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THE DEVELOPMENT OF THE PROTOTYPE ADVANCED PASSENGER TRAIN

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THE DEVELOPMENT OF THE PROTOTYPE ADVANCED PASSENGER TRAIN

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The development and performance of British Railways' three prototype Advanced Passenger Trains (APT-Ps) are discussed. The progression from design concept to construction, commissioning and testing prior to entry into passenger service is described. Performance aspects of the train and its sub-systems are assessed in relation to technical objectives.

The commissioning programme and highlights of the track proving trials are described. Important test results are discussed, including those relating to body tilt systems, ride quality, lateral track forces, braking performance, current collection, and thyristor interference. Account is given of various development problems which arose during commissioning trials and endurance running.

The paper concludes with a brief description of the design of the production train (APT-S), which is planned for fleet operation on BR's electrified West Coast routes.

1 INTRODUCTION

The Advanced Passenger Train (APT) occupies a central role in British Railways' Inter-City business strategy. The prime objective of this strategy is to attract passengers to rail travel by running fast comfortable trains at economic cost to maximize net revenues. The commercial attraction of shorter journey times is now well established. It is planned that most of the Inter-City network will ultimately be operated by 200 km/h trains.

In the late 1960s the Advanced Passenger Train and the diesel High Speed Train (HST) were conceived as the cornerstones of the high speed strategy. Whilst the APT promised a more advanced performance, with its faster curving ability and higher maximum speed, it involved considerable technical innovation and risk. It thus required an extended development timescale. The HST, on the other hand, was an extrapolation of existing technology so that rapid progress through a prototype phase to production was achievable. This was confirmed when in 1976 HSTs successfully entered commercial service.

The programme for APT was envisaged in three phases of diminishing technical risk: (*i*) an experimental phase for research and development proving of the novel technical concepts; (*ii*) a prototype phase to integrate all novel features into a total train design and to prove technical, operational and commercial performance in a limited public service; and (*iii*) a production phase to consolidate all developments into a final train design for series production and fleet operation.

The research origins of APT and the development programme associated with the gas-turbine experimental train APT-E have been described in an earlier paper (**1**). Also described were the considerations which led to the design of the 25 kV electric prototype train (APT-P). This paper continues the account by describing the development and performance of the three prototype trains prior to their entry into passenger service on the West Coast route between London and Glasgow.

2 DESIGN CONCEPT

The APT-P (Fig. 1) has been designed to reduce journey times on the sinuous West Coast Main Line by 15–20 per cent by a combination of both a high maximum speed—up to 250 km/h—and, more importantly, a capability for 20–40 per cent higher speeds round curves. The essential feature of the train is its tilt suspension, which leans vehicle bodies inwards on curves to fully counterbalance centrifugal forces and thereby maintain passenger comfort.

A business requirement for twelve passenger coaches (with potential for fourteen) necessitated two power cars to achieve satisfactory performance, particularly over the severe 1.5 per cent gradients encountered on the route. The prototype train was accordingly designed as a (2 + 12) fixed formation, with the power cars, each of 3 MW tractive power, positioned centrally between two six-car rakes of articulated trailer cars (Fig. 2). This arrangement was devised to permit satisfactory current collection, using a single pantograph, and to avoid excessive suspension buckling forces under traction.

The technical requirements for APT-P and its design features have been described in detail elsewhere (**1–8**). For completeness, however, the major characteristic features are summarized below.

Streamlined train profile Aerodynamic nose shaping, reduced vehicle cross-section and overall surface smoothness produce lower train resistance. This reduces traction power requirements and saves energy. Pressure pulses are decreased, enabling higher speed operation through tunnels. Also, trackside gusts and air-turbulence noise are diminished.

Articulated train configuration Adjacent trailer cars share common bogies (Fig. 3), resulting in fewer bogies

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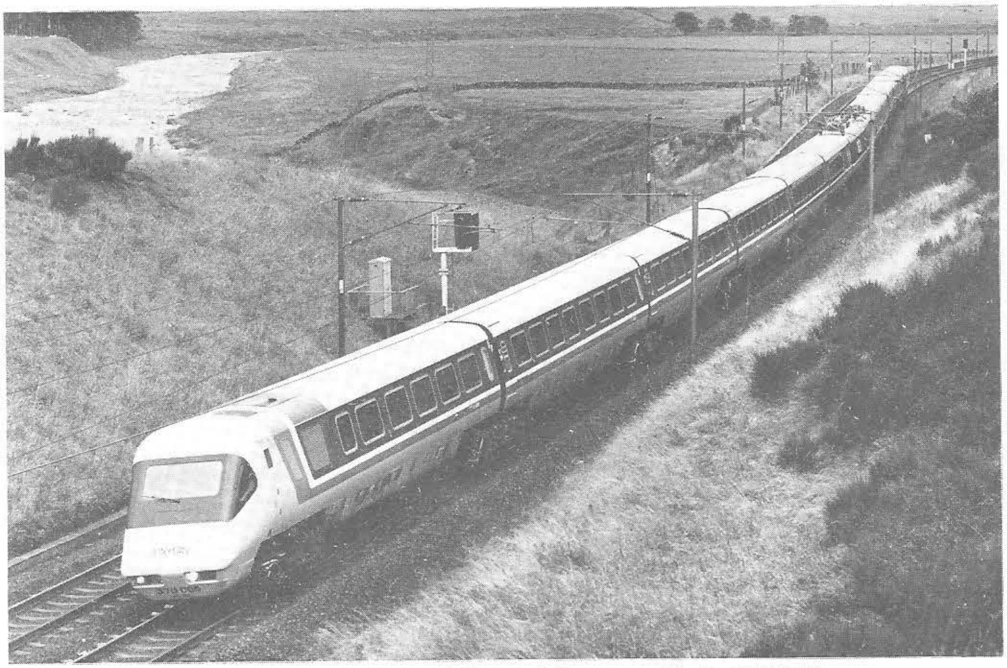

Fig. 1 The prototype Advanced Passenger Train (APT-P) demonstrates its high curving speeds during proving trials on the sinuous West Coast Main Line

and a better weight distribution. The consequent benefits are: reduced train resistance and mass, giving lower energy consumption; reduced wheel-generated noise; better track stability on curves; and lower capital costs.

Active vehicle tilt suspensions Each vehicle tilts independently up to an angle of 9° under the control of a closed-loop electro-hydraulic system. Tilt not only benefits passenger comfort on curves but also reduces track damage and maintains safety margins by retaining vehicles centrally on their suspensions. This reduces dynamic lateral forces on curves and decreases the quasi-static transfer of weight from inner to outer wheels to an acceptable 33 per cent. Tilt is therefore incorporated into both passenger and non-passenger vehicles.

Advanced bogie suspensions Parameters are chosen to give dynamically stable operation with fully-worn wheel profiles, together with the best achievable steering qualities on curves, thus minimizing track stresses and wear. To provide a high standard of ride comfort, coach bodies are isolated from track imperfections by very soft self-levelling air suspensions.

