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# Human Engineering Studies of High Speed Pedestrian Conveyors

*by*

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# HUMAN ENGINEERING STUDIES OF HIGH SPEED PEDESTRIAN CONVEYORS

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## SUMMARY

A study has been made of human engineering aspects of pedestrian conveyors designed to run at speeds of 10-16 km/h. Three broad aspects were studied; the tolerance of pedestrians to motion of the accelerator or decelerator, their ability to transfer between accelerators or decelerators and conveyors, and safety generally.

In addition to the application of existing data on human behaviour to the design of high speed pedestrian conveyors, three laboratory experiments were mounted to provide further data. For these experiments, a motion simulator was specially devised which was in the form of a wooden trolley towed by a battery electric tractor. The trolley was used (i) by itself to simulate an accelerating floor, (ii) alongside a fixed platform at the same height to simulate a pair of parallel surfaces moving at different speeds and (iii) in conjunction with hanging 'posts' to simulate the point of passenger transfer between accelerators or decelerators and conveyors. Approximately 1000 different persons took part in the tests as subjects, representing a wide variety of people and spanning an age range from 2 months to 85 years. Nearly 18000 subject-runs were made and films of many of these are available.

The laboratory experiments have provided new data which can help the engineer to choose appropriate accelerations, decelerations, speed differentials or transfer lengths. They have also highlighted some aspects of safety. Some additional recommendations on comfort and safety have been based on existing data and observation of people using escalators and slow-moving conveyors.

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* Replaces RAE Technical Report 71104 - ARC 34179

Attempts are made to estimate the length of the stations of real systems and the station lengths for various types of system are compared. Some suggestions are made on ways to reduce the station length.

This is a summary report, and represents the Final Report issued under contract to the Department of the Environment. It gives only an outline of the studies, the most important results and the recommendations made. Details, and the remainder of the results, are to be found in nine supporting papers, quoted as Refs.1-9.

# CONTENTS

## 1 INTRODUCTION

This paper is the final report presenting the work done by Engineering Physics Department, RAE, under contract to the Department of the Environment, on human engineering aspects of high speed pedestrian conveyors. The work was done during the period 1969 to 1972 and the complete studies are briefly presented here. More detailed information and discussion is to be found in separate supporting papers[1-9].

The need for these studies was appreciated in 1969 by the Transport Research Assessment Group who had assessed a number of proposals[10,11] for high speed, continuously running transport systems for use by standing passengers and had concluded that some systems were feasible. Proposals at the time were favouring a speed range of 10-16 km/h, complete systems being some 3 km in length and served by stations, about 400 m apart. Such systems could possibly find uses in congested urban areas, airports, railway stations, etc. and one of their most attractive features was the potentially high capacity, a full conveyor less than 2 m in width being theoretically capable of transporting over 20000 passengers per hour.

Operating such systems at speeds of over 10 km/h necessitates the use of some form of accelerator and decelerator at the stations to enable the passengers to match their speed with that of the conveyor, but little was known at that time of the passengers' reaction to the motion they would experience on such devices. It was also not known how easily passengers could transfer between conveyors and the accelerating or decelerating devices. The present work was undertaken specifically to gather evidence on these aspects.

The Transport Research Assessment Group also recommended that, in parallel with the human engineering studies, a general assessment and design study be made of various proposals with the object of defining the more credible schemes. This work was undertaken by the Atomic Weapons Research Establishment, Aldermaston, and both this and the human engineering studies began in mid-1969.

## 2 TERMS OF REFERENCE

The terms of reference for the RAE contract are given in Appendix A. Essentially, in the human engineering studies, three aspects were specified:-

(i) The tolerance of pedestrians to the motion of conveyors, accelerators and decelerators. This covered (a) the reactions of passengers to floor vibration, (b) the upsetting effect (staggering) caused by floor acceleration and (c) the difficulties which arise when pedestrians negotiate an accelerator or decelerator made up of a set of parallel moving surfaces with a speed differential between each adjacent pair. (Laboratory experiments were envisaged on b and c.)

(ii) The ability of pedestrians to transfer between conveyors and accelerators or decelerators moving, at that point, at the same speed. (A laboratory experiment was envisaged. This part of the studies has been referred to as the 'post problem' because the transfer section must be of limited length and is typically terminated by a post.)

(iii) Safety generally. (No laboratory experiments were envisaged but some field observations were to be made.)

## 3 PROGRAMME OF WORK

### 3.1 The original programme

A programme of work was prepared at the start of the contract and is given, together with some notes on the studies achieved, in Appendix B. A laboratory simulator was proposed using a flat trolley, running on rails and electrically propelled. Three experiments were planned and are outlined below:

(1) The upsetting effect of acceleration was to be studied by standing people on the trolley and accelerating it in a known fashion (Fig.1a).

(2) The ability of people to negotiate a speed differential type of accelerator was to be studied by asking them to step from the moving trolley to a fixed platform adjacent to it and at the same height, or from the platform to the trolley (Fig.1a). This would only simulate one pair of surfaces but to simulate several parallel surfaces would have lengthened the research programme considerably.

(3) The ability of passengers to transfer between conveyors and accelerators or decelerators,moving at that point at the same speed, was to be studied by using a fixed screen, slung from above, dividing the trolley along its length but not touching it. A gap in this screen could simulate the portion of a real system where the high speed end of an accelerator or decelerator runs alongside a conveyor. In the tests the passengers would cross from one side of the trolley to the other, through the gap in the screen, while the trolley moved at a realistic conveyor speed (Fig.1b).

In all of the above experiments, the subjects were to be filmed and their subjective assessments obtained by questionnaires.

The remainder of the proposed programme of work was merely to observe the public using various forms of public transport, to help in the assessment of safety standards for high speed pedestrian conveyors, and also to devise specifications for vibration, using existing data.

## 3.2 The studies achieved

In the event, the proposed programme was closely followed. The trolley actually constructed had removable side handrails and padded end plates, ran on pneumatic tyred wheels and was guided along a single rail bolted to the floor. Power was provided by a battery electric towing tractor, modified at the RAE from standard by the addition of a cam operated system for automatic control of the acceleration. The equipment, in the two forms corresponding to Figs.1a and 1b, is shown in Figs.2a and 2b.

Each of the three laboratory experiments was tackled in three stages. Initially some very simple tests were done, usually in a single afternoon, using no more than 10 subjects recruited from the author's colleagues. These experiments are termed 'exploratory tests'. The object was to define the scope of later tests, e.g. the maximum acceleration or speed which would be necessary.

The second stage was a set of tests termed the 'preliminary tests', designed with a statistical plan and using 60 to 90 adult subjects, drawn mainly from Engineering Physics Department, RAE. These tests were intended to give a preliminary assessment of the capabilities of fit adults and to gain evidence on the influence of certain parameters, e.g. age, sex, carrying of luggage, use of special techniques (passenger stance, etc.) or special equipment (handholds, etc.). This stage occupied 2 days for each of the three laboratory experiments.

The final stage involved between 150 and 300 adult subjects drawn from all parts of the RAE, together with a similar number of people from families of employees and a number of special subjects, i.e. groups of children and disabled people. The object was to assess the capabilities of the general public by using a very wide variety of people both individually and in family groups, carrying what was thought to be realistic amounts of luggage. This stage, termed the 'main tests', occupied, for all three experiments together, more than 10 weeks.

One further object of the laboratory experiments was to provide film of a sample of the later tests, to be made available for private viewing by engineers engaged on the design of a conveyor system and by any relevant approving or safety authority.

The objects given above were achieved in that assessments have been made of the capabilities of a very wide variety of people. Whether or not these assessments can be applied to the general public using a real system is discussed in section 5.1. Approximately 7 h of cine film was shot.

A list of the available films is given in Appendix C. One short film (15 min) has been specially made to show a small sample from all three stages of the three laboratory experiments together with some film taken during the observation of the public using existing continuously-running transport systems.

The remainder of this paper is comprised of a brief presentation of the main results obtained (section 4) and discussion of these results (section 5). The latter includes some examples of the application of the results and some comparisons between different types of system.

## 4 RESULTS

Details of the experimental laboratory studies and of the observations made of the public are given in the companion papers[1-9]. The main results are summarised below.

The tolerance of the general public to any transport system can only be found when that system is in operation, in competition with other forms of transport and surrounded by its own particular environment. The public will then show its tolerance by travelling on the system in larger or smaller numbers. Tolerance to one aspect of the system, e.g. the motion of the floor, is less easily measurable and, in practise, the engineer and approving or safety authority must themselves choose the features of the system which are, in their view, tolerable. This view will depend on many factors, including some which are not in any way dependent on the system itself, e.g. the comparison with other quite different forms of transport, the general economic and political situation and the possible effect of the image created at the inauguration, by press and television publicity.

For the above reasons, no attempt has been made to decide on firm 'tolerance' or 'acceptability' levels. Instead, the results of the laboratory experiments are presented, in three ways:

(a) Edited films, showing many people of a wide variety of types, taking part in the experiments.

(b) An analysis of the above films, made by the author or by a panel of observers, showing the consequences of the experiments without making any decision as to whether the conditions used are tolerable or not.

(c) An analysis of the written responses made by the passengers immediately after taking part in the experiments. These responses, being opinions of the users, can appear to give by themselves a measure of tolerance. However, many important factors are missing, e.g. there is a lack of realism in the simulator, a lack of need to make a journey and a lack of competition with other transport both in comfort and cost.

Recommendations are made, on the bases of b and c, for the most severe conditions which should not be exceeded but these must be regarded as tentative estimates of the true tolerance or acceptability.

## 4.1 Tolerance of pedestrians to the motion of conveyors, accelerators and decelerators

### 4.1.1 Tolerance to vibration of the floor surface

Three possible effects of vibration of the floor surface are to give passengers a feeling of discomfort, to make the maintenance of balance more difficult and to cause alarm. The ISO (International Organisation for Standards) is devising standards for comfort[12] and at present (1971) the proposed limit of vertical vibration to be applied to a standing person riding for several minutes is, for frequencies less than about 10 Hz, an rms acceleration of the order of 0.1 g (Fig.3). However, some experimental investigations[13,14] have indicated that vibration levels as low as 0.01 g rms can be regarded as 'annoying' by some passengers and current opinion at the RAE[15] is that the above mentioned ISO proposed comfort limit is too high and that the shape of the curve from 1-2 Hz is incorrect. The current ISO proposed limit, modified[8] at frequencies less than 2 Hz, is shown in Fig.3 and is regarded as an absolute upper limit of the vertical vibration which should be permitted. The lower curve on that figure is recommended as a target limit, and is approximately one quarter of the amplitude of the limit proposed by the ISO.

It has been found[1] that small amplitude, horizontal (fore/aft) vibration of the floor is effectively damped out by the legs of a standing person. The natural frequency of the balancing reaction seems to be at about 1 Hz and horizontal vibration of large amplitude (several cm) near this frequency can make the maintenance of balance difficult unless walking steps are taken.

Because of the short travelling time on accelerators or decelerators (about 10 s) the vibration which is likely to be acceptable on them could perhaps be considerably greater than that permissible on the conveyor itself, where the journey may occupy several minutes. It is however recommended[8] that the vibration of accelerators, decelerators and conveyors be not only limited by the same specification but should, if possible, give approximately equal sensations of discomfort so as to avoid causing hesitation at the transfer points by passengers expecting an unpleasant change in the floor vibration.

### 4.1.2 The upsetting effect of accelerating and decelerating floors

There is no doubt that the upsetting effect (causing staggering or stumbling) of acceleration depends not only on the level of acceleration but also on the time taken to reach this level, i.e. on the rate of change of acceleration[1,4]. In particular, very rapid changes of acceleration, reaching a given level in less than half a second, give a greater upsetting effect than do slower changes (e.g. rising in 1 s or longer) to the same acceleration level. In order to allow for both acceleration level and acceleration rise time, a simple acceleration pattern was chosen as a basis for the investigation. This consisted of a constant rate of rise of acceleration followed by a period of constant acceleration, followed in turn by a constant rate of fall of acceleration at the same rate as the rate of rise (Fig.4). In the experiments a wide variety of acceleration patterns were used, all of the form of the first part of the pattern of Fig.4, i.e. a linear rise followed by a constant acceleration level, and the upsetting effect found is assumed to be applicable to the complete pattern.

All of the test results have been obtained using acceleration and there is some justification in applying them also to the case of deceleration. This is because in most of the tests there was no restriction to the standing position of the passengers and those resisting an upsetting effect while facing 'backward' were behaving in a manner very similar to those who might resist a deceleration while facing 'forward'. The former were observed to maintain their balance as well as any others.

The upsetting effect, measured as the amount of (staggering) movement of the passengers relative to the floor, has been assessed by a panel of observers, viewing some of the cine films. The combinations of acceleration level and acceleration rise time of patterns observed to cause 'slight relative movement' to passengers are shown in Fig.5 and are recommended[1] as tentative 'acceptance' curves. They relate to passengers who are given no specific instructions to hold a handrail, but who have one available.

For a given line haul speed, acceleration patterns which cause the same upsetting effect are not equally attractive because they will not all require the same length of accelerator. It is found[1] that the choice of the pattern for the minimum length is almost independent of the line haul speed within the range 10-16 km/h and is:

| Upsetting effect | General public | Fit adults |
|---|---|---|
| Moderate relative movement | 0.070 g in ½ to 1 s | 0.115g in ½ to 1 s |
| Slight " " | 0.055 g in 1 s | 0.090g in 1 s |
| Virtually no relative movement | 0.040 g in 1 to 2 s | 0.065g in 1 to 2 s |

These acceleration patterns are shown in Fig.6.

The above selected patterns not only correspond to the minimum acceleration length for a given upsetting effect, but also have acceleration lengths which are approximately proportional to the square of the line haul speed:

$$\text{acceleration length} = \frac{u^2}{a} \quad \text{metres}$$

where u is the line haul speed (km/h), in the range 10-16 km/h

a is a constant, dependent on the upsetting effect, given in the table below:

| Upsetting effect | General public | Fit adults |
|---|---|---|
| Moderate relative movement | $a = 15\frac{1}{3}$ | a = 23 |
| Slight " " | a = 12 | a = 18 |
| Virtually no " " | $a = 8\frac{2}{3}$ | a = 13 |

The acceleration length appropriate to 'slight relative movement' has been chosen as the 'acceptance' minimum and this is shown, in terms of line haul speed, in Fig.7.

The acceleration pattern causing 'moderate relative movement' is suggested for use as the maximum emergency deceleration, i.e. 0.070 g for the general public and 0.115 g for fit adults, applied in ½ to 1 s in both cases. The corresponding deceleration lengths, from speed u km/h to rest, are $u^2/15\frac{1}{3}$ and $u^2/23$ respectively, e.g. 17m and 11m respectively for a line haul speed of 16 km/h.

These estimates of length do not account for any distance wasted in the recovery after stepping on or preparation for the next phase of the journey, e.g. on an accelerator, stepping on at about 2½ km/h and preparing for the transfer at the high speed end. Very simple allowances are suggested, 1 m at the low speed end and 1 s at the high speed end, leading to a length estimate[1]:

$$\text{estimated minimum length of accelerator} = \frac{u^2}{a} + \frac{u}{3.6} + 1 \quad \text{metres}$$

where u is expressed in km/h and a is given in the table above.

For the acceleration chosen as the 'acceptance' minimum, where a has the value 12 or 18, a rough approximation to this formula is

$$\text{estimated minimum length of accelerator} \approx \frac{u^2}{9} \quad \text{metres. (Fit adults)}$$

$$\text{estimated minimum length of accelerator} \approx \frac{u^2}{12} \quad \text{metres. (General public)}$$

where u is expressed in km/h.

