usually on nightshift, but fishplates are retained to reinforce the joint until tram traffic is withdrawn just prior to concreting.

As work progresses, and after the gang has left each day, the track is left in an excavated condition but signed and barricaded to prevent motor traffic following a tram. In the narrow (20 m) streets kerbside parking is prohibited on the side next to the excavation so that a single lane of traffic may pass through the works area in that direction. Traffic on the other side runs normally.

One of the fringe benefits of using "jump-up" cars for reconstruction in narrow streets is that, although the road must be closed to traffic in one direction during the mid-day off peak (for construction) it is open in both directions for the morning and evening peak periods, as well as at night. It is therefore a very useful method on roads where it is desirable to minimize disruption to peak period motor traffic, but it should be remembered that this is at the expense of an increased total number of work days for the project when compared with the temporary track method.

When approximately 150 m of track is excavated and re-railed, the concreting of this section is done. As for the concreting of the 'cut-ins' left by temporary track, all temporary fishplates and unnecessary packing blocks are removed just prior to concreting. This work is normally done during afternoon shift, with buses replacing trams after about 6.30 p.m.

Concreting of the pavement between tracks may be done dayshift under tram traffic.

iii) Reconstruction at Night:

In the very busy but wide (30 m) streets of the central City area, reconstruction by use of temporary track or "jump-up" cars would be unworkable because of the large volumes of motor vehicles and trams respectively. Excavation and rerailing is therefore done at night between the last and first trams. As work progresses the track is left in an excavated condition but signed and barricaded to prevent motor traffic following a tram. In streets carrying a very high traffic volume during the day it may be necessary to prohibit kerbside parking opposite the excavation to allow two lanes of traffic through. Temporary vehicular and pedestrian crossings are provided across the excavation opposite minor streets and laneways, but vehicular crossings are minimized as far as possible because of the short time available for their removal just prior to concreting. In order to speed their removal pedestrian crossings are prefabricated in timber and vehicular crossings are made of sand-bags topped with cold mix asphalt.

As with the reconstruction of tracks under tram traffic the rails must be properly supported on hardwood blocks, tightly tommed to maintain alignment, and all Kirby joints must be temporarily reinforced by fishplating. Provision for rail expansion is very important in this instance as the rail has been laid and welded in the cool of night. Watchmen are employed to patrol the track during the day, tightening toms and packing blocks loosened by the passage of trams.

When about 150 m of track is rerailed in this way concreting may commence. Concreting normally cannot be done at night after the last tram because of the minimum 5 hour curing period, so arrangements are made to remove trams from the rerailed section as soon as possible after the evening peak period. Tram services on City streets are naturally much more frequent than elsewhere and it is seldom possible to substitute buses for trams earlier than about 8.00 p.m.

In Swanston Street it is simply not possible at all, because the tracks service 9 basic routes to the south, and 2 to the north. To enable the Swanston Street tracks to be reconstructed (1977-78) it was necessary to install a temporary (rail) cross-over mid-way between the two existing permanent cross-overs located 1.0 km apart near each end of the City. When concreting (after 9.00 p.m. in this case) trams in both directions ran single line over the 0.5 km. Trams were dispatched in groups of 6 or 8, alternating from either end and under the control of two traffic officers in radio contact. The running track was barricaded to prevent motor traffic meeting on-coming trams, and police assistance was required at major intersections. (The temporary cross-over was removed and the last remaining straight tracks concreted during a weekend, with buses providing a frequent shuttle service between trams terminating at the permanent cross-overs near the City limits).

The reconstruction of Swanston Street is, however, an extreme example, and most City tracks are more easily concreted. Often it is possible to divert the evening motor traffic around the block, at least in one direction, so that concrete delivery trucks and other plant can move more freely within the works area - thereby expediting the project. As with all track concreting done in the evenings a special high early strength concrete is used, and the last concrete must be poured at least 5 hours before the first tram next morning. Concreting of the pavement between tracks may be done under tram traffic, although this is usually difficult in City streets because of the tram frequency. A better solution is to do this work nightshift and erect barricades to keep early morning motor traffic off it until the 5 hours have elapsed.

iv) Reconstruction at Weekends:

When none of the preceeding options is acceptable the last resort is to do the critical stages of the reconstruction work during a weekend.

Only about 20 weekends each year can be worked, and these are normally at fortnightly intervals. Weekends are therefore reserved for critical works such as :

a) Renewal of major track junctions and/or crossings
b) Renewal of curves
c) Reconstruction of (straight) tracks across major roads
d) Maintenance to Tramway-Railway crossings
e) Maintenance to paved ballast tracks in busy, narrow streets
f) Maintenance to wood-block pavements in busy, narrow streets
g) Realignment or relocation of tracks (often for other Authorities)
h) Reconstruction of those (straight) tracks which cannot be accomplished by any of the earlier options (i) - (iii)

Often, other small jobs (such as the concreting of junction components and short closure rails placed earlier by nightshift gangs) are done at weekends in conjunction with the main work.

Weekend work normally commences at about 1.00 p.m. Saturday and usually extends over three shifts until about 5.00 p.m. Sunday. Preparation for a major weekend job (such as a complete junction renewal) may begin up to 10 days prior by the breaking out of the pavement (over as much of the area possible, having regard to the need to preserve critical flows of motor traffic). On the larger more timely jobs, trams may be replaced by buses on the Saturday afternoon if possible. The changeover time varies according to the needs of the Civil Branch and the ability of the Traffic Branch to meet this need. As with all trackwork, close liaison and an understanding of each other's problems decide the strategy for each job.

Once trams are 'off' the serious business of changing rail begins. No time is wasted, as Melbourne's weather is known to change with little notice, at any time of the year. Usually, by the first change in shift at 11.00 p.m., most excavation is complete and the first new rails are in position. Through the night the next crew labours to complete any excavation and lay and weld the bulk of the new rail. Precise lifting and lining of the new track starts early Sunday morning and the first load of concrete is usually in place by 11.00 a.m. Concreting continues through the early afternoon, then during late afternoon the new work is 'married in' to the council roadway by asphalting the margins. Trams are normally replaced by buses all day on the Sunday, so the finish-grinding of welded joints and final clean-up is often left until Sunday night. By this time the high early strength concrete has cured, so all the protective signs, barricades and traffic diversions are removed - ready for normal tram, motor vehicle and pedestrian traffic first thing Monday morning.

Weekend reconstruction of straight tracks can be quite efficient in terms of the length reconstructed per calender day, due mainly to the ability to work 'around the clock' without interference from tram and motor traffic. The record stands at about 200m single track in one weekend.

PREPARATION FOR TRACK RELAYING:

Of the tracks being reconstructed nowadays, about two thirds are paved ballast and about one third are stringer tracks having a woodblock pavement. Very few tracks of the timber-tie-in-concrete construction are in need of reconstruction at this stage.