Lightweight bogies All bogies are designed for minimum mass, with special emphasis on attaining very low unsprung mass (1.5 tonne). Low mass is essential for stable riding qualities at high speed and for acceptable track impact forces. A particular requirement for APT on curved track is to generate small dynamic lateral forces relative to axle load, to avoid excessive sideways creep of the track.

Lightweight vehicles The use of lightweight construction techniques and equipment leads to lower train mass and fewer powered axles, so conserving energy. Also, track damage is reduced by ensuring modest loadings on articulated and powered axles. Weight is reduced by fabricating coach bodyshells in aluminium. Also, coach length is saved, without loss of revenue-earning space, by fitting only two power-operated sliding-plug doors, positioned at diagonally opposite corners. Toilet compartments at the remaining two corners have lightweight chemical toilet units.

Low centre of gravity This, together with a low coincident centre of tilt and low centre of pressure, maintains safety margins by avoiding excessive wheel load transfer on curves and under extreme wind conditions.

Hydrokinetic braking The arduous braking duty is handled by compact hydrokinetic fluid brake units which, on trailer cars, are mounted within the axles. These deal with the very high levels of power and energy dissipation, whilst complying with the limitations on unsprung mass and bogie mass. At low speeds the hydrokinetic brakes are supplemented by simple auxiliary friction brakes acting on the wheel treads.

Transmission The 750 kW drive to each powered axle is taken by a mechanical transmission from electric traction motors mounted in the power car body (Fig. 4). Power is transmitted via a body-mounted transfer gearbox, a cardan shaft, a final drive gearbox—fully suspended on the bogie frame—and a flexible quill to the axle. This arrangement enables the low targets for unsprung mass and bogie mass to be met.

3 CONSTRUCTION

Construction of the prototype APTs began in 1976. Because of the novel design features, some development of manufacturing techniques was necessary, as exemplified below.

The major area for development was the aluminium bodyshell. This features extensive use of wide-section extrusions of full vehicle length. These are seam-

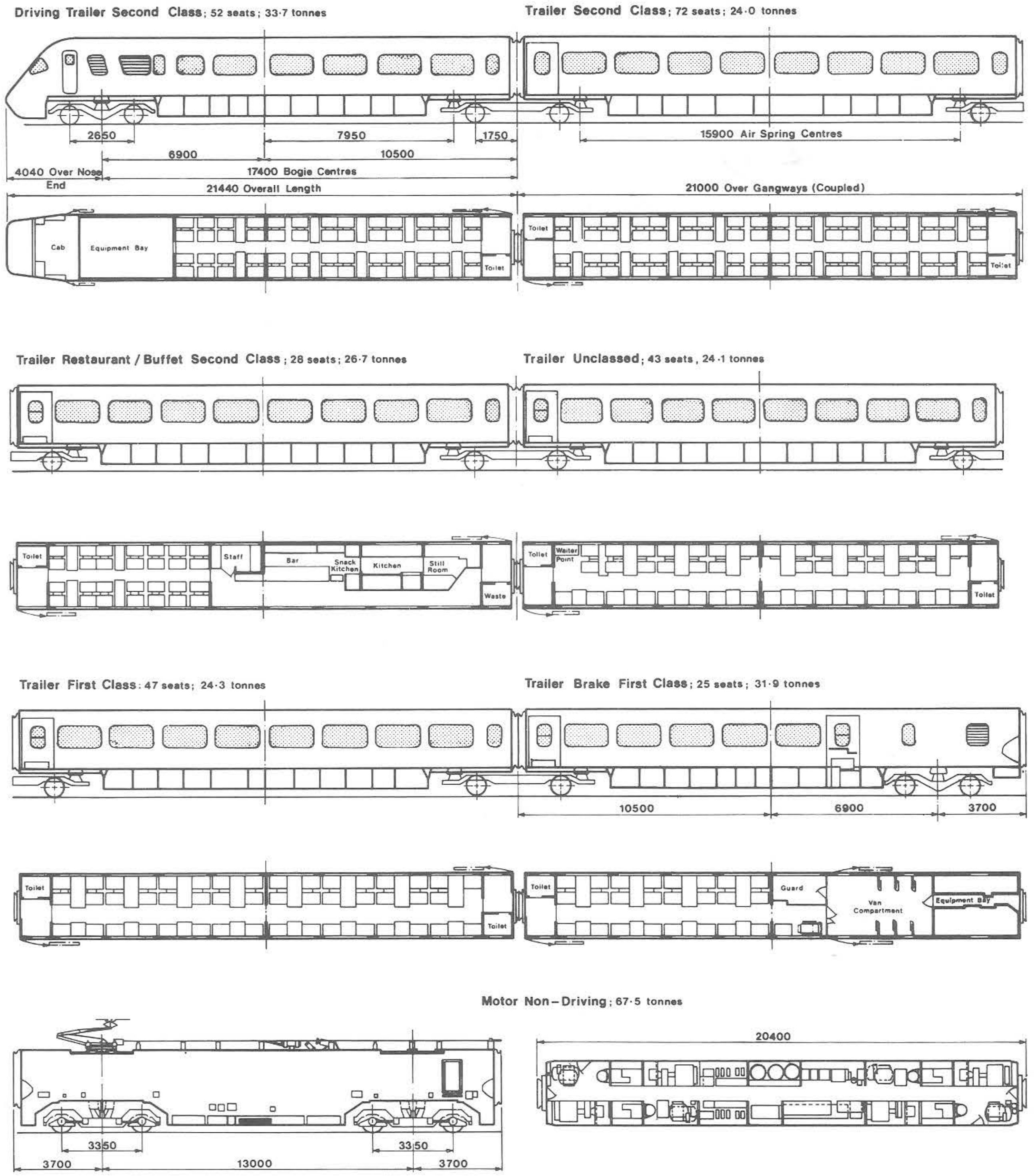

Fig. 2 APT-P prototype train configuration: (2 + 12) formation comprises a symmetrical arrangement of two of the above half-trains

welded together automatically. To develop production methods and welding techniques, a pilot bodyshell was constructed and proved ahead of the main production run (**2**). Tests confirmed that the bodyshell, weighing less than 5 tonnes, met its design strength and stiffness requirements.

As reliable operation of the tilt system depends vitally on a very high standard of oil cleanliness, a means of achieving this in railway workshop and maintenance depot environments had to be developed. Accordingly, a portable oil cleaning machine was designed. This is able to flush dirt from a system at high velocity (7.5 m/s), to clean oil (including oil direct from the supplier), and to measure cleanliness using a non-specialist operator to check oil samples against 'go' and 'no-go' standards. Once clean, oil is maintained to the required standard by the tilt system's own one micron filter.