The denominators in these formulae are not dimensionless. Equivalent formulae using non-dimensional constants are:

$$\text{estimated minimum length of accelerator} \approx \frac{u^2}{0.071\ g} \quad \text{(Fit adults)}$$

$$\text{estimated minimum length of accelerator} \approx \frac{u^2}{0.094\ g} \quad \text{(General public)}$$

If passengers are expected and instructed to use a handhold during acceleration, the acceleration level[1] for the general public can be as high as 0.115 g, if the rise time is between ½ and 1 s, and the emergency deceleration in excess of 0.2 g, with the same rise time. However, the emergency deceleration for the line haul conveyor should not be greater than that recommended earlier because many passengers must be assumed to have relinquished the handhold.

The following types of person are likely to have much more than average difficulty on accelerating or decelerating floors:

(a) young, standing children,

(b) persons with slow reactions to an upsetting effect,

(c) persons able to provide only a small restoring moment against an upsetting effect.

Young standing children, whilst possibly staggering a great deal, will usually recover quickly and are catered for in the recommendations made above. Persons in categories (b) and (c) may be either temporarily or permanently disabled and could include very elderly people and those under the influence of alcohol or drugs (e.g. after a tooth extraction). They will probably only be able to withstand the recommended maximum accelerations if they hold a handrail firmly.

### 4.1.3 The upsetting effect of a speed differential between adjacent floors

Studies of persons negotiating a speed differential between two adjacent floor surfaces have been complicated by the large variety of styles which people choose and it is not easy to give an unbiased account of the good and bad points of any style. However, an attempt has been made to do this and it is clear that stepping across in a direction approximately at right angles to the line separating the two surfaces gives a larger upsetting effect than stepping in other directions unless a specially learned technique is used. This is particularly so if the 'upstream' foot is used first (the right foot if the surface stepped-on moves from right to left, as it did in the laboratory tests). The reason for this is that the feet can become crossed and an example of this kind of stumbling, which very frequently occurred in the tests when that particular direction was chosen, is shown in Fig.8. The supporting papers[2,5], include a detailed discussion of the merits of different styles and it is concluded that passengers should be encouraged to step on to a faster moving surface whilst walking partly 'with' the motion of the faster surface, in a direction making an angle of about 45° with the line separating the two surfaces. Also, passengers should be encouraged to step from a faster to a slower moving surface whilst walking largely 'against' the relative motion of the slower surface in a direction making an angle of about 22½° with the line separating the two surfaces*. The main reasons for these choices are that the upsetting effect is well below that for stepping across at right angles to the separating line, that these styles are near to those in universal use on escalators and slow moving pedestrian conveyors and that there is a sizeable component of the walking speed across the surfaces, necessary for rapid negotiation of a set of several parallel surfaces with successively increasing or decreasing speeds. Another reason is that these styles can easily be used by

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* In the supporting papers, this angle is defined as 67½° with the normal to the line separating the surfaces.

people who prefer to face in the direction in which they are moving, a tendency which appears to be almost universal and ensures a good view of the approach of 'posts' at the transfer points.

When no handholds are provided, the speed differential which causes little apparent upsetting effect, even after several practice attempts, is modest, being of the order of 2 to 3 km/h, no faster than current escalators and slow-speed pedestrian conveyors[8]. In detail, the recommended maximum speed differentials, presupposing that the directions of walking are as given above, are:

| | General public | Fit adults* |
|---|---|---|
| Speed differential on an accelerator | 2 km/h | 2½ km/h |
| Speed differential on a decelerator | 2½ km/h | 3 km/h |

* If this population has a high proportion of women aged 15-24, the speed differential appropriate to the general public is recommended.

An estimate of the distance moved by a passenger during the negotiation of a set of surfaces of an accelerator having these speed differentials is shown in Fig.9 and a similar estimate for a decelerator is shown in Fig.10. Calculation of these estimates[2] assumes a natural walking speed of 4 km/h but takes into account the tendency for the walking speed to be reduced on an accelerator and to be increased on a decelerator. The lengths are proportional to the total width of the set of surfaces and in the calculations a width of 1 m for each surface has been assumed (see also section 5.2.2).

Within the line haul speed range 10-16 km/h, the acceleration or deceleration length is approximately proportional to the square of the line haul speed:

$$\text{acceleration or deceleration length} = \frac{u^2}{a} \text{ metres}$$

where $u$ is line haul speed (km/h)

$a$ is a constant, given in the table below

| | General public | Fit adults* |
|---|---|---|
| Accelerator | a = 7½ | a = 10 |
| Decelerator | a = 7 | a = 9 |

* If this population has a high proportion of women aged 15-24, the value of a appropriate to the general public is recommended.

The parameter 'a' in the above formula is not dimensionless. An equivalent formula, using a non-dimensional parameter $\bar{a}$ is:

$$\text{acceleration or deceleration length} = \frac{u^2}{\bar{a}g}$$

where $\bar{a}$ is given by

| | General public | Fit adults* |
|---|---|---|
| Accelerator | $\bar{a} = 0.059$ | $\bar{a} = 0.079$ |
| Decelerator | $\bar{a} = 0.055$ | $\bar{a} = 0.071$ |

* See table above.

Persons walking very slowly will need longer surfaces than are estimated here and in practice would have to be encouraged to walk more quickly or be nudged from surface to surface by barriers placed obliquely across all of the set of surfaces. Such people would include those who naturally walk slowly and also perhaps those in charge of dogs or several small children.

It has been found that the use of pushchairs and prams leads to great difficulty because of the slewing motion which often results and which can be both awkward and unexpected.

When vertical pole handholds are provided, fit adults, with light luggage and not in crowds, can make one transfer to or from a moving surface with surprising ease after very little training. The recommended maximum speed differential for this case[5] is 5.3 km/h and, if passengers carry no luggage at all, could perhaps be 7 km/h. A single surface could be by itself a complete conveyor system but it would be very difficult to use in crowded conditions. Untrained adults and less able people (e.g. young children, persons over 80 years old) would probably regard it as an extremely hazardous device. It is therefore only recommended for possible use by an extremely restricted population, perhaps in large business areas. Two- or three-stage devices, the fastest surface moving at 10.3 or 15.9 km/h, could be even more useful as a conveyor system.

In the laboratory tests, some very small speed differentials, less than 1 km/h, were also used and it was found that the threshold of speed differential, below which the relative motion is hardly noticeable, and causes no serious upsetting effect, is between 0.6 and 0.8 km/h. This suggests that the difference in speed between the high-speed end of accelerators (or decelerators) and conveyors, nominally at the same speed, should be less than 0.6 km/h and so also should be the relative speeds of adjacent floor plates in those systems where an accelerating floor is not continuous.

### 4.1.4 The upsetting effect of accelerators and decelerators using rotary motion of the floor

The upsetting effect of the motion of any device having a rotary motion of the floor is in two parts, that due to the apparent forces which act on pedestrians and that due to the effect of rotation on the fluid in the vestibular organs (semi-circular canals) to cause modification to the sense of balance. The magnitudes of these effects depend on the design of the device and to obtain some idea of their relative importance, three types of device have been studied briefly[7]. This activity was undertaken over and above the original programme of work. The types of device are (i) a large rotating disc on which passengers walk from centre to edge or *vice versa*, (ii) a system made up of a set of carriages in the form of a folding chain, folded at the stations and unfolded between them and (iii) a system using sets of floor plates which both accelerate and slew.

Generally, in any design of accelerator or decelerator the duration of time spent on it by passengers will be limited to about 10 seconds and it is thought[7] that this may be sufficiently brief to avoid serious physiological effects of rotation of the floor on the sense of balance. However, the apparent forces which might be experienced by passengers on some of the systems which have been proposed can be considerable. These 'forces' are now considered in some detail.

On an accelerator of the form of a disc rotating at a constant speed, a walking passenger will experience, if he regards the disc as fixed, two apparent forces, the centrifugal 'force' and the Coriolis 'force'. The centrifugal 'force' can be neutralised by a slight dishing of the disc but the effects of the Coriolis 'force' are thought to be sufficiently serious to set a limit to the angular speed[7]. The magnitude of the Coriolis 'force' (in acceleration units) is shown in Fig.11. It acts in a 'sideways' direction on the passenger at his centre of gravity and is proportional to the product of the angular speed of the disc and the passenger's walking speed relative to it. A limit of 0.22 rad/s is suggested[7] on the grounds that a passenger, walking casually (4 km/h) will experience a Coriolis 'force' equivalent to 0.05 g which is thought to be sufficient to cause the feet to become crossed and modify the walking path considerably. The relationship between the disc diameter and the edge speed is shown in Fig.12 for various angular speeds and it can be seen that small discs with large edge speeds will inflict very large Coriolis 'forces' on passengers.

To achieve an edge speed of 16 km/h within the suggested maximum angular speed, a disc larger than 40 metres diameter is required. It should be noted that the Telecanapé system[10], constructed in 1964 rotated at only about 0.13 rad/s (see Fig.12) to achieve an edge speed of 6½ km/h.

Accelerating systems made up of a set of carriages in the form of a folding chain impart to the passengers apparent forces which are derived from linear acceleration, centrifugal acceleration and acceleration resulting from the rate of change of angular velocity. There is no Coriolis 'force' because passengers are not expected to walk while being accelerated. The motion is complicated and the acceleration varies not only in magnitude but also in direction. It is hoped that the data provided for linearly accelerating floors[1] will be useful in assessments of this type of device but the effects of a varying direction of acceleration on passengers is not known.

Systems using sets of floor plates which both accelerate and slew can be assessed in much the same way as can the folding chain system but, because passengers are expected to walk, the Coriolis 'force' must be considered. A limit of 0.22 radian per second angular speed, suggested for rotating disc types, is therefore applicable. With this type of system the floor plates may be the only part of the system which has any rotary motion and, if the passenger does not use them as a visual frame of reference, he will experience no Coriolis 'force'.

### 4.2 The ability of pedestrians to transfer between conveyors and accelerators or decelerators moving at the same speed

The ability of the general public to transfer to or from a conveyor in a limited length can be objectively measured, in a laboratory simulation just as in a real system, by the proportion of attempted transfers which are successful. At first sight, firm estimates of the minimum length should be obtainable but, when the population being assessed is the general public, it is not easy to establish when sufficient tests have been done to give a high confidence that persons who perform very badly are represented. However, if in the real device the consequences of failing to transfer correctly are 'safe', e.g. the 'posts' and any barriers are suitably padded and the possibilities of trapping shoes or fingers, etc. are negligible, then the most pessimistic transfer length found in the laboratory, where no failures to transfer occurred, could be near to the length which an engineer should allow in his design. This is the method used in a companion report[3], the results of which are shown in terms of transfer length in Fig.13 and in terms of transfer time in Fig.14. The relationship between transfer length and transfer time is

$$\text{transfer length} = \frac{u}{3.6} \times \text{transfer time}$$

where u is the line haul speed (km/h)
transfer length is expressed in metres
transfer time is expressed in seconds.

The recommended minimum transfer time which should be made available is about 7 s for members of the general public to transfer to or from a conveyor moving at 10 km/h though 5 s may be sufficient if the patronage is restricted to fit adults under the age of 65. Slightly longer time may be necessary at higher line haul speeds, around 13 km/h, which was the highest speed used in the tests. It is thought that the curves may be extrapolated to 16 km/h as shown in Figs.13 and 14.

This recommended transfer length is expected to be sufficient for a passenger flow of up to 10000 per h [3]. A transfer time of 7½ s is considered[3] to be sufficient up to passenger densities of 20000 per h but in the prototype testing of any real system, the effect of higher passenger flows should be carefully investigated because with densities greater than 20000 per h there may not be room for some passengers to transfer, a situation which could lead to panic and perhaps mass injuries.

In some proposed designs of accelerator, there is no choice of courses of action at the transfer point and all must transfer. A barrier, set obliquely, could be used to 'sweep' passengers across. It is recommended that the minimum transfer length for such systems be the same as that given above.

If the same section of a conveyor is used for transfer both to and from it, this section should be twice the length recommended above, i.e. equivalent to about 14 or 15 s for the general public and 10 s for fit adults under 65, but it is possible that a shorter transfer length than this might be sufficient[3,6] (see also section 5.2.6).

In addition to being padded, the posts or angled 'sweep' barriers should be large and be suitably coloured and illuminated so that they are easily visible. Devices should be provided to warn passengers of the approach of the end of the transfer section, even if they are not looking directly at the post or angled barrier. Such devices could be flashing lights, extra floor vibration or audio tones. Propaganda will probably be necessary to instil thoughts of safety into the guardians of small children, individual children who may be careless and potentially reckless adults, because it will be all too easy for a person to be struck by a post if they linger, deliberately or carelessly, in its path (i.e. on the line separating the conveyor and the accelerating/decelerating device).

The following types of person are likely to have more than average difficulty when transferring:-

(a) persons who walk or think slowly,

(b) persons carrying bulky or heavy luggage (very large luggage should be prohibited, see section 4.3),

(c) persons leading dogs or with (unfolded) pushchairs (initially puschairs and prams should be prohibited).

All these classes of people are catered for, to a large extent, in the transfer lengths recommended.

### 4.3 Safety

The terms of reference for the contract did not ask for comprehensive studies of safety. The limited studies of safety which have been made are specifically aimed at assisting the relevant safety authority in its deliberations. The work is presented in Ref.8, where each phase of a passenger's journey is considered in turn. What are thought to be the most important conclusions are summarised in the remainder of this section.

There is probably a need to prohibit some prospective passengers from travelling on a high speed pedestrian conveyor because of the risk of accident, e.g. if a parcel some 2 m long became wedged against a post at the end of a transfer section it could cause many people to fall. This suggests that it will not be possible to dispense with a human controller at the entry gates of stations. The prevention of unsuitable passengers from travelling could lead to some embarrassment, in particular, in the prohibition of elderly and perhaps disabled people, who can in fact cope well with the system. This is a problem which, in the event, the relevant Transport Authority would have to consider carefully.

Passenger flow control will be necessary on a system-wide basis to prevent the conveyor becoming over filled by large numbers of passengers boarding at several stations, leading to a situation where there may not be room for passengers to transfer, (see the previous section). This is another reason for the provision of staff members at the entry gates. The gates themselves could be automatic but, without supervision, intending passengers may try to get through them when they are closed.

Control of passenger flow at the entry point of each accelerator may not be necessary because in many designs it is expected that the conveyor will be easily visible from the accelerator entry point. A passenger, seeing that the conveyor was temporarily full, could voluntarily wait there until it became less crowded, in much the same way as pedestrians, wishing to cross a road, wait for a lull in the passing traffic. An example, using a shape of accelerator similar to the current Dunlop scheme[16], is shown in Fig.15. In addition to watching for a suitable space on the conveyor, the passenger has 5 to 10 s ride on the accelerator in which he can adjust his walking speed if necessary.

An emergency procedure in the event of a sudden increase of passenger flow throughout a large part of a system could be to run the complete system at a reduced speed. Doing this would reduce the upsetting effect of accelerators and decelerators and also increase the transfer time available (see sections 5.2.1 and 5.2.2 for numerical examples). If there are no spaces between passengers on the conveyor, increasing the transfer time cannot of course create spaces but will allow more time in which passengers joining the conveyor can find what spaces there are. The control of speed will therefore be extremely important and the speed should be rapidly adjustable to suit the passenger density.

When accelerating floor types of device are used it is not necessary for the entry speed to be as high as possible, consistent with passenger acceptance and safety. This is because an accelerator with an entry speed of 3 km/h is very little shorter than one with an entry speed of 2 km/h, and if time is allowed for the passenger to recover from the upsetting effect of the stepping-on, it may be longer. Entry speeds about the same as that of London Transport escalators at the present time[8], 2-2½ km/h, are therefore recommended.

Emergency stopping of any one part of a system (accelerator, conveyor or decelerator) by itself is not recommended on account of the very high risk of injury to passengers who attempt to step across a speed differential of more than 10 km/h (see Ref.2).

Unfortunately, the studies have given little indication of what emergency procedures should be used to assist fallen or collapsed persons.

## 5 DISCUSSION OF THE RESULTS

Two important questions are now discussed, (i) are the laboratory experiments valid for use in the design of real systems and (ii) if so, are the systems likely to be practical.

