Design & Construction of Roller Coaster Rides

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Introduction

For many hundreds of years, and across the developed world, mankind has enjoyed the pleasures of "fairs", initially on a travelling basis but for more than three hundred years in Europe and then the USA also at fixed fairgrounds. During the last century or so the introduction of mechanical passenger carrying devices at fairgrounds has tested to the limit both the skills and ingenuity of ride designers and builders, and also the capacity of humans (body and soul) to be thrilled to the point of near fear whilst actually being kept safe and sound.

This paper traces the development of modern 'fast and furious' rides (particularly roller coasters), provides a basic description of how they operate by reference to both ride performance and human tolerance, and finally examines some very recent developments in ride technology.

Historical Review

In a loose sense fast "gravity-powered" rides, which are now generically termed roller coasters, derive from ice slides constructed in Russia from the mid seventeenth century onwards. Elevated toboggan runs were constructed using a timber framework and an ice surface, and of course at the end of each run the toboggan had to be manhandled back up to the top of the slope again. In France, where a reliable period of freezing conditions was not available, similar constructions (inspired by the Russian ice slides) were built wholly from timber and the toboggans were fitted with wheels. The first example opened in 1804 and was called, predictably, "La Montage Russe". Within the next twenty years or so major timber toboggan rides were built in a number of "pleasure parks" in France and around Paris in particular.

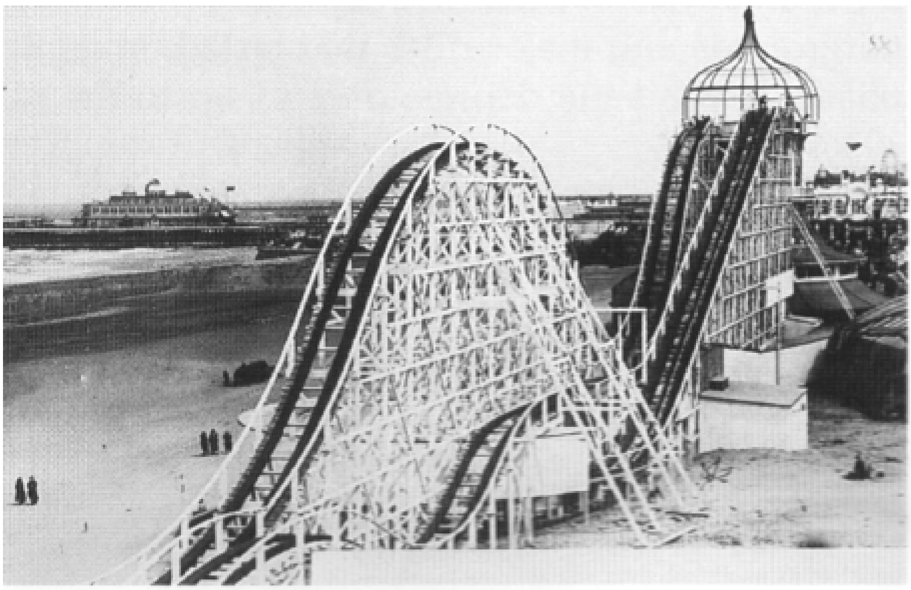
Wheeled Toboggan Slide, Beaujon Garden

In 1870 in Philadelphia an abandoned coal mine provided the opportunity for the conversion of a mine train to carry passengers over an eighteen mile route down a hillside - definitely a "gravity powered ride" although perhaps not a true roller coaster. The first purpose-built "switchback railway" was constructed in 1884 at
Coney Island, New York laying the foundation for a massive explosion of both fixed fairgrounds and major rides that lasted, in its first phase, beyond the depression and up to the mid 1930s.