Articulation introduced the need for special handling arrangements, particularly when marshalling vehicles into rakes. Consequently, a new facility was built for bogieing vehicles. This enables an articulated bogie to

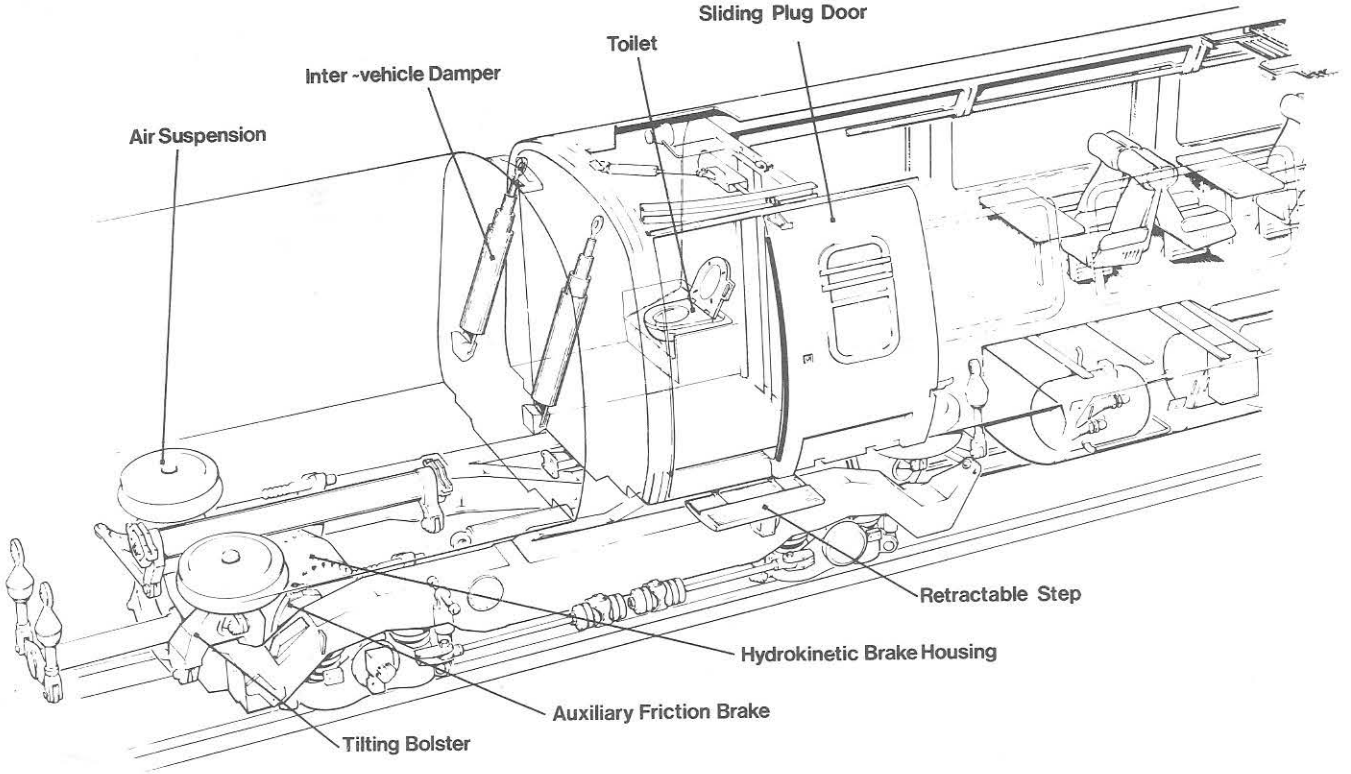

Fig. 3 APT-P trailer car articulation

be traversed into position whilst two vehicle ends are simultaneously raised on jacks.

Deliveries of vehicles for commissioning and track testing began in June 1977, when the first power car was completed. The first rake of trailer cars was delivered in June 1978.

4 COMMISSIONING AND TESTING PROGRAMME

Well before construction of the first vehicles, testing and development of prototype equipment was initiated. As APT-P, unlike APT-E, was electric powered there were several new design features, such as the pantograph, electric traction equipment, mechanical transmission, and a transmission-mounted hydrokinetic brake. The more novel of these, and other major components which differed from APT-E, were subjected to rigorous laboratory and track testing.

Pilot versions of the prototype trailer bogies, brakes, and tilt system were fitted to special test vehicles. Similarly, track testing of the power bogie, mechanical transmission, and the pantograph—mounted on its anti-tilt mechanism—was carried out on a specially converted vehicle. In the laboratory, transmissions were endurance tested in a back-to-back rig, simulating torque/speed profiles for a representative journey cycle. Axle-mounted and transmission-mounted hydrokinetic brakes were exhaustively tested on the laboratory dynamometer.

Once the first prototype vehicles were constructed, a programme of static endurance testing was carried out on several components and systems, particularly those related to passenger environment. Accelerated life tests, involving continuous duty cycling, were performed on air conditioning, tilt systems, inter-vehicle gangways, automatic external and internal doors, chemical toilets and wash basins. For example, vehicles were oscillated continuously through tilt angles of ±7°. Also, the external access door with its retractable step was twice cycled through the equivalent of fifteen years' service operation, enabling reliability to be assessed and design weaknesses to be corrected.

In readiness for commissioning and preliminary track testing of APT-P vehicles, arrangements were made to haul individual power cars and trailer rakes at speeds up to 200 km/h. For this purpose, the two prototype HST power cars were each fitted with a special driving console. This allowed APT test trains to be either diesel-hauled by HST power cars on non-electrified lines or electrically-propelled by APT power cars on electrified lines.

Preliminary testing with the power car and trailer rake test trains was carried out from late 1977 to mid-1979. These tests were principally to eliminate 'teething' problems, to explore thyristor interference effects, to measure pantograph performance, and to assess ride quality. Progress was restricted during this period by a series of industrial disputes.

The first prototype train was marshalled early in 1979 as a short (2 + 6) formation, with two power cars and two three-car trailer rakes. One rake was fitted out as a mobile laboratory with comprehensive instrumentation for performance monitoring and recording.

After further delays caused by industrial disputes, the main series of performance tests took place between mid-1979 and early 1980. These covered braking, tilt response and ride quality, lateral track forces, and high speed traction and pantograph performance. During the latter tests, a maximum speed of 260 km/h (162 mile/h) was achieved.