### 5.1 Validity of the laboratory experiments

In all experimentation using human subjects in a simulated environment, there is the possibility that the environment is not sufficiently realistic, in which case the results, when applied to the real situation, may be of doubtful value. In the tests aimed at the reactions of subjects to simulated accelerator or decelerator motion, the motions chosen were those which could occur in a real system, but no attempt was made to provide a realistic visual scene. In the event, many of the worst performers behaved passively and their reactions were largely instinctive. This suggests that, even if the visual environment provided was not unimportant, it did not assist them to maintain their balance and persons in a real situation, perhaps with a specially contrived visual environment, can be expected to perform no worse than did the subjects in the laboratory.

In the tests aimed at establishing the acceptable transfer length, it was thought from the beginning that the level of realism needed to be greater than that used in the simulation of accelerator or decelerator motion. Consequently, in addition to lane widths, accelerations, speeds and transfer lengths being such as might occur in a real system, attention was paid to visual and mental stimuli to the subjects, there were some realistic dummy passengers, side walls were provided along the track and the impression of a journey was created by a verbal description of an imaginary conveyor system, backed by realistic signs and tickets. The subjects' task in the transfer tests occupied some 10-15 s, during all of which time he was moving, and the least realistic part of the visual environment was only viewed by peripheral vision. It is thought that the simulation was sufficiently realistic, but of course this cannot be proved. Those readers who view the cine films can make their own judgement of this because they include sequences, at each test speed, shot from the passengers' viewpoint.

It is possible that the sample of the population used as subjects in the laboratory experiments was not representative of the population who will use a real system. In particular, all were volunteers, who could be unrepresentative if they were generally people who would willingly try new things. If there was a strong bias of this kind, there would be expected to be a greater proportion of the real population being hesitant at stepping across a speed differential or transferring to or from conveyors. Against this, however, is the fact that the younger subjects (play group, infants school, junior school) were brought by the teachers, and did not volunteer individually, and these groups proved to be the worst performers in many respects. It is thought that many families were encouraged to participate by the member who was an employee at the RAE and these can also be regarded as not volunteering individually. Little is really known of the background of the subjects, but the questionnaires which were used did establish that the sample of fit adults under 65 years of age used public transport very little and used escalators infrequently. They were not as restricted a sample as might be expected of employees at the RAE, because they did in fact work at a very wide variety of occupations. The 22 disabled persons who participated are not claimed to be a representative sample of all disabled people who might use a real system.

At the beginning of the study, it was not clear how many subjects would be needed to give reasonable confidence that the results obtained would be applicable to the general public. For this reason the policy was to err if anything on the side of too many subjects rather than too few and the numbers planned for were as large as could conveniently be managed by the staff in several weeks of tests. Groups of up to 40 subjects were not an embarrassment because no instrumentation of any kind was attached to them. In all, approximately 1000 different subjects took part in the laboratory experiments, their ages ranging from 2 months to 85 years distributed as shown in Fig.16a. There was a bias toward the younger age groups but more than 50 persons over the age of 45 attended. Approximately 31% of the adult subjects were female.

The progressively more comprehensive nature of the three stages of each experiment is illustrated in Fig.16b, which gives the number of subject-runs in each case. The 'main tests' of each experiment comprised about 4000 subject-runs and the total number for all of the tests was nearly 18000. As the experiments passed through the three stages of approximately 100, 1000 and 4000 subject-runs, the assessments of the capabilities of the 'general public' decreased progressively and considerably. This gives a warning against drawing too many conclusions about the behaviour of the general public from experiments using only a small number of subjects.

It is easy to operate experiments using human subjects in a manner biased in favour of results which are in accord with preconceived ideas of the experimenter and it is impossible to eliminate all bias of this kind. An attempt to reduce such bias was one reason why the author took no part in the routine running of the preliminary or main tests except to give the briefing (which was largely background information) and to explain any changes in the conditions or procedure during the sessions. The use of written questionnaires, rather than personal interview, also helped to reduce bias and was used in all of the tests except a few very early ones and those with disabled subjects*.

An attempt was also made to provide a very informal and 'relaxed' atmosphere during the tests, sometimes to the extent of using unobtrusive background music. In this way, opportunity was given for the subjects to become well accustomed to the experimental situation and, it was hoped, treat the tests as nonchalantly as they might the use of an escalator or an underground train. The author believes that this was largely achieved, because of the similarity in the appearance of the behaviour of the subjects to that of people filmed using public transport. Many of the subjects, especially the adults, quickly learned to treat the tests extremely casually, and normally questionnaires were given to them at this stage. In order to obtain some information on the rapidity of learning any skill involved, a special point was made of filming the first attempt by each subject, as well as later runs. The film cameraman was of course not hidden from the subjects, but the films show very few subjects looking directly at the camera and it is thought that it was sufficiently inconspicuous to avoid a large modification to their natural behaviour.

Control of the acceleration was not as good as it could have been because there was not sufficient time allowed to devise the best possible cams for the acceleration controller, in particular, the acceleration rise was not always a straight line[1]. However, the effects of this non-linearity have been shown to be small because of the large damping effect of the subjects' legs. Control of speeds (in the speed differential and transfer experiments) was manual but sufficiently good to give a distinction between the chosen test speeds.

## 5.2 Practicality of high speed pedestrian conveyors as transport systems

No attempt is made to assess the practicality of the detailed engineering design of any particular system but the size of stations is a major feature and

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* It should perhaps be recorded that the interview with one of the subjects, filmed by the BBC on Thursday, 25 June 1970, was not genuine. Generally, the attendance of the 12 or so BBC staff on two occasions is not thought to have interfered with the behaviour of the subjects a great deal.

is determined largely by human engineering considerations. This is considered below. The actual stations will include concourses, gates, etc.[16,17] but the station size is largely governed by the lengths of the accelerators, decelerators and transfer sections. In the following three sections these lengths are considered for various types of station and in section 5.2.4 a comparison is made between them. Section 5 ends with some remarks on composite systems and possible methods of reducing the station length.

### 5.2.1 Systems using accelerating floor types of accelerator

For the accelerating floor types of system, the length recommended, for passengers to join the conveyor, is[1,3]:

$$\begin{aligned} \text{length} &= \text{accelerator length} + \text{transfer length} \\ &= \left(\frac{u^2}{a} + \frac{u}{3.6} + 1\right) + \frac{ut}{3.6} = \text{metres} \end{aligned}$$

where $u$ is the line haul speed (km/h)

$a$ is a constant (see section 4.1.2)

$t$ is the transfer time allowance (seconds, see section 4.2).

Substituting the values of 'a' and 't' selected in sections 4.1.2 and 4.2 (12 and 7 respectively, for the general public, to a passenger density of 10000/h 10000/h) the length is:

| u (km/h) | Accelerator length $\frac{u^2}{a} + \frac{u}{3.6} + 1$ | Transfer length $\frac{ut}{3.6}$ | Total |
|---|---|---|---|
| 10 | 12.1 m | 19.5 m | 27.8 m |
| 13 | 18.7 m | 25.3 m | 39.4 m |
| 16 | 26.8 m | 31.1 m | 52.4 m |

Passengers leaving the conveyor and decelerating would require a similar length, hence the minimum station length will be twice that shown in the last column of the above table.

The above formula can also be used to show how safety will be improved if the speed of a system is reduced. For example, consider a system designed to run at 16 km/h, with accelerator and transfer lengths of 26.8 m and 31.1 m provided. If this system were run at 13 km/h then the accelerator length would be that appropriate to values of 'a' and 't' of 7.6 and 8.6 respectively. This would reduce the upsetting effect (see section 4.1.2) from 'slight relative movement' ($a = 12$) to, approximately, 'virtually no relative movement' ($a = 8\frac{2}{3}$) and the transfer time available is increased by 1.6 s.

The time taken in accelerating to 16 km/h is about 11 s, including 2 s spent covering the length allowed for recovery of balance at the ends (see section 4.1.2), so that a journey of 400 m between successive stations will be divided approximately in the following way:

| Phase | Distance | Time | |
|---|---|---|---|
| | | Not walk at all | Walk at 4 km/h |
| Accelerate | 27 m | 11 s | 7½ s |
| Transfer to conveyor | 31 m | 7 s | 5½ s |
| Travel on conveyor (16 km/h) | 284 m | 64 s | 51 s |
| Transfer to decelerator | 31 m | 7 s | 5½ s |
| Decelerate | 27 m | 11 s | 7½ s |
| Total | 400 m | 100 s | 77 s |
| Average speed | - | 14½ km/h | 18½ km/h |

The last column shows the breakdown if the passenger walks throughout at a speed of 4 km/h. This increases the average speed for the journey to more than that of the conveyor itself but also reduces the time on the accelerator and decelerator, thereby increasing the acceleration and deceleration levels and rates of change. On the accelerator, the acceleration level, for passengers who do not walk is, in this example, 0.055 g ('slight relative movement', see section 4.1.2) but walking at 4 km/h will raise this by about 50% to 0.082 g. This level is approximately that corresponding to 'slight relative movement' for fit adults, so that the example chosen would be expected to be equally acceptable to the general public when standing, or fit adults while walking at 4 km/h.

With 'parabolic' accelerators (where the acceleration of the floor is always in the same direction but one which is at right angles to the direction of motion at the entry point) walking passengers will tend to be toppled sideways. The upsetting effect is similar to that found in the studies of speed differential devices (see section 4.1.3 and Fig.8). It has been suggested in section 4.1.4 that a sideways acceleration of no more than 0.05 g could cause crossing of the feet and it is thought that parabolic accelerators will impart a larger upsetting effect to walking passengers than do linear accelerators using the same acceleration pattern. If this is so it may be necessary to discourage passengers from walking on parabolic accelerators or decelerators.

The width of the line haul part of a high speed pedestrian conveyor system is expected to be not less than 2 m, comprising two parallel conveyors, one in each direction, each having a width of at least 1 m to enable passengers to walk past one another if they wish. At the stations, the transfer section for each conveyor is expected to be at least 1 m wider to accommodate the high-speed end of the accelerator or decelerator. If these devices are straight, lying alongside the conveyor, and with a constant area flow at any point, their width at the slow-speed end will be proportional to the speed ratio. For example, the width at the entry of an accelerator of speed ratio 6:1 will be 6 times that at the transfer section to give a total station width some 12 m greater than that of the conveyor part, i.e. at least 14 m. A complete station could be comprised of a transfer section, decelerator, accelerator and a second transfer section, these being provided for the conveyors travelling in both directions (Fig.17a). The above example of a station is drawn, to scale, in the upper diagram of Fig.17b. The accelerators and decelerators are of non-constant width, due to the constant area flow, and 10 m has been added (at the centre) to allow for entry and exit.

### 5.2.2 Systems using speed differential types of accelerator

Calculations, similar to those made in the previous section, can also be made for systems using speed differential types of accelerator. For example, an accelerator for use by the general public of 8 stages, each with a speed differential of 2 km/h and surfaces of width 1 m, is estimated to be about 33½ m in length (Fig.9). No extra length need be added for transfer to the conveyor because the conveyor will be the last of the parallel surfaces[2]. At the decelerator, transfer time will be needed[2], e.g. approximately 7 s for standing passengers and only 7 stages will be required because a larger speed differential can be used on a decelerator (see section 4.1.3, the speed differential would be 2.3 km/h, slightly less than the recommended value of 2½ km/h). The deceleration length estimate, for surfaces 1 m wide (approximately, Fig.10 applies) is 39½ m and the complete breakdown of a 400 m journey is:

| Phase | Distance | Time | |
|---|---|---|---|
| | | Not walk on conveyor | Walk at 4 km/h on conveyor |
| Accelerate | 33½ m | 12 s | 12 s |
| Transfer to conveyor | Nil | - | - s |
| Travel on conveyor (16 km/h) | 296 m | 66½ s | 53½ s |
| Transfer to decelerator | 31 m | 7 s | 5½ s |
| Decelerate | 39½ m | 11½ s | 11½ s |
| Total | 400 m | 97 s | 82½ s |
| Average speed | - | 15 km/h | 17½ km/h |

The third column relates to passengers who walk on the accelerator and decelerator but do not walk on the conveyor itself. The last column relates to those who walk throughout. The estimated length of the decelerator is greater than that of the accelerator, despite the larger speed differential used, because the shallower direction of walking (22½°) leads to more time spent being carried on each surface and also the walking speed along the surfaces is expected to be increased to above the normal walking speed by the changes of speed, the passengers covering more distance along them.

If the system described above were run at 13 km/h instead of 16 km/h, the speed differential would be reduced to 1.62 km/h on the accelerator and 1.86 km/h on the decelerator, reducing the upsetting effect (see section 4.1.3) and leaving 5m length to spare on the accelerator and also 5m length to spare on the decelerator.

The width of conveyors was discussed in the previous section. The width of accelerators and decelerators of the speed differential type is expected[2] to be of the order of 1 m per surface and for the above example of an 8-stage accelerator, the total width of two accelerators and two lanes of conveyor (see Fig.17a) would be of the order of 18 m. This is somewhat wider than the estimated width of the comparable accelerating floor type of station (14 m). However, the speed differential type of station would be narrower if surfaces narrower than 1 m were used, a feature which is further discussed in section 5.2.4 where different systems are compared.

A complete station, to the above dimensions, is drawn to scale in Fig.17b (middle diagram).

A single moving surface, with many vertical pole handholds mounted on it, can possibly be used as a conveyor without any accelerating device at all. It is only expected to be feasible (see section 4.1.3) if the patronage is very restricted, but the station size could be very small indeed, comprising small platforms only a few metres in length. A speed of about 5.3 km/h, or perhaps 7 km/h if no luggage at all is carried, could possibly be used which, whilst not being a great speed for a conveyor, may provide useful transport in small business areas.

Two-stage systems, similar to that built in Paris in 1900[10], with speed differentials of this order, may also be feasible, especially if built as complete circuits but it is expected that boarding and alighting difficulties will arise if the passenger flow is high[2]. Three-stage systems would provide transport at nearly 16 km/h and, while suffering the same disadvantages as do 2-stage systems, could be very attractive for some, very specific, locations.

The laboratory experiments have given only very rough estimates of station length, based on the time taken at each stage and the estimated acceleration length is[5] approximately 4 m for a 2-stage system and 10½ m for a 3-stage system. These must be regarded as minimum lengths, allowance must certainly be made for delays in stepping from one stage to the next.

### 5.2.3 Systems using other types of accelerator

The station size when rotating discs are used as accelerators and decelerators is easily estimated from the disc diameter. For a system using a line haul speed of 16 km/h, the minimum diameter of a single disc accelerator is just over 40 m if it is to have an angular speed less than the suggested limit of 0.22 rad/s. Such a disc is drawn, to the same scale as the other systems, in Fig.17b. It is, however, recommended that experiments be done to provide a better estimate of this limit to the angular speed.

Station sizes for folding chain devices and devices using sets of floor plates which both accelerate and slew can be roughly estimated by the methods of section 5.2.1 but will depend on the particular motion which will vary from design to design. No attempt is therefore made here to make comparative estimates of station length for these systems.

### 5.2.4 Comparison between station sizes for various types of system

The calculations of the previous three sections serve to illustrate how the data derived from the studies (section 4) can be used to assess station size. The examples chosen were intended to be realistic and the estimates for the minimum size of the resulting stations are compared in Fig.17b.