1884 Coney Island, Switchback Railway

This first switchback railway was built by L.A. Thompson, was a staggering financial success
, recovering its construction cost in about 20 days and carrying about 12,000 passengers a day. Within two years numerous innovations had been introduced, including the use of a continuous loop of track and a chain lift to take the cars to the high point of the ride. In 1885, less than 12 months after the Coney Island ride, a switchback railway was operating here in the UK, on the beach at Skegness - designed, built and owned by the L.A. Thompson company. By the turn of the century over one hundred such timber roller coaster rides were operating at both major cities and holiday resorts around Great Britain. One of these was a switchback railway built in 1891 on the sand dunes at Blackpool, which stood there until 1921 when it was demolished to make way for another, larger, timber coaster - the Big Dipper - which is still operating today.

The Big Dipper was the first ride in Europe to incorporate an American patent - the use of under wheels to allow the cars (and therefore the passengers) to be subject to negative g forces (i.e. weightlessness) on the crests of hills.



Big Dipper, Blackpool Pleasure Beach

By the middle of the 1930s timber coaster construction had reached its zenith, with over 1,200 rides operating in the USA and more than 200 in Great Britain.

The depression and the second world war combined to produce a decline in the fortunes of fairgrounds which was not reversed until the opening of Disneyland in Arnheim, California in July 1955. Actually, Disneyland was not an immediate success - it was constructed at more than 50% over-budget ($17 million) and on the first day more than 30,000 visitors led to near chaos. By the next season the problems were resolved and over 4 million visitors attended that year, generating $16 million in income. Surprisingly, however, few other entrepreneurs were tempted to copy this updated fairground - the first modern theme park - for at least another decade. It is probably no coincidence that the start of this "second phase" of fairground mania (still evident today) occurred at the same time as the baby-boom years following 1945. Interestingly, Disneyland and Disneyworld remain dominated by adult visitors, who outnumber children by 4 to 1.

Whilst not renowned for major rides, Disneyland in fact provided the next major step forward in coaster technology. In 1959 the Arrow Development Company built (to Disney designs) a steel roller coaster where the train wheels ran on circular steel tube tracks. Previous rides (for example, the Cyclone of 1927 at Coney Island and the Steel Stella of 1937 at Clacton) had used a steel structure but the tracks remained in familar timber construction.

Use of steelwork opened up the possibility of more complex track geometry and in l975 the Corkscrew at Knotts Berry Farm, California incorporated a loop or inversion with riding (albeit briefly) upside down at the crown of the loop. Once again, this development spread rapidly arriving in Europe in 1979 when the Revolution ride opened at Blackpool Pleasure Beach (Less than 100 metres from the site where, in 1891, the 'Switcback Railway had similarly crossed the Atlantic). Actually, inverted loop tracks have a history going back about 150 years, although at that time these were ridden by professional riders as a show, and the public paid to watch rather than take part - an action probably considered sensible by a sizeable minority of the population today.

Revolution, Blackpool Pleasure Beach

In the last two decades steel coasters have been built in a number of formats such as:

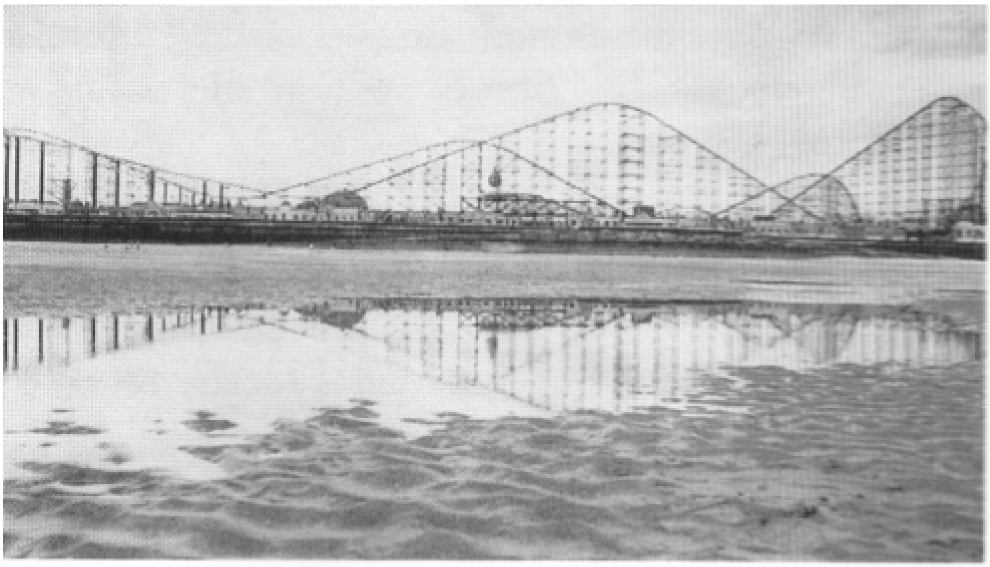
suspended coasters
stand up coasters
toboggan coasters
pipeline coasters