These tests identified the need for a number of design modifications, particularly to the tilt system, and

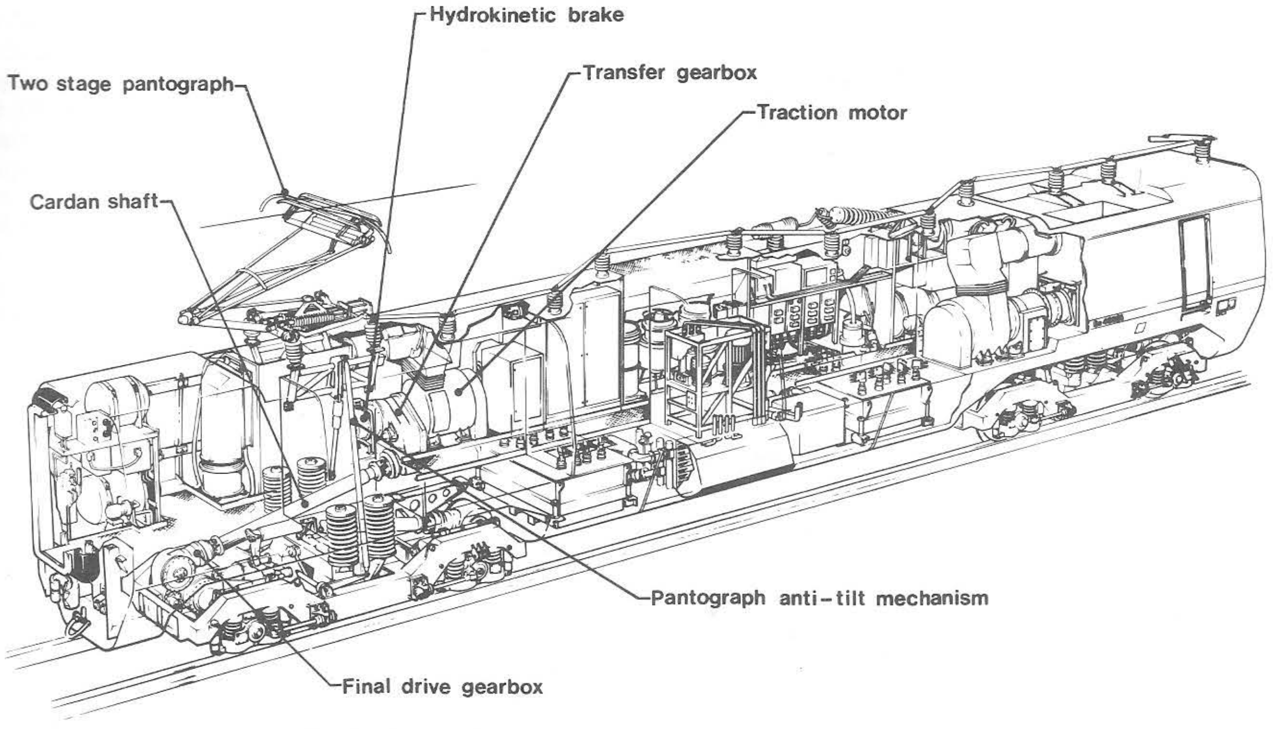

Fig. 4 APT-P 25 kV electric power car: tractive power 3MW

consequently a rolling programme was instituted to modify all vehicles.

In late 1979 the second prototype train was commissioned and committed to an extensive programme of driver training. The third train, when completed in spring 1980, embarked on a programme of endurance running between Glasgow and London to build up mileage, reliability and staff experience prior to entry into passenger service.

Unfortunately, this programme was seriously disrupted when the train suffered the derailment of an articulated bogie whilst travelling at 200 km/h. Fortunately, nobody was injured and both train and track suffered minimal damage—even though the train negotiated a 1400 m radius reverse curve at high cant deficiency before braking to a halt.

The derailment was caused by a broken axle, following failure of a ring of bolts between the conical axle and its central hydrokinetic brake housing. Investigation showed that failure had been caused by mal-assembly, resulting in low-cycle fatigue fracture. Subsequently, assembly and inspection procedures were strengthened to ensure non-recurrence. No further problems have been revealed by continual monitoring of the axle bolts.

With the recommencement of proving trials in mid-1980, momentum was re-established. It was short-lived, however, as new technical problems emerged with the accumulation of mileage. Occasional dragging auxiliary friction brakes caused a number of hot wheels, and instances were discovered where a wheel had moved on its axle. Coincidently, doubts were expressed about the running clearances of the train under particular failure modes of the tilt system. It was therefore decided in late 1980 to suspend running whilst these safety questions were resolved.

This necessitated several months of testing and development activity before mileage accumulation tests were resumed in the spring of 1981. Intensive running at maximum performance was carried out against a ‘ghost’ timetable to enable reliability and maintenance procedures to be developed under approximate service conditions.

By autumn 1981 the three trains had aggregated a distance of 220 000 km prior to introduction into passenger service.

5 TRAIN PERFORMANCE

5.1 Tilt system

Tilt is fundamental to APT. Hence the development of a successful tilt system has been of paramount importance.

Performance requirements are dominated by the transition curves between straight and constant-radius track. The specification requires that each vehicle shall tilt by up to 9° in response to a 5 °/s rate of change of cant deficiency, and a 8.3 °/s rate of change of cant plus cant deficiency, without passengers experiencing more than 10 per cent g acceleration. To achieve the implied high tilt rates, an electro-hydraulic tilt system is used.

The basic problem of the tilt system, as with any closed-loop control system, is to achieve fast response whilst retaining adequate stability margins. Also, unwanted disturbances caused by random track roughness must be rejected to safeguard ride quality and minimize power consumption. In solving these problems, the APT-P tilt system, has undergone three phases of development (Fig. 5).

In the original Mark I prototype system, the accelerometer was mounted on the tilting bolster within the bogie. This provided a mechanical feedback loop to null

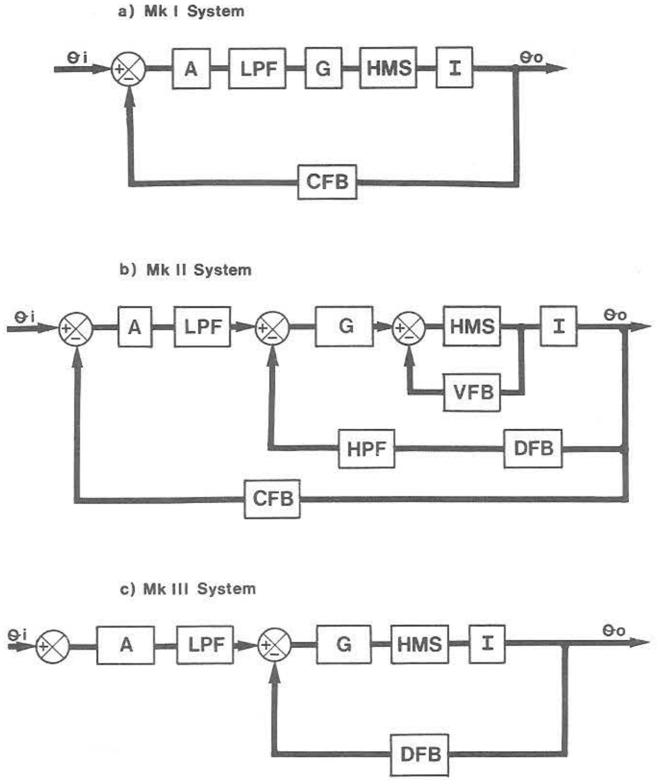

Fig. 5 APT-P tilt control system: the three stages of development

θ_i	tilt demand
θ_o	tilt angle
A	accelerometer
LPF	low-pass filter
HPF	high-pass filter
G	gain stage
HMS	hydromechanical system
I	integrator
DFB	displacement feedback
VFB	velocity feedback
CFB	complex feedback

the accelerometer. A low-pass filter was used to filter out track irregularities. It was found, however, that phase lags were sufficient to degrade stability margins. Hence, gain had to be reduced, so limiting the response capability of the system.