As most reconstruction is done by use of a temporary tram track, the following descriptions apply to that option.

(i) Paved Ballast Track: In the case of old paved ballast tracks, preparation for track laying and concreting consists of the following operations: (refer to Fig. 8).

1) The common works of survey set-out, temporary electrical work, laying a temporary track and constructing drive-way crossings.
2) Paint on council pavement the locations and depths of underground services which pass beneath the tracks (Shallow services are located by hand digging prior to deep ripping).
3) Saw cut the outside edge of the margin pavement (asphalt saw).
4) Scarify and remove the asphalt (or Macadam) pavement at the 'Cut-ins' (4 W.D. front end loader with asphalt ripper).
5) Remove old tracks, excavate cut-ins, and install swings (2 loaders and 2 cranes, working nightshift).
6) Divert trams onto temporary tracks.
7) Rip asphalt (Macadam) pavement over entire length of job (Traxcavator with asphalt rippers).
8) Remove pavement to sleeper level (Loader with special bucket attachment and 4 *Trucks to tip). (See Fig. 19).
9) Lift out and dismantle old track skeleton (Crane).
10) Stack and tie sleepers into bundles of 25 (Manual labour).
11) Load old rails on to scrap truck (Crane).
12) Deep ripping and bulk excavation of original track ballast to a depth of 270 mm below new top of rail design level (measured relative to survey reference pins located just outside margin, on Council pavement). (Traxcavator and 4 * trucks to tip).
13) Spread, grade and roll a blinding layer of 20 mm "B" grade fine crushed rock (Trucks tipping in trench, Small Grader, Diesel Roller). (Fig. 20).
14) Place arch bridges across trench, opposite driveways (Crane).

The major items of plant involved in this preparatory work are common to several different operations and consist of:

2 Four wheel drive rubber tyred front end loaders, fitted with single asphalt rippers and special bucket attachment. (e.g. Volvo BM-LM846).

1 (hired) Traxcavator (tracked) fitted with one or two asphalt rippers and multi-action bucket. (e.g. Caterpillar 955).

2 Articulated cranes of 8 tonne capacity, with telescopic jibs, (e.g. BHB Mobilift).

1 (hired) small motor grader (Cat. Model D).

1 Diesel Roller (8 tonne, 3 point) and low loader transporter trailer.

4*Tip Trucks (5 tonne capacity). *Depends on lead to tip site.

2 (hired) flat bed semi-trailers to deliver temporary track panels, and to remove sleeper bundles and scrap rails. (Permits required for 14 m rails).

1 Self propelled asphalt/concrete saw.

The workforce involved in the preparatory work usually consists of (in order of seniority) :

1	Foreman -
2	Sub-Foremen [illegible] +
2	Special Gangers Groun[illegible]
1	Track Ganger - [illegible]
16	Track Repairers (2 of which act as Dogmen when required)
3	Watchmen
Total 25	men on site, plus plant operators and truck drivers.

The apparently high proportion of supervision is due to the many different operations involved, and the need to keep each operation proceeding at the rate of at least 200 m/day.

The nightshift maintenance gang are also called upon to assist with 'Cut-ins'.

(ii) Stringer Track (Concrete Foundation):

The preparation of old stringer track (usually having a woodblock pavement), essentially involves the removal of all paving and track components, while retaining the original concrete foundation slab. (See Fig. 9)

This is achieved through the following operations:

1) The common works of survey set-out, temporary electrical work, laying a temporary track and constructing drive-way crossings.
2) Rip and remove woodblock pavement (Fig. 21) at the 'Cut-ins'. (4 W.D. front end loader fitted with special woodblock ripper, heavy skirts beside all wheels to catch woodblocks propelled by the squeezing action of rubber tyre and roadway, and a multi-action bucket to facilitate pick-up of blocks for loading).
3) Remove nuts and clips from anchor bolts (Pneumatic impact wrench).
4) Break concrete away from both sides of timber stringers (High impact hydraulic rock breaker attached to boom of large back-hoe).
5) Cut old rails and lift clear (Crane).
6) Remove timber stringers through anchor bolts and stack (Pneumatic Jack Hammers and Manual labour). (Fig. 22)
7) Clean debris, exposing bare concrete of foundation slab (Manual labour). (See Fig. 23).
8) Install swings at both ends (Steps (5) to (8) for 'Cut-ins' are done at night).
9) Divert trams onto temporary track.
10) Repeat steps (2) to (7) for the whole length of the job, done during dayshift.
11) Place arch bridges across excavation, opposite driveways (Crane).

The major items of plant normally required to perform this preparatory work are :

2 Four wheel drive rubber tyred front end loaders fitted with special woodblock rippers, skirts at all wheels, and multi-action buckets.
1 (hired) Kato 750 tracked, swivelling back-hoe fitted with Montabert BRH 501.L high impact hydraulic rock breaker (moll point).
2 Articulated Cranes of 8 tonne capacity, with telescopic jibs.
4 Tip Trucks (5 tonne) to cart away woodblocks and stringers for disposal.
2 (hired) Flat bed (14 m) semi-trailers for temporary track and scrap rail.
Air compressors, impact wrenches and jack-hammers.

Although the amount of plant required is less than for paved ballast tracks, the number of labouring personnel required is about the same.

To ensure the proper support of new rail by new concrete, a vertical clearance of at least 76 mm (3") beneath the new rail foot must be achieved when breaking the stringer out of the original concrete slab. Design levels are normally slightly higher than the original levels in order to ensure that this is achieved simply by removing the stringer, but in some cases it may be necessary to break out additional concrete beneath the level of the stringer.

iii) Sleepers or Timber Ties in a Concrete Slab: (Fig. 9)

Some straight tracks having transverse timbers cast into a concrete slab have been reconstructed, but this track structure is more often encountered in the reconstruction of worn out curves.

If the timbers are very closely spaced it may be necessary to cut away that part of each timber near both rails, or to completely remove them if practical. Unsound timbers must be entirely removed. Sound timbers at wide spacings may often be left intact, and the concrete between them channelled out to achieve a clearance of at least 76 mm (3") around and beneath the foot of the new rails. Some channelling out work may be started under tram traffic, and in a few cases it is even possible to re-concrete under traffic (if necessary).

iv) Old Concrete-to-Surface Track: (Fig. 9)

No major reconstruction of straight concrete-to-surface track has had to be done as yet, but many of the early curves and junctions laid in concrete-to-surface have been re-railed in recent years.

The first step is to saw-cut around the limits of the work, usually, offset 300 - 450 mm along each side of the worn-out rails. A self propelled concrete saw is used for long cuts, or a portable hand-held model may be used for the smaller jobs. If the area of concrete to be broken out is extensive (e.g. if both rails of a track are to be renewed, when it is best to remove the full width of the slab between the rails to a depth of at least 120 mm), then frequent deep transverse saw cuts will assist in removing the concrete.