The station length derived from the example incorporating the speed differential type of accelerator and decelerator is much the same as that estimated for a station having accelerating floor devices. However, the estimated length of speed differential stations includes only one section for transfer while the lengths of accelerators and decelerators are greater than that of the accelerating floor type. It is instructive to consider why this is so and what would be needed to shorten them. The longer acceleration length is basically due to the longer time spent by the passenger in acquiring the same increment of speed (see the tables in sections 5.2.1. and 5.2.2). At first sight, it would seem that speed differential types ought, if anything, to be shorter because the frequent adjustment of the feet, during walking, would reduce the consequences of the upsetting effect of the change of speed. This may be so but the feature of speed differential devices which has been found to be extremely important is the possibility of being unable to recover from an induced sideways stagger (see Fig.8). To traverse a set of parallel surfaces rapidly demands an appreciable component of walking speed across them, with the surfaces themselves as narrow and as few in number as possible. It has been shown[2] that a large proportion of the general public will be unable to learn quickly a safe method of negotiating a speed differential of the order of 5 km/h, which would be necessary to reduce the number of stages, in a direction almost directly across the surfaces, even though it can be demonstrated[5] that this is possible. Perhaps speed differential devices can be smaller than the estimates, both in length and width, if surfaces narrower than 1 m are used. Experiments to establish the minimum practical width are therefore recommended. Against this, it is not known whether the value chosen for the walking speed, an assumption necessary for an estimate to be made at all, is sufficiently pessimistic and whether the length estimate includes sufficient time for those slower walkers who are willing to use the devices. In the tests recommended above therefore, the resulting walking speeds should be measured. With these weaknesses in the estimate of length of speed differential devices it is difficult to make a useful comparison of station size, but at this stage, both the accelerating floor and speed differential types of device appear to be feasible, provided that space can be found to accommodate stations some 100m long.

The example of the rotating disc type of station is of a comparable area to the others (see Fig.17b) but there remains the possibility that it should be made larger if the maximum tolerable angular speed is shown to be less than 0.22 rad/sec.

### 5.2.5 Systems using combinations of different types of accelerator

The various types of accelerator have differing attractive features, for example the rotating disc is attractive for its simplicity but only at low edge speeds (e.g. 6 km/h) for which it can be relatively small, and the accelerating floor type has perhaps the shortest acceleration length. Also, the transfer length can be reduced if passengers are already walking obliquely as they would be on a speed differential accelerator. These considerations suggest that there may be advantage in combining several types to produce a more complicated system but one which exploits the good features of each type. Some examples of this approach are described in Ref.10. It is hoped that the data from this study can be applied, at least as a first approximation, to the assessment of such composites.

### 5.2.6 Some possible methods of reducing the station length

One possible method of reducing the station length may be to use one transfer section for simultaneous transfer both to and from the conveyor ('mixing' transfer). This scheme is shown in Fig.18a and stations would need only one transfer section instead of two. Further experiments are recommended[3] to establish whether or not the length required for a single mixing transfer section is less than that for two one-way transfer sections.

Possibly the shortest, and simplest, station of all may be a speed differential type which uses one single set of parallel surfaces for acceleration, transfer both ways and deceleration (Fig.18b). Further experiments are recommended[2] to establish at what passenger density this is feasible.

## 6 CONCLUSIONS

The conclusions which have been drawn from the studies are given in detail in the supporting papers [1-8]. The four most important recommendations are given below. They relate to the general public, carrying some hand luggage, using a conveyor system which has a line haul speed of 10 to 16 km/h.

It is *not* assumed that passengers will always be within reach of a handhold.

(1) The acceleration pattern recommended for use in the initial design of devices in which the floor accelerates linearly has a maximum level of 0.055 g, with the time of rise to this level equal to approximately 1 s, the acceleration falling to zero also in approximately 1 s. The same pattern is recommended for the deceleration of decelerators. The minimum length (metres) of such a device is approximately $u^2/12 + u/3.6 + 1$ metres (u being the line haul speed, km/h). A rough approximation to this formula is $u^2/9$ metres*.

(2) The maximum speed differential recommended for use in the initial design of devices incorporating a set of parallel surfaces moving at different speeds is 2 km/h if the passenger steps from a slower to a faster surface and 2½ km/h if the passenger steps from a faster to a slower surface. These speed differentials presuppose that passengers are channelled to walk in particular directions. The minimum length of an accelerator of this type, using equal speed differentials, depends on the natural walking speed of passengers and the widths of the surfaces and a rough estimate is $u^2/7\frac{1}{2}$ metres** (u being the line haul speed, km/h). A similar estimate for the length of a decelerator is $u^2/7$ metres**.

(3) The minimum length recommended for use in the initial design of those parts of systems where passengers transfer between conveyors and either accelerators or decelerators, moving at the same speed, depends on the conveyor speed and is equivalent to a transfer time of approximately 7 s if the passenger density is less than 10000 per h, or 7½ s if the passenger density is between 10000 and 20000 per h.

(4) Rotating disc types of accelerator or decelerator must be limited in angular speed because of the sideways Coriolis 'force' felt by passengers when they walk. A suggested limit is 0.22 rad/s but this needs to be substantiated by further experiments.

## 7 RECOMMENDATIONS FOR FURTHER STUDIES

Some recommendations for further studies are given in the supporting papers[1-8] and those which are perhaps the most important are listed below.

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* An equivalent formula, using a non-dimensional parameter, is given in section 4.1.2.

** An equivalent formula, using a non-dimensional parameter, is given in section 4.1.3.

(1) Experiments using a speed differential device of several stages to determine the narrowest surface which could be used by the general public and to observe the resulting walking speeds.

(2) Experiments using a speed differential device of several stages to establish the passenger density above which it is not feasible to use one set of surfaces, simultaneously, as an accelerator and a decelerator.

(3) Experiments with a rotating disc device to determine the maximum angular speed which should be used.

(4) Experiments to establish whether or not the length required for simultaneous transfer both to and from the conveyor (mixing transfer) is less than that for two, separate, one-way transfers.

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## Appendix A

## TERMS OF REFERENCE FOR EP DEPARTMENT, RAE (14/7/69)

### A.1 Human tolerance to the motion of conveyors, accelerators and decelerators

(a) To define tolerance limits of the standing and walking human to vertical and fore/aft vibration of a horizontal platform which is moving forward at a constant mean speed.

(b) To study the upsetting effects of non-oscillatory horizontal acceleration of a horizontal platform on individual persons of all ages and types, both with and without some form of disability or impediment. The objectives are to define acceleration/time curves which are both acceptable and can be produced by practical devices and to establish when it is necessary to provide handholds or to enclose passengers in a protective structure.

(c) To establish the maximum speed differential which should be specified for a parallel multiple surface accelerator.

### A.2 Passenger judgement of transfer between accelerators and conveyors

To study the ability of passengers of all types, both individually and in crowds, to judge when to make the transfer between accelerators and conveyors. The objectives are to establish the length of conveyor needed for the transfer and to assist in the engineering design of emergency equipment for use when a passenger fails to transfer successfully.

### A.3 Safety

To give advice on the passenger handling aspects of the safety of any pedestrian conveyor system currently under investigation, and to make studies to this end.

# Appendix B

## THE ORIGINAL PROGRAMME OF WORK AND SOME NOTES ON THE STUDIES ACHIEVED

### Programme of work - EP Department, RAE (8 July 1969)

### B.1 Human tolerance to the motion of conveyors, accelerators and decelerators

#### (a) Tolerance to vibration

Initially, no experimental work is envisaged because it is in principle possible to base a specification on the draft recommendations which are currently under consideration by the ISO. We propose to write a draft specification in collaboration with the RAE consultant on vibration and, if necessary, will do some simple experiments using an existing seat vibrator with the seat removed. The ISO Draft Recommendations cover the standing man and can be extended to include the walking man by applying the results of the RRL work on vibrating bridges[14]. Because journey times are short it is expected that problems of tolerance to vibration will be secondary to the upsetting effects of acceleration and the vibration specification need only be a simple guide.

#### (b) Upsetting effects of non-oscillatory horizontal acceleration

EP Department propose to construct a trolley test rig (see Fig.1) which will have a flat top, about 4m wide and 6m long and be propelled by an electric motor, the power of which can be accurately controlled. The trolley will accelerate from rest, coast at about 10 km/h and decelerate in the length of the laboratory in Q153 Building, RAE (some 40 m). Mounted on the trolley will be a platform, some 2½m wide and 6m long, which will have a limited sideways travel of about 1½ m. The motion along the laboratory will simulate the acceleration of a linear or parabolic accelerator and the sideways motion will crudely simulate the slowing down of a parabolic accelerator as it lines up with a conveyor belt. It is anticipated that the simplest such rig will cost some £5500 and can be operational, given a reasonable priority, in about six months (the driving power and acceleration control equipment account for about one third of the cost). For the tests, subjects will stand on the platform and may or may not be provided with handholds.

The experiments are intended to include motion violent enough to cause a passenger to fall and, when elderly or handicapped persons are used as subjects, the trolley rig may be considered to be too dangerous. For these cases we propose to use a much simpler rig to simulate the acceleration, e.g. a tilting floor or a harness to apply a horizontal force to a subject. Outside assistance will be required (e.g. from the IAM) in the design of such a simulator and in interpreting the results obtained.

(c) Speed differential of parallel surfaces

To enable the laboratory trolley rig to be used to establish the maximum acceptable speed differential between parallel surfaces we propose that a fixed platform, at the same height as the trolley, be built alongside the trolley track (see Fig.1a). This is expected to cost about £1250, and construction could be concurrent with that of the trolley. For the tests, subjects will step off the moving trolley at various speeds or, with appropriate safety precautions, step on to it.

With all the tests on human tolerance to the motion, subjective opinions will be collected and measurements made to assess the probability of the motion causing injury or damaging passengers' personal property.

## B.2 Passenger judgement of transfer between accelerators and conveyors

We propose to investigate the transfer, or 'post' problem by dividing the trolley platform, along its length, by a screen (slung from overhead) which does not move with the platform and which, except for a gap, will extend along the complete length of the trolley run (see Fig.1b). In the trials, subjects will be asked to cross from one side of the platform to the other through the gap in the screen. There is some information available[18] on how much time an individual person needs to cross a road between cars and the trolley experiment can be used to show how this data should be modified when the time for action is limited and the subjects are crowded together.

For items 1(b), 1(c) and 2, it will be necessary to ensure that the subjects tested do span the distribution of skill abilities of the expected passenger population and this will require routine balancing and judgement testing. The apparatus required is expected to be inexpensive but outside advice by psychologists on the design and programming of these tests will be obtained.

### B.3 Safety

It is envisaged that EP Department could act as a safety focus for pedestrian conveyors, collecting and summarising relevant information. As and when time permits, we propose to study:

(a) How a practical system can be designed to prevent passengers being forced onto a conveyor which is already full.

(b) The standards of safety already accepted by the public, to ensure that pedestrian conveyors are no less safe (the intention at the moment is to film crowds of people using public transport).

(c) Emergency procedures for fallen or collapsed persons, etc.

We propose to use the trolley rig to establish the greatest deceleration which should be applied when an accelerator/conveyor system is stopped in an emergency.

## Some notes on the studies achieved

In the event, no experiments to assess the discomfort of vertical vibration of the floor were done but, in a few of the trolley tests, a horizontal fore/aft vibration of very low frequency was superimposed on the acceleration to assess the possible extra upsetting effect (see section 4.1.1).

The possible effect of vertical floor vibration on the ability of passengers to maintain their balance when riding on an accelerator or decelerator has not been investigated experimentally. Routine testing of the balancing and judgement ability of subjects was omitted because of the very limited time available in the test sessions. Side movement of the trolley top surface was not provided because the proponents of parabolic accelerators found that by using diamond shaped floor plates, the approach of the accelerator to the conveyor could be made smooth.

An item done, in addition to the original programme was some theoretical study of passenger tolerance to the motion of rotating accelerating devices. In order to base the thoughts on first hand experience, some very simple tests were done (2 days) using a small trolley towed in a circle, (see section 4.1.4).

The tests of tolerance to a speed differential between adjacent surfaces included a small number of runs to establish the threshold speed, below which the relative movement was not noticeable (see last paragraph of section 4.1.3).

The observation of the general public using transport systems was restricted[8] to two visits by the author to Victoria Station, London, to observe and film people using escalators and a visit by a cine photographer to a slow-speed pedestrian conveyor in Paris.

The timing of the various parts of the study was that the first 8 months was devoted to the provision of the trolley and the design and construction of the cam operated automatic acceleration controller for the tractor. During this period all of the exploratory tests and the preliminary acceleration and speed differential tests were done. The next 3 months saw the completion of the main tests concerned with acceleration and speed differential and the preliminary transfer ('post problem') tests. After three more months all of the experiments were completed and in the remaining 14 months the analysis and writing-up of the reports was done.

## Appendix C

### LIST OF FILMS - EDITED POSITIVES

(All film is black and white, silent, 16 mm, 24 frames per second)

| Date | Content | Approximate duration (min) | |
|---|---|---|---|
| | ACCELERATION | | |
| December 1969 | Preliminary acceleration tests | 7 | |
| May 1970 | Main acceleration tests, adults, families, schools | 31 | |
| | Main acceleration tests, disabled | 20 | |
| December 1969 and May 1970 | Acceleration tests, panel observation film (includes a copy of preliminary tests film) | 27 | |
| | | | 85 |
| | SPEED DIFFERENTIAL | | |
| March 1970 | Preliminary speed differential tests | 32 | |
| May 1970 | Main speed differential tests, adults, families, schools | 61 | |
| | Main speed differential tests, disabled | 20 | |
| | | | 113 |
| | TRANSFER (POST PROBLEM) | | |
| July 1970 | Preliminary transfer tests | 32 | |
| October 1970 | Main transfer tests, adults, families | 91 | |
| | Main transfer tests, disabled | 8 | |
| | | | 131 |
| | OBSERVATION OF THE PUBLIC | | |
| April 1970 | Victoria line escalators | 29 | |
| September 1970 | Paris (Montparnesse) conveyor | 40 | |
| | | | 69 |
| | MISCELLANEOUS | | |
| - | Sample film from all tests | 15 | |
| May 1970 | Disabled subjects, walking gait and step climbing | 6 | |
| | | | 21 |
| | | | 419 |

# SYMBOLS

| | | Units |
|---|---|---|
| $a$ | constant defined in section 4.1.2 and 4.1.3 | $\mathrm{Mm\ h^{-2}}$ |
| $\bar{a}$ | constant defined in section 4.1.3 | - |
| $g$ | acceleration due to gravity | $\mathrm{ms^{-2}}$ |
| $t$ | transfer time allowance | s |
| $u$ | line haul speed | km/h |