The Mark II system aimed to improve performance by separating out two conflicting problems, that of responding quickly to low frequency tilt demand signals and that of rejecting higher frequency track irregularity 'noise'. A second loop was added to the control system by fitting a tilt displacement transducer and a high-pass filter. The high- and low-pass filters together formed a complementary pair, so that phase lags could be counterbalanced. The second loop minimized high frequency movements of the tilt jacks; and a third loop, with velocity feedback, stiffened up the response of the hydro-mechanical system. The Mark II system gave some improvement in performance. However, the lags inherent in the complex feedback function of the main loop caused the stability margins to still be inadequate for acceptable tilt response rates.

The elusiveness of success using a full closed-loop system led to the Mark III tilt system. In this system, the accelerometer is mounted on the bogie frame, rather than on the tilting bolster, so that it, together with the low-pass filter, is external to the control loop. Tilt feedback is provided via a displacement transducer. Having removed several phase lags from the control loop, the gain of the system can be greatly increased without prejudicing stability margins. Thus, the required tilt rates can readily be achieved.

As the accelerometer is no longer nulled, advantage has been taken of anticipating changes in cant deficiency. The accelerometer for each vehicle is therefore positioned on the leading bogie of the preceding vehicle (except for the driving vehicle). Tilt system performance is optimized for 200 km/h running, which gives roughly half-second anticipation. With this advance signal, the system responds with exceptionally close matching between the actual tilt angle and the ideal.

Comparative track testing of the three tilt systems on APT-P showed that the Mark III system was excellent and by far the superior. The tilt action was smooth and positive, with minimal tilt deficiency through transition curves (Fig. 6). Following the tests, all vehicles were modified to take the Mark III tilt system.

Inevitably, an active tilt system gives rise to various failure modes. The design approach adopted for APT has been to revert a vehicle to its upright position if a system failure occurs.

When the Mark III system was adopted, system duplication was partially impaired because of practical difficulties in modifying existing vehicles. Thus, the chances of a 'hard-over' (9°) tilt failure were increased. To overcome this, a supervisory system for detecting tilt failure was devised. A detection unit mounted in each vehicle body continuously monitors tilt deficiency. If tilt is erroneous by a threshold angle for a set period, the vehicle is actively uprighted. A tilt locking device mounted on the bogie is then engaged, so retaining the vehicle in its upright attitude.

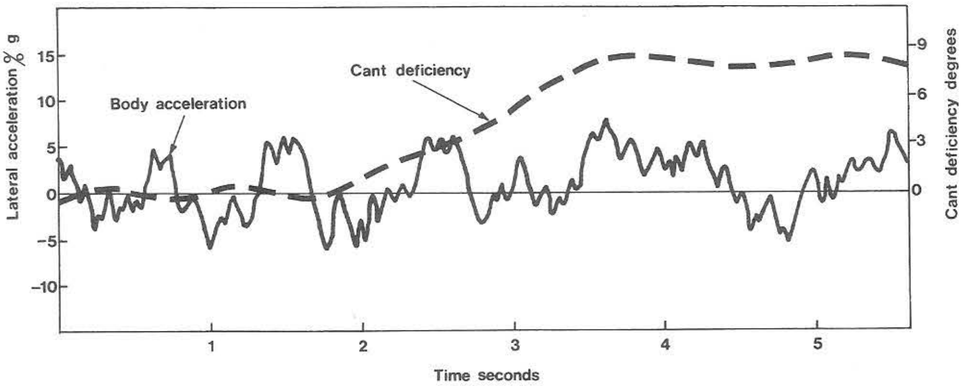

Fig. 6 Tilt response at entry to 1270 m radius curve: speed 195 km/h, cant deficiency 8°, rate of change of cant deficiency 4.5 °/s

5.2 Ride quality

The APT-P bogies are required to have adequate lateral stability margins at all speeds up to 250 km/h, with worn wheel profiles having an equivalent conicity of up to 0.3. During tests up to a maximum speed of 260 km/h, the bogies have not exhibited any signs of hunting instability. The articulated bogie in particular shows itself to be highly stable.

As lateral ride and tilt system performance are closely related, improvements in tilt performance have brought corresponding improvements in lateral ride quality.

One aspect of ride that has proved difficult to satisfy by improved suspension design is related to long (above 40 m) wavelength track irregularities. These are beyond detection and correction by present track maintenance methods. As APT-P suspension frequencies correspond to wavelengths of 45–80 m at 200 km/h, low frequency oscillations can be pronounced on certain stretches of track.

Vertical ride development has been concentrated mainly on the articulated bogie. To compensate for the outboard positioning of the secondary suspensions, the air springs were designed to be very soft, with auxiliary surge reservoirs to provide damping. Nevertheless, the vertical ride was found to be unsatisfactory, even after tuning the air suspensions and increasing their volume. Body pitch oscillations were excessive, particularly at low speed, when large gangway shear movements were induced by resonance with bogie pitch oscillations. These problems were solved by fitting vertical hydraulic dampers between the ends of adjacent vehicles. These inter-vehicle dampers also slightly improved the ride about the roll axis.

On average good quality track at 200 km/h, the measured r.m.s. values of ISO weighted body accelerations were typically 2.0–2.5 per cent g laterally and 2.5–3.0 per cent g vertically. Further development tuning of stiffness and damping characteristics is expected to bring additional ride improvements.

Suspension tuning will similarly further improve vehicle interior noise levels.

The design limits of 68 dBA and 76 dBB for the passenger accommodation have in general been met towards the centre of the coach. Towards the coach ends, however, the acoustic environment is not yet entirely satisfactory because of low-frequency structure-borne sound transmitted via the connections between bogie and body.

5.3 Track forces

As tilt is fundamental to APT, so is the attainment of acceptable lateral track forces. Higher curving speeds generate higher centrifugal forces, which must be reacted by the track. To compensate, the objective has been to decrease dynamic forces, so that the total forces (quasi-static plus dynamic) are comparable with those for conventional trains. The design aim has therefore been to keep bogie mass low in comparison with axle load, the latter being the major track stabilizing force.

Detailed investigations into track strength and into curve movements under traffic have been undertaken, with a view to establishing criteria for acceptable lateral track forces. A simple criterion which may be used as an indicative check is the Prud'Homme formula which, for concrete-sleepered main line, suggests a lateral force limit of $L = (10 + P/3)$ kN, where P is axle load.

To determine the acceptability of APT-P, a series of comparative tests was carried out. These compared the lateral forces generated by APT-P with those of a Class 87 locomotive over a sequence of seventy-two curved and straight sites between Glasgow and Carnforth. The two test trains were run at their limiting speeds: 200 km/h and 9° cant deficiency for APT-P, and 160 km/h and 4¼° cant deficiency for the Class 87 locomotive. Lateral track forces were deduced from measurements of primary lateral suspension forces, H, and wheelset accelerations, $\ddot{y}$, giving $L = H + m\ddot{y}$, where m is the lateral unsprung mass.