As with other types of concrete track it is essential that, along the line of each rail, the old concrete is channelled out to achieve a clearance of at least 76 mm (3") around and beneath the foot of the new rail. As the old rails rely entirely on this concrete for support, the removal of concrete beneath the rail foot cannot proceed under tram traffic. However, breaking out the concrete in the upper parts of the slab may proceed under tram traffic provided that care is taken not to damage the original tie bars (cast into the slab) nor the (worn) rails themselves.

Bulk concrete is best broken with a high impact hydraulic rock breaker mounted on the boom of a large back-hoe, while the finer work is best handled by pneumatic jack-hammers.

v) Over New Ground: (Fig. 7)

Inherited from the original paved ballast track was a sub-soil, or agricultural, drain beneath the centre of each track. The cable track conversions also copied this practice by retaining part of the original cable tunnel as a sub-soil drain.

Sub-soil drains have proved useful under paved ballast track, but are of little use beneath a concrete slab unless a cross-flow of ground-water is encountered.

They are generally retained under tracks being reconstructed, as their retention is a cheap form of insurance against possible ground-water problems.

However, the laying of sub-soil drains beneath concrete-to-surface tracks built over new ground is generally not justified, except in selected locations on the high side track to intercept a significant cross-flow of ground water. Experience with concrete slab tracks laid well over 50 years ago, without sub-soil drains, has shown that the tracks can perform quite satisfactorily over normal ground conditions.

Preparation of a sub-grade for new concrete tracks is, therefore, quite simple.

Bulk excavation of the natural surface to a level of 370 mm below top of rail will reveal the ground condition. If the ground at this level is sound a 100 mm layer of wet 'B' grade fine crushed rock is spread and rolled (in layers), forming a sub-grade at 270 mm below top of rail. Small areas of unsuitable material are removed to a depth of about 500 mm. Extensive tracklyaing over uncertain ground warrants proper soil testing and design of the sub-base, but if work is done in conjunction with roadworks use of the road's sub-base design is usually more than adequate for concrete slab tracks.

One job which must be done before laying concrete tracks over new ground is the provision of underground piped outlets for stormwater (which will be collected by surface level track drains located at low points in the longitudinal profile.) Where provided, underground ducts and pits to accommodate electrical feeder cables, etc., must also be completed prior to tracklaying. (Normally, these facilities are already existing under tracks being reconstructed to their original alignment).

TRACK LAYING:

i) Rails:

The rail used since April 1975, is a checkless (T-head), non-symmetrical medium manganese steel rail weighting 43.3 kg/m (87.3 lb/yd), (refer to Fig. 5). It is generally supplied in lengths of 14.0 m (about 46 ft.), with ends cut to a positive under-cut of 1.0 to 1.5 mm, and tie-bar holes pre-drilled through the web at 3.0 m centres. No holes are provided specifically for fishbolts, but the tie-bar hole nearest each end can be used for a fishbolt in conjunction with the temporary fishplates sometimes used during construction. The chemical composition of the rails complies with Table I of A.S. 1085 Part 1, 1975, for medium manganese rails except that the manganese content lies in the range 1.20 - 1.60%. Their height and flange dimensions are both 127 mm (5"). Rail ends are marked to avoid on site confusion as to which edge is the running edge.

Rails are transported from the Board's Store to the site on a road jinker. At the site they are laid out in pairs close to their final location, either along the kerb, or beside the excavation.

In the case of earthern sub-bases, precast concrete blocks 130 mm thick are laid at 3.5 m centres along the alignment of each rail. (Fig. 20). On concrete foundations, pre-sawn red-gum blocks 75 x 100 mm in section are laid out at the same spacing. (See Fig. 23).

ii) The Kirby Joint:

The rails are then lifted onto the supporting blocks by crane, making sure that rail ends tightly abutt any previously laid rails. At 3.0 m centres, steel tie-bars, 20 mm in diameter, and threaded at both ends, are used to join the rails of each pair by means of nuts tightened against both sides of the rail webs. The rail pairs are thus set exactly to gauge, then accurately aligned horizontally by measurement from the off-set survey pins at 10 m centres.

Vertical alignment, or a 'good top' through each joint is achieved by use of pairs of opposing (thin) hardwood wedges lodged beneath the foot of the rail at each supporting block. The mating rails are then pulled tightly together using a hand operated wire-rope winch attached (near the rail) to nearby tie-bars. Should the rail head joint fail to close completely, the joint is released to allow grinding of the rail ends as required. However, this is seldom found necessary now that rails are delivered with a positive under-cut at both ends.

Once the rail head joint is completely closed and the alignment along both the head and running edge is correct, a large vertical double "U" clamp is applied to hold the rails in position for welding. (Fig. 24). A mild steel sole plate (230 x 200 x 12 mm) is then wedged up underneath the joint and fillet welded along both sides of the rail foot. A mild steel strip (250 x 25 x 12 mm) is also welded to each side of the upper face of the foot of the mating rails. At crest-vertical curves it is often necessary to weld an additional steel strip on each side of the rail web. This prevents the joint at the rail head opening up when the rails take up their convex profile.

At very small radius crest-vertical curves the joint must be "head-and-tail" welded. This joint has a welded sole plate (as above), as well as a V-cut in the mating heads which is fillet welded. (This joint may also be used in place of the "butt welded" joint, used as a final closure joint, provided the gap across the joint is small).

At each Kirby joint a length of mild steel reinforcing bar is tack welded around the inside of the joint (see Figs 5 and 25). This bar, when cast into the concrete, lends extra tensile strength to the rail joint. (Steel reinforcing mesh, cast into the concrete at least at the rail joints, also lends extra tensile strength to each Kirby joint).

Welding of all Kirby joints is necessarily done in-situ, with one welding crew aligning the joints and welding on the sole plates by semi-automatic or manual arc equipment. The upper strips and reinforcing bars are then welded by a second crew using either type of equipment. (See Fig. 24).

The semi-automatic units consist of a diesel-engine driven DC welding unit and a semi-automatic welding head, complete with a wire feed unit which allows the use of flux-cored wires. Manual arc welding units are powered by DC motor-generators which are driven by power from the overhead trolley wire. The welding units may be mounted on trolleys and moved along the track as it is welded. Welding is performed with an open circuit voltage of 70 - 80 volts and an arc voltage of 25 - 26 volts at 300 - 320 amperes. Extension leads permit welding up to 45 metres from the power supply.

iii) Negative Bonds:

Opposite every fifth overhead pole (i.e. about every 150 m) negative copper bonds are welded to the rail foot, linking all four rails together. At every tenth pole bonds are also linked between the outside rails and the foot of both the overhead poles, for a safe earthing system.

iv) Lifting and Lining:

When all welding is complete, the track is lifted and lined accurately. Lifting is accomplished by use of the pairs of opposing hardwood wedges (every 3.5 m), and horizontal alignment is accomplished by first re-checking the gauge, then using timber toms (30 x 30 mm) jammed between the rail web and the edge of the trench or the edge of the adjacent track, as necessary. Edge formwork (if required) is to be placed before any tomming commences.