and in addition the maximum height (and consequently the input energy and resultant speed) has increased steadily throughout this period. These developments will be reviewed next.

Ride Types

Roller coasters can be categorised initially as timber or steel on the basis of the track construction. Most timber rides have a "traditional" timber support structure and utilise mine-train-type cars that bear a remarkable resemblance to coaster cars from the 1920s. These cars typically seat either 4 or 6 people and are run in series as a train with anything from 2 to about 7 cars.

Steel rides use two circular steel tubes as the track in place of the traditional timber track and normally use a steel supporting structure. As has been already briefly mentioned, the first steel coaster was built in 1959 at Disneyland, California (The Matterhorn, Arrow Development Company). This was followed by a succession of steel track "runaway mine train' types of ride that are still popular today. Current examples are the Pepsi Max Big One at Blackpool (1994) and the Magnum XL-200 at Cedar Point, Ohio (1989) which are both major steel structures over 60m high. The tradition of building replica steel-tracked "runaway mine trains" with timber support structures continues, for example "The Ultimate" at Lightwater Valley (1991) and "El Diablo" at Port Aventura, Spain (1996).

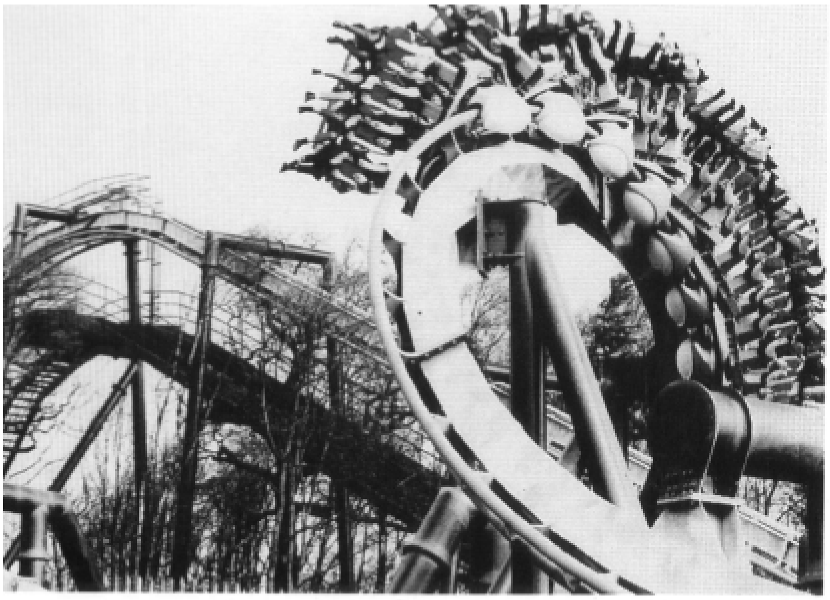


Pepsi Max Big One, Blackpool Pleasure Beach

Steel tracked looping coasters, which invert the car (and hence the passengers) in a variety of loop profiles, were "introduced" in the USA in 1975 (Corkscrew, at Knotts Berry Farm, California, now re-created at Silverwood Theme Park, Idaho). The first in the UK was built in 1979, the Revolution at Blackpool Pleasure Beach. Looping rides are not new however. Examples of circular loop rides from the mid l9th century operated at fairground or pseudoscientific shows, carrying professional riders - the public paid to watch rather than participate! Around the turn of the century some short-lived examples existed in the USA (for example the "Loop-the-Loop", 1901 at Coney Island) but these were not really successful. The majority of steel coasters now incorporate multiple "loops" of different geometry, a good recent example being the "Dragon Khan' at Port Aventura (1996) which includes 8 inversions per ride.