A favourable comparison was demonstrated between the APT-P power car and the Class 87 locomotive (Fig. 7). The peak lateral forces were similar at their respective maximum cant deficiencies of 9° and 4¼°, and were generally contained within the Prud'Homme criterion.

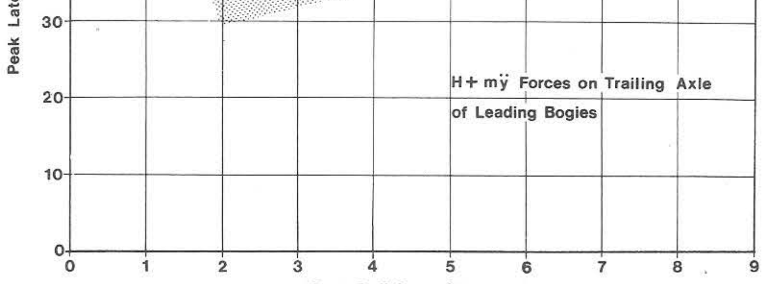

Fig. 7 Envelope of peak lateral track forces: comparison of APT-P with Class 87 locomotive

However, because of its higher cant deficiency operation, APT-P spent comparatively more time at the higher force levels. On straight plain track, APT-P lateral forces were only half those of the Class 87 locomotive. Similar results applied at points and crossings.

The APT-P trailer bogies generated comparatively low lateral track forces, and these were comfortably within the Prud'Homme criterion. They were lower than the power bogie forces by more than the proportional difference in axle loads. This resulted principally from the better isolation provided by the soft 'flexicoil' primary lateral suspensions on trailer bogies.

The comparative lateral force tests confirmed the superior dynamic performance of APT-P. Accordingly, APT-P was sanctioned for operation at 200 km/h and 9° cant deficiency without restrictions, other than those applied to conventional trains at standard speeds.

5.4 Braking

The braking system has been designed with the potential to stop APT-P from 250 km/h with an average deceleration rate of 14 per cent g, assuming adequate adhesion (**6**). However, as the maximum operating speed is limited initially to 200 km/h, the minimum braking requirement is the same as for HST.

The service braking distance from 200 km/h (125 mile/h) is 2039 m on level track under all track and weather conditions. The design average deceleration rate from this speed is 9 per cent g, corresponding to a stopping distance of 1768 m. There is therefore a 15 per cent contingency, which includes allowance for repeated applications of wheel slide prevention (WSP) equipment (**9**) under adverse adhesion conditions.

To retain a performance margin, APT-P has aimed to meet the above 'wet' and 'dry' stopping distances with 10 per cent of brakes isolated.

Braking tests were carried out over the relevant speed range in both wet and dry conditions, and with the rails treated with a 1 per cent detergent solution to simulate worst adhesion conditions. With dry rails, a stopping distance of 1675 m was achieved from 200 km/h with 90 per cent nominal braking effort. The test results for all rail conditions (Fig. 8) show that the performance objectives were successfully met. The results imply that with 100 per cent braking APT-P could operate at 210 km/h within existing minimum signalling distances for 160 km/h trains.

At high speeds the braking performance of the train was particularly impressive. The hydrokinetic brakes demonstrated smooth and powerful braking characteristics, well liked by drivers.

5.5 Train resistance

The train resistance characteristics for APT-P were estimated from running trials with APT-E and by wind tunnel experiments (**10**). The total resistance to motion in still air conditions on level track is predicted to be:

$$\begin{aligned} R = {} & (450 + 880\,N_p + 380\,N_t) \\ & +(7.9 + 37.1\,N_p + 5.8\,N_t)\,V \\ & +(1.8 + 0.825\,N_p + 0.571\,N_t)\,V^2 \text{ Newtons} \end{aligned}$$

where V is train speed (m/s) and N_p and N_t are the numbers of power cars and trailer cars in the train formation ($N_p + N_t \geq 7$).

To date it has not been possible to verify accurately the above resistance equation, because of the difficulties inherent in testing on the West Coast Main Line with its frequent severe curves and gradients. During high speed testing up to 260 km/h, there was reasonable correlation between predicted and actual acceleration profiles. However, as the high speed test section was only 20 km long, of variable gradient, and included five curves taken at between 9° and 12° cant deficiency, conditions were not ideal. Further resistance tests, under more favourable conditions, are planned.

5.6 Current collection

To achieve satisfactory current collection on overhead line equipment originally designed for only 160 km/h, improved pantograph performance was required. Initially, the pantograph was designed with a three-stage suspension, incorporating a lightweight head and a long-travel secondary suspension. The tertiary suspension was removed, however, when tests showed that it conferred no benefits.

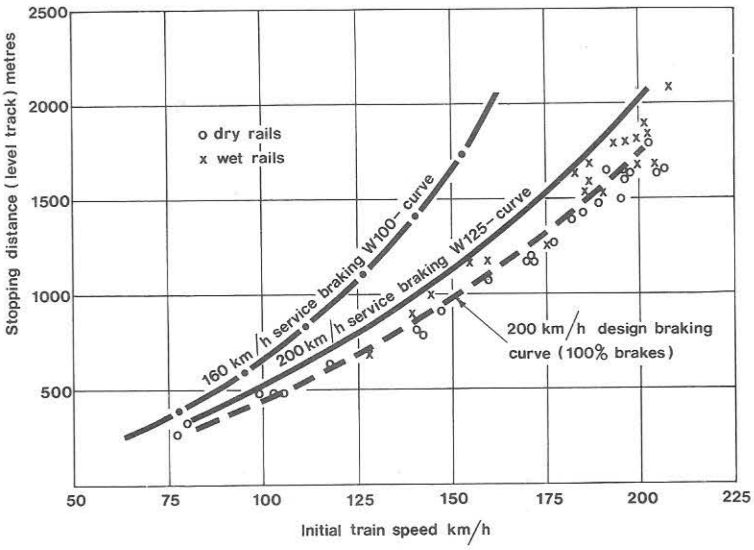

Fig. 8 APT-P braking performance (with 10 per cent of brakes isolated)

Performance at 200 km/h was found to be generally satisfactory, being as good as the standard pantograph at 160 km/h. There were, however, a number of discrete locations, particularly at neutral sections, where carbon contact strips were chipped as a result of excessive impact forces. Because neutral sections were massive compared with the pantograph head, the only solution was to improve the overhead alignment. Accordingly, an improved design of neutral section was fitted throughout the route, enabling APT-P to be fully cleared for 200 km/h running.

Testing at higher speeds indicated that pantograph performance was ultimately limited by aerodynamic uplift. This, in fact, was the feature which limited the high speed tests at 260 km/h. An alternative pantograph with more neutral aerodynamic properties and potentially better current collection performance is presently being developed.