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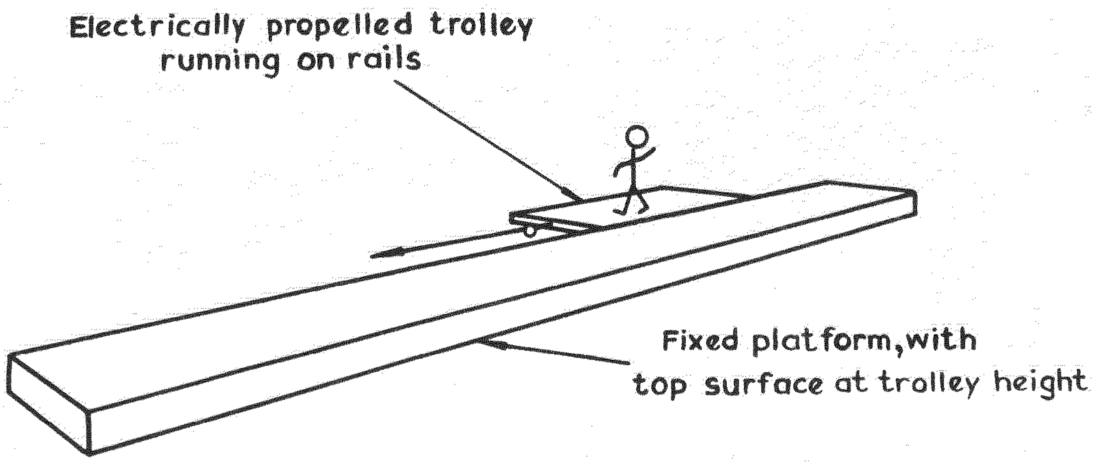
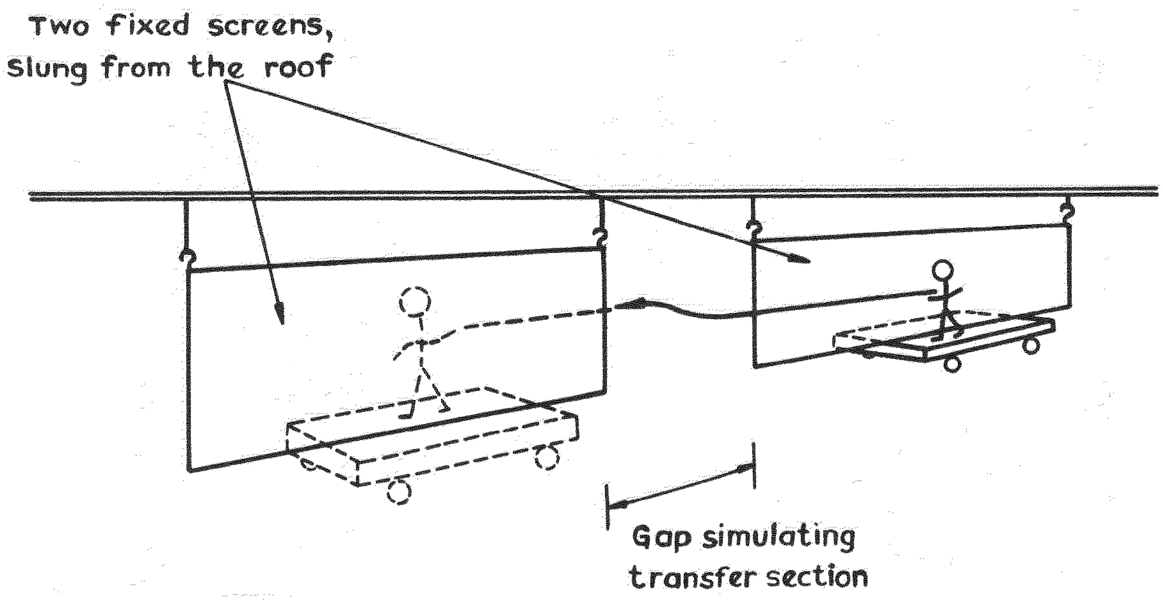
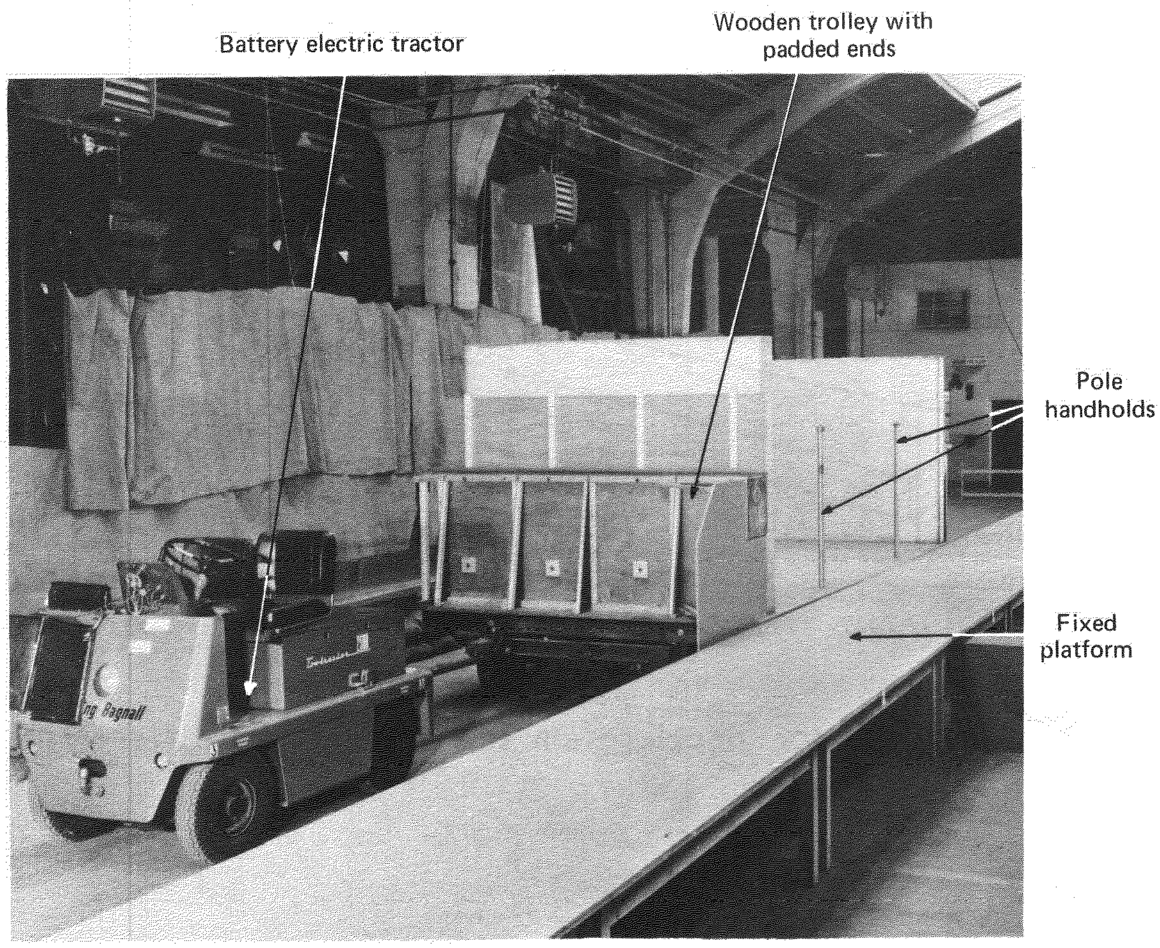


a Simulator for acceleration tests and speed differential tests

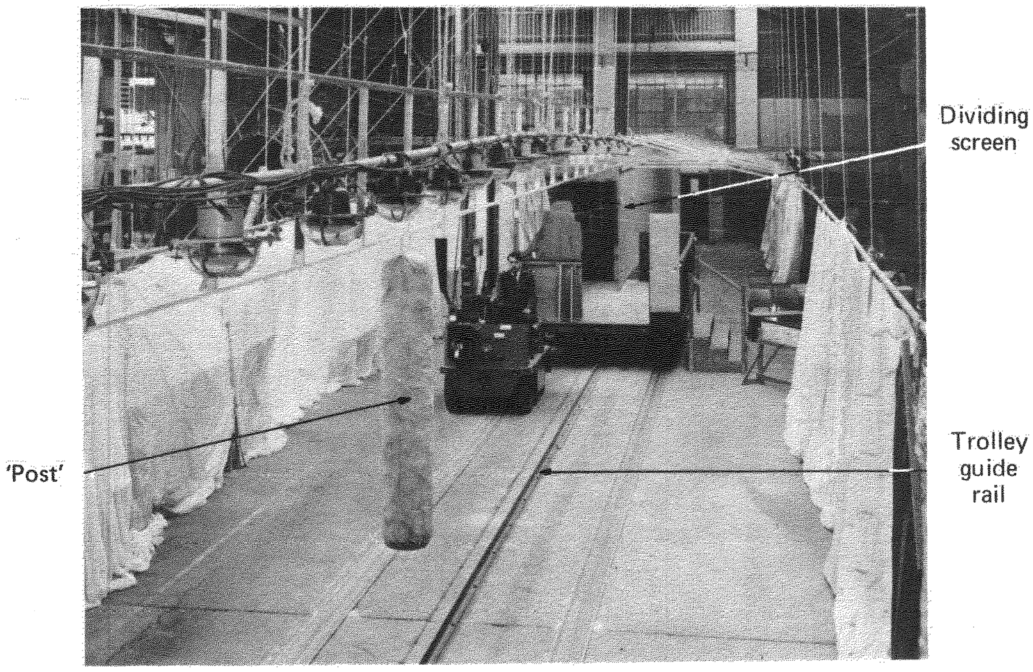


b Simulator for transfer tests

Fig. 1 a & b Laboratory simulators as originally conceived



(a) Simulator for acceleration tests and speed differential tests



(b) Simulator for transfer tests

**Fig.2 The laboratory simulators**

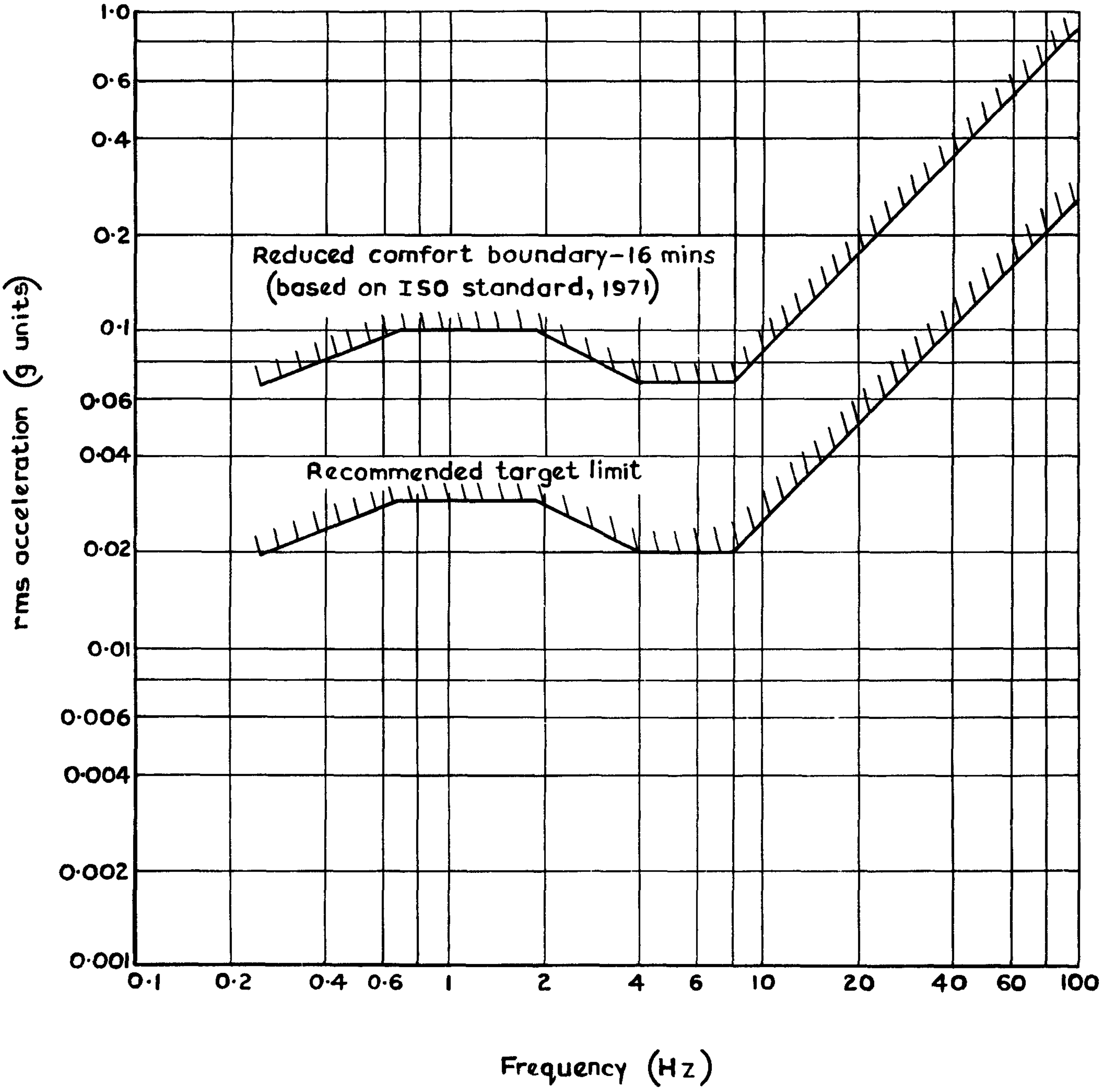


Fig. 3 Recommended maximum vertical vibration

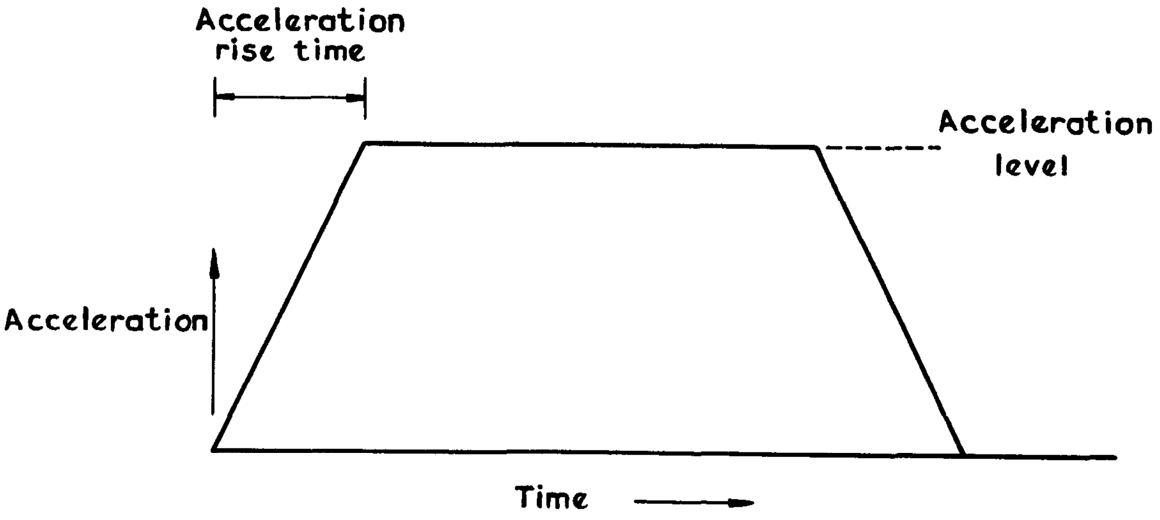


Fig. 4 The type of acceleration pattern studied

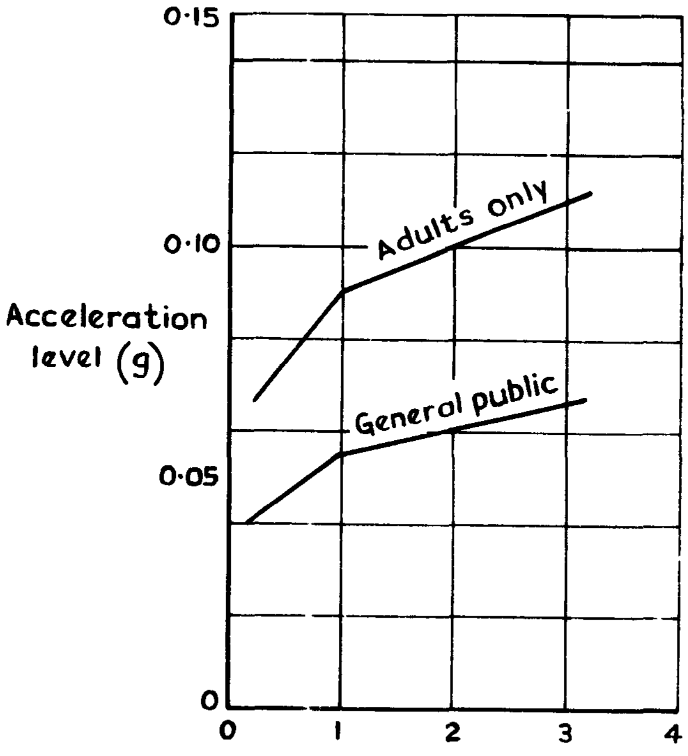
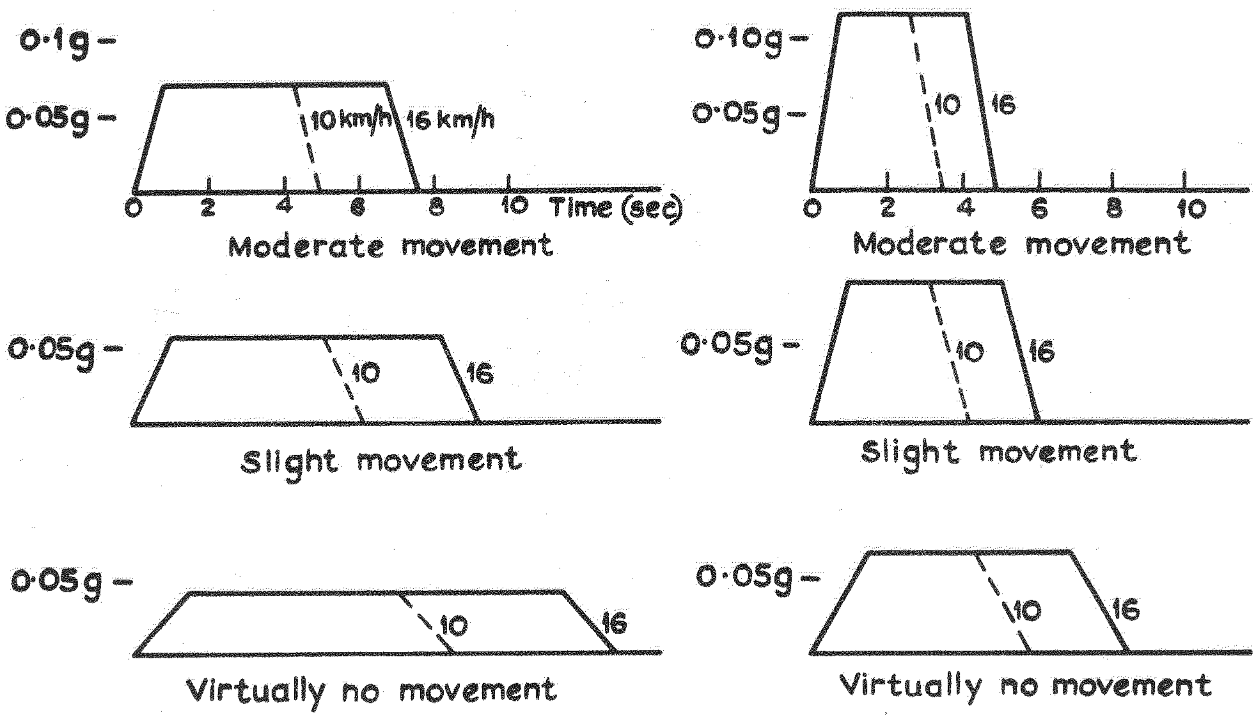