Both vertical and horizontal alignment are taken by reference to the survey pins which are normally at a constant off-set of 1.300 m, just outside the edge of the excavation, and spaced at 10 m intervals.

Firstly, the rails are lined and levelled opposite each survey pin, then they are 'eye-balled' between pins. The second step is so accurate that it can also detect any minor errors at the pins themselves.

The tie-bars, supporting blocks, wedges and toms all remain in place during the concreting, thereby becoming cast into the structure. (See Fig. 26).

v) Concreting:

At the beginning and end of each day's pour, lateral timber formwork is constructed around and beneath both rails to give a clean edge for adjoining (later) pours. Along the "margin" next to the council roadway a straight concrete edge is achieved by use of old sheet piles laid on their side as formwork. The "inner margin" (between the tracks), being the lower part of a "stepped" construction joint, needs only a rail lying on its side to act as a stop for the wet concrete. Edge formwork is generally not required when reconstrucing tracks having a concrete foundation, unless for some reason it is desired to concrete the margin up to the surface.

When the new concrete slab is to be full depth (270 mm), steel reinforcing mesh is only laid over an area of 1.2 x 1.2 m at each rail joint.

If reconstructing over an existing slab, and the depth of the new slab is to be less than 150 mm deep, then steel mesh is laid over the full length of the job for each track as well as between tracks.

The reinforcing mesh used is F615 which consists of 5 mm diameter bars laid in a 300 x 100 mm grid (larger number of bars laid longitudinally).

The mesh is laid on top of the tie-bars and supported at intermediate points by small concrete blocks to achieve a concrete cover of about 70 mm.

Concreting is normally commenced when at least 300 m of single track has been laid. With use of the "concrete train" (see Figs 26 & 27), the concrete gang is capable of pouring up to about 300 lineal metres of single track on one shift. The concrete gang normally consists of a Sub-Foreman and ten men, working the "train" as follows :-

2 Men operate the hand-winch for forward movement.
1 Man controls concrete delivery at agitator chute.
4 Men (with shovels) control distribution of concrete ahead of vibrating screed
2 "Trowel hands" finish off groove and pavement surface
1 Man sprays emulsion over surface.

The 'concrete train' consists of a winching trolley which draws the main unit, screeds and sled. The main unit acts both as a (diesel-electric) power plant for vibrators and as a supporting structure for the vibrator leads so that the leads are kept clear of concrete leaving the chute of the delivery agitator. Both the concrete train and the delivery truck move forward at the same rate.
The weight of the main unit is restricted to less than 800 kg. to prevent rail deflection affecting alignment during concreting.

The four electric vibrating pokers do most of the work in ensuring the concrete is properly distributed - especially beneath and around the two rails. The concrete is always poured between the rails and vibrated beneath the foot before placing any concrete outside the rails. This ensures that the rail foot is properly packed with concrete. Two men (with shovels) on each side of the "train" manoeuvre the vibrating pokers and transfer concrete as required to obtain the desired concrete profile. Part of their task is to ensure a slight over supply of concrete ahead of the vibrating screeds.

The profile of the concrete surface of each track includes a 6 mm camber at the centre to shed stormwater to the rail grooves. This prevents puddling on the pavement surface of near level tracks. (Water is collected from the rail grooves at low points and upstream of switches and other special work.) The surface profile of the concrete also includes the shape of the two rail grooves (see Fig. 6).

The concrete pavement between tracks is likewise designed with a centre camber (9 mm), and to allow for future rail wear is laid 6 mm low at each rail.

The pavement surface of each track is levelled by two (electric) vibrating screeds drawn along behind the main unit. These (lateral) screeds are connected together by two longitudinal steel runners, each 3 m long, which are located against the two (inside) running edges of the rails. The runners do the main work of pushing the coarser aggregates away from the running edge of the rails - roughly forming the groove - and because they are incorporated with the surface screeds they also ensure that the correct volume of concrete is "cut-out". (See Fig. 27).

Much of the vibration in the screeds is transferred to the rails, so that the medium to fine range particles near the rails are still 'flowing' as the screed runners depart. It is then necessary to move these finer range particles away from the running edges to reform the grooves. Since the magnitude of vibration of the rails decreases with increased distance from the vibrating screeds it is possible to reform the grooves by towing a passive (non-vibrating) sled at some distance behind the screeds. The sled consists of a pair of 3 m long taper-nosed timber runners shaped to the desired groove profile, and supported beneath a light timber frame. The distance between screeds and sled may be varied to optimize the "slip-forming" of the grooves, as factors such as the type of concrete used, average speed of the 'train' and atmospheric conditions, may vary from job to job. (See Fig. 27).

Before final hand-finishing is done, a longitudinal hand screed 4.8 m long is used to remove any waves in the concrete surface left behind by the vibrating screeds. To assist screeding, the surface is watered as as required. (See Fig. 28).
Hand finishing of the groove and pavement surface is done by two 'trowel hands' - working on each side of the track. Each man is equipped with normal flat wooden and steel trowels and a specially shaped steel grooving trowel. The profile of the grooving trowel is very slightly larger than the desired (final) shape of the groove, (Fig. 6), as determined from experience. After each pass by the profiled trowel, a flat trowel is used to spread the excess fine cement mortar back towards the centre of the track. (Fig. 29)

A damp sheet of hessian cloth is then dragged along the fresh concrete surface to give a textured anti-skid finish, and the surface sprayed with a white plastic membrane type of curing compound. (See Fig. 29).

The following day, before surface cracks develop, a small hand held concrete saw is used to cut a lateral groove across the new concrete surface at rail joints. This prevents the formation of uncontrolled surface cracks which could lead to fretting under motor traffic.

Minor surface cracking will occur above tie-bars but this does not warrant concern.

The concrete pavement between the tracks is levelled using a single wide screed (having the correct centre camber built into it, as do the track screeds), fitted with an electric vibrating motor drawing its power from either a portable generator or (when possible) by way of a long lead from the 'concrete train' moving along the adjacent (unused) track.

This screed is pulled along by a man at each end, one of whom has to move clear each time a tram comes along. The 4.8 m longitudinal hand screed is again used to remove small waves in the surface left by the vibrating screed. Normal hand-finishing, bagging and emulsion spraying then follow, with saw cutting done the next day.

After the initial set "Wet Concrete" signs and rope barricades are erected at regular spacings to help keep pedestrians off, but at least one "trowel-hand" stays behind to attend to any mishaps.