The pantograph anti-tilt mechanism, which maintains the pantograph centrally over the track as the power car tilts, has performed as designed and without any problems.

5.7 Thyristor interference

As previous experience with thyristor-controlled electric traction equipment was limited, extensive tests were undertaken with the APT-P power cars to explore interference effects on trackside telecommunication and signalling circuits. Tests were carried out over a wide range of traction conditions within a feeder section. Train formations with single and double power cars were used together with diode locomotives and BR's only other thyristor locomotive (87101).

The results showed that the interference on telecommunications with a single power car was satisfactory. With double power cars, the interference was acceptable for the prototype trains, but for fleet operation some improvement in immunization might be necessary. No interference problems were experienced with the signalling circuits. Maximum psophometric currents measured on APT-P power cars were typically 8 A and 12 A for single and double power car trains (**8**).

In general, the performance of the electric traction equipment has proved successful, there having been only a few minor problems.

6 DEVELOPMENT PROBLEMS

Besides the development problems associated with train performance, other technical problems became evident during commissioning trials and endurance running. These arose from deficiencies in the functioning, reliability, and maintainability of various systems and components. Whilst often mundane in character, these development problems were equally important to the total APT-P programme. The most significant problems are discussed below.

6.1 Brakes

Early in the test programme a design weakness in the trailer hydrokinetic brake became evident when blades disintegrated within the aluminium brake toroids (Fig. 9). The fault was traced to the loosening of small dowel pins in the fluid seal units. Interestingly, the collapse was totally contained within the toroidal shells, causing no further structural embarrassment. Reliability analysis (**11**) indicated that brakes were only likely to fail within the first 8000 km of running. Therefore, after a minor design change, a campaign modification of wheelsets was instituted on a last-in/first-out basis. As safety was not in question, test running was continued, utilizing to good advantage the performance margin available on braking.

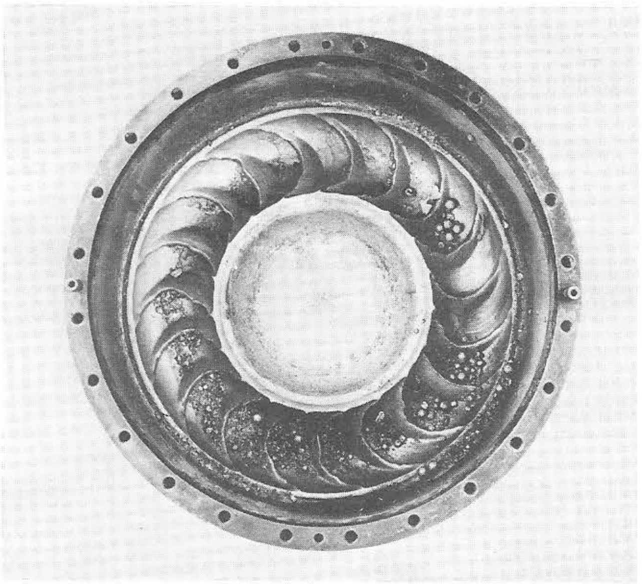

Fig. 9 Failed hydrokinetic brake toroid after blade disintegration

Ironically for a high speed train, braking at low speed has proved the most problematic. Initial control problems of blending the auxiliary friction brake, to compensate the hydrokinetic brake's declining characteristic at low speeds, were soon resolved. However, reliability problems which caused dragging friction brakes and shortfalls in slow speed braking effort proved more intransigent.

Several sources of brake unreliability were identified in the control system and in the brake actuation and slack-adjuster mechanisms. Consequently, design modifications and improved maintenance procedures were initiated. Dragging brakes, however, although not an unusual problem on existing trains, led to more severe consequences for APT-P because of its smaller wheels of lower thermal capacity. Cases were discovered where excessive heating of a wheel rim had relieved the interference fit between wheel and axle sufficiently to permit axial movement.

As an interim solution, a brake monitoring system was installed to warn of a dragging brake by detecting errors in brake arm position and brake fluid pressure. In addition, as a final safeguard, all wheels were fitted with collars to restrain axial movement. Longer term solutions are being pursued. These include the possibility of dispensing with tread brakes and fitting light-duty auxiliary disc brakes.

6.2 Tilt reliability

In changing to the Mark III tilt system, as described earlier, problems arose because of a delay in the development of the supervisory tilt failure detection unit. Until that unit was fitted and proved, the risks of uncorrected hard-over failures were substantially

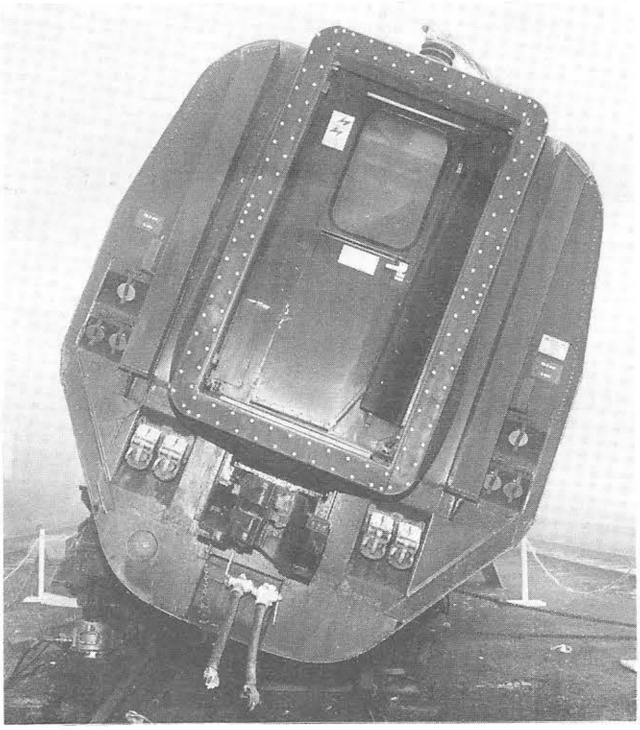

Fig. 10 Power car undergoing kinematic envelope test, simulating hard-over tilt failure under maximum cant deficiency

higher. There was thus the need for firm assurance that running clearances along the West Coast route were adequate for APT-P if this rare failure mode occurred.

Static tests simulating vehicle behaviour up to 9° cant deficiency with 9° hard-over tilt failure were carried out (Fig. 10). The measured displacements confirmed the accuracy of the calculated kinematic envelopes. The kinematic envelopes for APT-P and other vehicles were used in conjunction with geometric data on lineside structures and track spacings, together with speed profiles, to check running clearances. These studies confirmed that the clearances were adequate for APT-P to run with minimal restriction.

Track proving tests on the tilt failure detection units have demonstrated that injected 9° hard-over tilt failures are quickly detected and corrected. To improve the situation still further, it is planned to fully restore duplication of the tilt system at the earliest opportunity, so that the risks of hard-over failure become negligible.