Dragon Khan, Port Aventura

In suspended coasters, as the name implies, the car is slung below the track, running on a chassis / wheel assembly at track level. Two main variants exist. The first suspended coasters were built in the USA by Arrow Dynamics and feature a car on a pivoted suspension system with shock absorbers / dampers to control the rate of lateral pivoting. One such ride exists in the UK, the Vampire (1990) at Chessington World of Adventures. The second type adopts rigid connection between the chassis and the seating and in fact dispenses with a car body altogether; passengers sit in individual seats, their legs freely trailing, ski-lift fashion. In the UK this ride type is represented by the Nemesis (1994) at Alton Towers, designed and built by the Swiss firm of Bolliger & Mabillat. This ride and similar US versions also invert the suspended cars, thus combining two types of coaster into one.



Nemesis, Alton Towers

Stand-up coasters were introduced in 1984 ("King Cobra" at Kings Island, Cincinnati) but interestingly this ride was designed and built by a Japanese firm, and subsequent stand-up coasters, such as the "Vortex" rides at Great America, California (1991) and Carowinds, North Carolina (1992) are also "imports" to the home of roller coasters, being designed and built by a Swiss firm. In the UK the genre is represented by a single example - the Shockwave (1994) at Drayton Manor, again a Swiss ride.

Vortex, Carowinds, North Carolina

Toboggan coasters differ from other steel coasters in that the cars run inside a semi-circular trough formed from small diameter steel tubes. The cars are free to move sideways and as a result they take up a location on the trough that reduces lateral forces to a minimum, giving a smooth ride compared to some other coasters. A modern example, the only such ride in the UK is the Avalanche (1988) at Blackpool Pleasure Beach, but a well known predecessor (with a trough built of timber strips) operated at Coney Island, New York in the 1930s.

Avalanche, Blackpool Pleasure Beach

Pipeline coasters (sometimes called "heart-line" coasters) place the car body/passenger centre of gravity at track level rather than above it (in conventional coasters) or below it (in suspended coasters). Whilst this produces an inherently stable configuration that would allow excellent '"handling" characteristics" on this type of ride the cars are rotated about their own longitudinal axis. In so doing they breach the physical rules applying to all other coasters, where the lateral track tilt (or camber) is designed to balance out the lateral forces generated by lateral centripetal motion. Design of totally fail safe passenger containment is therefore critical in a pipeline coaster since at numerous points in the ride the passengers would actually "fall out" of the car if not so restrained. No public access rides of this type yet exist in the UK or the USA, although a demonstration ride exists at the factory of Arrow Dynamics near Salt Lake City, Utah.

Ride Performance.

The basic phenomenon common to all coasters is the utilisation of centripetal motion to impose variable forces onto the passengers. It is common practice to 'normalise' such forces by reference to an acceleration of lg (about 9.85 metres/second^2) but this has led to widespread misunderstandings about the effect and particularly the direction of such accelerations and associated forces.

From Newton s Laws of Motion, we know that:

Force = mass x acceleration

and we also know that centripetal acceleration = $\frac{V^2}{r}$

Where V = velocity

r = radius of motion

On the characteristic vertical ride profile of "dips" and "crests", the car is travelling on a "circular" path (at least instantaneously) and is therefore subjected to downward (dip) or upward (crest) acceleration, normal to the direction of travel. If the track is straight on plan and uncambered then it is easy to analyse the ride performance. For example, if the centripetal acceleration at the bottom of a dip is 30m / sec^2 (or 3g) down then the net normal acceleration is 4g (3g from centripetal action, lg from gravity) and the passengers will feel four times heavier than normal (Fig. 1).