Fig. 5 Tentative acceptance curves for the acceleration of a floor



a General public

b Fit adults

Fig.6a&b Acceleration patterns relating to various upsetting effects for minimum acceleration length

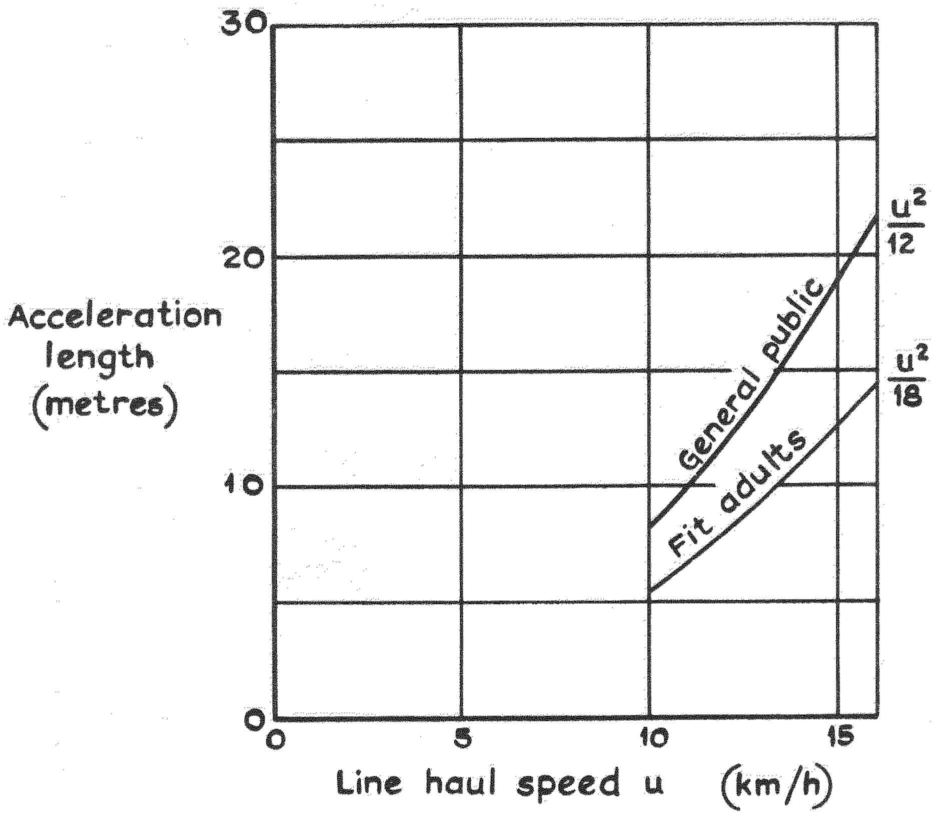
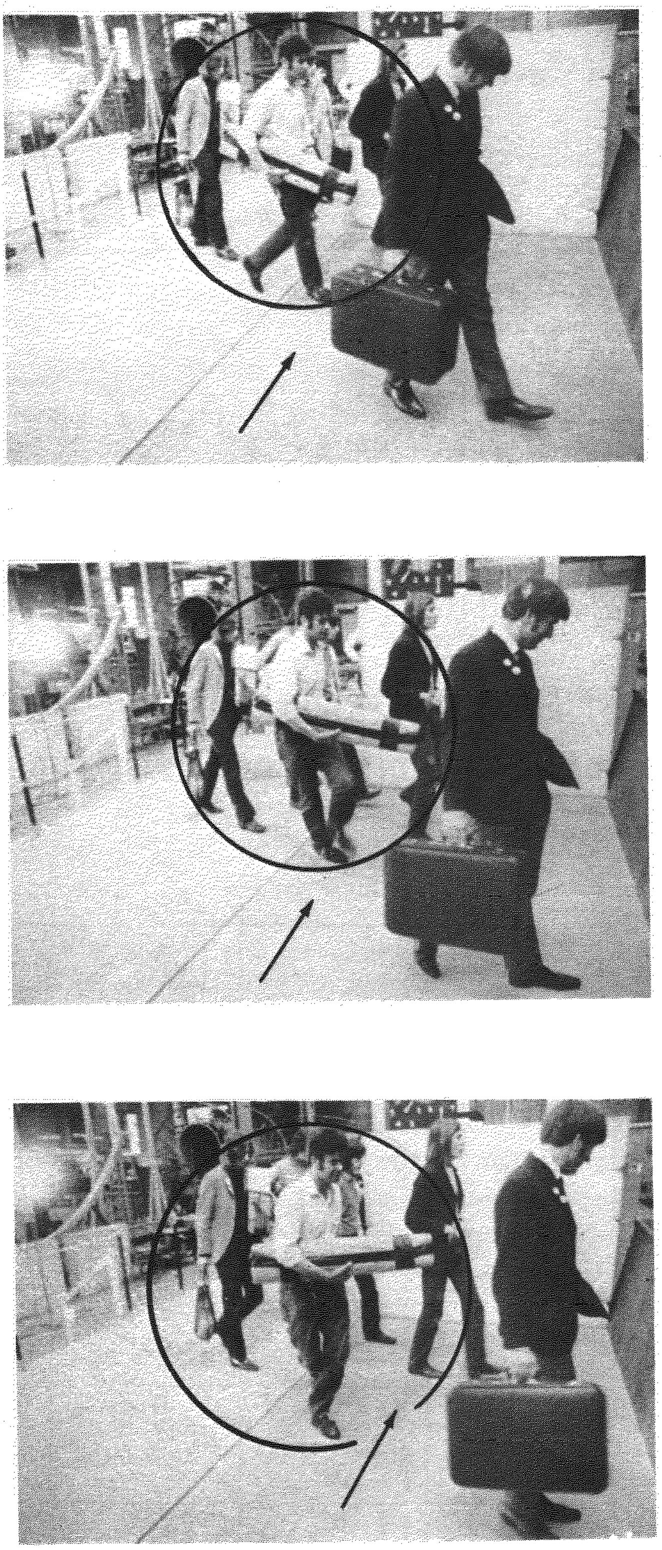


Fig. 7 Minimum acceleration length for "slight relative movement"



Stepping on
with the
right foot
t = 0

Left foot
passing across
the right
t = ¼ s

Left foot placed
to the right of the
right foot to maintain balance
t = ½ s

**Fig.8** A typical example of stumbling caused by a speed differential of 3 km/h

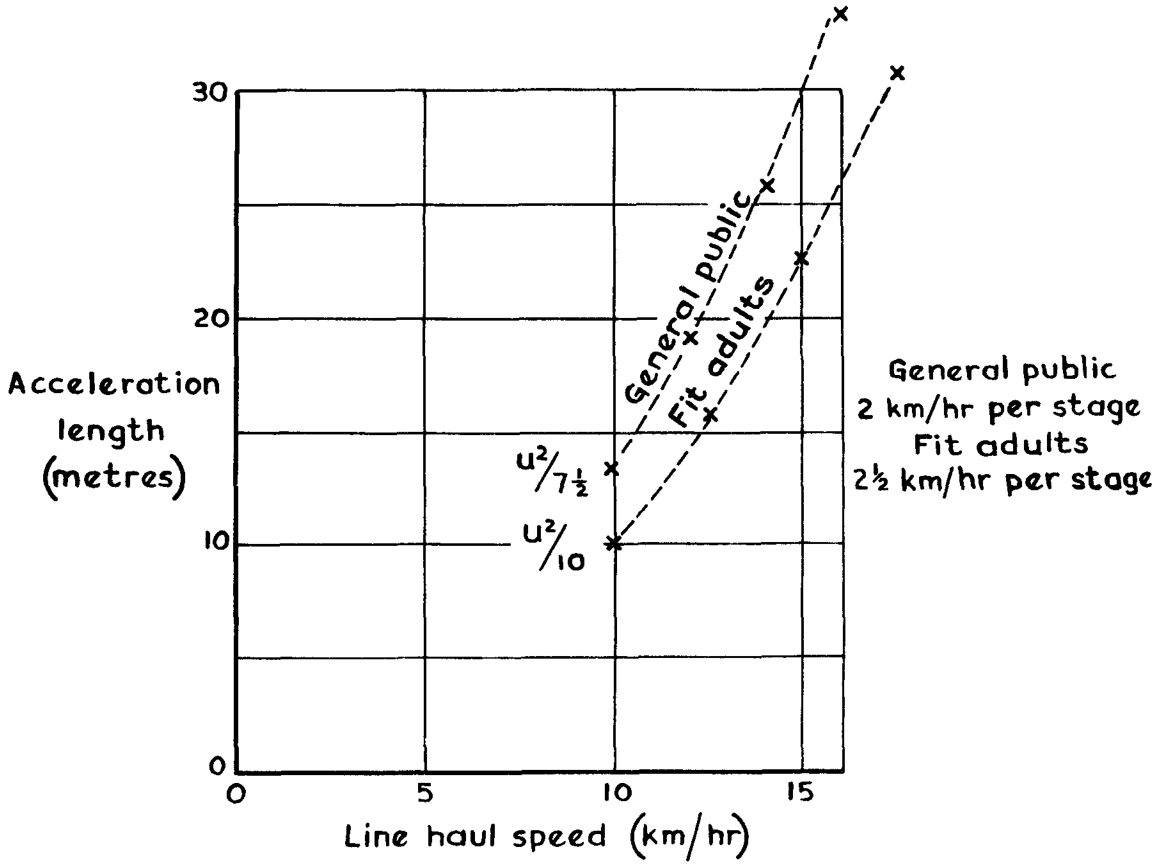


Fig. 9 Estimated length of a speed differential accelerator using surfaces each 1m wide

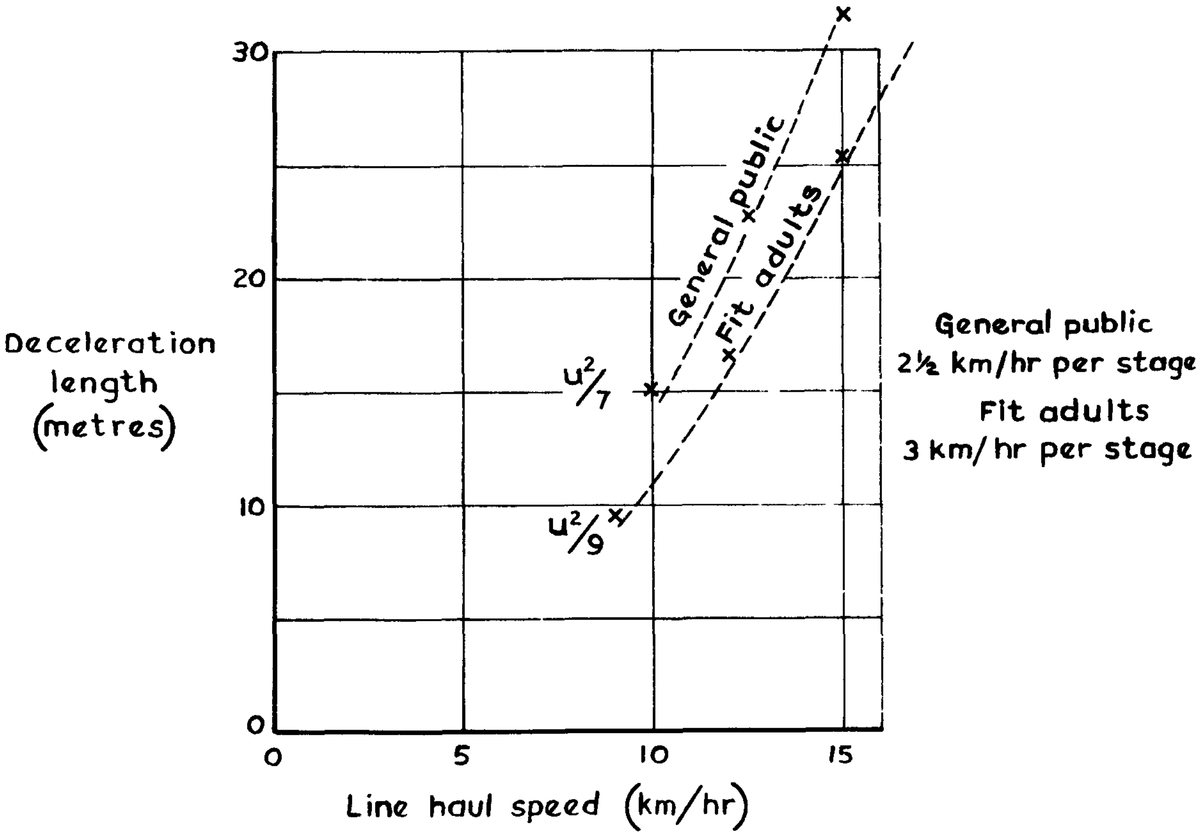


Fig. 10 Estimated length of a speed differential decelerator using surfaces each 1 m wide