6.3 Mechanical transmission

The lightweight final drive and transfer gearboxes are both dry sump designs, which rely on forced lubrication and balanced scavenging. Even though laboratory development had resolved some lubrication and labyrinth sealing problems, further problems became apparent with track running of the first power car. At very low speeds heavy oil losses occurred from the lower labyrinths on both gearboxes. Priming problems and imbalances in pump outputs were solved only after prolonged development.

Once full-duty endurance testing commenced over the full Glasgow to London route, several gearbox failures occurred. Failure diagnosis led to a number of design modifications and improvements in maintenance procedures. Provision was made for more effective protection against lubrication system contamination, and for better maintenance facilities and access. Also, after tests which indicated excessive oil temperatures in the transfer gearbox, oil coolers were fitted. These had been provided for in the original design, but until then they were not deemed necessary.

A secondary development problem associated with the transmission system is that of longitudinal train vibrations. These are induced intermittently whilst under traction at moderate speeds. Whilst not yet resolved, the problem appears unrelated to dynamic torques in the transmission. Measurements have confirmed that these are very small, consistent with the excellent kinematics of the final drive suspension.

6.4 Passenger amenities

The power-operated sliding-plug doors for passenger access have required considerable development. To promote passenger safety, actuation forces have to be limited, which conflicts with the requirements for reliable operation. This conflict is accentuated by manufacturing tolerance problems in fitting a very wide door to APT's curved body profile, by the need for an automatic retractable step, and by the provision of pressure sealing. Special attention to sealing has been necessary to resist the entry of excessive air-borne noise into the coach end.

Various developments and modifications relating to vehicle interiors, toilets, air conditioning, and catering facilities have been progressed during commissioning and proving trials. The thorough testing of passenger amenities, however, awaits their regular use in passenger service.

7 SERVICE INTRODUCTION

When introduced into passenger service, APT-P will operate a single daily return service between Glasgow and London at a maximum speed of 200 km/h. The journey time, with two intermediate stops, will be 4 h 15 min. This is comparable with 5 h 10 min for conventional 160 km/h trains.

The permissible speed profiles for APT have been embodied into the route by installing 2000 transponders on the tracks. These control a special speed advisory system, which provides a continuous display of permitted speed in the cab (**4**).

Initially, the train will operate as a (1 + 8) formation, comprising a six-car trailer rake and a power car (as in Fig. 2) plus a two-car rake having a driving trailer. As passengers will be accommodated in the six-car rake only, the train capacity will be half that of the (2 + 12) formation. Once the service is established, the train capacity will be increased.

In the interests of a balanced overall programme, it is no longer planned to introduce a second daily APT-P service, as originally envisaged. Consequently, the second train will be used as a maintenance spare, leaving the third train available to cover workshop overhauls, modifications, and development testing in support of the production train programme.

The operational base for the prototype trains is Glasgow. Servicing and light maintenance are undertaken at Polmadie depot, and heavy maintenance is carried out at Shields depot. Apart from modifications

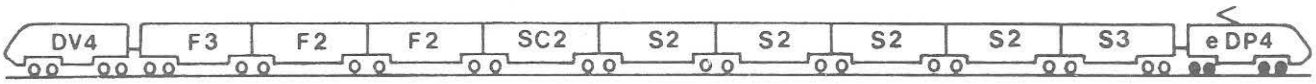

Fig. 11 APT-S production train configuration: (1 + 10) formation
F2, F3 first class trailers (47, 33 seats)
S2, S3 second class trailers (72, 60 seats)
SC2 unclassed catering car (28 seats)
eDP4 25kV driving power car
DV4 driving van trailer

to the washing plant, to facilitate washing of the APT body profile, all special provisions for APT maintenance are located at Shields depot.

In maintaining an articulated train it is essential to be able to replace modularized equipment packs rapidly. Accordingly, an overhead crane was installed for replacement of power equipment packs; and fork-lift facilities were provided for side access to underbelly packs, such as tilt hydraulics and air-conditioning. As wheelset assemblies are also treated as replaceable packs, a wheel-drop facility has been installed.

Other maintenance support facilities include brake and tilt system diagnostic rigs, and automatic test equipments for brake and power control electronics (**7**, **8**).

8 PRODUCTION TRAIN

Prior to embarking on the design of the production train (APT-S), the business requirements for fleet operation on the West Coast routes were re-assessed. This study concluded that the best returns on total investment were realized by operating shorter and lower-powered trains than the fourteen-car 6 MW prototypes. This conclusion led to a revised train configuration for APT-S.

By adopting a shorter and lighter train formation, weighing about 400 tonnes, only one power car is needed to negotiate the 1.5 per cent gradients on the London to Glasgow route. Furthermore, the use of a single power car avoids the problems associated with multi-pantograph operation and excessive propulsive thrust that led to the central positioning of the two power cars in the prototype train formation. It was therefore concluded that the optimum formation for APT-S was a (1 + 10) formation, with one power car and ten trailer cars. Additionally, the opportunity has been taken to reposition the power car at the end of the train, so increasing revenue-earning space, improving passengers' freedom of movement, and easing catering arrangements.

An implication of adopting the (1 + 10) train formation is that of limiting the maximum speed potential to 225 km/h (140 mile/h). Studies have shown, however, that the savings in journey time for speeds higher than this are limited on the West Coast routes. Nevertheless, if commercially required, higher speed operation could be achieved on less sinuous routes. This would require either a shortened train formation or the use of two end power cars, with dual pantograph operation under high-performance overhead line equipment.

The production APT (Fig. 11) comprises a single rake of nine articulated trailer cars between a four-axled driving power car at one end and a four-axled driving trailer car at the other. Passenger accommodation is provided only in the articulated rake; power equipment is located only in the driving vehicles. These vehicles can be readily detached from the articulated rake for heavy maintenance purposes.

A single articulated rake has been adopted to minimize design changes between APT-P and APT-S, and to maximize train performance by reducing mass and aerodynamic drag. Intermediate vehicles, including the single catering car with kitchen and buffet facilities, derive directly from APT-P. The outer vehicles, however, differ at their outer ends and are designed to provide passenger access doors on both sides, wheelchair accommodation, and an above-floor equipment bay.

The major change to the power car for APT-S is clearly the addition of a driving cab. A further change is that of installing the primary auxiliary power supply within the power car. These changes necessitate a revised equipment layout, including some re-arrangement of the body-mounted transmission.

The driving trailer car, whilst being a new design, is structurally similar to the power car, being made of steel. It also incorporates the same cab design. The driving trailer houses a large parcels van area, with multi-door access, a guard's compartment, and secondary auxiliary power supply equipment.

9 CONCLUSION

The APT project is now well advanced through the prototype phase and is on the threshold of the production phase.

The technical proving trials with APT-P have successfully demonstrated that the required advanced performance can be achieved within the constraints of the existing track and infrastructure. Not unexpectedly, there have been some development problems, but these have yielded to sustained technical effort. Technical success has now to be translated into commercial success in passenger service.

Authorization of the production fleet awaits successful service operation with APT-P. Once achieved, APT will be poised to fulfil its planned strategic role as mainstay of the future Inter-City fleet.

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