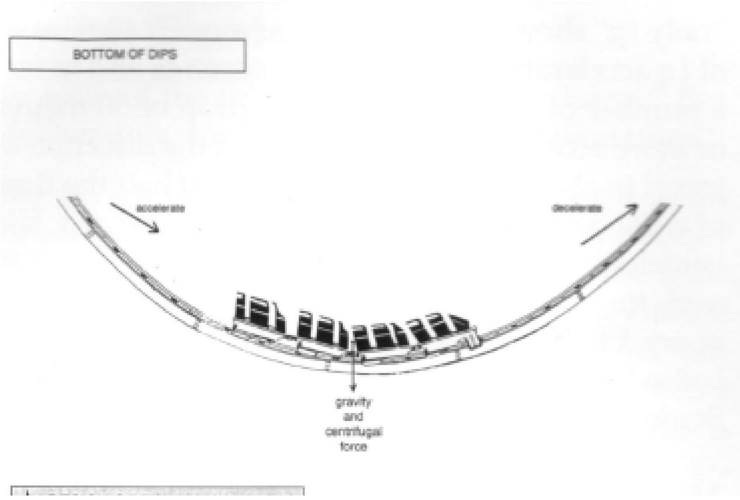


Fig. 1

Similarly if the centripetal acceleration at the top of a crest is, say, 15m / sec^2 (1.5g) up then the net normal acceleration is 0.5g up or -0.5g down (-1.5g from centripetal action, +1g from gravity) and the passengers will feel less than weightless, i.e. they will actually lift out of their seats (Fig. 2).

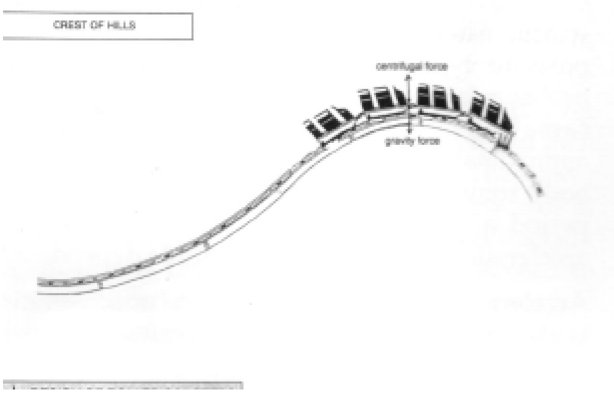


Fig 2

During a looping inversion the same analysis can be used. At the crown of the loop, if the centripetal acceleration is, say, 20m / sec^2 (or 2g) up, then the net normal acceleration is 1g up or -lg down, but since the car is upside down then in fact both the car and the passengers feel relatively normal, i.e. they feel +1g in the "correct" direction (Fig. 3).

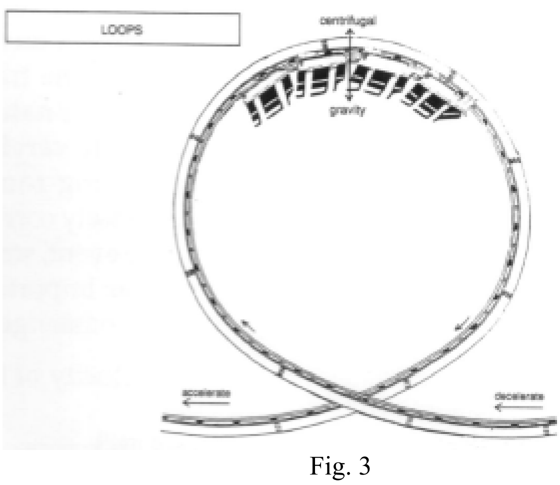


Fig. 3

Bends on plan can be analysed in the same way - the principles of providing camber to both vehicle roadways and railways is well established. Camber, or tilt of the track, is introduced to balance out the lateral forces generated by centripetal accelerations on the bends (Fig. 4).