Concrete is supplied to the Board on a contract basis. The type of concrete used is largely determined by the curing time available before resumption of tram or motor traffic. Typical mix proportions are as follows :

Metric Units:

	Type 1	Type 2	Type 3	Type 4
Compressive Strength (megapascal)	17.5 @ 7 days	17.5 @ 3 days	14.0 @ 1 day	3.5 @ 5 hrs. 35.0 @ 7 days.
Cement content (kg/m^3 concr.)	315	345	515	515
Course (20 mm) Aggr. (kg/m^3 concr.)	500	500	605	605
Course (14 mm) Aggr. (kg/m^3 concr.)	770	770	595	595
Fine Aggr. (dry conc. sand) (kg/m^3 conc.)	755	725	600	600
$CaCl_2$ admixture ($litre/m^3$ concr.) (relative density 1.274 @ 20/20)	-	13.4	20.8	20.8
Slump required (mm)	25 - 50	50	75	100
Water Temperature	Ambient	Ambient	Ambient	Hot (70° C ma
Tram and heavy motor traffic may resume after:	7 days	3 days	5-24 hrs. (see text for conditions)	Approx. 5 hrs. (Emergency use only)

Type 1 concrete is laid in areas where it will have at least 7 days to cure before trams resume. It is therefore one of the main types used when reconstructing tracks with the aid of a temporary track. Temporary track thereby permits concrete costs to be kept to a minimum. Type 1 is also used when constructing any new tracks not subject to immediate traffic.

Type 2 concrete is used towards the end of the concreting of each track being reconstructed with the aid of a temporary track - i.e. in areas which will have only 3 - 7 days to cure before trams resume. It is also used for most of the paving between the tracks.

Type 3 concrete is used for concreting the 'cut-ins' and all other parts of the track having less than 3 days before trams resume. It is the only type of mix suitable for track reconstruction work done without the aid of a temporary track, and is the only type suitable for weekend works. When the curing time available lies in the range 5 - 24 hours extreme care must be taken that all welds to the rail head are properly ground, that the rail head and groove are clean, and that tram speeds over the work are restricted to less than 10 km/h during the initial resumption of traffic. Type 3 concrete is also used (in conjunction with temporary track) for those parts of the pavement between tracks which are opposite driveways and side streets. This minimizes the period of restriction to local vehicle access.

Type 4 concrete is rarely used nowadays. It is quite difficult to handle because of its very rapid initial set, and for this reason is reserved mainly for emergency situations.

In favourable weather conditions reliable suppliers have been able to consistently exceed the required standards by a fair margin. Where appropriate, engineering judgement may be exercised in deciding the type of mix warranted for border-line situations.

vi) Asphalting:

As a result of the 'dropped margins' now used, a depression 50 - 100 mm deep by at least 460 mm wide is left to enable proper 'marriage' of the newly laid concrete surface to the existing council roadway. (See Figs. 7, 8 and 9).

X

In the case of reconstructed paved ballast track, the deep narrow gap (left after the sheet piling formwork is removed) has to be filled with compacted fine crushed rock. An Arrow Hammer is a useful machine in achieving proper compaction of this strip.

The exposed concrete and side of rail head are primed with bitumen emulsion from a spouted can. Hot mix 20 mm asphalt is then tipped on the move from a truck fitted with narrow gates built into its tail-gate. The hot asphalt is spread manually and rolled by an 8 tonne, 3 point dieselroller. In most cases the new track's design levels differ only slightly from the levels of the adjacent council roadway, so the standard 460 mm margin is adequate. However, in some cases the local council may want to take the opportunity to improve the road's cross-section, so that the new tracks are laid signficantly higher (or, sometimes, lower) than the existing roadway for the time being. In these cases it is necessary to avoid a steep asphalt margin by extending the asphalt work out until a reasonable cross-fall is achieved. A limit of 1 in 15 is usually adopted for temporary work, but the desired cross-fall for permanent work is negotiated with the road authority.

If the local road authority is contemplating reconstruction or resheeting of their pavement following the track reconstruction, then the Board's hot-mix asphalt margin is kept about 10 mm low against the rail and a temporary continuous cold-mix asphalt wedge is laid (to make the track safe for pedestrians and motor vehicles). It is then a simple matter for the road authority to remove this cold-mix wedge as they lay their final wearing course.

When the adjacent road pavement is in good condition and not likely to be resheeted in the foreseeable future, the Board's hot-mix margin is finished at rail level.

PRODUCTION:

Reconstruction of Melbourne's tram tracks in concrete-to-surface, as described, is usually accomplished at an overall production rate of 9.4 - 11.7 man-hours/metre of Double Track.

For a particular job, the exact production figure achieved depends mainly on the type of track being reconstructed, the ability to use temporary track, and the working environment (traffic conditions, working space available, proximity to private dwellings, etc.).

Under normal conditions, using temporary track, the Board is able to reconstruct 1.6 km of Double Track in 40 - 50 working days, with an average gang strength of 45 - 50 men (including Foremen, Plant Operators and Welders).

CURVES, JUNCTIONS AND CROSSINGS:

i) Curves:

Large radius curves away from busy intersections may be renewed as part of the bulk reconstruction of straight track. Small radius curves turning through angles over about 30°, many of which occur at busy intersections, are usually reconstructed at weekends using the techniques already mentioned. Such curves occur at about 160 locations, being equivalent to about 320 single track curves. (These figures include curves leading up to double track Y junctions, but do not include curves joining two Y junctions within an intersection since these curves are usually reconstructed as part of the junctions).

The minimum curve radius preferred is 30 m, although some curves of 17.5 m radius occur at a few junctions. Due to problems of excessive rail wear and consequent increase in the risk of derailment, the larger minimum curve radius is preferred. Despite cubic parabola transitions and provision of super-elevation whenever possible, most curved rails suffer from considerable wear, both horizontally and vertically.

Fig. 11 illustrates the effects of curve wear on grooved rails. (Fig. 10). Horizontal wear from low speed vehicles on small radius curves is peculiar in that wear may occur in both radial directions. The wheel flanges of the leading axles of each bogie cause the usual outward wear, but the flanges of each trailing axle will try to 'cut the corner' at low speed. In the extreme this will result in two distinct flange paths worn into the floor of each rail groove, and if not detected and removed by grinding, the ridges between these flange paths may contribute to derailments.

Vertical wear on curves is mainly caused by wheel slip generated by the fixed wheel-axle sets. A differential on each axle (were it practical) would help in this respect, but it is only the larger radius curves which wear out vertically before horizontally.

Curves worn horizontally by about 8 mm or more are brought back to gauge by building the high (outer) rail running edge and low rail check with weld material deposited by manual arc, semi-automatic or fully - automatic machines. (The manual and semi-automatic machines have already been described. The fully-automatic machine consists of a self propelled submerged arc unit, specially designed for curve building, and powered by a DC motor generator connected to the overhead power supply).