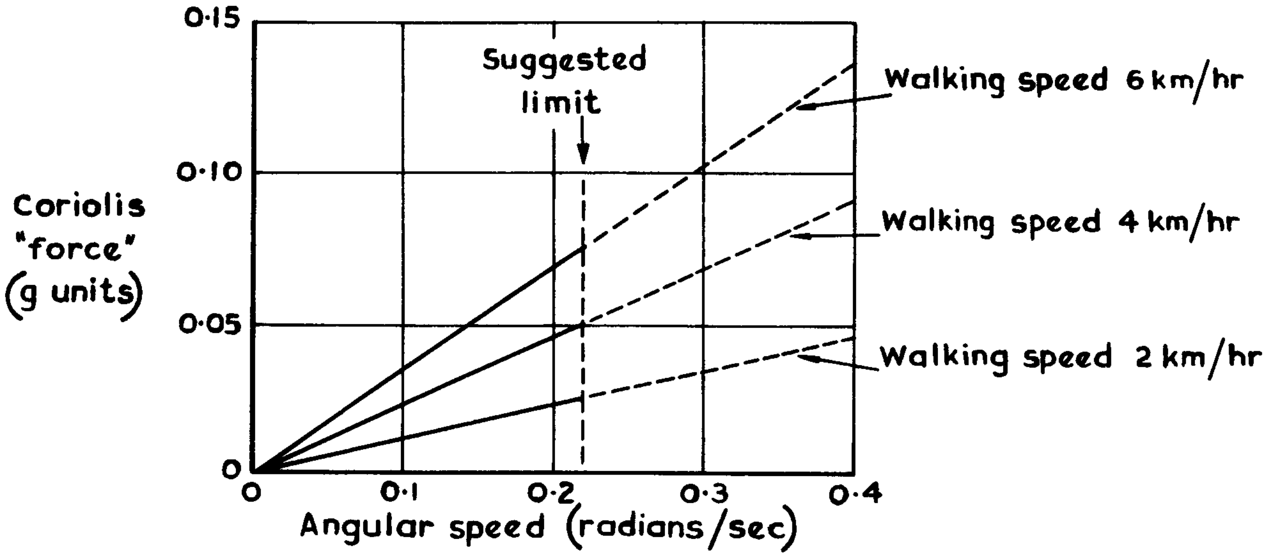


Fig. 11 The Coriolis "force" acting on a person walking on a rotating disc

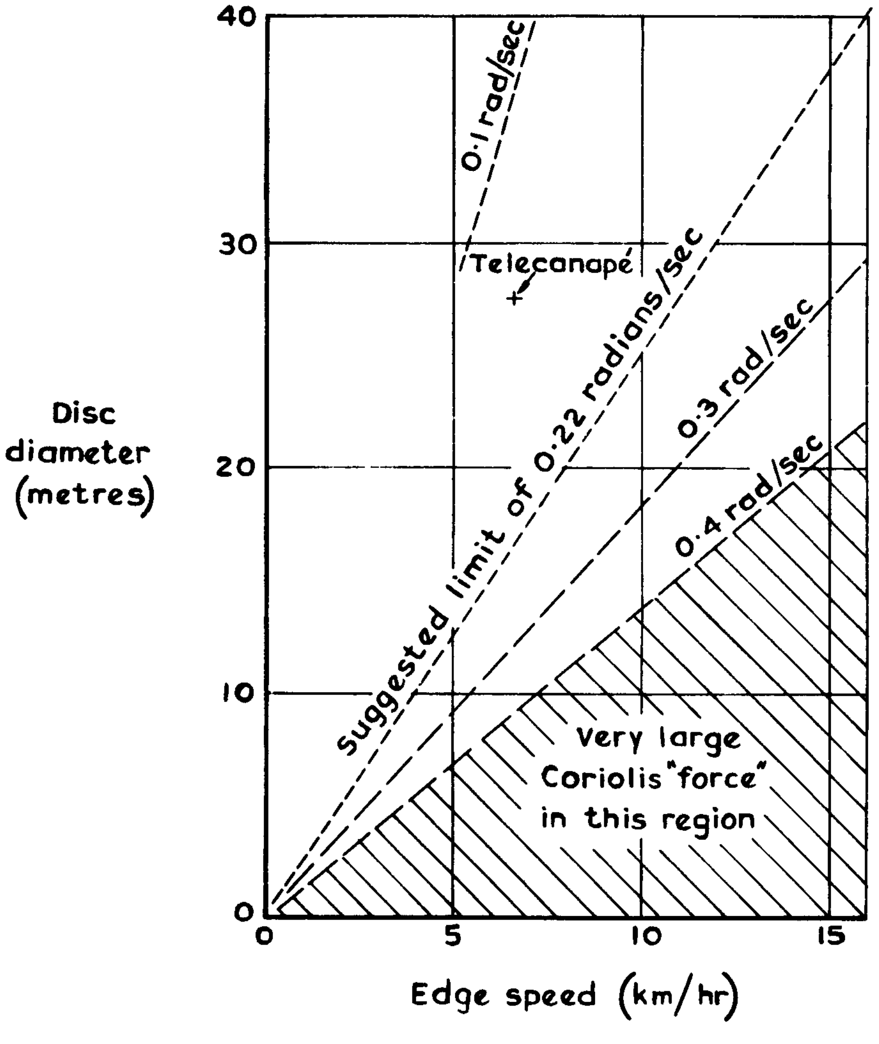


Fig. 12 Limitations to the size of rotating disc types of acceleration

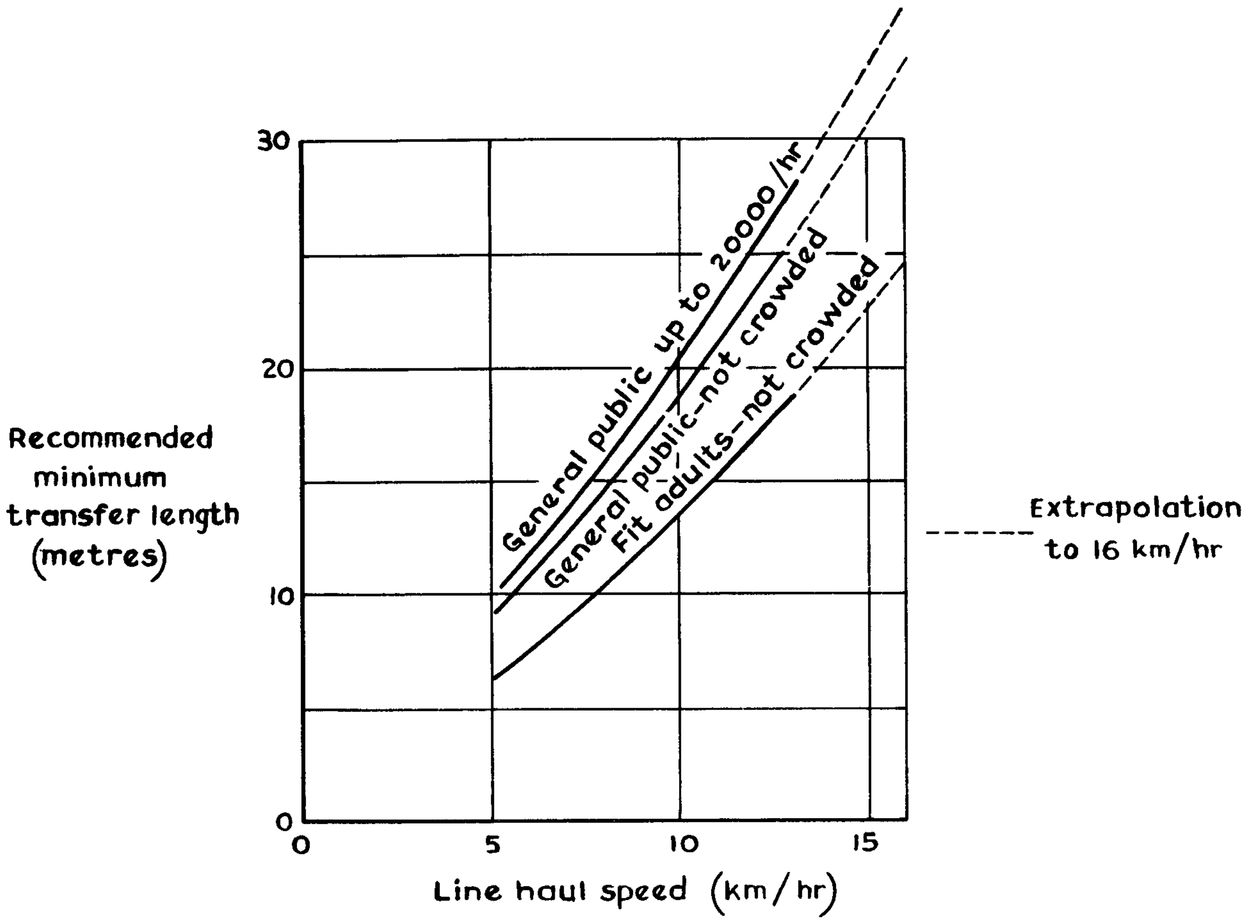


Fig. 13 Recommended minimum transfer length, one-way transfer, no speed differential

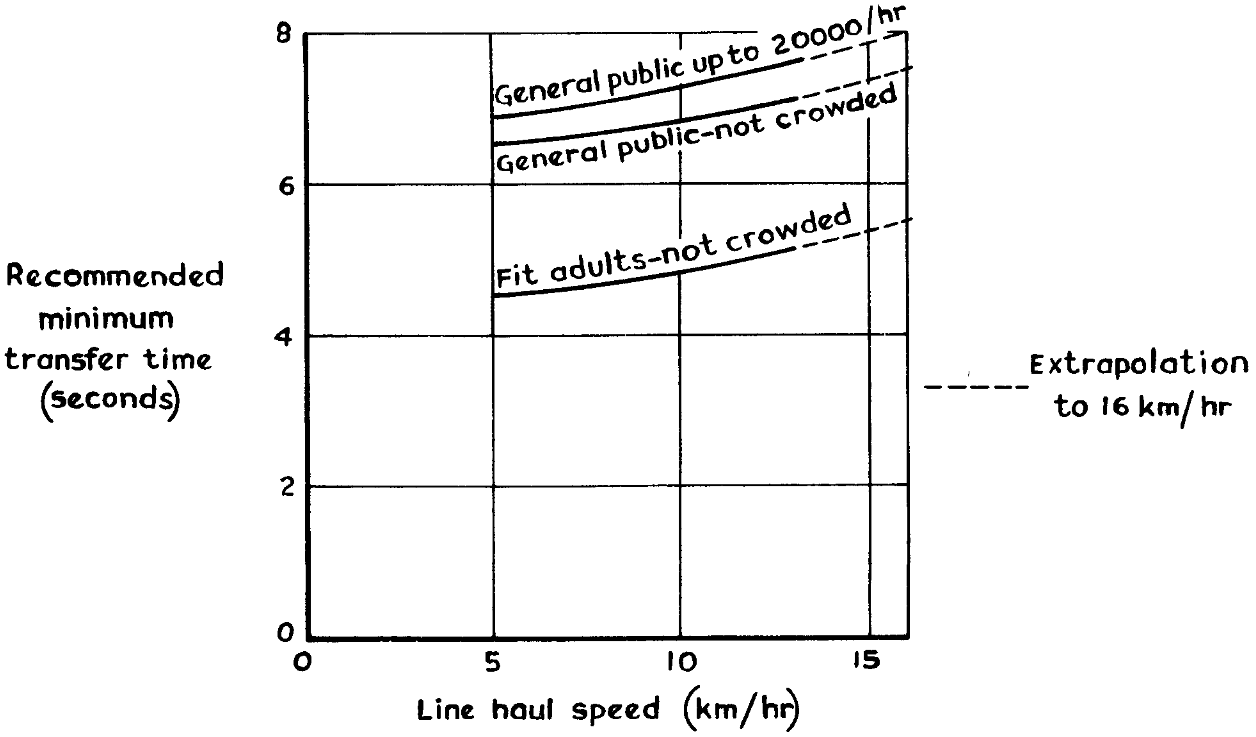


Fig. 14 Recommended minimum transfer time, one-way transfer, no speed differential