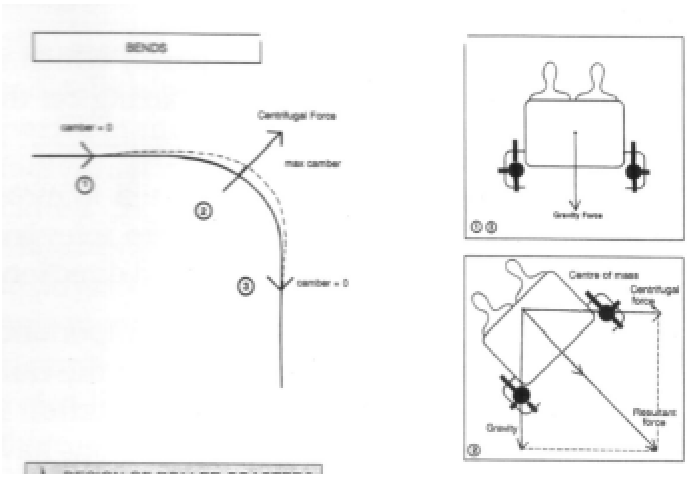


Fig. 4

Whilst bends on coaster tracks are often extreme compared to those on roads and railways (i.e. the velocity of cornering relative to the radius of the corner is very high), coasters have the advantage of reasonably consistent ride performance. This is because, while velocity does vary somewhat due to differing passenger weights and wind conditions, it does not have the wide range associated with individual driver control. Therefore precise design of camber for a particular velocity is possible, at least in theory. In practice, since lateral forces are proportional to velocity squared even small variations in velocity can introduce quite high lateral forces, and this is further complicated by the finite length of coaster trains. For any specific point on the track, the velocity of one particular car in the train passing that point is likely to vary, as it is the nature of most rides for velocities to be constantly varying as the train travels around the undulating route. Therefore the camber cannot ever be precisely correct and some lateral forces will occur. In any event, some degree of lateral force is considered to be an important element in the overall ride experience of passengers. As regards the actual motion, i.e. the velocity of the train, the basic theory is very simple:

- potential energy is supplied to the coaster train by electric power on the lift hill; this energy is proportional to the mass and the increase in height.

- this potential energy is converted to kinetic energy as the train descends the "first drop" and for the rest of the ride there is a continuing energy balance as the train gathers momentum on the down slopes and converts this back to potential energy on the up slopes.

Real life, of course, it is not this simple as energy losses occur and these depend on:

(i) Rolling friction (of all moving parts) which is proportional to the applied force acting on the friction contact surfaces
(ii) Drag resistance, being the energy used to move the train through still air (or, where relevant, through wind of an assumed speed and direction).

Friction losses are inherently of enormous importance for roller coasters as the effect of failure of the train to complete the ride and return to the station is dramatic! Therefore very detailed calculations have to be carried out to arrive at a likely "envelope" of velocity performance, affected by passenger mass, wind speed and direction and other secondary effects such as temperature of the wheel bearings and the environmental condition of the track surfaces.

One popular misconception is that the roller coaster car "accelerates" at 4g in the direction of travel. This it cannot do - in fact it is easy to show that the acceleration in the direction of travel cannot conceivably exceed lg, since this would only apply anyway if the train was taken to the top of the lift hill and dropped over the edge in the condition of no air drag (i.e. in a vacuum). Not that an acceleration of "only lg" should be considered as modest - 0-60 mph at lg acceleration takes just 2.73 seconds and in fact a number of coasters with a first drop of 50 metres or more accelerate from 0-60 mph in the direction of travel in about 3 to 3.5 seconds - about half the time of a modern "supercar". Just for the record, if a vehicle did accelerate at 4g it would record a 0-60 mph time of 0.68 seconds and indeed a ride which opened to the public in the UK early this year does indeed provide this sort of performance (the Play Station, at Blackpool Pleasure Beach).

Human Tolerance

It is well known that at the dawn of the railway age, eminent scientists expressed the opinion that the human body would not be able to survive the projected speeds of these new devices. Speed itself may "thrill" and no doubt "fear" but it is, again, acceleration that can, and does, cause problems. The human body is "designed" to be subjected to a constant l0m/sec^2 acceleration acting from gravity and by and large adapts well to the force this acceleration causes when the body is upright, sitting or prone. Most humans are less comfortable when turned upside down, which is a reasonable approximation to what happens if the body is subjected to a negative g force whilst travelling on a coaster. The body is actually better able to cope with positive g forces in excess of the standard lg, probably because it only represents "more-of-the same". Nevertheless, at forces of above approximately 4g to

6g acting on a sitting or standing body, some discomfort can be felt depending on the period of application of the force - the effects of acceleration are time-and-magnitude dependent.