Repeated welding of worn out grooved rails eventually leads to cracking of the rail section at close intervals, and if left too late the inner rail's check may become too thin to reweld properly. When excessive vertical wear combines with significant horizontal wear, the low rail's check is likely to fracture near the floor of the groove and come adrift. Continued maintenance then becomes expensive, so re-railing is the better solution.

As labour costs have increased over the years so it has become more attractive to increase the steel section of re-railed curves. At first the British Standard 96 lb Tramway Rail was used, especially on low rails. This rail differs from the Australian Standard 102 lb rail by having a thicker check, but a thinner head. Later, curves of less than 45 m radius were re-railed by using a fabricated low rail and a 96 lb high rail. The fabricated rail was made from 102 lb rail turned around backwards with the check removed. To this was bolted a heavy guard plate of S1042 grade steel located 30 mm from the 102 lb rail's new 'running edge' by specially prepared spacer blocks at each bolt. This arrangement has proved very successful, so forms the basis for the design now used.

Fig. 12 , shows the cross section now used for curved rails fabricated from 43 kg/m rail. Heavy guard plates 32 mm thick, made from S1042 grade steel (hard wearing) are bolted at 600 mm intervals beside mild steel flame-cut spacer blocks 45 mm thick. Guard plates are provided on both high and low rails. The guard on the high rail prevents the trailing axle of each bogie 'cutting the corner', thereby ensuring the smooth, gradual turning of each bogie and minimizing "scalloping". "Scalloping" is a very destructive (and dangerous) form of uneven horizontal wear of the high rail running edge and low rail check. It arises from over-wide grooves permitting the lurching of each bogie as it negotiates the curve, so that the leading wheel's angle of attack to the rails is not constant. This causes a horizontal wave pattern, the depressions of which have been caused by the leading flanges biting into the running edge and check. (If not detected and repaired at an early stage, deep "scallops" may lead to derailments).

On long curves over about 50 m radius, and carrying only light tram traffic, it may be economical to reduce the thickness of the high rail guard plate. A 'medium' guard of 20 mm thickness has been found satisfactory.

"Light" guards of about 15 mm thickness have been used for very short term diversions but are not suited to permanent tracks because of slight buckling of the guard between spacer blocks.

All curved rails under about 350 m radius are pre-bent using a roll-fed "Scriven" reciprocating machine, and are prefabricated as a complete simulated curve using survey controls. The rails are designed and fabricated in transportable lengths for transfer to the site by semi-trailer.

ii) Junctions, Crossings and other 'Special Work':

Connecting together the 444 single track-kilometres and 12 depots and workshops requires various configurations of junctions, crossings, cross-overs, sidings, turn-outs and catch-points. The most complex junction is the 'grand-union' at Balaclava Junction (4 approaches each having 3 directional alternatives, requiring 16 sets of switches and 8 curves within the intersection of two 20 m streets). Other junctions vary in complexity down to the 'simple' double track Y junction. Effectively, all the major tram junctions in Melbourne are equivalent in total to more than 90 double-track Y junctions. Cross-overs, which join the two tracks, total more than 130 (left hand), and there are also 2 scissors cross-overs. There are 25 stub-tracked Y termini, 12 street storage sidings, and 8 Vic Rail controlled catch-points protecting railway crossings. In total the Board's trackwork involves more than 700 sets (or pairs) of switches, of which about 500 occur in the street. Switches vary in useage, but the busiest sets undergo about 3,000 one-way changes each day.

Rectangular (or near-rectangular) tramway-tramway crossings (all double-double track 'meets') occur at 32 locations. Half of these are pure crossings, and the rest are related to junctions.

Tramway-railway crossings occur at 7 locations. Four of these are double-double track 'meets' on Vic Rail's suburban electric system, and the other three are double-single track 'meets' on a lightly trafficked goods line. The MMTB is responsible for maintenance of all these crossings, and the latest renewal (at Glenhuntly) was fabricated by the Board.

Tramway rails intersecting at angles flatter than 1 in 5 perform in a similar way to most railway crossing 'frogs'; that is, the wheel load is carried entirely by the head of the rail. At angles steeper than 1 in 5 the gap in the rail head is such that the wheel tread is unable to span the break without dropping into it, so it becomes necessary to support the bottom of the wheel flange by means of a "ramp" built into the floor of the rail groove. The beginning (and end) of each ramp is sloped at about 1 in 120, so that the wheel flange is gradually lifted until the wheel tread rises just clear of the rail head. This results in a smooth crossing of the intersecting rail grooves by wheels travelling in any direction. Ramps are very heavily stressed and will deform and wear relatively quickly. Regular building up by welding followed by more frequent precision grinding is necessary if ramps are to remain effective and quiet. Wherever possible, ramps are continuous through closely spaced rail crossings.

In early days the standard rectangular double track crossings, and some other standard crossing components, were cast in pearlitic manganese steel (0.18 - 0.33% carbon, 1.2 - 1.7% manganese), but cost and the need to provide for a great many intersections at angles other than 90°, or other than the standard 1 in 5 of cross-overs, forced a change to fabrication. Using tramway rail and rolled structural steel sections welded together allows a greater flexibility in both design and production.

Fig. 13 shows the method of providing ramps with 43 kg/m rail. The stresses imposed on the ramps by the wheel flanges will cause significant 'flow' of the weld material in the ramp surface. This 'flow' will attempt to spread the rail head and guard plate, so high tensile, 20 mm diameter bolts (with Lock Washers) are provided at 300 mm centres. On heavily trafficked rectangular crossings "Huck" bolts are preferred. (Due to one half of the rail foot being effectively shielded by the heavy guard plate this method of fabrication is only suited to installation within mass concrete slabs. A false rail foot would need to be provided for use with conventional rail fastenings).

As with fabricated cuves, all junctions, crossings and cross-overs are prefabricated as a complete simulated unit using survey controls laid out in the fabrication yard. Close inspection at this stage eliminates many on-site problems.

Most 'special work' is able to be dismantled or cut into readily transportable sections which will also suit the method of installation. However, the Tramway-Tramway and Tramway-Railway double track rectangular crossings (because of their continuous ramps) are usually transported and installed as a single unit measuring about 8 metres square. Movement of these units through the streets is restricted - requiring a police escort and pilot vehicle. The installation of a complete rectangular crossing is performed by two large mobile cranes (about 30 tonne capacity) operating through the overhead electrical network (which is isolated).

Work of this nature is almost always done at weekends with trams replaced by buses at least on the Sunday, but also after about 1.00 p.m. Saturday for the more extensive works (See Fig. 31). Some cross-overs may be reconstructed as part of the bulk track reconstruction work, but most are required for the daily operation of the service so are also done at weekends.

RESILIENT TRACKS:

As with other developments in Melbourne's street trackwork there were early experiments with resilient rail joints, resilient straight track (especially on bridges), and resilient crossings. All were aimed at reducing structural vibration, track maintenance or noise level.