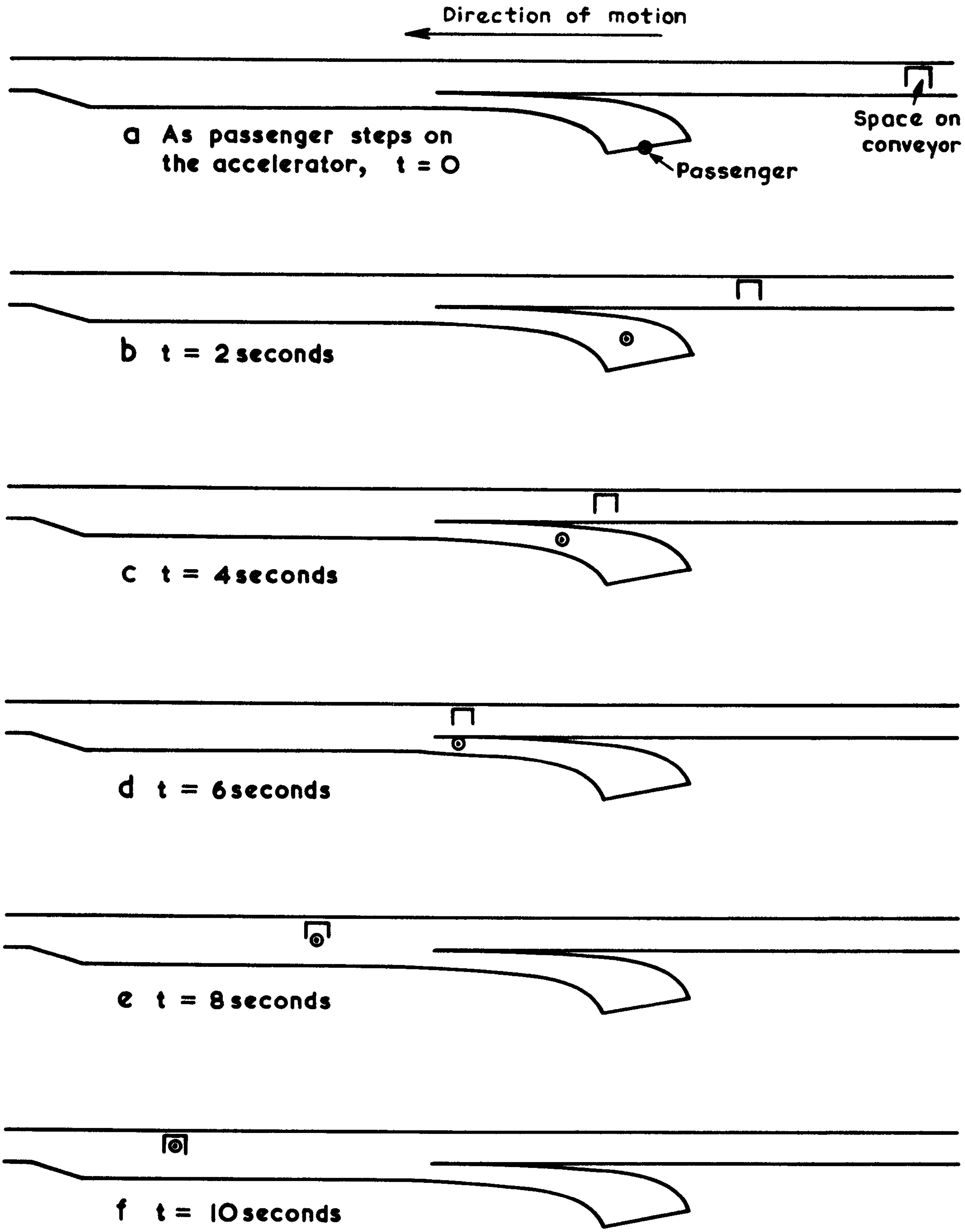
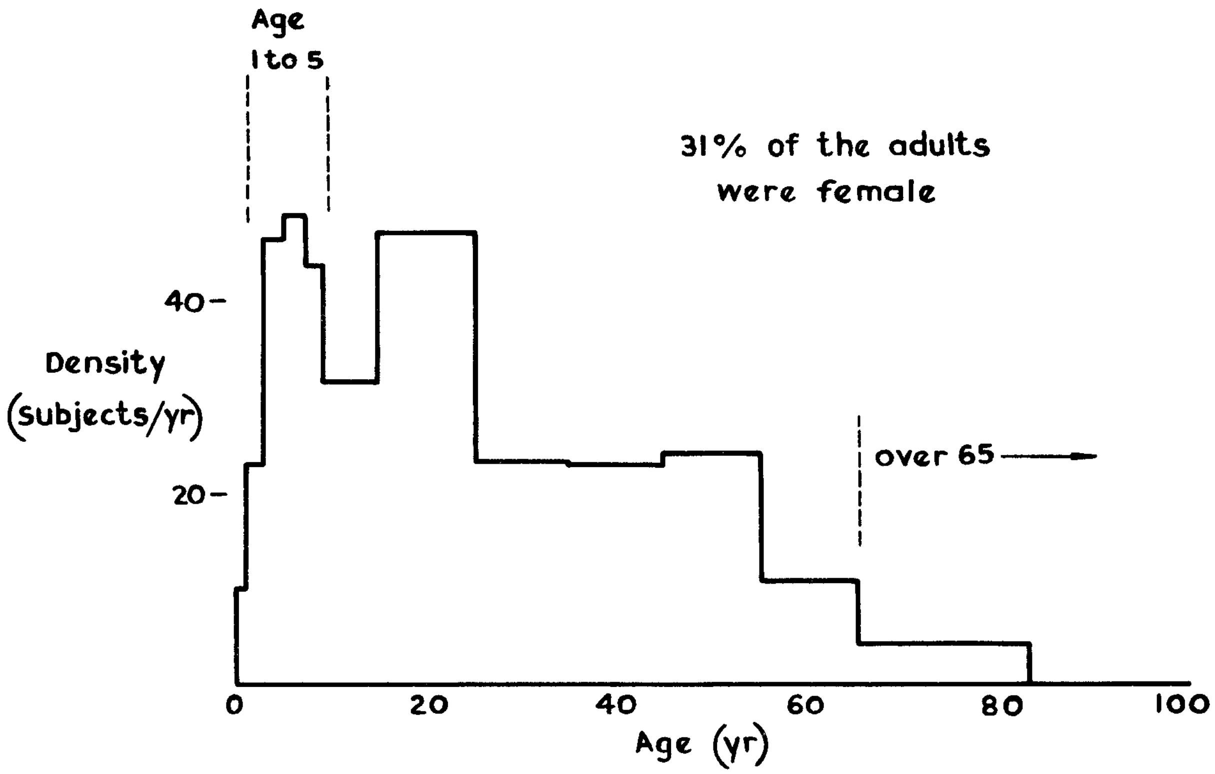
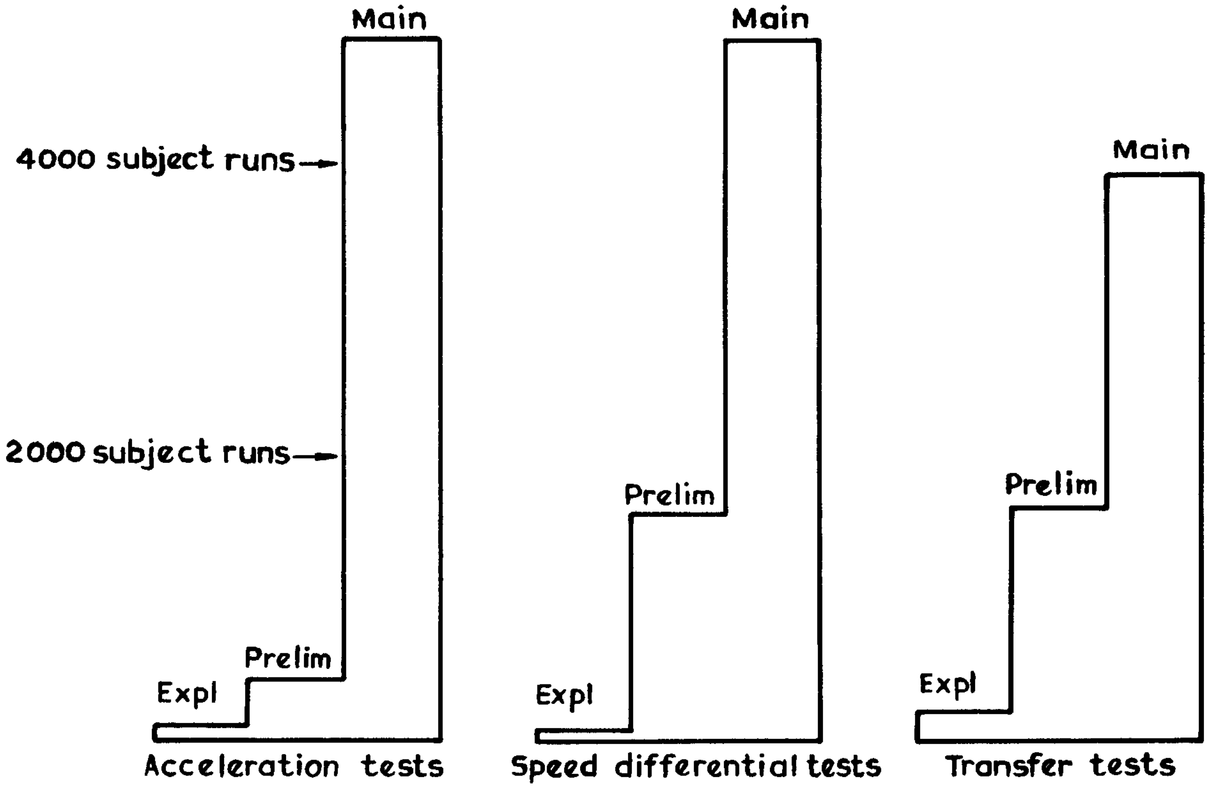


Fig.15a–f Matching of an unoccupied space on a conveyor with a passenger who does not walk

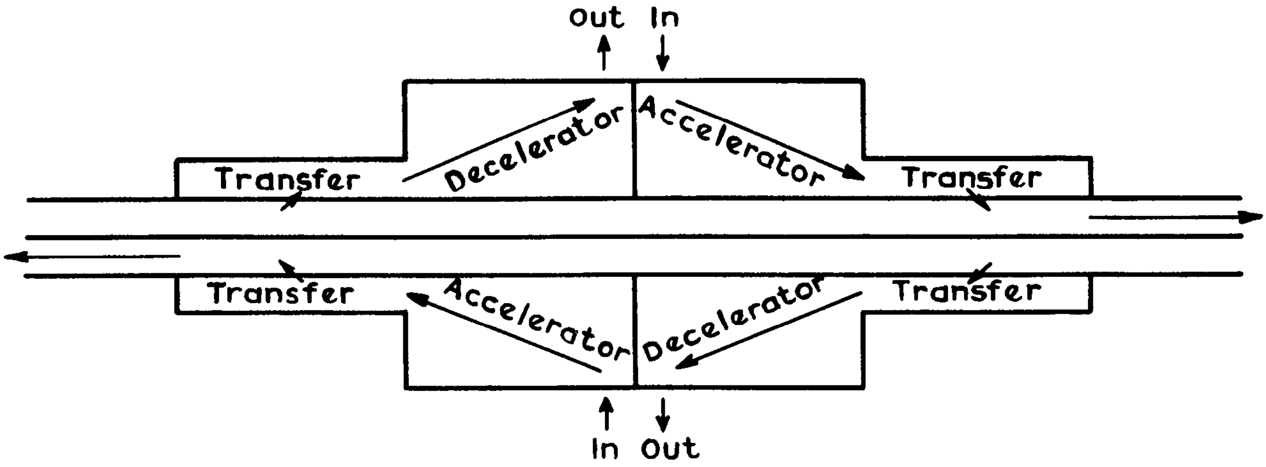


b Age distribution of the subjects

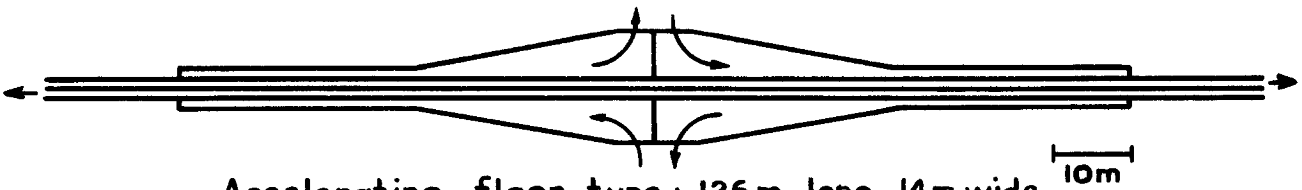


b Subject runs for exploratory, preliminary and main tests

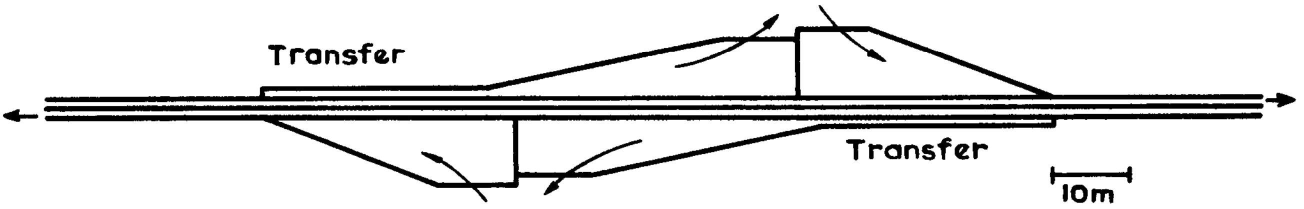
Fig. 16 a & b The scale of the laboratory tests



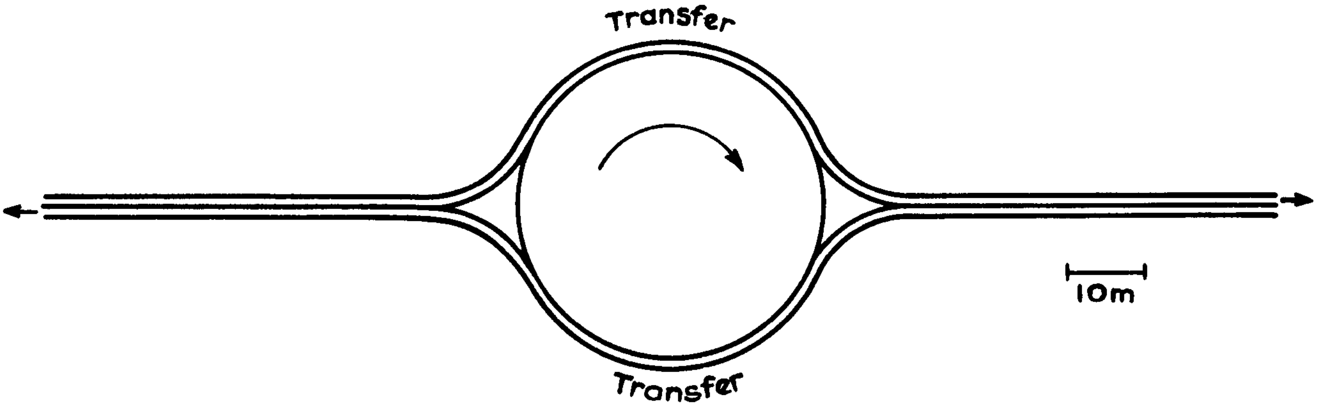
a A typical station layout—assumed for the purpose of comparison



Accelerating floor type: 126m long, 14m wide



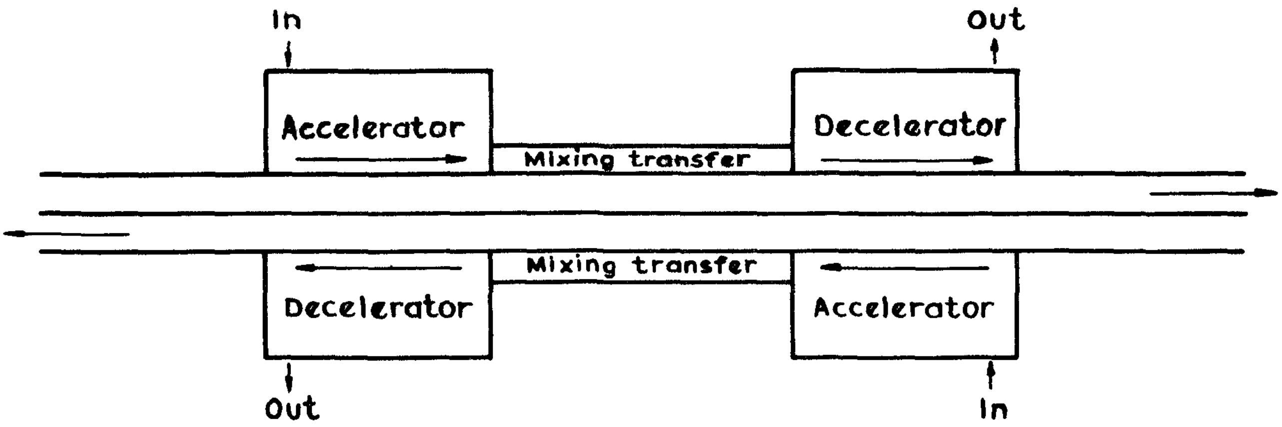
Speed differential type: 104m long, 18m wide



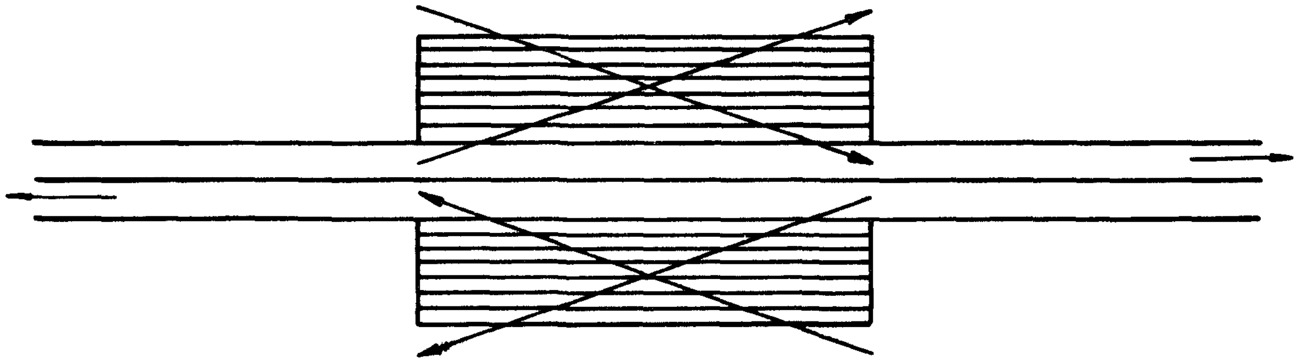
Rotating disc type: 65m long, 42m wide

b Comparison of stations

Fig. 17 a&b Comparison of estimated station sizes for different types of system



a Accelerating floor system using mixing transfer



b Speed differential system using one set of parallel surfaces for mixing transfer and simultaneous acceleration & deceleration

Fig.18 a&b Possible methods of reducing the station length

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Browning, A. C

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In addition to the application of existing data on human behaviour to the design of high speed pedestrian conveyors, three laboratory experiments were mounted to provide further data. For these experiments, a motion simulator was specially devised which was in the form of a wooden trolley towed by a battery electric tractor. The trolley was used (i) by itself to simulate an accelerating floor, (ii) alongside a fixed platform at the same height to simulate a pair of parallel surfaces moving at different speeds and (iii) in conjunction with hanging 'posts' to simulate the point of passenger transfer between accelerators or

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decelerators and conveyors. Approximately 1000 different persons took part in the tests as subjects, representing a wide variety of people and spanning an age range from 2 months to 85 years. Nearly 18000 subject-runs were made and films of many of these are available.

The laboratory experiments have provided new data which can help the engineer to choose appropriate accelerations, decelerations, speed differentials or transfer lengths. They have also highlighted some aspects of safety. Some additional recommendations on comfort and safety have been based on existing data and observation of people using escalators and slow-moving conveyors.

Attempts are made to estimate the length of the stations of real systems and the station lengths for various types of system are compared. Some suggestions are made on ways to reduce the station length.

This is a summary report, and represents the Final Report issued under contract to the Department of the Environment. It gives only an outline of the studies, the most important results and the recommendations made. Details, and the remainder of the results, are to be found in nine supporting papers, quoted as Refs.1-9.

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