Acceleration and the rate of change of acceleration is also important as the body is sensitive to inertial or momentum effects, particularly on the head ("whiplash" effects). Yet it is precisely these changes in accelerations as coasters plunge down drops and rise over crests which give the desired ride characteristics. The designer has therefore to balance carefully safety and comfort against the desired thrills to achieve the intended effect. And because this is to some degree subjective, and because some people have different perceptions of ride experiences, it is an art as much as a science to simultaneously satisfy all these requirements.

Recent Developments
In spite of the title of this paper, the "future" has, deliberately, not featured yet in this presentation. My review of the history of rides has shown how developments have linked with technology but they have not been driven by it - if anything the main factors have been the cultural and behavioural background of society in general and leisure pursuits in particular. One clear message is that the recent "re-awakened" interest in theme parks and rides is just that - for example by 1930 there were about 1,400 roller coasters operating in the USA and about two hundred in the UK. Today there are about 225 and 30 respectively, and the best remaining examples from that earlier golden age stand comparison in every way with most modern rides.

Recent developments that open to the public this year include two interesting rides which take a quite different approach to providing "fast and furious" thrills.

At Blackpool Pleasure Beach the "Play Station" integrates the high speeds and high accelerations of modern coasters with the visual excitement of ascending a slender vertical tower standing over 50 metres tall (about equal to a 17-storey building). Perhaps "ascending' does not do justice here - 12 people are seated on individual seats on a doughnut shaped passenger cart that circles the tower. The cart is shot upwards with an initial acceleration of over 4g, although this has to be rapidly reduced and then reversed to prevent overshoot at the top. The power is then reversed, and the cart is shot downwards at about 2g (i.e. at twice the acceleration rate of freefall). Again this is rapidly reduced then reversed to prevent the cart reaching the ground. A further cycle of up-and-down follows with each successive leg of the journey reducing in velocity, acceleration and distance travelled. The first four cycles, i.e. up, down, up, down are completed in about 5 $^1/_2$ seconds and then the carriage "bounces" at about midheight of the tower as the energy is dissipated. The carriage is then lowered to the ground to allow the passengers to unload.
The motive power is compressed air, and the ride has a sophisticated control and safety system using programmable logic controllers (PLCs) to select the correct air pressure (which varies on each cycle

Play Station, Blackpool Pleasure Beach

depending on the combined mass of the 12 passengers, measured by load sensors before the ride is dispatched) and then to start the ride and monitor the performance. An initial charge of compressed air is released into 4 cylinders and acts on 4 pistons which are directly connected by flexible steel cables to the passenger cart. This provides both motive and braking power so that the whole ride cycle is both self-calibrated and fail safe. It is a very well engineered concept and a real innovation in ride design.

The second example takes a familiar concept and radically alters the passenger perception of the ride performance by the simple step of isolating individual riders onto a personal "car". The ride is called SkyTrak, at Granada Studio Tours at Manchester and once again the description "car" fails to do justice. In fact it is a suspended coaster running on a monorail of one steel tube, and each passenger is carried lying face down in the prone position inside a bird-like body but with the head protruding. Since there is no means of support visible to the passenger (the car body is suspended from the wheel carriage, behind the head) then psychologically the passenger is experiencing something close to "flight". This is a real roller coaster, operating under gravity and imposing variable normal forces on the passenger of similar magnitude to most other such rides. What of the immediate future, which in the theme park world means the next 2 or 3 years? I suggest you observe major construction operations underway now at Alton Towers and next year at Blackpool Pleasure Beach and see if you can decide what thrills are in store. I know, of course, but I wouldn't like to spoil the fun!