The first application of resilient materials to the concrete-to-surface construction came in 1968 when the straight tracks across the south tramway bridge at St. Kilda Junction were laid. The cross-section then used was similar to that in Fig. 14 except that the continuous grooved rubber base pad was only 12 mm (½") thick. Heavy motor traffic using Queensway travels under this bridge, so it was decided to minimize tram related vibration of the superstructure in order to keep the total noise level under the bridge at an acceptable level.

For the same reason, a similar treatment was afforded the tracks in St. Kilda Road over the newly constructed City Road Underpass, in 1971.

For the replacement of the tracks over a shallow pedestrian underpass in the City during 1974 it was decided to increase the degree of resilience by using an 18 mm (3/4") thick grooved rubber pad (as in Fig. 14). These tracks performed satisfactorily so it was decided to adopt the 18 mm thick x 165 mm wide continuous pad for similar applications in the future.

The grooved rubber pad essentially consists of five rubber strips, 19 and 25 mm wide, separated by 12 mm grooves across which the strips are joined by a thin (3 mm) web. The pad is extruded in lengths of 6.7 m (two per rail, leaving an allowance for field welding of joints) from natural rubber having a Shore Durometer Hardness of 45 - 55. To date, for ordinary straight track, the pad has only been used in conjunction with grooved 102 lb rail. Rail deflection under load (less than 9 tonnes/axle) is of the order of 1 mm.

Fig. 14 shows the general arrangement of the rubber pad and other resilient materials used to wrap 102 lb rail prior to concreting (to surface level). The general purpose of the other resilient materials is simply to provide for small rail deflections within the surrounding concrete slab, and to prevent entry of water and road silt into the cavities thus formed.

Closed cell polyethylene strip, 6 mm thick, is used to cover the upper rail foot, web, and underside of head and check. It is also used for all on-site coverage of tie-bar nuts and welded joints (except under the sole-plate, where grooved rubber pad is used). A thin sponge rubber strip shields both outer edges of the rail foot.

Against the rail's head and check are fixed specially fabricated strips of cork expansion jointing, via a 6 mm thick strip of closed cell Neoprene which permits the vertical movement of the rail without disturbing the keying of the cork material into the surrounding concrete. The upper surface of the expansion joint material is covered with a waterproof sealing tape which is removed the day after concreting to permit moisture to expand the cork and seal the joints.

All these resilient materials, and the rubber pad, are fixed to the (cleaned) rail by a water-proof neoprene based contact adhesive (e.g. "Beta Special"). At the centre of each rail a short length of expansion jointing is omitted to enable handling by crane "scissors" and at both ends about 150 mm of rail is left bare for joint welding. In inclement weather the rails are wrapped in plastic sheeting to prevent moisture entering the expansion material prior to concreting.

On site, the rails are lifted and lined in exactly the same manner as ordinary (non-resilient) rails, except that extra care must be taken to minimize damage to the resilient materials. All rail joints are "head and tail" type (as previously described). When welding work has cooled, the joints are wrapped in the usual resilient materials. Tie-bars are enclosed in over-length closed-cell flexible foamed-plastic pipe wrap, then fitted and used to gauge the rails in the usual way. All tie-bar nuts are spot welded to prevent them loosening in service. The inner tie-bar nuts are then enclosed within the pipe wrap, and the outer nuts are covered with a glued square of the polyethylene material. Any copper (earthing) bonds attached to the resilient rail are also enclosed in pipe wrap over their first 300 mm away from the rail. Track drains (if any) must not be welded to the rails and space must be left for deflection of the rail under load.

Just before concreting, a thorough check is made of all resilient materials. Any pieces damaged (e.g. by tomming) or missing (e.g. at lifting points and joints) are made good.

Since the rail is isolated from the concrete slab it cannot act as longitudinal reinforcement (as indeed it does in the conventional concrete-to-surface tracks). The usual reinforcing mesh is therefore provided throughout the entire slab, regardless of slab thickness. Slab depths beneath the rail foot are, naturally, increased by 18 mm to allow for the continuous grooved rubber pad.

"Dropped margins" cannot be used against resilient track as concrete is required at the surface to retain the expansion jointing material. Properly constructed formwork is therefore required along the outer edge of both margins. "Stepped" construction joints between tracks may be used, provided the inner-most expansion jointing strips are not damaged or wetted between pours. In some cases it may be better to omit these inner jointing strips until just prior to the concreting of the pavement between tracks.

In 1977 the engineers for the Melbourne Underground Rail Loop Authority (M.U.R.L.A.) conducted field measurements as to the possible effectiveness of the Board's resilient track design in controlling tram related vibrations transmitted to the two underground stations located beneath the La Trobe Street tram tracks. The test was carried out by installing lengths of both rigid and resilient concrete-to-surface tracks within a temporary deviation around the cut-and-cover excavation for the Flagstaff station booking hall. The results confirmed the effectiveness of the resilient design, so the permanent tram tracks re-instated over both Flagstaff and Museum stations were laid (1977 and 1978) using resilient rail in a concrete-to-surface slab. The 220 m of double track reinstated at Museum is the longest continuous length of resilient concrete track in Melbourne.

A recent development is an expansion strip suitable for use on the inside (running) edge of the new checkless 43 kg/m rail. To date this has only been tested in short lengths leading up to a resilient crossing, but it appears to be satisfactory. Its design, in principle, could be applied to any T-head rail.

Typically, the total cost of converting rail for use in resilient track plus the (slight) extra cost in laying it, could be expected to increase the cost of constructing a plain concrete-to-surface track by about 60 - 70%.

Concurrent with the development of resilient straight track, work was being done to reduce air-borne noise levels at rectangular ("H") crossings, major junctions and the like.

The first resilient "H" crossings and junctions (as well as a 1 in 5 crossing in a standard cross-over) were installed during 1967 and 1968. This 'special work' is mounted on 13 mm thick square grooved rubber pads (at 600 - 700 mm centres) resting on sleeper plates fastened to timber sleepers or (in one case) to a concrete foundation. Pandrol clips hold the rail foot down on the pads. In most cases the road pavement is established by numbers of precast reinforced concrete covers resting on the sleepers. (There are two covers per square, each being triangular to reduce rattling).

During 1974 another "H" crossing and a large junction (which includes a near-rectangular crossing) were constructed in a similar way, except that the covers were supported at their corners on brackets welded to the intersections of the running rails. This permitted the addition of fine aggregate to fill the cavities around the rails, in an attempt to absorb any noise emanating from the crossing itself.

To assess the degree of success of this design, and to test other alternatives, the Board engaged two members of staff of the Monash University Department of Mechanical Engineering (Dr. H. Nolle and Dr. R. Alfredson) to act as consultants to Board's officers concerned with the design of City tram crossings.

In 1976 three test crossings were installed in one of the Board's test tracks at Preston Workshops. Each crossing was simply the intersection of two perpendicular tracks, so each represented one quarter of a typical City "H" crossing. To establish a reference, one crossing was constructed as a typical rigid crossing - that is, rails cast directly into a non-reinforced concrete slab 270 mm thick.

To establish whether the crossing should be more rigid or more resilient, one of each of these types was also constructed within the test track. The very rigid crossing had bracing rails welded diagonally beneath the running rails and was cast into a concrete slab 760 mm thick. The resilient crossing adapted the same resilient materials and configuration that had been proved successful on resilient straight tracks since 1968 and 1975 (See Figs. 14 and 30). To ensure complete resilience at the rail crossing points the resilient rails extend 5 m beyond all the outer crossings.

The results of these trials (See Fig. 15) indicated that a resilient "H" crossing (on an 18 mm thick continuous grooved rubber pad, and cast into a concrete-to-surface slab) shouldreduce the Peak Sound Level of a tram crossing it by about 4 - 6 dB(A), when compared with either of the rigid crossing alternatives.

These results were better than those of earlier designs so it was decided to construct the next City "H" crossing to the new resilient design (See Fig 30). This crossing was installed at the intersection of Swanston and Flinders Streets in June, 1977 (See Fig. 31). Since then the diamond crossings of the two busiest "Y" junctions of the system have also been renewed with resilient rail.

Since the installation of the new resilient "H" crossing many field noise tests have been carried out in the City to compare its performance with that of other City crossings. At each intersection the observation point was at the footpath in one corner of the intersection (about 18 m from the centre of the crossing). The general result of all these tests is that, when traversed by W class trams with solid wheels travelling at the normal range of speeds in service, the new resilient "H" crossing results in a mean sound levelof 79 dB(A), compared with 85 - 86 dB(A) at the other City crossings. (When traversed by the new Z class trams (resilient wheels), the mean sound levels are reduced by a further 7 dB(A) for all types of crossing).

(A reduction of 10 dB(A) in sound level is equivalent to a halving of the noise level perceived by an observer).

Because sound levels of noise from other sources in the City are usually of the order 65 - 70 dB(A) ("base" level), 75 - 80 dB(A) (motor cars) and 75 - 90 dB(A) (trucks and buses), it is generally not easy to distinguish the noise of trams passing over this resilient crossing (mean 79 dB(A)) through the noise of other traffic. This helps to give an observer a slightly exaggerated impression of it being a "very quiet" crossing.

It is expected that when all crossing ramps are properly machine ground, these (W class) mean sound levels will be reduced to about 77 dB(A) on the new type resilient crossing, and about 82 dB(A) on other City crossings.

From the measurements taken on the original resilient test crossing it was determined that :

i) the resiliently supported rail section of the crossing vibrates at an amplitude of the order of 30 times that of the surrounding concrete slab.

ii) the concrete slab radiates noise mainly at low frequencies below 300 - 400 Hz. On the dB(A) scale this (low amplitude) noise is relatively insignificant.

iii) the rail contributes noise mainly at frequencies up to 700 Hz. Both the higher frequencies and higher amplitudes of the rail vibration make it a fairly significant contributor to the total noise level. The enclosing of all but the rail head and groove in resilient materials cast into a mass concrete slab appears to restrict the ability of the rail to generate a very significant noise level.

iv) the unsprung mass in the tram bogies and the many components making up their complex structure appear to be the main contributors of noise at all frequencies of measurement.

v) although the total Sound Pressure Levels are found to be the same for both the Rigid and Resilient crossings, the Resilient crossing displays a significant shift towards the lower frequencies. That is, the higher frequency vibrations of the (resilient) track bed are attenuated while the lower frequencies are slightly amplified. This shift towards the lower frequencies favours the resilient crossing when the Sound Pressure Levels are expressed on the dB(A) scale.

Since the wheels and rail are in contact it is to be expected that the many components and unsprung masses in the tram bogie also experience a significant reduction in the higher frequency vibrations as a consequence of the resilient material in the crossing. This reduction in bogie noise appears to be the main reason that the overall noise level from this type of crossing is significantly less than that from a rigid crossing (See Fig. 15).

FUTURE TRACK DEVELOPMENTS:

i) Switches:

Work is currently being done on the development of flexible tongued (or heel-less)switches. The existing switches used by the Board have non-flexible tongues (about 3 m long) which rotate about a fulcrum at their "heel". The joint at the heel is a source of noise and maintenance.

The flexible tongued switches are designed to the same (plan) geometry as the Board's standard 45.7 m (150 ft.) radius switches. Each tongue has a relatively broad cross-section at the toe (or mechanism) end but thins out considerably at the "heel" position. Beyond this flexible section the tongue's cross-section changes to that of the parent rail, to which it is welded. While being welded the tongues are set at their outer-most positions - creating a "split-points" configuration. The tongues are then pulled together at the operating mechanism's inter-connecting bar so that their natural setting is in the "half-cocked" position. (The operating mechanism ensures that both tongues are held fully across to either side). This pre-stressing of both tongues helps prevent fatigue failure by ensuring that a reversal in the sign of the bending moments does not occur each time the switches are changed.

The first pair of switches have been installed at a busy point in the service for over 12 months, but apart from needing some minor modifications, appear to be satisfactory.

ii) Plain Resilient Track;

Its possible use on curves (or on the very busy straight tracks) as a long term investment to reduce rail wear, may warrant investigation.

iii) Concreting:

The concrete train, as described, has developed in several stages over many years. Now that its important design features have been established a new improved train is being built.

The possible use of concrete additives which enable the workability of the concrete to be retained while lowering the water content, should be studied.

iv) Open Ballast Tracks:

There are about 16 km of open ballast (double) tracks in the system. The possible development of 'sleeperless' track (as used on European tramways) will be studied, and some other alternatives to the conventional timber sleeper (e.g. C.S.I.R.O. composite sleeper) should warrant consideration.

v) Reconstruction and Maintenance Equipment:

Environmental aspects will continue to be of particular influence in the design of the Board's on site equipment. This applies especially to the conversion of small petrol driven machines to electric operation, and the development of quieter more expedient methods of removing road pavements when required.

vi) Ramped Crossings:

The development of special machines to precisely grind the running surfaces of all crossing ramps is now well advanced. In the immediate future it is expected that these machines will go into regular use removing small irregularities and corrugations in the ramps. Ramps will be slightly over-built by welding, then machine ground at regular intervals until rebuilding is again required.

This work will initially take place at busy rectangular crossings in noise sensitive areas (such as in the City), but the work will eventually extend to diamond crossings and other crossings throughout the network.

By this means, it is expected that noise levels over 'special work' will be reduced by about 5 dB(A), and that ultimately resilient wheeled trams over 'special work' consisting of resilient crossings and heel-less switches will result in noise levels as low as about 70 dB(A) at the footpath. When this is achieved the sounds of trams passing along the streets and through junctions and crossings will seldom be distinguishable over the street's minimum background noise (65-70 dB(A)).

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